An interdisciplinary study of the hazards associated with an AD1754 style eruption of Taal Volcano, Philippines

Perla J. Delos Reyes

A thesis
submitted in fulfilment
of the requirements for the degree
of

Doctor of Philosophy in Science

School of Geosciences
Faculty of Science
The University of Sydney

2019

Statement of Originality

This is to certify that this work has not been submitted for a higher degree or diploma at any other university or institution. To the best of my knowledge and belief, the thesis contains no materials written or published by any other person, except where acknowledgement is made in the thesis. All of my sources of information have been acknowledged in the reference list.

The research presented in this thesis was approved by the University of Sydney's Human Research Ethics Committee (Project Number 2014/560)

PERLA J. DELOS REYES 02 September 2019

Use of Pseudonyms

To protect confidentiality and anonymity, the names of the research participants referred to in this thesis are pseudonyms in code format.

... aging is not lost youth...but a new stage of opportunity and strength....

ACKNOWLEDGEMENTS

This thesis would not have been written, completed and submitted if not for the support, guidance, expertise and encouragement of great people and institutions. To them I am deeply indebted and grateful.

First and foremost, I would like to thank the Australian Government, the Department of Foreign Affairs and Trade (DFAT), through Australia Awards, for providing a Development Scholarship that supported my research. My thanks also go to the management and staff of the Philippines-Australia Human Resource and Organisational Development Facility (PAHRODF), headed by Ms. Milalin Javellana, for facilitating all administrative arrangements that supported my candidature.

I will forever be indebted to my two supervisors, Professor Dale Dominey-Howes and Dr. Christina Magill. To Dale for his patience, tenacity, guidance, care, and tireless mentoring and encouragement so that I can complete this thesis amidst the many emotional and physical challenges and trials I experienced. He wears many hats: kept me grounded, cracked the whip when needed, and a counsellor that cared for my health and wellbeing and lifted my spirit when I am stressed or experiencing low esteem. He is like a perfectly chosen gift that I was fortunate to have at the start and end of my postgraduate journey. Thank you Dale for believing in me. My deepest gratitude also goes to my co-supervisor Dr. Christina Magill, of Macquarie University, and formerly of Risk Frontiers, who provided not just her expertise in numerical modelling but also helped with editing and improving this thesis. She was another shoulder I was able to lean on during times of hardships. My deepest gratitude to her for taking time for me.

The staff of the International Office of The University of Sydney gave assistance throughout my stay in Sydney while doing my PhD studies. Likewise, the special people of the School of Geosciences under the leadership of Professor Phil McManus provided such great administrative support. Likewise, I will forever be grateful that at the tail end of my PhD research endeavour, Professor McManus and Professor Dominey-Howes painstaking worked hard for me to obtain the Faculty of Science International Fee Completion Scholarship that enabled me to enrol and submit my thesis. My thanks to our Postgraduate Coordinator, Associate Professor Derek Wyman, for his guidance and advise pertaining to administrative procedures in Higher Degree Research. To all the very supportive Administrative officers of Higher Degree Research who provided guidance and assistance especially near the end of my thesis.

To my Sydney Family, that mostly consisted of international and Filipino students and friends from the University of Sydney, the University of New South Wales, and the Macquarie University, thank you for providing company during my four years in Sydney, most especially my co-PhD scholars Yami, Eva, Trina and Faridah, my African sisters Isha, Evelina, Evelyn, Juliet, Unani and my dearly beloved and departed friend Martha, my dearest Malaysian Lander flatmate Zyuin, my room mates and Hazards Research Group Sarah, Matt, Tom, and most especially Annie who was my constant room companion during my last year at USyd, my co-students and professors at the School of Geosciences, and my former PHIVOLCS officemate and friend Canie and her family, thank you all for your precious friendships.

I also wish to thank the Provincial, City, Municipal and Barangay officials of the Province of Batangas who provided their invaluable assistance to my PhD research and provided data, insights and views about Taal, especially to the ten Barangay Captains, two of which had sadly passed away before the completion of my thesis, whom I have interviewed and shared opinions and ideas with, and to the residents who allowed me and my colleagues to invade their properties in order to map and sample the eruptive products of Taal.

To my Department of Science and Technology-Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS) Family headed by DOST Undersecretary and concurrent Officer-In-Charge of DOST-PHIVOLCS, Renato Solidum, Jr., and DOST-PHIVOLCS Deputy Director Bartolome Bautista, my heartfelt gratitude for providing endless financial and moral support throughout my PhD journey and for allowing me to go on study leave DOST-PHIVOLCS for four years. I will forever be grateful to the late Dr. Raymundo Punongbayan, my dearly departed first mentor and former Director of DOST-PHIVOLCS, for providing his legacy of hard work, integrity, drive to always do my best, tireless energy, love and loyalty to my Institute, and the push to further my education. Likewise, to all my other 'pseudo' mentors who have provided encouragement and advise when I needed them most.

To my dear friends and colleagues at DOST-PHIVOLCS who gave much of their time and company during the data gathering phase of my thesis and for supporting my thesis writing when I returned to the Philippines and my work after the completion of my Australia Awards scholarship. Special thanks to Danikko who took charge of the volcano section and more; to Rob and Abigail for field and GIS support, the Taal Volcano Observatory (TVO) staff Paolo Reniva, our TVO Resident Volcanologist, Jojo, Ric, Laurence and Allan for their logistical assistance and friendships while conducting my fieldwork; Dynie and Joan for field assistance; my Volcano Research Group (Danikko, Thessa, Cathy, Rob, Ericson, Raymond) who provided encouragements and who worked really hard to ensure that our section provides high quality accomplishments with minimal senior mentor guidance in my absence. To my dearest friends: Mariton for our endless valuable discussions on Taal and other issues and our after office food and massage trips; Myla for welcoming me into their home when I needed the break; Leyo, Marose, Charms, Jo, Marge and Kat- my additional morale boosters; Art for being considerate of my need to spare time for my thesis writing; Daniel for patiently reading through my final thesis drafts; and to the rest of my GGRDD colleagues for their continuing support at times I need it most; Trina for welcoming me and making my transfer to USyd easier; and Abigail, my long-standing field partner, dear friend and UNSW flatmate who made my first year in Sydney less lonely and bearable, my devil's advocate and pseudo-daughter - my heartfelt gratitude and love to all of you.

Lastly, I give this ultimate accomplishment to my family: my dearly departed *Mama* and *Papa*, and my siblings, their children and their partners, and families who were always there to support me and my children and their families, and most especially to my caring and loving children, *Katri-Karla* and *Jurro-Karlo*, dear daughter-in-law *Candy*, son-in-law *Gelo*, and lovely grandson *Kaell Cid*, baby in the womb grandson, *Gab,* my inspirations and support during my PhD journey. Without them my life would not have been complete and life would not be so beautiful.

To everyone, I give my heartfelt gratitude, eternal friendship and love.

ABSTRACT

Taal Volcano, located approximately 60 km south of Metro Manila in the province of Batangas, is one of the most active volcanoes in the Philippines. With 33 known eruptions, Taal has caused tremendous impacts on lives, property, the economy and environment. The exposure of people and assets on, and around Taal, has increased greatly in recent years with approximately two million people living within a 35 km radius – all at risk from various volcanic hazards. The significant risk from Taal poses multiple challenges for local volcano disaster risk reduction (DRR) efforts.

This interdisciplinary study combines a synthesis and critical review of historical eruptions of Taal; physical hazard investigations and analyses (geologic mapping, stratigraphic analyses and grain size measurements of the Plinian AD1754 tephra deposit); reconstruction of tephra dispersal for the AD1754 event using *TEPHRA2* inversion modelling; and consideration of the social aspects of volcanic hazard and risk related to Taal (e.g. socio-economic, political and DRR contexts for the Province of Batangas, and a pilot study assessing the knowledge, education, awareness and preparedness of Barangay Captains who are responsible for local level volcano disaster preparedness and response).

Key outputs of the research include: 1) the first single, comprehensive chronology of all identified historical eruptions of Taal; 2) the discovery, mapping and sampling of 41 suspected AD1754 tephra outcrops; 3) the first detailed field-based verification of two of the four identified phases of the AD1754 event; 4) determination of likely eruption source parameters for the AD1754 Plinian event and new tephra dispersal isopachs through inversion modelling; and 5) preliminary insights into the knowledge, awareness and preparedness of the Barangay Captains, which show that while they do take volcanic risk seriously, they are ill-prepared to effectively support their communities in the case of a major volcanic crisis at Taal. The results are used to make a series of recommendations towards strengthening volcano disaster risk management plans for the Province of Batangas.

ACRONYMS

ABC	Association of Barangay Captains, also known as "*Liga ng mga Barangay*"
AFP	Armed Forces of the Philippines
BDC	Barangay Development Councils, also known as BDRRMC
BDCC	Barangay Disaster Coordinating Councils
BDRRMC	Barangay Disaster Risk Reduction and Management Council
BFAR	Bureau of Fisheries and Aquatic Resources
CALABARZON	Cavite, Laguna, Batangas, Rizal and Quezon Region (Region IV-A)
CLUP	Comprehensive Land Use Plan
CMCI	Cities and Municipalities Competitiveness Index
COMVOL	Commission on Volcanology
DENR	Department of Environment and Natural Resources
DepEd	Department of Education
DILG	Department of the Interior and Local Government
DND	Department of National Defense
DOST-PAGASA	Department of Science and Technology-Philippine Atmospheric, Geophysical and Astronomical Services Administration
DOST-PHIVOLCS	Department of Science and Technology-Philippine Institute of Volcanology and Seismology
DPWH	Department of Public Works and Highways
DRM	Disaster Risk Management
DRR	Disaster risk reduction
DRRC	Disaster Risk Reduction Coordinator
DRRM	Disaster risk reduction and management

DRRM-CCA	Disaster Risk Reduction and Management and Climate Change Adaptation
DRRMC	Disaster Risk Reduction and Management Council
GMT	Generic Mapping Tools
GSO	General Services Office
GVP	Global Volcano Program
HREC	Human Resource Ethics Committee
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior
IDNDR	International Decade for Natural Disaster Reduction
LBMA	Luzon-Bataan-Mindoro Arc
LDRRMO	Local Disaster Risk Reduction and Management Office
LGU	Local government unit
MDRRMO	Municipal Disaster Risk Reduction Office
MIA-VITA	MItigate and Assess risk from Volcanic Impact on Terrain and human Activities
MLDPO	Modele Lagrangian de Dispersion des Particules
MSWDO	Municipal Social Welfare and Development Office
NCEP/NCAR	National Centers for Environmental Prediction/National Center for Atmospheric Research
NDCC	National Disaster Coordinating Council; former name of NDRRMC under the Department of National Defense
NDRRMC	National Disaster Risk Reduction and Management Council
NOAA/OAR/ESRL	National Oceanic and Atmospheric Administration/Office of Oceanic and Atmospheric Research/Earth System Research Laboratory
NTC	National Telecommunications Commission
PACD	Provincial Assistance for Community Development
PAWD	Parks and Wildlife Bureau
PCDO	Provincial Cooperative Development Office

PDRRCMC	Province Disaster Risk Reduction and Crises Management Council
PDRRMO	Province Disaster Risk Reduction and Management Office
PDZ	Permanent Danger Zone
PEZA	Philippine Economic Zones Authority
PFZ	Philippine Fault Zone
PGENRO	Provincial Government Environment and Natural Resources Office
DOST-PHIVOLCS	Philippine Institute of Volcanology and Seismology under the Department of Science and Technology (DOST)
PIO	Provincial Information Office
PNP	Philippine National Police
PPA	Philippine Ports Authority
PPDO	Provincial Planning and Development Office
PRC	Philippine Red Cross
PSA	Philippine Statistics Authority
PSWDO	Provincial Social Welfare and Development Office
RA	Republic Act
RMSE	Root mean square error
TVI	Taal Volcano Island
UNISDR	United Nations International Strategy for Disaster Reduction
UP-SURP	University of the Philippines School of Urban and Regional Planning
VAAC	Volcanic Ash Advisory Centre
VAFTAD	Volcanic Ash Forecast Transport And Dispersion
VEI	Volcanic Explosivity Index

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Appendices

CHAPTER 1
Thesis Overview

1.0 Introduction

When I first started to consider what I wanted to do for my dissertation, I knew I wanted to conduct research that not only provides new geological information about past eruptions of Taal Volcano, but which also provides information to underpin improved understanding of the human context in which the new scientific information might be applied. Being a geologist by profession, I used to think that avoidance was the best approach to the prevention of disasters associated with hazards such as volcanic eruptions. This was because traditionally, my interaction with communities living on and around volcanoes was related to my participation in volcano hazard information, awareness and preparedness campaigns and as a facilitator in workshops conducted around the Philippines by my employer - the Philippine Institute of Volcanology and Seismology of the Department of Science and Technology (PHIVOLCS-DOST). However, Filipino volcanologists like myself are increasingly required to assist in managing the impacts of volcanic hazards, as well as addressing the concerns of people living near or around volcanoes.

In general, most volcano-related studies conducted in the Philippines to date have mainly concentrated on hazard mapping and assessment (Pratt, 1911; Moore et al., 1966; Wolfe, 1986; Geronimo, 1988; Janda et al., 1996; Paladio-Melosantos et. al., 1996; Scott et al., 1996; Martinez & Williams, 1999; Behncke, 2009; Jenkins et al., 2013) although a few have focused on volcanic risk assessment and management (Johnston et al., 2000; Chester et al., 2002; MIA-VITA, 2012). A holistic approach to volcanic risk reduction has been undertaken for one volcano - Kanlaon - that combined geologic information with an effective monitoring network and a structured framework for managing volcanic risk that involved participation of communities through communication and consultations (MIA-VITA, 2012). However, monitoring and review of the effectiveness of that framework has not yet been tested via an actual volcanic crisis.

Taal Volcano (Figure 1.1) is one of the most active volcanoes in the Philippines and was one of the 16 Decade Volcanoes selected by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Sub-Commission in 1995. Taal is located in Batangas Province (and is adjacent to three other provinces) in southern Luzon and lies just 60 km south of Metro Manila. Taal covers an area of 23 km^2 and despite its explosive nature, no comprehensive risk assessment and management study for Taal has been undertaken. In the event of a catastrophic eruption similar to the AD1754, how will the communities around Taal Volcano cope and what measures are in place? A major eruption at Taal today would expose more than two million people within a 35 km radius to various volcanic hazards. The increasing population and expanding economic activity in the province pose significant challenges for local volcano disaster risk reduction (DRR) efforts. Consequently, I chose Taal Volcano as the case study for my PhD.

1.1 Significance of the research and my motivation

As a mature-aged, senior geologist working for PHIVOLCS-DOST, part of my role requires me to understand why people living close to volcanoes continue to stay even

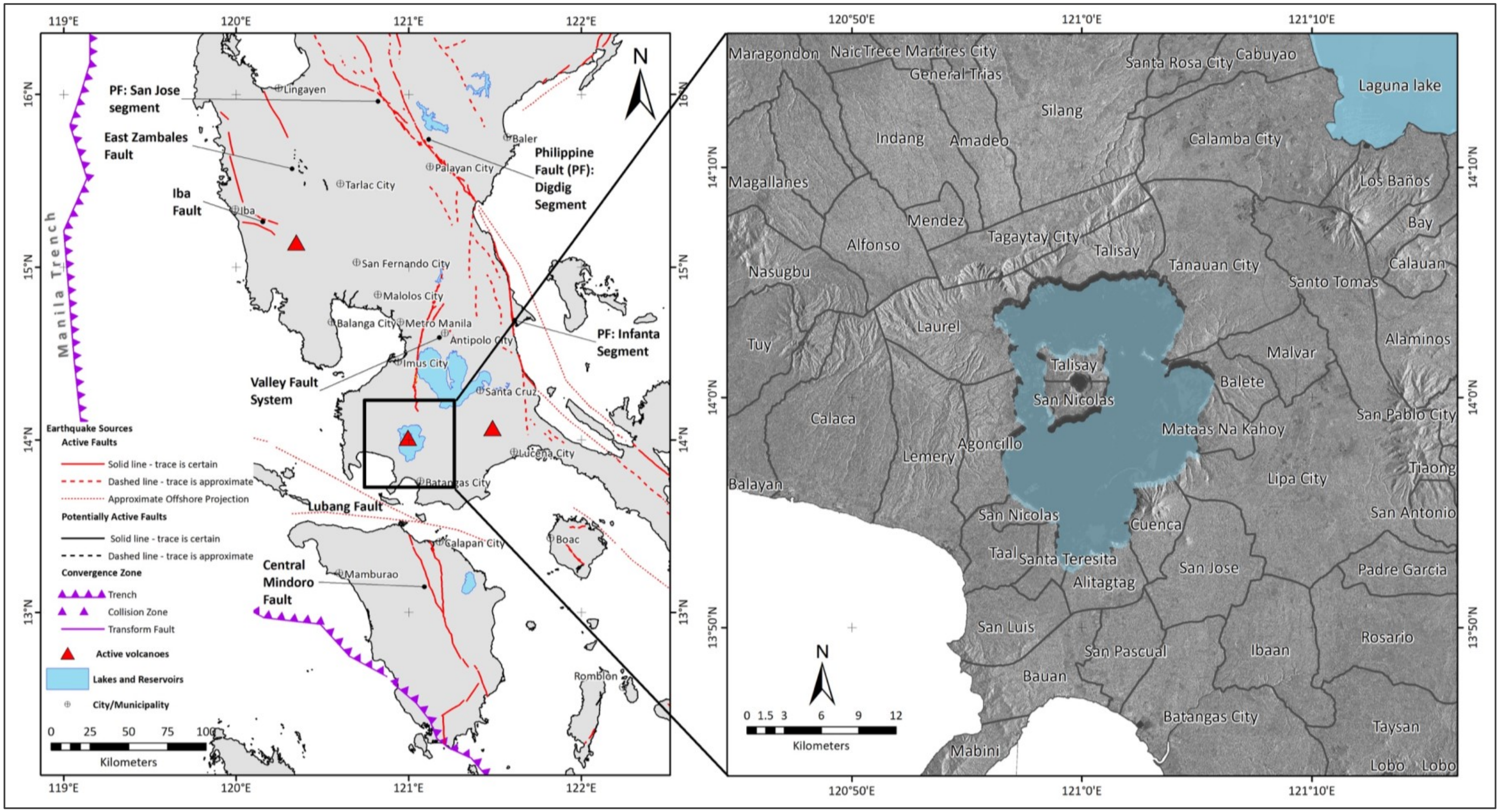


Figure 1.1. A) Regional tectonic and local setting of Taal Volcano. Location of Taal Volcano Island (TVI) identified by the black box. B) Taal is within the provincial jurisdiction of the Province of Batangas. Gray lines delineate municipal/city boundaries. TVI is located in the centre surrounded by Taal Lake. Base map is from the National Mapping and Resource Information Authority (NAMRIA) Interferometric Synthetic Aperture Radar (IfSAR) -Orthographic Rectified Image (ORI), 2013.

when faced with the constant threat of eruption. Consequently, I chose to pursue research that combines elements of more classical geological work (e.g., historical and archive analysis, field mapping and laboratory analysis and numerical modelling) with aspects of the emerging field of 'social volcanology' (Donovan, 2010; Donovan et al., 2012a; Donovan et al., 2012b; Donovan & Oppenheimer, 2015; Haynes et al., 2008; Lavigne, 2008). My 'social volcanology' research involved undertaking interviews with one critical stakeholder group – Barangay Captains who are the local elected representatives whose role is to undertake local level disaster planning, preparedness and response activities - to better understand their knowledge, education, training, awareness and preparedness and how these factors might impact on their behaviour and response in the event of a volcanic crisis).

Why choose Taal for this interdisciplinary research? Having worked for PHIVOLCS-DOST for more than 30 years, and gaining considerable experience in the field, I have had very meaningful sharing of the life and livelihood of communities living near active volcanoes. Taal is one of the most active with 33 identified eruptions, four of which are considered catastrophic (e.g. AD1749, AD1754, AD1911 and AD1965) resulting in tremendous impacts on lives, property, the economy and environment. Figure 1.2A provides an aerial view of Taal Volcano Island (TVI) with three of the major eruption centers identified: Main Crater located in the center of TVI, Binintiang Malaki located northwest, and Mt. Tabaro located in the southwest portion of TVI. Figure 1.2B shows the tephra fallout impacts of the AD1965 eruption of Taal with reported tephra thicknesses from 20 to 50 cm with tephra dispersed as far as 60 km from the eruptive

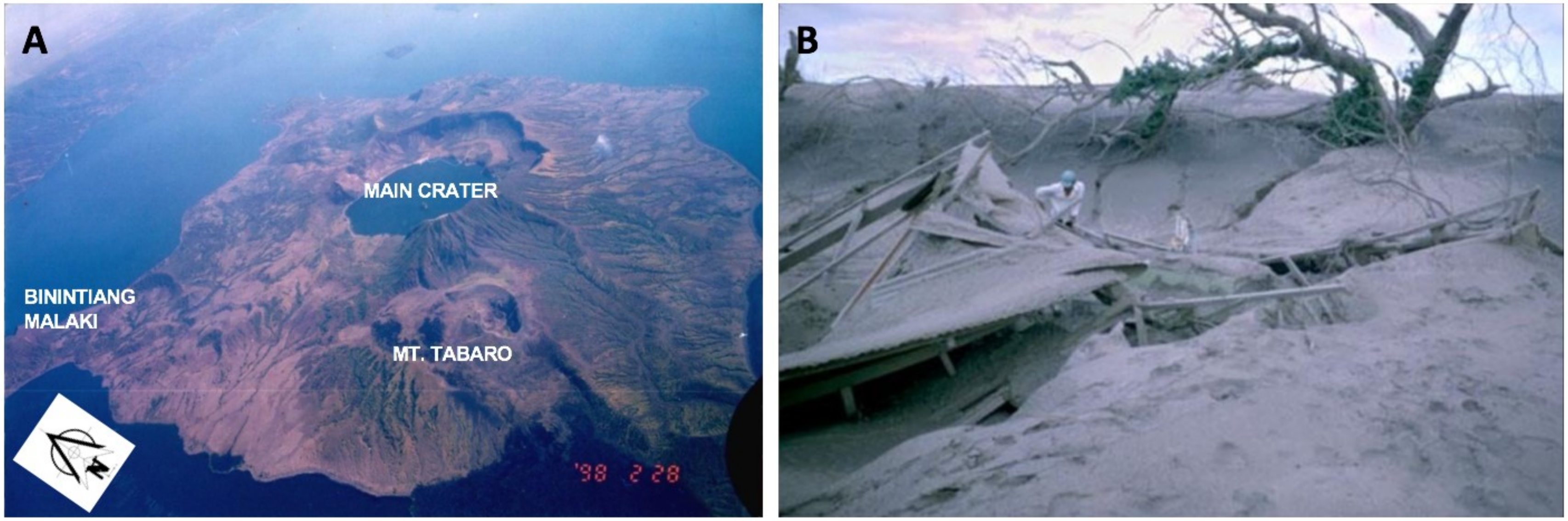


Figure 1.2. Location and impacts of the eruptions of Taal Volcano. A) Aerial view of TVI, surrounded by Taal Lake. The Main Crater, Binintiang Malaki and Mt. Tabaro are some of the major eruption centers during the past historical eruptions of Taal. B) Tephra fallout impacts of the AD1965 eruption at TVI with estimated tephra thicknesses ranging from 20 to 50 cm and dispersal to more than 60 km from the vent. Photo source: DOST-PHIVOLCS.

vent. The entire TVI was affected by tephra fallout, as well as municipalities of Batangas Province located in the south and southwest portion of the mainland.

One of the most explosive and destructive eruptions of Taal occurred in AD1754 and was described by Saderra Masó (1911, p. 9) as "*the greatest recorded in the history of Taal Volcano*". The more recent AD1965 eruption generated a 20,000 m eruption column that was dispersed up to 80 km away (PHIVOLCS-DOST, 1991), resulting in the death of around 200 people, most of whom drowned while evacuating TVI.

Since the AD1965 eruption, population and urbanisation has grown substantially on TVI and within the surrounding areas. The study conducted by Saquilon & de Guzman (2005) at TVI estimated the population count at TVI to be 5,666 and calculated annual growth rate of 1.6%. Unfortunately, no other attempt was made to count the total population of TVI inhabitants and is now being presumed to be more than 6,000. The residents of various sitios at TVI are split up to different barangays in the Municipalities of Talisay at San Nicolas in the mainland, and the population of these '*sitios*' or '*puroks*' are subsumed to the barangays they are officially a part of. *Barangays*, formerly known as barrios, the smallest administrative division in the Philippine governance structure, are defined in the Republic Act 7160 (known as the Local Government Code of the Philippines (DILG, 1991, p. 158) as the "*primary planning and implementing unit of government policies, plans, programs, projects, and activities in the community, and as a forum wherein the collective views of the people may be expressed, crystallized and considered, and where disputes may be amicably settled*". Sitios or puroks are political subdivisions of a barangay. *Barangay Captains*, popularly known in Philippine communities as "*Kapitan*" or "*Punong Barangay*", are the elected head of the Barangay government (DILG, 1991). With increasing population at TVI since the AD1965 eruption, it can be presumed that a considerable number of the contemporary residents actually living on TVI and its surrounding regions have no direct experience with an eruption which would act as a limiting factor to hazard awareness and preparedness.

Important to effective volcano DRR is how scientific information is communicated to, received and processed by, and enacted by communities and responsible actors (e.g., local area disaster managers) living near an active volcano (Cronin & Cashman, 2008; Doyle et al., 2011; Donovan et al., 2012a; Donovan et al., 2012b; Doyle et al., 2014a; Greene et al., 1981). As such, analysis of the social, cultural, political and institutional factors that influence people's behaviour and action towards volcanic risk and DRR activities are a vital element in ensuring DRR efforts are appropriate and sustainable. Whilst acknowledging that undertaking an interdisciplinary volcanic risk assessment and management study will be very challenging (and would result in a particularly large thesis), I consider the effort well worth while so that in my own way, I can make a small contribution towards ensuring the safety of communities living on and around Taal in the event of a future eruption.

I set out to gather as much information as possible about Taal and its surrounding environment and people. Whilst PHIVOLCS-DOST knows about the devastation wrought by past eruptions and has publicly shared that information, communities continue to live on and around Taal. It does not seem to matter to local communities that TVI is designated by PHIVOLCS-DOST as a Permanent Danger Zone (PDZ) (DOST-PHIVOLCS, 2008) and that DOST-PHIVOLCS recommends that there should be no permanent habitation at TVI. Consequently, the need to provide early warning places a significant responsibility on DOST-PHIVOLCS and was the driving force for the establishment of a volcano monitoring system at Taal. Residents of TVI are constituents of two municipalities - Talisay and San Nicolas (Figure 1.1B) which means that volcano-related warnings need to be relayed to two local government bodies. PHIVOLCS-DOST employs various techniques to monitor Taal and have identified potential eruption centers within TVI. However, understanding when and how extensive the impacts of an explosive eruption may be needs to be further studied using narrative accounts of historical eruptions combined with field mapping of past eruptive deposits. There is a need for a comprehensive and critical review of published and unpublished references describing the 33 known historical eruptions. This undertaking aimed to elucidate new information about past eruptive behaviour, processes, and products. No tephra fallout hazard maps have been generated for Taal and this in turn resulted in the Taal communities not including disaster risk reduction (DRR) measures for this hazard in their plans. The tephra modelling results can provide predictive scenario-based results that can identify potentially threatened communities in the event of an AD1754 style eruption. Following on from such fundamental work, questions arise about how communities on and around Taal will react when faced with an eruption. What preparedness measures are in place and how will they be implemented?

Even with increased understanding of volcanic hazards and with corresponding mitigation measures, physical scientists like me are now realising the importance of a people-centered treatment of hazards and risk. This is essential to generating more effective and sustainable hazard and risk reduction and management strategies and policies (Paton et al., 2008). Going beyond scientific knowledge, Donovan et al. (2012a, p. 677) emphasised that with increasing demand for risk assessment and management, there is a need for *"new, integrated methodologies for knowledge* *collection that transcend scientific disciplinary boundaries"*. Interdisciplinary approaches to volcano risk assessment and management are now being widely used (e.g. Ambae Island, Vanuatu by Cronin et al. (2004); Merapi in Indonesia by Donovan et al. (2012b) and Jenkins et al. (2013); Tristan da Cunha in South Atlantic by Hicks et al. (2014), to name a few). This PhD dissertation seeks to contribute to that growing body of work.

1.2 Taking a hazard and risk assessment and management approach

In taking an interdisciplinary approach to hazard and risk assessment and management, this thesis combines investigation and analyses of some of the physical and social aspects of Taal and its associated communities. Specifically, in relation to the physical aspects, it synthesises and reviews the historical eruptions of Taal, conducts geologic mapping and laboratory processing of eruptive deposits, and completes numerical modelling. In relation to the social context, the thesis explores the socio-economic, political and DRR contexts for the Province of Batangas and undertakes a pilot study (later referred to as a 'vignette analysis' in Chapter 2, Chapter 3 and Chapter 7) of the knowledge, education, awareness and preparedness of ten elected Barangay Captains living at various locations on and around Taal. This represents a first in the Philippines as Barangay Captains are at the center of preparing for, and responding to, volcanic crises and keeping their communities safe.

To guide my approach, I utilised a globally accepted risk assessment and management framework and used this to design a research flow process (UNISDR, 2015) (Figure 1.3). Analysis involved a synthesis and critical review of the eruptive history of Taal (including eruption processes and products) gathered from original and translated Spanish clerical reports, reports of Spanish and American scientists, government workers and recent scientific studies. This provides the first, single, comprehensive chronology of all identified historical eruptions of Taal. Next, I conducted geological mapping and stratigraphic analysis of the suspected AD1754 eruption deposits. Both field information on location and thicknesses of tephra deposits, and the subsequent bulk density tests and grain size analyses provide input parameters for tephra modelling.

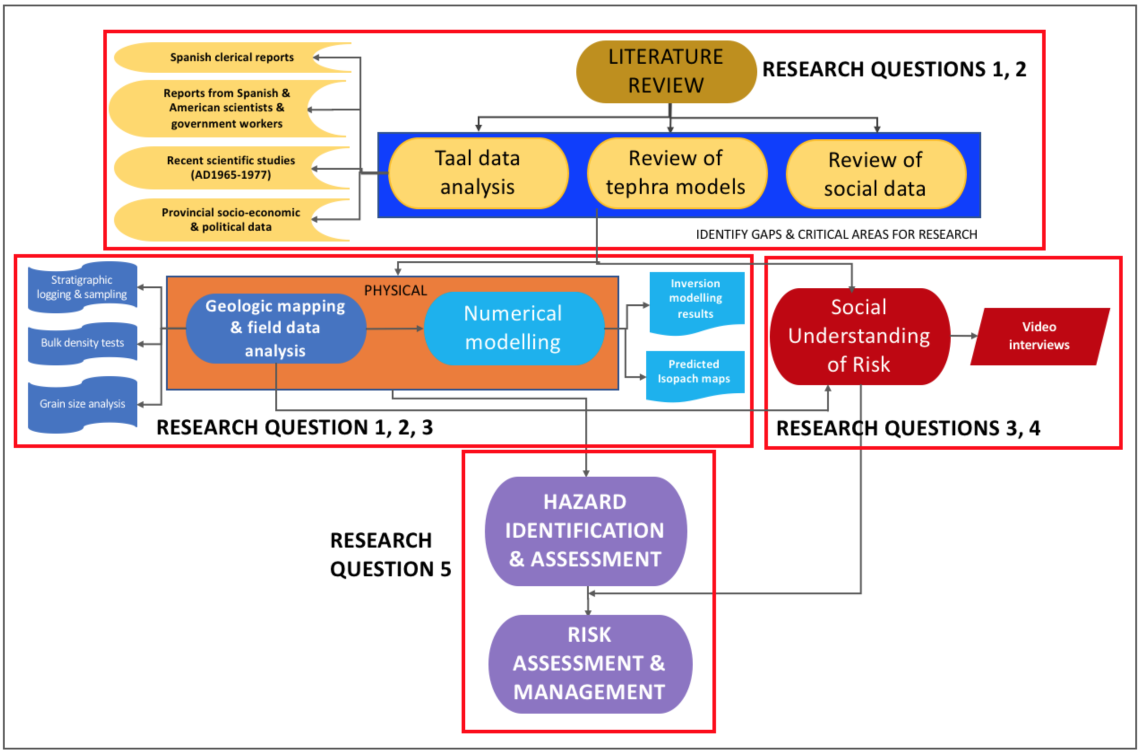


Figure 1.3. Research process flow for the interdisciplinary research conducted at Taal.

A review of tephra models is undertaken to provide understanding of the application of these models - especially *TEPHRA2*. I utilise *TEPHRA2* as the tool for simulating and obtaining best fit results that would reconstruct the dispersion of tephra during an AD1754-type eruption. By obtaining best fit modelling results, data gaps on eruption source parameters are obtained and are used as modelling input parameters for future probabilistic volcanic hazard and risk assessment. The dispersion direction and impacts gained from the review of eruption accounts, the geologic mapping and the tephra modelling results then serve as inputs to the selection of participants for the pilot (vignette) study of the knowledge, education, awareness and preparedness of Barangay Captains. The scenario-based tephra modelling results are used to identify which communities are likely to be affected following a particular scenario, in this case an AD1754-type eruption.

To aid the generation of a questionnaire to guide structured interviews with Barangay Captains, I review selected literature contributing to the emerging field of 'social volcanology' (Barberi et al., 2008; Bird, 2009, 2010; Cashman & Cronin, 2008; Dominey-Howes & Minos-Minopoulos, 2004; Donovan, 2010; Greene et al., 1981; Gregg et al., 2004; Haynes et al., 2008; Johnston et al., 1999; Njome et al., 2010; Ricci et al., 2013). The review seeks, amongst other things, to understand the socio-cultural, political, economic, religious, institutional and decision-making contexts that shape human knowledge, behaviour and action/inaction in relation to disaster risk reduction (DRR). Specifically, I focus on the roles, functions and knowledge of community leaders responsible for managing volcanic emergencies.

1.3 Location of my research and my positionality

I 'locate' my research within the risk assessment framework designed in the Handbook for Volcanic Risk Management under the MIA-VITA Project (2012) where PHIVOLCS-DOST was a key player. Figure 1.4 illustrates the methodological framework designed for managing volcanic risk (MIA-VITA, 2012) that I have modified to show where my research and each key research activity fit. The numbers (in red font) assigned to each flowchart action indicates where my research activities are located: (1) synthesis and review of literature on the different aspects of my interdisciplinary research; (2) geologic mapping and laboratory analysis of samples; (3) inversion modelling of tephra dispersal for the AD1754 event; and (4) qualitative social survey research related to volcanic risk.

Comparing this with the National Emergency Risk Assessment Guidelines (NERAG) structure for undertaking assessment and management of risk related to emergency situations (AIDR, 2010), I found that all essential elements within the said structure and methodological framework for managing volcanic hazards and risk that I applied for my research are similar in scope and methodology. I have established the essential components of risk assessment and management as identified in NERAG: 1) provided the context of my research (e.g. scope, objectives, key elements of my research, identified the stakeholders, and conducted knowledge gathering including the review of eruption history of Taal); 2) identified existing hazards and risks in my study area, conducted data gathering, and analysed and evaluated the hazards and risk information; 3) monitoring and review of effectiveness will be future work after my thesis recommendations are considered; and 4) continuous communication and consultation with stakeholders, keeping in mind our goal to provide a sustainable and effective DRR strategy to address volcanic emergencies. In the context of international and global approaches, I also tried to frame my research with the priorities for action of the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) that included: 1) understanding risk; 2) strengthening governance in the management of risk; 3) investing in DRR for resilience; and 4) enhancing disaster preparedness. The same goals and objectives are presented in my research. It is my hope that with the results gathered from my thesis and the recommendations I present at the end, Priorities 3 and 4 can be achieved so that the communities around Taal

Volcano can be safe from and resilient to volcanic eruptions and other related hazards and risks.

Much of the scope of my research work took on a pragmatic approach in that, ontologically, I wanted my research to make a difference, focusing more on usefulness and not theory (Donovan, 2019). However, I have adopted a critical realism perspective, where I have analysed primary and secondary data that I have interpreted critically. Whilst my ontological perspective involves a mix of critical realism and pragmatic approaches that help guide the way in which I ask my questions, my epistemological perspective is likewise mixed. The geological mapping aspect of my research involved interpretivism (e.g. identification of the AD1754 deposits, spatial correlation of outcrops etc.) while measurements of thicknesses was generally quantitative. My numerical modelling was likewise quantitative. My vignette social research covered phenomenological and critical realism epistemological approaches using mixed methods and discourse analysis. In essence, my interdisciplinary study utilised a mixed ontology, mixed epistemological and mixed methodology approach.

Likewise, I would like to express my positionality in my research. As I interview my respondents, I face them first and foremost as a PhD student trying to seek answers to my questions. However, as a long-time government employee and geologist who has experienced numerous volcano and earthquake related crises, I have views and experiences that influence my interpretations of my interviewees. My being a woman and a Filipino is both a strength and an opportunity because as a woman, it was easy for me to gain the trust and confidence of my interviewees. More often than not, at home and even in disaster situations, women generally play the role of care taker and are deemed more capable of handling stress and emotional and physical pain (Gokhale, 2008). As a Filipino, I speak the language that my respondents are comfortable with and while I was following a structured questionnaire as guide, I was able to maintain a conversational interview that put them at ease.

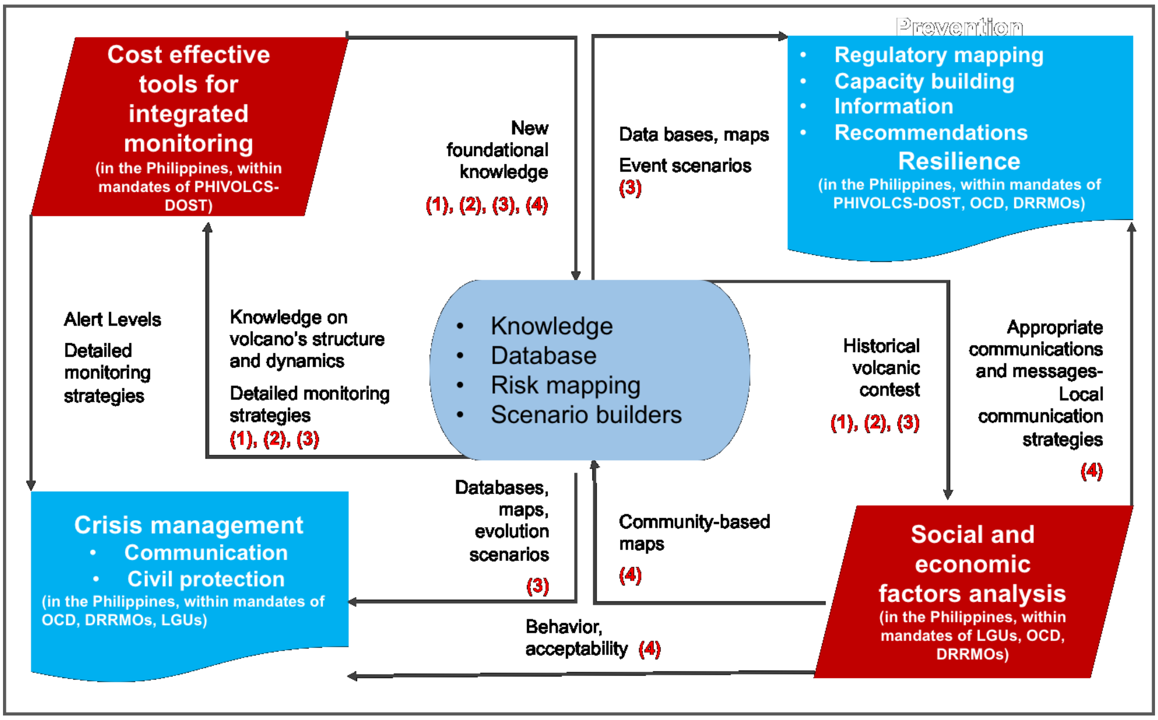


Figure 1.4. Methodological framework with related information flows for managing volcanic threat modified from MIA-VITA (2012). Numbers in red assigned in each flowchart action indicate the locationality of my interdisciplinary research activities to each dimension of risk assessment and management: (1) literature review; (2) geologic mapping and laboratory analysis of samples; (3) numerical modelling of tephra dispersal; and (4) vignette qualitative study of the knowledge, education, awareness and preparedness.

However, my being culturally linked to my respondents, plus the fact that I work for the government, also presents challenges. Have my respondents been honest in their responses or would they have reacted differently if a non-government and non-Filipino interviewer was asking the same questions? In reality, they could be hesitant to tell me issues and problems because they fear that any criticism they describe might reach the authorities they are criticizing. On my part, in exploring their experiences, I struggled to be critical of my fellow Filipinos. In the end, I hope I am able to balance both strengths and challenges so as to undertake a meaningful assessment of the knowledge, education, awareness and preparedness of the Barangay Captains that will serve to provide preliminary insights that may be expanded upon in the future.

1.4 Research questions

My key research questions are as follows:

1. What do we know, and not know, about the eruptions of Taal Volcano? What can a collation, synthesis and reinterpretation of information tell us about the record of past eruptions at Taal, their processes, products and hazards?

2. What is the expected distribution of tephra deposits in the event of an explosive eruption such as the AD1754 Plinian/Sub-Plinian eruption of Taal?

3. How would a major/plinian eruption affect communities around Taal?

4. Given that the Barangay Captains and their communities are located on or close to Taal, and as the key stakeholder in the community, how are the Barangay Captains responding to volcanic risk? What is the level of education, knowledge, experience, risk perception and preparedness of these specific stakeholders?
5. How can the key results obtained from this interdisciplinary study be utilised for developing or strengthening disaster risk management plans of the province?

1.5 Thesis outline

Chapter 1 provides a short overview of the entire thesis. Chapter 2 presents and reviews the relevant literature and sequentially focuses on: 1) historical review of narrative accounts of the 33 identified historical eruptions of Taal in order to extract details and provide new interpretations on eruption styles, processes and products, as well as evaluate sources for confirmation of eruptions and eruption characteristics; 2) description of the existing socio-economic, political and DRR structures that provides an overview for considering risk assessment and management, and disaster risk reduction and management (DRRM) structures of the province to better understand how communities around Taal deal with volcano emergencies; 3) description and review of various tephra models to determine usage and applicability, especially *TEHPRA2* which I have chosen to use; and 4) overview of social volcanology with a particular focus on risk perception. Chapter 3 provides a detailed description of the 'approach and methods' used in this thesis. Chapter 4 details the results and new interpretations gathered from the critical review of narrative descriptions of the historical eruptions of Taal. Further, from the narrative analysis, I gather information on the most affected and most threatened communities that serve to guide subsequent geologic mapping, tephra modelling and the selection of respondents for interview. Chapter 5 presents the results of the geological mapping and laboratory analysis conducted related to the inferred AD1754 tephra fallout deposits. These data are used as inputs for the subsequent tephra modelling. Chapter 6 details the results of the tephra modelling aimed at replicating a plinian/sub-plinian eruption such as the AD1754 event and reconstructing eruption source parameters for such an event. The results of the modelling affirm potential dispersal patterns and provides estimates of fallout thicknesses of a maximum expected event (Barberi et al., 1990) eruption scenario that will be used to identify threatened communities potentially exposed to tephra hazard. Chapter 7 presents the interview responses of Barangay Captains and details and discusses their knowledge, education, awareness and preparedness related to DRR during volcanic emergencies. This is explicitly presented as a 'vignette' case study – that is, a mini-study that seeks to provide base line information that act as an entry point to guide future research. Since time did not permit me to conduct a more comprehensive social study, the use of vignettes to explore perceptions, beliefs, attitudes and norm in the field of social science provides an appropriate approach. Finally, Chapter 8 integrates all research results and summarises the key findings in order to explicitly address key Research Question #5. Chapter 8 also identifies limitations of this study and identifies future research directions.

1.6 Explanation about prior published work arising from this thesis and text matching

Significant sections of Chapters 2 and 4 have been published in a major peer reviewed article in *Earth Science Reviews* as Delos Reyes et al. (2018) (Appendix A). Consequently, significant sections of text contained in Chapters 2 and Chapter 4 cross match text appearing in the article published in *Earth Science Reviews*. I acknowledge this here but do not see this as plagiarism since to write for *Earth Science Reviews* required writing in a clear and efficient style that was near impossible to completely rewrite for this thesis.

Further, to clarify, whilst the *Earth Science Reviews* publication has multiple authors (including my two supervisors and professional colleagues), here I state that the complete manuscript was written by me. Detailed and critical peer-reviews of the manuscript were completed by my co-authors, Ma. Antonia Bornas, my research supervisors Professor Dale Dominey-Howes and Dr. Christina Magill, and the Department of Science and Technology (DOST) Undersecretary and DOST-

PHIVOLCS Officer-In-Charge Renato Solidum, Jr.. Invaluable insights of the historical eruptions of Taal were provided by M.A. Bornas. Manuscript figures were designed by me and generated with the help of Abigail Pidlaoan, while the Summary Tables were compiled by me.

CHAPTER 2
Literature review

2.0 Introduction

This thesis takes a risk assessment and management approach for Taal (Figure 1.1). Risk is defined as "*the combination of the probability of an event and its negative consequences*" (UNISDR, 2009, p. 25) and is thus, both a mathematical probability of occurrence (e.g. 60% probability of a VEI 6 in the next 100 years) and the "consequence" (or impact/effects) of an eruption of a given (say VEI 6) eruption. Risk is inevitable when natural hazards are combined with physical, social, economic and environmental vulnerabilities. In practical terms, *risk assessment* involves the process of "*analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend*" (UNISDR, 2009, p. 26). Risk assessment can be further defined as a "*process of identification, estimation and evaluation*" (Kates and Kasperson, 1983, p. 7029). The United Nations International Strategy for Disaster Reduction (UNISDR) (2009) defines *risk management* as "*the systematic approach and practice of managing uncertainty to minimise potential harm and loss*" that includes administrative decisions, organisation, operational skills and capacities to implement policies and strategies for vulnerable communities.

This thesis takes an 'applied' approach to the research – that is, it is designed to generate information useful to underpinning the development of appropriate, effective and sustainable volcano DRR plans, policies and practices. Consequently, the research employs a risk assessment and management framework that comprises several multidisciplinary steps. It is therefore, extensive and ambitious in scope. In undertaking the risk assessment, a number of critical questions are asked to understand and evaluate the risk (e.g. how often and how big have past eruptions been; what have been the impacts and effects of these past eruptions; how do Taal community leaders perceive an eruption would impact their lives and communities; what is the process of disaster preparedness/risk reduction of communities around Taal; what is the level of knowledge and awareness of community leaders to volcanic hazards generated by Taal and what are the preparedness measures of communities?).

To follow this approach and address these questions, first, I examine the geographic setting of Taal, review information about the provincial setting, explore the character of Batangas Province and summarise the socio-economic and governance structures. This is undertaken in order to relate local government information to issues like volcanic hazard awareness, risk perception, and preparedness of communities. Socially-oriented research for this thesis focused on one specific stakeholder group, the Barangay Captains. *Barangay Captains*, popularly known in Philippine communities as "*Kapitan*" or "*Punong Barangay*", are the elected head of the Barangay government (DILG, 1991).

Next, I examine the tectonic and geologic setting of Taal and provide a review of historical accounts of past eruptions. Archival analysis involves systematic identification, analysis and evaluation of written sources to reveal detailed information about past eruptions, their processes, products and impacts. Such work serves to highlight geographic locations of areas severely affected during past eruptions that may then serve as a guide for geological investigations, hazard modelling and social surveys in the future.

The next step involves investigating how hazards might impact communities surrounding Taal should a major eruption occur in the future. In this thesis, I specifically concentrate on tephra hazard and have chosen the AD1754 Plinian/Sub-Plinian eruption as the case study to represent a maximum expected event scenario. Determination of the exposure of communities around Taal to tephra hazard is completed by combining empirical evidence (e.g. geologic and stratigraphic mapping and laboratory sample analysis) with numerical analysis of tephra fallout. Therefore, a review of various tephra models is undertaken to identify what models are available and where they are useful, in order to determine the most appropriate model to use.

While identification of tephra hazard is a vital component of risk assessment and management, just as important is knowing more about the Barangay Captains – their knowledge, education, preparedness etc, since they are the local government officials that have the mandated responsibility to help prepare and protect their communities from volcanic emergencies. The remaining portion of the literature review focuses on the social understanding of risk, specifically in a volcanic setting. A review of global and Philippine-based case studies related to the emerging field 'social volcanology' is undertaken to provide summary information on the objectives, results, sampling method(s) and size, and more specifically to search for details on knowledge, awareness, behaviour and emergency preparedness of community leaders to volcanic hazards and risk. The concluding section of this chapter defines the research questions for the thesis emerging from the literature review.

2.1 Introduction to the society, economy and governance structures in the region

Understanding socio-economic and political structures is necessary to make sense of how the Batangas communities deal with crisis related to volcanic eruptions. Hollis (2015, p. 3) cites the importance of understanding the role of political structures in DRM when he said, "*Gaining a more fine-tuned and holistic understanding on the current functions and future possibilities of regional DRM can provide important insights for increasing the resilience of states from natural hazards*."

2.1.1. Batangas Province

Batangas Province was established in AD1581 (Figure 2.1). Table 2.1 lists the three cities, 31 municipalities and 1,078 barangays in Batangas (PSA, 2018). The three cities consist of Tanauan City located northeast of Taal Volcano Island (TVI), Lipa City situated southeast of TVI, and Batangas City located south southeast of TVI (Figure 2.1). Batangas City (*pop.* 329,874 or 12.2%) and Lipa City (*pop.* 332,386 or 12.3%) are the largest cities in the province. Tanauan City (*pop.* 173,366 or 6.4%) became a city in AD2001 (Table 2.1). In 2015, the Municipality of Santo Tomas in Batangas, one of the 31 municipalities of Batangas Province, was ranked 10th of 18 municipalities across the Philippines for highest regional density.

2.1.2. The people

A comparison of the 2010 and the 2015 Census of Population conducted by the Philippine Statistics Authority (PSA) showed a 13.33% increase in the total population of Batangas Province (PSA, 2018) (Table 2.2). Thus, the population and associated exposure of people and assets is increasing rapidly.

Annual population growth in the region remains at *c.*2.7%. Further, an estimated 5,000 people are currently residing on TVI (PPDO, 2016) - a Permanent Danger Zone (PDZ). PDZs are areas where no permanent settlement is recommended by PHIVOLCS-DOST. According to PSA (2010), a significant proportion of the population of Batangas Province range in age from 15 to 64, with a median age of 24.5 (Table 2.2). In 2010, the dependent population comprised of young people between the ages of 0 to 14 (760,986) and people aged 65 and over (113,744). In 2000, the total number of persons with disability was 22,621. Literacy rates are high at 89.23% according to PSA (2010) and 98.05% according to the 2016 Socio-Economic and Physical Profile in terms of Filipinos being able to read and write and having attained at least an elementary or high school level of education (PPDO, 2016).

The predominant language spoken by 99% of Batangeños is Tagalog. English is the second most common language.

Roman Catholicism is the dominant religious denomination in the province, with the remaining population being Baptist, Aglipayan, Muslim, Iglesia ni Kristo practitioners, atheist and agnostic. In the Philippines, social and cultural influences including religious traditions generally have a great impact on how people live their lives and how they confront and cope with hazards and disasters (Bankoff, 2004; Gaillard, 2008; Gaillard, 2015). Chester et al. (2008, p. 216) described the importance of religion in shaping people's behaviour when they said, "*the idiosyncratic religious character of disaster responses has been maintained following eruptions that have occurred during the past one hundred years, including the small number of eruptions of Etna that have taken place in the early years of the twenty-first century*". The

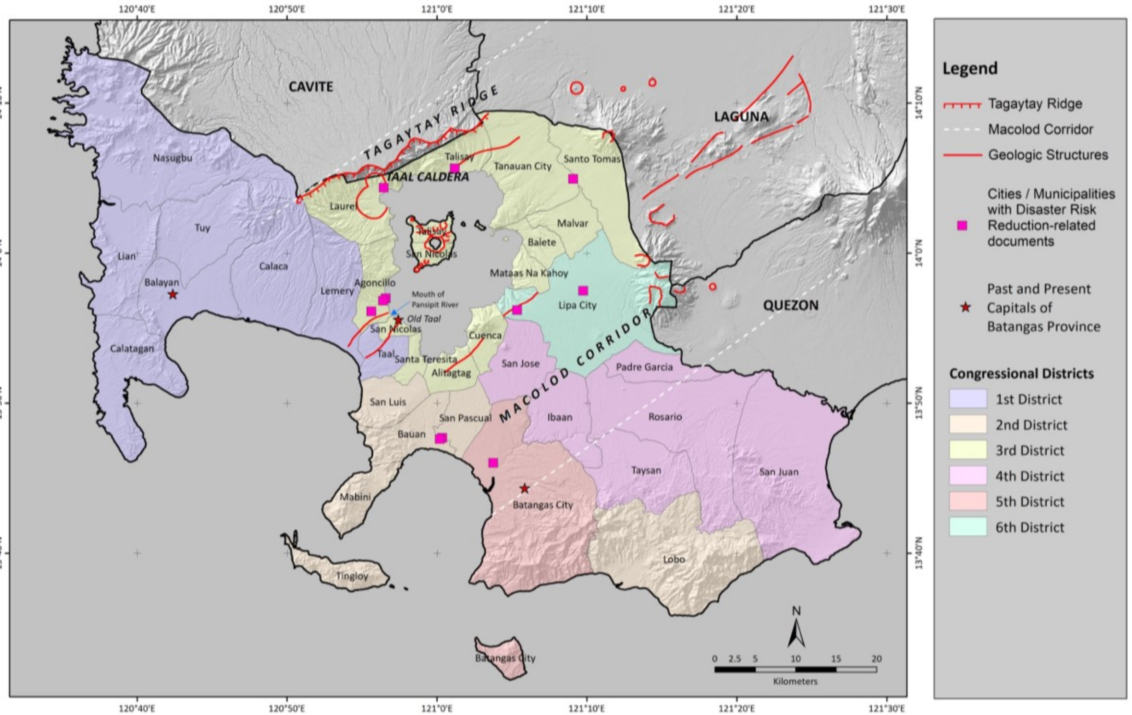


Figure 2.1. Map of Batangas Province showing the three cities and 31 municipalities of Batangas Province. The map also shows the local tectonic setting near Taal. Red solid lines are interpreted structures and craters. Boundaries of the Macolod Corridor are shown as white dash lines. Gray lines delineate boundaries between the cities and municipalities that are assigned to six Congressional/Legislative districts. The current seat of the provincial government is in Batangas City. Star symbols represent past and present capitals of Batangas Province. Communities in and around Taal are all within the jurisdiction of the 3rd District. District boundaries are adapted from the 2016 Socio-Economic and Physical Profile of Batangas Province, Batangas Provincial Planning and Development Office, Planning & Programming Division, Provincial Government of Batangas. The map also shows the location of the 25 km x 30 km-wide Taal Caldera surrounding TVI. The mouth of the Pansipit River is shown by a blue arrow that was dammed by eruptive deposits and subsequently resulted in flooding on the eastern and northern lakeshores with Old Lipa and Old Tanauan. TVI is the central island surrounded by Taal Lake. Locations of cities and municipalities with disaster risk reduction (DRR) related documents collated during data gathering are also shown in the map plotted as pink squares. The map is overlain on NAMRIA IfSAR-DTM, 2013 and Administrative boundaries are adopted from the Philippine Geographic Information System (PhilGIS), 2011.

Table 2.1. Population per municipality/city in Batangas Province. Location and distance relative to Taal are indicated. Each municipality/city has a designated political district called a Barangay abbreviated as BRGY. The barangays where the Barangay Captains reside and govern are shown in BLUE. Source: PSA, 2015.

MUNICIPALITY/ CITY	LOCATION RELATIVE TO TAAL	DISTANCE FROM TAAL	DISTRICT	NO. OF BRGYS.	POPULATION (%)	BRGY WITH LARGEST POPULATION
Agoncillo	West	4.6	3rd	21	38,059 (1.4)	Subic Ilaya/3833
Alitagtag	South	13.1	3rd	19	25,300 (0.9)	Muzon Segundo/ 2288
Balayan	West	19.4	1st	48	90,699 (3.4)	Caloocan/6113
Balete	East	6.4	3rd	13	22,661 (0.8)	Malabanan/4637
Batangas City	South	21.2	5th	105	329,874 (12.2)	Santa Rita Karsada/18276
Bauan	South	18.5	2nd	40	91,297 (3.4)	Manghinao Proper/10789
Calaca	West	14.6	1st	40	81,859 (3.0)	Dacanlao/6177
Calatagan	Southwest	34.4	1st	25	56,449 (2.1)	Lucsuhin/4528
Cuenca	Southeast	9.2	3rd	21	32,783 (1.2)	Dita/4579
Ibaan	Southeast	21.0	4th	26	52,970 (2.0)	Coliat/4026
Laurel	Northwest	5.0	3rd	21	39,444 (1.5)	San Gregorio/ 3433
Lemery	Southwest	9.2	1st	46	93,157 (3.5)	Sambal Ilaya/ 4265
Lian	West	33.0	1st	19	52,660 (2.0)	Matabungkay/ 4938
Lipa City	Southeast	10.3	6th	72	332,386 (12.3)	Sabang/23535
Lobo	Southeast	38.0	2nd	26	41,504 (1.5)	Balibago/3454
Mabini	South	27.3	2nd	34	46211 (1.7)	Solo/2725
Malvar	Northeast	11.1	3rd	15	56,270 (2.1)	Santiago/7754
Mataas Na Kahoy	East	9.4	3rd	16	29,187 (1.1)	District III (Pob.)/ 3158
Nasugbu	Northwest	17.4	1st	42	134,113 (5)	Wawa/15328
Padre Garcia	Southeast	25.0	4th	18	48,302 (1.8)	Pansol/4660
Rosario	Southeast	24.6	4th	48	116,764 (4.3)	Bagong Pook/ 5757
San Jose	Southeast	12.3	4th	33	76,971 (2.9)	Banaybanay I/ 6418
San Juan	Southeast	42.9	4th	42	108,585 (4.0)	Laiya-Aplaya/ 6005
San Luis	South	16.2	2nd	26	33,149 (1.2)	Dulangan/2868
San Nicolas (Mainland)	South	10.3	3rd	18	22,623 (0.8)	Bancoro/2648
San Pascual	South	17.5	2nd	29	65,424 (2.4)	Poblacion/10188
Santa Teresita	South	11.2	3rd	17	21,127 (0.8)	Saimsim/2730
Santo Tomas	Northeast	17.6	3rd	30	179,844 (6.7)	Santa Maria/ 27843
Taal	South	12.1	1st	42	56,327 (2.1)	Butong/4926
Talisay (Mainland)	North	7.8	3rd	21	45,301 (1.7)	Aya/6215
City of Tanauan	Northeast	6.3	3rd	48	173,366 (6.4)	Darasa/17561
Taysan	Southeast	30.8	4th	20	38,007 (1.4)	Mapulo/3084
Tingloy	South	39.3	2nd	15	17,919 (0.7)	San Juan/1916
Tuy	West	21.6	1st	22	43,743 (1.6)	Magahis/3351

concept of disasters as "acts of God" have been recorded in several narrative accounts related to historical eruptions of Taal (Saderra Masó, 1911) and have been the subject of a significant number of studies (Belshaw, 1951; Chester, 2005; Chester & Duncan, 2010; Gaillard & Texier, 2010).

2.1.3. Economy

A major reason why people choose to live in areas prone to natural hazards relates to sources of livelihood (Nofrita & Krol, 2014; Sutton & Restrepo, 2013). This is the case in Batangas Province. According to the PSA (2010), the income classification of Batangas Province is considered as 1st Class with major income sources being agriculture, forestry, services, manufacturing, cottage industries, and tourism. Batangas Province is also ranked 9th in the 2016 Cities and Municipalities Competitiveness Index (CMCI) amongst 147 provinces. About 86% of the total land area is alienable (transferrable or disposable) consisting of agricultural and built-up areas, and 14% is protected/forest, including TVI. Crops such as rice, corn, coconut fruit trees, mango, banana, coffee, sugarcane, and vegetables account for 57% of production. Built-up land (28%) includes commercial, residential, industrial, tourism, road networks, and pastures for the livestock and poultry industries.

Rich volcanic soils and excellent irrigation sources make the province ideal for farming. The main source of income for communities surrounding Taal Lake and the Batangas coast is fishing. Aquaculture is also very popular around Taal Lake. In 2015, the production volume for aquaculture was valued at almost PhP19 million (~USD 365,000). Another major source of income and livelihood for the province is livestock and poultry production. As of July 2016, the swine sale inventory of

Table 2.2. Batangas Quickstat (PSA, 2018).

Geography (Sourced from PSA, February 2016)			
Number of cities		3	
Number of municipalities		31	
Number of barangays		1078	
Demography (Sourced from PSA 2010 Census of Population and Housing and 2015 Census of Population (total population only).			
	2015-2016	**2010**	**2007**
Total population	2,694,335	2,377,395	2,245,869
Urban	--	776,789 (32.7%)	588,498
Rural	--	1,600,606 (67.3%)	1,657,371
Male	1,335,187	1,192,583	1,129,593
Female	1,339,148	1,184,812	1,116,276
Sex ratio *(number of males for every 100 females)*	--	100.7	101.2
Population density *(square kilometers)*	865	763	720
Median age	--	24.5	23.3
Dependency ratio: *Young dependents*	--	50.7%	55.7%
Dependency ratio: *Old dependents*	--	7.6%	7.5%
Elderly population *(60 years old and over)*	--	176,095	155,256
Proportion by age group *(0-14)*	--	32	34.1
Proportion by age group *(15-64)*	--	63.2	61.3
Proportion by age group *(65 and over)*	--	4.8	4.6
Persons with disability *(both sexes)*	2000: 22,621 *(37.17% w/ low vision)*	--	
Highest educational attainment *(both sexes)*	2,418,724	2,120,413	1,984,154
Literacy rate *(minimum simple literacy)*	99.4	89.23	88.35
Highest educational attainment		2,120,413	
No grade completed		55,490 (2.62%)	
Pre-school		68,319 (3.22%)	
Elementary		727,482 (34.31%)	
High School		756,118 (35.66%)	
Post-secondary		73,524 (3.47%)	
College graduate		188,560(8.89%)	
Academic degree holder		237,265 (11.19%)	
Post-baccalaureate		3,317 (0.16%)	
Not stated		10,337 (0.49%)	
Overseas workers *(both sexes)*	115,134	80,763	70,481
Registered voters	1,526,196	1,379,072	--

Batangas Province covered more that 46% of the total livestock inventory for the entire Region IV-A, also known as CALABARZON. Batangas ranks second highest in CALABARZON for broiler production.

Batangas is identified as an industrial growth center exhibiting an increase in the number of taxpaying business establishments (PPDO, 2016). Being one of the important industrial/economic zones in the Philippines, Batangas Province has numerous industries operating in industrial parks. The industrial parks contribute power and water distribution, telecommunication facilities, petroleum and sugar refineries, food and beverage manufacturing plants, cement factories, footwear industries, dairy farms, and small to medium scale mining. As of 31 January 2015, economic zones and industrial parks in Batangas Province consisted of: 1) information technology parks and centers located in Lipa City (Figure 2.1); 2) manufacturing economic zones with the largest located in Tanauan City and Sto. Tomas (Figure 2.1); 3) an operating medical tourism zone; 4) a tourism zone; 5) an agro-industrial economic zone; 6) manufacturing economic zones; and 7) an industrial park under the Philippine Economic Zones Authority (PEZA). Tourism is another major income earner and Batangas has become one of the most popular tourist destinations near Metro Manila, with Taal Volcano and Taal Lake acting as major draw cards to the region (PPDO, 2016). Batangas also has the second largest international seaport in the Philippines. The reported total income generated by the Provincial Government of Batangas continue to grow yearly. The rich livelihood opportunities in Batangas Province, which are generally situated near or at the volcano island, inadvertently encourage residents and migrants to live in this highly vulnerable and hazard prone environment (Nofrita & Krol, 2014).

2.1.4. Government structure in Batangas Province

Understanding the government structure of the province, including the DRRM process and operational capacity of the province, is critical to appreciating the complexity of, and challenges to emergency planning and mitigation faced by communities generally, and by Barangay Captains, specifically (Baxter et al., 2008).

When Batangas was established in AD1581, the capital was Balayan until AD1732 (Figure 2.1) when it shifted to the location of Old Taal (Figure 2.1). The AD1754 eruption of Taal resulted in the town's destruction, and by AD1889, the capital had been moved to Batangas City.

There are twenty main departments in the Batangas Provincial Government structure (Figure 2.2). The same offices and officers constitute the Batangas Province Disaster Risk Reduction and Crises Management Council (PDRRCMC) whose responsibility includes formulating DRR plans covering disaster preparedness, mitigation, response, rehabilitation and recovery for natural and man-made crises. Also playing vital roles in the government structure is the Office of the Sangguniang Panlalawigan or the Batangas Provincial Board whose members constitute two elected representatives from six districts, and three ex-officio members including the president of the Association of Barangay Captains (ABC), the League of Councilors, and the president of the Provincial Sangguniang Kabataan (League of Youths).

Each District Congressman represents a specific geographical district in Batangas Province. Their general legislative power involves enactment of laws that could impact on the communities they represent. They also have supervisory control over the administrative branch of the national and local government and have control over funds appropriation. There are six congressional/legislative districts in the province (Figure 2.1) (PPDO, 2016). Each district has representation in the Philippine House of Representatives. Communities in and around Taal are mostly within the jurisdiction of the 3rd District.

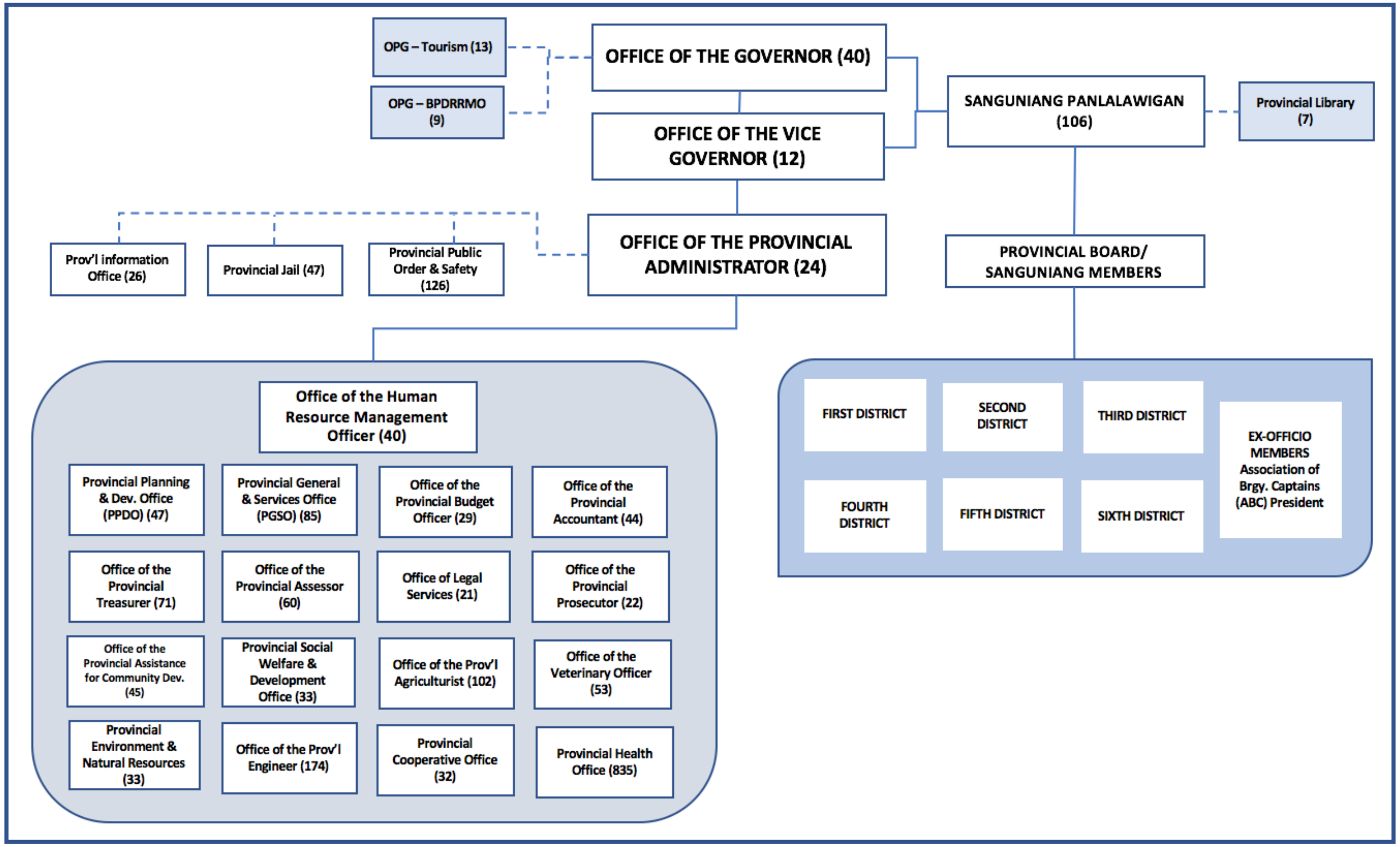


Figure 2.2. The Batangas Government Organisational Structure. Inset numbers specify the number of employees working for each office. Source: 2016 Socio-Economic and Physical Profile, Provincial Planning and Development Office, Planning & Programming Division, Provincial Government of Batangas.

2.1.5. Provincial Government involvement in disaster risk reduction

The PDRRCMC was created as a response to the RA 10121 and is the local arm of the National Disaster Risk Reduction and Management Council (NDRRMC). Prior to the enactment of RA 10121 and the Philippine Disaster Risk Reduction and Management Act of 2010 (Congress of the Philippines, 2010), the NDRRMC, formerly known as the National Disaster Coordinating Council (NDCC), under the Department of National Defense (DND), was tasked with undertaking the role of preparing for, and responding to, natural disasters including typhoons, earthquakes, volcanic eruptions, tsunami, as well as monitoring man-made crises such as armed conflicts, maritime incidents, and terrorism (NDRRMC, 2011).

The RA 10121 is described as "*an act strengthening the Philippine Disaster Risk Reduction and Management System, providing for the National Disaster Risk Reduction and Management Framework and institutionalizing the National Disaster Risk Reduction and Management Plan, appropriating funds therefore and for other purposes*" ("*Philippine Disaster Risk Reduction and Management Act of 2010*") (NDRRMC, 2011). It aims to enhance and strengthen the power of national and local government units (LGUs) to enable and support communities to be disaster resilient and have coping mechanisms for disaster risk reduction through preparedness and response capabilities. With the enactment of the bill, existing Disaster Coordinating Councils at the provincial, city and municipal levels were subsequently known as the Provincial, City, and Municipal Disaster Risk Reduction and Management Councils (DRRMCs). The Barangay Disaster Coordinating Councils (BDCCs) were replaced by Barangay Development Councils (BDCs) or Barangay Disaster Risk Reduction and Management Councils (BDRRMC), whose function are to serve as the local DRRMCs at the barangay level.

To further boost the importance of DRR in Batangas Province, the Batangas PDRRCMC was officially established, chaired by the Provincial Governor through Provincial Ordinance No. 001, which was passed and approved on 27 April 2011. The ordinance is described as "*an Ordinance institutionalizing a holistic disaster risk reduction and crisis management genre for the Province of Batangas, which should be replicated in all the component cities and municipalities designed to respond to both the reality, perception and aftermath of crisis*" (De Loyola, 2011). The structure of the Batangas PDRRCMC is shown in Figure 2.3. The NDRRMC provides support to PDRRCMC and local government units but expects them to be the first disaster responders in any crisis. Non-government organisations and the private sector as stakeholders are encouraged to work with the DRRM committees pertinent to their area of concern and mandates the following mechanisms for coordination as regulated by NDRRMC and PDRRMC. A similar structure also holds true for the DRRMC of each City and Municipality of Batangas Province. As per the directive of the Provincial Ordinance No. 001, a Disaster Risk Reduction and Management and Climate Change Adaptation (DRRM-CCA) Plan (2013-2016) was drafted spearheaded by the then Governor of Batangas Province, Hon. Vilma Santos Recto (PDRRMC, 2013). The plan provided for the composition and establishment of duties and responsibilities of every sub-committee and support sectors to have an efficient system of actions and controls during the process of attaining the DRR objectives (Table 2.3).

Perhaps more crucial to the effectiveness of DRR activities in the province is the role of the BDRRMCs. The head of the council is the Barangay Captain who is the highest elected barangay officer. The composition of the BDRRMC is shown in Figure 2.4. Members of each committee consist of member of the barangay community including Barangay Sergeant-at-Arms known as "*Barangay Tanods*", and are generally headed by a Barangay Councilor or "*Barangay Kagawad*". Other essential members of the BDRRMCs are key officers of the Elementary and High Schools that are located in each barangay, most frequently the School Disaster Risk Reduction Coordinator (DRRC). Each school is required to have a School DRRC. More often than not, the School DRRCs act as the representatives of the school in the BDRRMCs. As part of the DRR program in schools, the Department of Education (DepEd) requires each school to develop and implement a School DRR Development Plan aimed at integrating DRR activities into the daily lives of all stakeholders in the school, including parents of enrolled students (Figure 2.5). The crucial roles that barangay and school officials play in DRR can mean the success or failure of response to a particular emergency including volcanic crisis. They are in immediate and direct contact with the communities that are vulnerable to various hazards. The structure of the DRRMCs are well defined and the roles of each subcommittee are designated. The key challenge to the DRRMC system is the fact that since 1977, there has been no major periods of volcanic unrest at Taal that could test if the system is effective.

Having provided an overview of the socio-economic and governance structures of the region, the review now turns to the geologic and tectonic setting of the region.

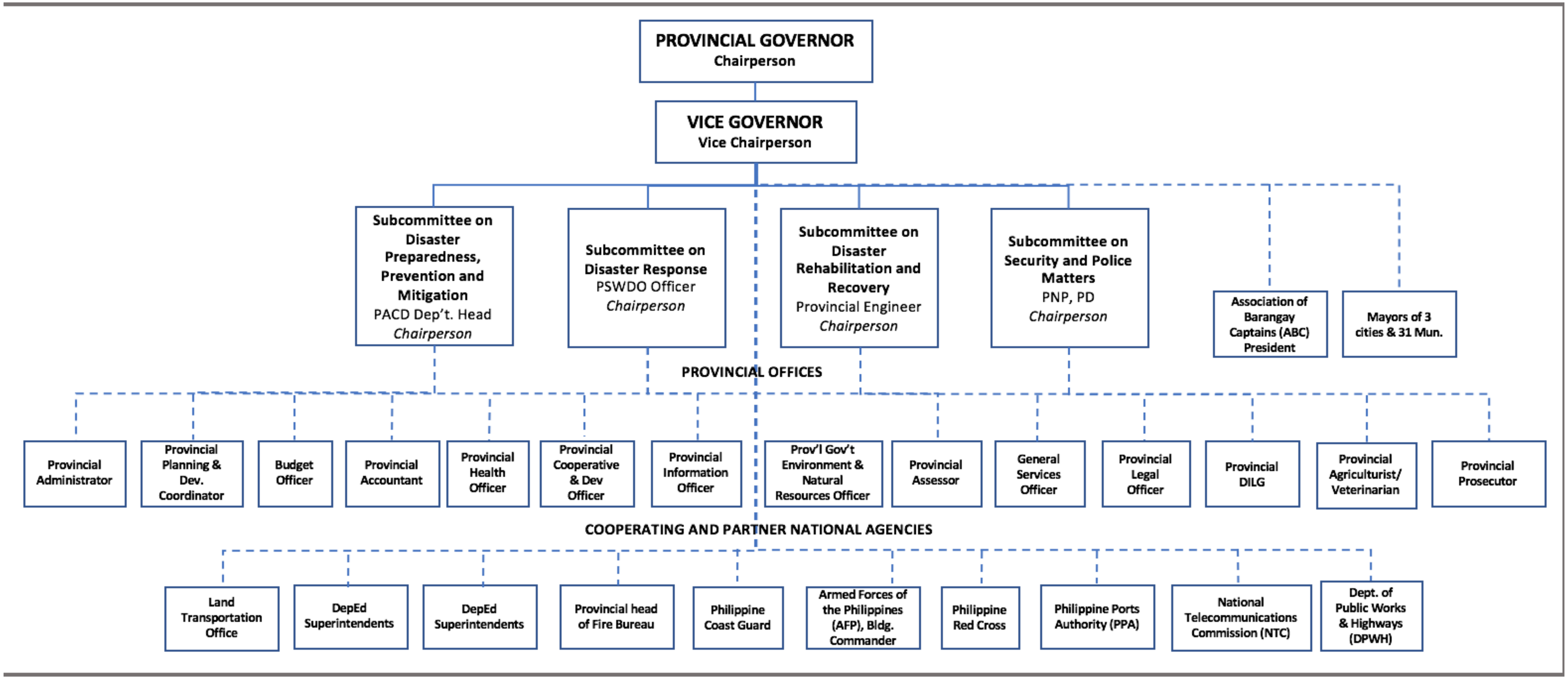


Figure 2.3. Provincial Disaster Risk Reduction and Management Council Organisational Structure for Batangas Province. Source: Provincial Government of Batangas.

Table 2.3. Summary list of the Provincial Disaster Risk Reduction and Crises Management Council (PDRRCMC) Subcommittees, members and their duties and responsibilities identified in Figure 2.5. Source: Disaster Risk Reduction and Management and Climate Change Adaptation Plan (2013-2016), currently still being implemented (PDRRMC, 2013).

SUBCOMMITTEE	CHAIR	MEMBERS	ROLE(S)
Disaster Prevention & Mitigation	Head of Provincial Assistance for Community Development (PACD)	Representatives of the Department of Interior and Local Government (DILG), Provincial Government Environment & Natural Resources Office (PGENRO) Officer, Provincial Information Office (PIO) Officer, Provincial Assessor, Provincial Liga ng mga Barangay (PLMB) president, and Mayors of three cities and 31 municipalities	Prevention/mitigation of adverse effects of various hazards through hazard mapping, development of early warning systems, contingency planning, flood prevention through structural intervention, implementation of land use regulations to avoid settlements in areas highly prone to various hazards, strict implementation & application of building codes in design & construction of infrastructure to ensure quality & safety especially during earthquake events, stockpiling of emergency supplies & equipment, and capacity building for disaster risk reduction through information drives, trainings & drills
Disaster Response	Head of the Provincial Social Welfare and Development Office (PSWDO)	Provincial Health Officer, PIO Officer, Provincial Director of Bureau of Fire Protection, Department of Education (DepEd) superintendents, Provincial Veterinarian, and Philippine Red Cross (PRC) & National Telecommunications Commission (NTC) representatives	Provide immediate & short-term emergency services & assistance to the public during and after a crisis with the aim of saving lives, provide for basic needs of affected communities & individuals, & reducing impacts of a calamity to health of affected individuals
Disaster Rehabilitation & Recovery	Provincial Engineer	Provincial Administrator, General Services Office (GSO) Officer, Provincial Cooperative Development Office (PCDO) Officer & Provincial Agriculturist	Restore affected area to its previous state & initiate repair of physical, social and economic damage including lifelines, health & communication facilities, as well as utility systems; preparation, implementation, monitoring and reporting of rehabilitation a& recovery phase in any crisis
Security and Police Matters	Provincial Director of Philippine National Police (PNP)	Philippine Coast Guard, Armed Forces of the Philippines (AFP) Brigade Commander, Provincial Legal Officer, Provincial Prosecutor	Safety & security of the communities in crisis situations, peace and order, and prosecution of pertinent crimes and violations of all penal laws
Provincial Finance Committee		Finance-related Provincial Offices	Serves all the subcommittees with specific responsibilities: Provincial Budget Officer - responsible for budgetary aspect of all proposed legislation, projects & security measures related to settlement of any crisis; Provincial Accountant - provide Sanggunian & all offices concerned with financial status; Provincial Planning Officer - responsible for the preparation of the socio-economic & physical development plans & policies, & monitor & conduct researches & trainings aimed at capacity building of action officers to crisis management; Provincial Treasurer - responsible for providing supervision of Treasury Offices of 31 municipalilties of Batangas
Sangguniang Panlalawigan (SP)	Chairperson of each SP Committee	Committee on Rules and Ordinances, Committee on Appropriation, Committee on Environmental Protection, Committee on Health & Sanitation, Committee on Peace, Order and Public Security	Augment and support various PDRRCMC Subcommittees

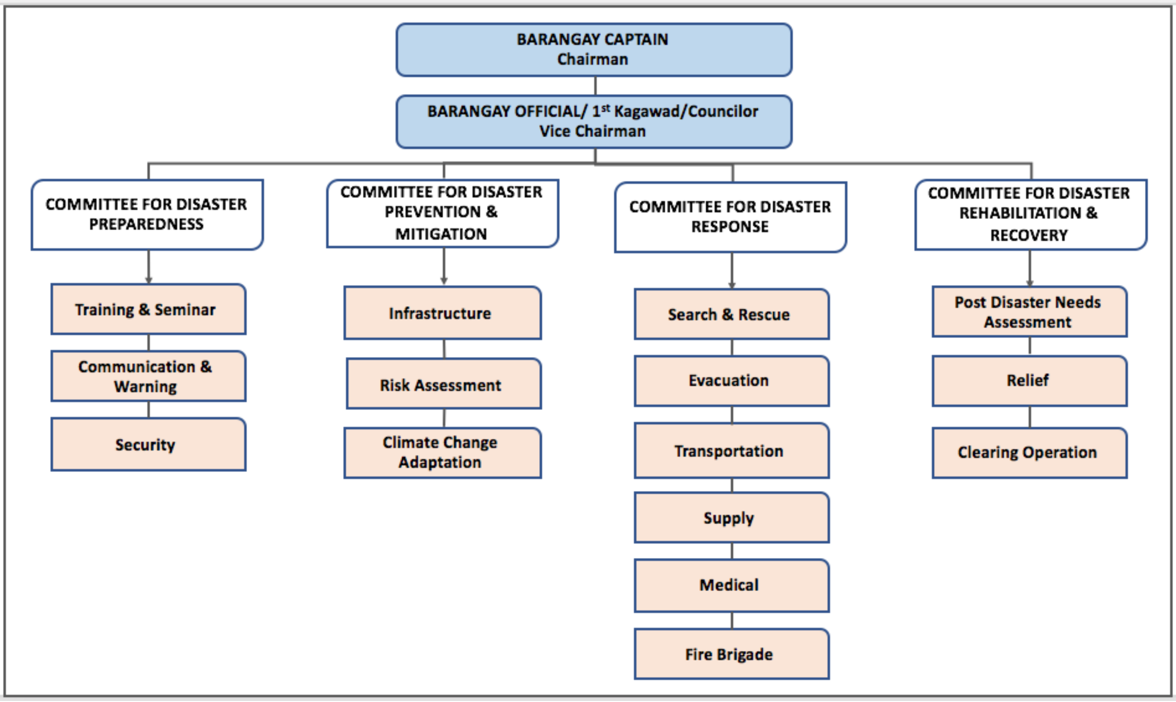


Figure 2.4. Barangay Disaster Risk Reduction and Management Council Organisational Structure for Batangas Province. Source: Provincial Government of Batangas.

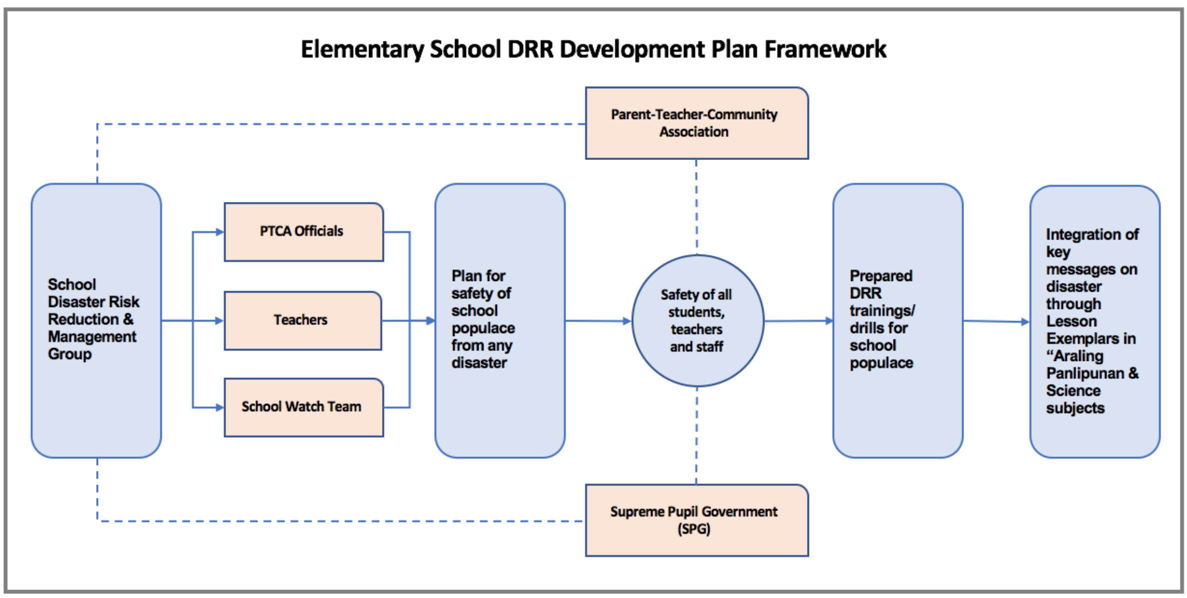


Figure 2.5. School Disaster Risk Reduction and Management Council Organisational Structure for Batangas Province. Source: Subic Ibaba Elementary School, Barangay Subic Ibaba, Agoncillo, Batangas Province.

2.2 Philippine tectonic setting and Taal

The Philippines setting makes it prone to multiple geological and meteorological natural hazards (Figure 2.6). Twenty-four of some 400 known volcanoes in the Philippines are classified as active (Table 2.4).

An active volcano is defined by PHIVOLCS-DOST (2016a) as "*having erupted within the last 600 years, the earliest archival record in Philippine history, or may have erupted within the last 10,000 years as determined from datable materials*". Information gathered from the Smithsonian Global Volcano Program (GVP) (2018) lists 320 volcanoes while PHIVOLCS-DOST lists a total of 407 volcanoes (active and non-active).

The 1991 Pinatubo eruption, and the frequent eruptions of Mayon, show the extent and devastating impacts of volcanic eruptions in recent times (Moore & Melson, 1969; Ramos-Villarta et al., 1985; Usamah and Haynes, 2012; Wolfe & Hoblitt, 1996). Although Taal has not erupted for four decades, it continues to be one of the deadliest, with past violent eruptions causing numerous casualties and destruction of properties (Torres et al., 1995). A future explosive eruption, similar to that in AD1754 (thought to represent a maximum expected event scenario) (Delos Reyes et al., 2018), would have a tremendous impact on lives, properties, the economy, and the environment in the CALABARZON Region. Even Metro Manila may see adverse environmental impacts with consequences for health, aviation and land transport.

An essential part of the proposed multidisciplinary risk assessment process at the

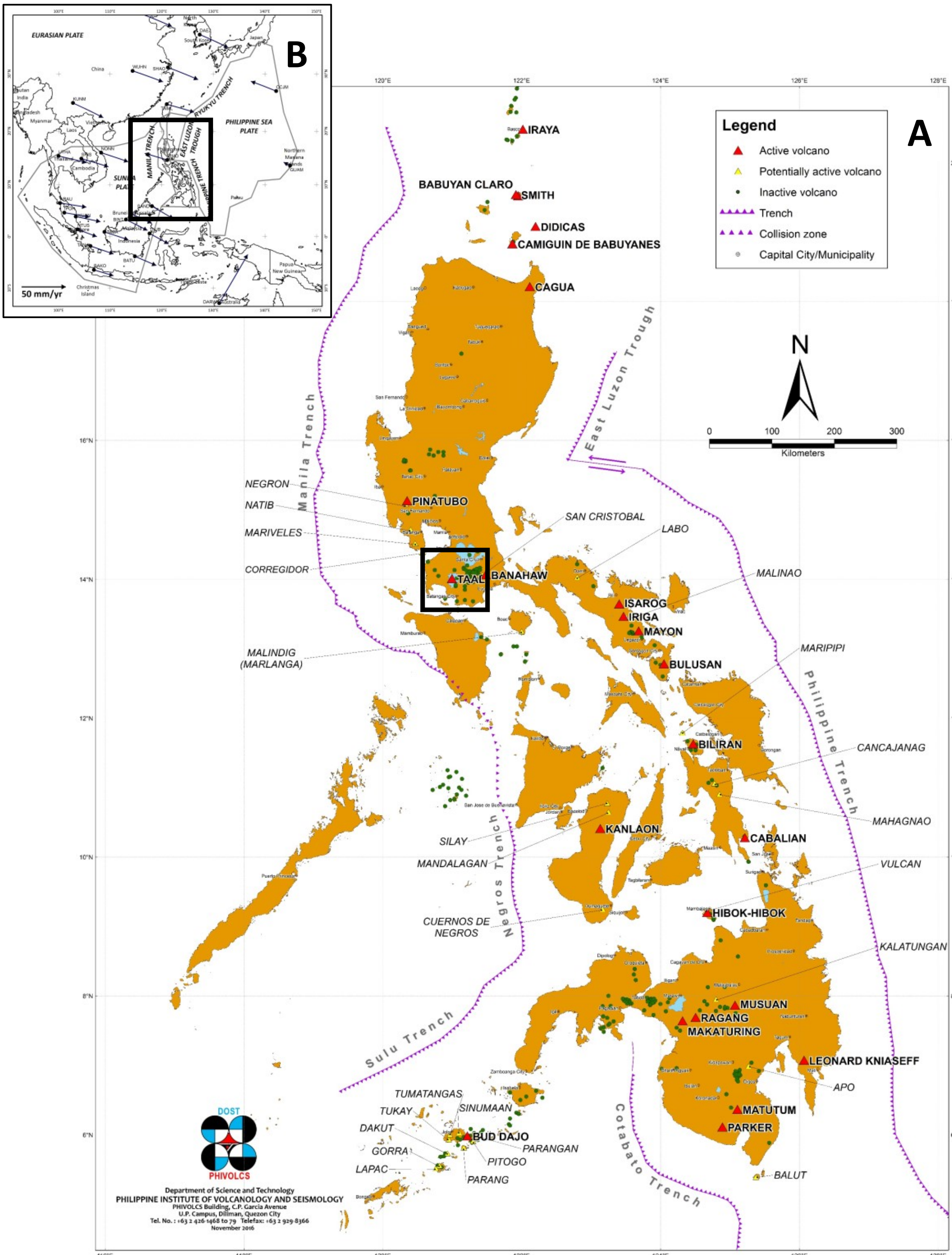


Figure 2.6. Local tectonic setting of Taal with identified active fault, trenches and volcanoes in the Philippines. (A) The location of Taal is bounded by gray square. Source: PHIVOLCS-DOST, 2016a. (B) Inset shows the regional tectonic setting of the Philippines. Vectors show GPS velocities indicating rate and direction of movement of the major tectonic plates. Modified from Hsu et al., (2016), overlain on data from Global Self-consistent, Hierarchical, High-resolution Geography (GSGGG) Database version 2.3.6 from NGDC-NOAA (Wessel and Smith, 1996).

Table 2.4. List of active volcanoes in the Philippines with geographic locations in World Geodetic System (WGS) 84. Source: PHIVOLCS (2016a).

NAME OF VOLCANO	LATITUDE	LONGITUDE	LOCATION/ PROVINCE
Babuyan Claro	19.52408	121.95005	Babuyan Island Group, Cagayan in Luzon
Banahaw	14.06038	121.48803	Boundaries of Laguna and Quezon in Luzon
Biliran (Anas)	11.63268	124.47162	Leyte in Visayas
Bud Dajo	6.01295	121.05772	Sulu
Bulusan	12.76853	124.05445	Sorsogon, Bicol Region in Luzon
Cabalian	10.27986	125.21598	Southern Leyte in Visayas
Cagua	18.22116	122.1163	Cagayan in Luzon
Camiguin de Babuyanes	18.83037	121.86280	Babuyan Island Group, Cagayan in Luzon
Didicas	19.07533	122.20147	Babuyan Island Group, Cagayan in Luzon
Hibok-Hibok	9.20427	124.67115	Camiguin in Mindanao
Iraya	20.46669	122.01078	Batan Island, Batanes in Luzon
Iriga	13.45606	123.45479	Camarines Sur in Luzon
Isarog	13.65685	123.38087	Camarines Sur in Luzon
Kanlaon	10.41129	123.13243	Boundaries of Negros Oriental and Negros Occidental in Visayas
Leonard Kniaseff	7.39359	126.06418	Davao del Norte in Mindanao
Makaturing	7.64371	124.31718	Lanao del Sur in Mindanao
Matutum	6.36111	125.07603	Cotobato in Mindanao
Mayon	13.25519	123.68615	Albay, Bicol Region in Luzon
Musuan (Calayo)	7.87680	125.06985	Bukidnon in Mindanao
Parker	6.10274	124.88879	South Cotobato/General Santos/North Cotabato/Sarangani Provinces in Mindanao
Pinatubo	15.14162	120.35084	Boundaries of Pampanga, Tarlac and Zambales in Luzon
Ragang	7.69066	124.50639	Lanao del Sur and Cotobato in Mindanao
Smith	19.53915	121.91367	Babuyan Island Group, Cagayan in Luzon
Taal	14.01024	120.99812	Batangas in Luzon

heart of this thesis is to review existing knowledge about the regional tectonic setting, evolution of Taal Caldera and TVI, narrative records of the 33 known historical eruptions from AD1572 to AD1977, and the hazards posed by Taal. Details of the eruptive activities and subsequent reinterpretation of all known and available literature related to Taal and its eruption history are summarised in Chapter 4. The following sections provide an overview of the regional tectonic setting, and the evolution and eruption history of Taal.

2.2.1. Regional tectonic setting

The Philippine Archipelago is situated at the interface of the Eurasian and Philippine Sea Plates and was formed by the oblique convergence of the eastward-subducting Sunda/Eurasian Plate along the Manila Trench and the marginal basins of the Sulu and Celebes Seas along the Negros and Cotabato Trenches, and the westward-subducting Philippine Sea Plate along the Philippine Trench and the East Luzon Trench (Acharya and Aggarwal, 1980; Hamburger et al., 1980; Hayes and Lewis, 1985; Knittel et al., 1988; Galgana et al., 2007; Yu et al., 2013b) (Figure 2.6B). Subduction resulted in the complex formation of sedimentary and island arc terranes and ophiolite assemblages. Subduction along the Manila Trench is thought to have commenced in the Mid-Oligocene while westward subduction of the Philippine Sea Plate is thought to have commenced in the Late Mesozoic to Early Cenozoic (De Boer et al., 1980; Hamburger et al., 1983; Karig, 1983; Ludwig, 1970; Schweller & Karig, 1982; Schweller et al., 1984; Wolfe, 1988).

The arc-parallel component of the oblique convergent motion of the Philippine Sea Plate is taken up by shear with the 1,200 km-long left-lateral strike-slip Philippine Fault Zone (PFZ) as the most prominent shear partitioning feature that transects the Philippine Archipelago (Allen, 1962; Aurelio, 2000; Barrier et al.1991; Fitch, 1972; Förster et al., 1990; Holloway, 1981; Rangin et al., 1999; Repetti, 1935; Willis, 1937; Yu et al., 2013b) (Figure 2.6).

As a consequence of subduction-related magnetism, volcanic arcs trending north-south developed, with more than 300 volcanoes formed in the Philippines during the Cenozoic. In particular, the Luzon region is dominated by products of arc-related volcanism associated with subduction along the Manila Trench (Torres, 1989; Torres et al., 1995; Wolfe and Self, 1983). Located in eastern Luzon Island, Taal Volcano forms part of the Luzon-Bataan-Mindoro Arc (LBMA) and belongs to the group of volcanoes that formed within the northeast-southwest trending Macolod Corridor - a rift zone that is 50 to 60 km wide (Defant et al., 1988; Defant et al., 1989) (Figure 2.1). The Macolod Corridor consists of other volcanoes including Mt. Makiling, the Banahaw Volcanic Complex, the Seven Lakes of San Pablo, and other small maars and cones (Defant et al., 1988; Defant et al., 1989; Förster et al., 1990). While Torres (1989) and Förster et al. (1990) estimated commencement of volcanic activity at 1 Ma to 0.6 Ma B.P. based on K-Ar dating of Makiling lava, Oles (1991) obtained a K-Ar dating of 2.3 Ma B.P. for even older Macolod rocks. More recent ground deformation studies by Bacolcol et al. (2012) affirm a north-northeast to south-southeast trending extensional deformation in southern Luzon that is associated with activity in the Macolod Corridor and may have important implications for volcanic activity at Taal.

2.2.2. Evolution and prehistoric eruptive activity of Taal

This section presents a brief overview of the evolution of Taal Caldera and the prehistoric eruptions of Taal.

A major geologic feature surrounding TVI is Taal Caldera, a 25 km x 30 km wide caldera flanked by extensive and thick successions of dacite-basaltic andesite ignimbrite and base surge deposits (Figure 2.1). The caldera is the product of a series of eruptions and edifice collapses but no confirmation of age is available (DOST-PHIVOLCS, 1991; Wolfe & Self, 1983). It is postulated that Taal Caldera is made up of two calderas influenced by an extensional setting combined with fault activity (Listanco, 1994). The seminal work of Listanco (1994) establishes the evolutionary history of Taal Caldera. He identified four major ignimbrite deposits generated by four caldera-forming events that include: the oldest silicic Alitagtag (ALI) and Caloocan (CAL) Pumice Flow Deposits, the dacitic mixed scoria-pumice Sambong Ignimbrite (SAM), and the youngest basaltic-andesitic scoria-rich pyroclastic flow initially referred to by Listanco as SFL (1994), and later renamed Taal Scoria Pyroclastic Flow (SPF) (Martinez & Williams, 1999). While there are no age constraints or estimates of extent for the three older deposits, the uppermost and best-studied deposit is the SPF (Martinez,1997; Martinez & Williams, 1999). The ^{14}C dating yielded an age of 5,380 ± 70 to 6,830 ± 80 BP with estimated total bulk volume of 20 ± km^3 (Martinez & Williams, 1999). The estimated total bulk volume of the four caldera-forming deposits is about 50 km^3; and these can be found in the now highly urbanised and densely populated areas of Batangas, Cavite and Laguna. The calderagenic activity terminated with an eruption that emplaced ashfall and base surge deposits (ABS) found as a prominent layer in the caldera walls. Part of the post-caldera ABS deposits is the Buco Base Surge deposit with an estimated bulk volume of about 5 km^3, but with no established eruptive age (Geronimo, 1988).

TVI is a 25 km^2 scoria-tuff cone-maar complex that is a post-caldera constructional edifice, which emerged above the surface of Taal Lake (Figure 2.7A). The presence of northwest-southeast and northeast-southwest structures cutting through TVI control the location of eruption sites (Listanco, 1997; Torres et al., 1995). The highest peak is approximately 300 m above sea level (asl) (Listanco, 1997).

There are more than 40 volcanic vents on TVI, formed during various eruptions, with pyroclastic density current, tephra fallout and lava flow deposits emplaced on various parts of the volcano edifice (Listanco, 1994; PHIVOLCS-DOST, 1991) (Figure 2.8B). Major historical eruption centers include the Main Crater or central caldera, Pira-piraso (northeast), Calauit (southeast), Binintiang Munti (southwest), Mt. Tabaro (southwest), and the Binintiang Malaki (northwest). The Main Crater is the largest volcanic vent and is occupied by a 1.9 km diameter and 80 m deep acid lake (PHIVOLCS, 1991) (Figure 2.7B).

2.2.3. Previous works on Taal

Numerous, comprehensive studies on various topics related to Taal have been completed that provide information on the *geology* (Adams, 1910; Geronimo, 1988; Listanco, 1994; Martinez, 1997; Martinez and Williams, 1999; Moore, 1967; Paris, 2014; Pratt, 1911a, 1911b; Torres, 1989; Waters and Fisher, 1971; Wolfe, 1986; Worcester, 1912), *tectonics and geophysics* (Acharya & Aggarwal, 1980; Alcaraz & Datuin, 1974; Bartel et al., 2003; Bacolcol et al., 2012; Fikos et al., 2012; Galgana et al., 2014; Hamburger et al., 1983; Hsu et al., 2012; Kumagai et al., 2014Lim, 1983; Listanco, 1997; Lowry, et al., 2001; Maeda et al., 2013; Nishigami et al., 1994;

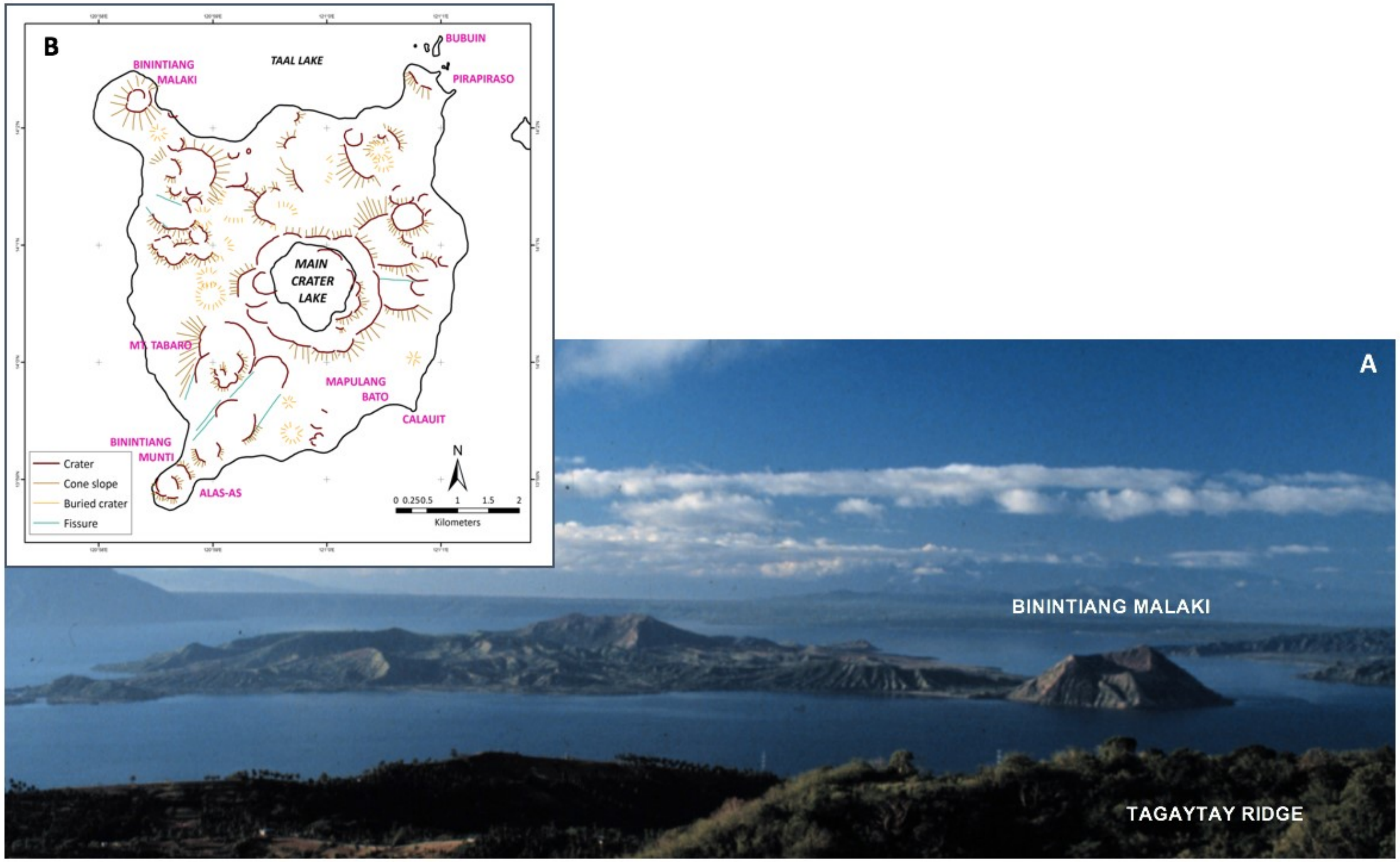


Figure 2.7. Taal Volcano Island (TVI) in Batangas Province, Southern Luzon, Philippines. A. Aerial view of the volcano as seen from the Tagaytay Ridge in Cavite Province. B) Location map of major eruption centers at Taal Volcano Island (TVI): Binintiang Malaki (northwest), Pira-piraso (northeast), Calauit (southeast), Binintiang Munti (southwest), Mt. Tabaro (southwest), and the Main Crater or the central caldera. Brown lines and hachured lines delineate existing craters. Source: Modified from Ruelo (1983).

Ohkura et al., 2001; PHIVOLCS-DOST, 1991; Wolfe & Self, 1983; Wolfe, 1988; Yu et al., 2013a), *stratigraphy and geochemistry* (Arpa et al., 2008; Arpa et al., 2013Castillo & Newhall, 2004; De Luna, 1988; Geronimo, 1988; Martinez, 1997; Martinez and Williams, 1999; Miklius et al., 1991; Ragland, 1983; Sudo et al., 2000; Vogel et al., 2006; Wolfe and Self, 1983), and *geomorphology* (Ramos, 2001; Ruelo, 1983; Saderra Masó, 1904).

2.2.4. Historical eruptions of Taal

The 33 identified eruptions of Taal were recorded in reports from friars and other authors during and since the Spanish and American occupations, as well as in scientific studies from AD1572 to AD1911 (Centeno, 1885; Pratt, 1911a, 1911b; Pratt, 1916; Saderra Masó, 1904; Saderra Masó, 1911; Worcester, 1912), and from published and unpublished scientific reports from AD1965 to AD1977 (Alcaraz, 1966; del Barrio Muñoz, 2015; Delos Reyes et al., 2018; Javellana, 1992; Listanco, 1994; Moore et al., 1966; Oppenheimer, 1991; PHIVOLCS-DOST, 1991, 1995; Ruelo, 1983; Smithsonian GVP, 2018; Torres, 1989; Torres et al., 1995). At least four of the 33 eruptions were considered violent (e.g. AD1749, AD1754, AD1911 and AD1965), with VEI values between 3 and 5 (Delos Reyes et al., 2018; Newhall and Self, 1982; PHIVOLCS-DOST, 1991) (Appendix A). The VEI is an estimation of the explosive character of an eruption considering information such as plume height, volume of ejecta, duration of the eruptive activity, eruption style, qualitative description of the magnitude of the eruption, and type of eruptive deposits (Newhall and Self, 1982).

A critical review of previous research on the historical eruptions of Taal should enable a better understanding of processes and products during each of the eruptions and provide information on the possible dynamics of future eruptions. While the abovementioned authors made their own interpretations on eruption styles and related processes and products for most of the historical eruptions of Taal, reinterpretation of the same narrative accounts is deemed necessary here, because of the acquisition of more extensive volcanology literature that provides greater insights and knowledge about products and processes that past researchers did not have access to. I also have the benefit of field experience while working in the aftermath of the 1991 Pinatubo eruption and several eruptions of Mayon (e.g. AD1984, AD1993, AD2000-2001, AD2006, and AD2009) that is valuable for interpreting historical accounts, records and reports.

The eruptions of Taal are divided into four series based on the locations of the eruption centers and eruption repose periods (PHIVOLCS-DOST, 1991). The eruptions in *Series A* were centered at the Main Crater and included all eruptions from AD1572 to AD1645 (Figure 2.7B, Appendix B). The cluster of eruptions from AD1707 to AD1731 are classified as *Series B* and were alternately centered between the flank craters located around the volcano (Figure 2.7B, Appendix B). Eruptions from AD1749 to AD1911 are grouped as *Series C*, centered again at the Main Crater (Figure 2.7B, Appendix B). The last series of eruptions from AD1965 to AD1977 are classified as *Series D* and were centered at Mt. Tabaro located on the southwestern flank of the volcano island (Figure 2.7B, Appendix B). The repose period between the end of Eruption Series A and start of B was 62 years, there were 18 years between

Series B and C, and 54 years between Series C and D. The current repose period (since the most recent eruption of Taal in AD1977) is nearly 40 years.

A more detailed discussion of the comprehensive review of historical eruptions is provided in Chapter 4 where each identified eruption is critically evaluated and where deemed appropriate, reinterpretations of eruptive style, processes and products including assigned VEIs are provided. A related manuscript was generated and published in the journal *Earth-Science Reviews* as Delos Reyes et al., (2018) (Appendix A).

2.2.4.1. Eruption Series A: Main Crater

Descriptive accounts for the eruptions between AD1572 and AD1645 were generally sourced from chronicles and reports written by Augustinian friars assigned to a parochial church located at the original town of Taal (Buencuchillo, 1754; Centeno, 1885). The Spanish-written documents were subsequently translated, and Saderra Masó (1911), Worcester (1912), and DOST-PHIVOLCS (1991, 1995, 2016b) collated, reviewed, and provided interpretations of processes and products related to some of the historical accounts. I re-examined all available translated eruption accounts and provide new interpretations for some of the identified eruption styles, processes, and products. In *Eruption Series A*, only the eruptions in AD1572, AD1591 (DOST-PHIVOLCS, 1991) and AD1641 (DOST-PHIVOLCS, 2016b) have eruption style classifications. The other eruptions listed in this series including the AD1605 to AD1611, AD1634, AD1635, and AD1645 events, have interpretations of eruption style but no identified processes or products. Further, while all eruptions in the series have assigned VEIs, I am downgrading the VEIs for the AD1605 to AD1611, AD1634, AD1635, AD1641 and AD1645 events. Detailed description and justifications for the changes in interpretations are provided in Chapter 4.

2.2.4.2. Eruption Series B: Flank eruptions

Eruption Series B eruptions from AD1707 to AD1731 were alternately centered between the flank craters located around the volcano, including from Binintiang Malaki during the AD1707 and AD1715 events, Binintiang Munti during the AD1709 and AD1729 events, near Calauit in AD1716, and at Pira-piraso during the AD1731 eruption (Figure 2.7B).

All the eruptions in *Series B* are confirmed and supported by limited (i.e. AD1709, AD1715 and AD1729) or more detailed (i.e. AD1716 and AD1731) historical observations and documentation. As in Series A, some eruption styles, identified processes and product in *Series B* are reinterpreted and reclassified. No changes in the classifications of eruption style for the AD1707 and AD1709 events are provided. However, new eruption classifications are provided for the AD1715, AD1729 and AD1731 events. While no description of processes and products for the AD1709, AD1715 and AD1729 eruptions are found in the available literature, I have identified or added new processes and products through reinterpretation of the eruption accounts. Detailed description and justifications for the changes in interpretations are provided in Chapter 4.

2.2.4.3. Eruption Series C: Main Crater

Eruption Series C consists of eruptions from AD1749 to AD1911 that were again centered at the Main Crater. It is important to note that some of the eruptive events in this series have more detailed descriptions, perhaps due to the fact that the eruptions (e.g. AD1749, AD1754 and AD1911) were more explosive than many others. With more detailed observations, an attempt to separate phases is undertaken but does not go as far as identifying controls to the transitions in eruptive activity. The AD1808, AD1874, AD1878 and AD1904 events have identified eruption styles based on limited reported observations. The AD1790, AD1825, AD1842, AD1873 and AD1903 events have no historical documentation but are listed as part of the 33 eruptions of Taal (PHIVOLCS-DOST, 1991), and are now considered as uncertain and reinterpreted as solfataric activities or very minor phreatic eruptions. Detailed description and justifications for the changes in interpretations are provided in Chapter 4.

2.2.4.4. Eruption Series D: Mt. Tabaro

The eight eruptions from AD1965 to AD1977 are classified as *Eruption Series D* and were centered at the Mt. Tabaro eruption site located on the southwestern flank of TVI (Figure 2.7B, Appendix B). All the eruption styles of the events listed in this series (e.g. AD1965, AD1966, AD1967, AD1968, AD1969, AD1970, AD1976 and AD1977) have been previously interpreted and classified (PHIVOLCS-DOST, 1991, 2016b). However, re-interpretation and reclassification is undertaken here for some events. The AD1965 event is one of the last explosive and damaging eruptions of

Taal. Based on a critical review of detailed eruption accounts, three different eruptive phases of the AD1965 event are identified. Likewise, I am postulating three eruptive phases for the AD1968 event and two eruptive phases for the AD1969 eruption based on the availability of more detailed eruption descriptions. Further, with these detailed descriptions, additional eruptive processes and products are also identified. The narrative accounts provide enough information to enable the confirmation of all the eruptions in *Series D*. Detailed description and justifications for the changes in interpretations are provided in Chapter 4. Since AD1977, Taal has not erupted but has sporadically manifested unrest. At least 20 significant episodes of seismic swarms have been recorded that did not culminate in eruption (Table 2.5).

2.3 Volcanic hazards overview

Further to understanding past eruption styles, processes and products, the review of historical records provides information about the potential adverse impacts of each individual volcanic hazard to communities, lifeline facilities, business and commerce, agriculture, and the environment. This is a vital element of volcanic risk assessment (Bonfils et al., 2012; Harris, 2015). The potential dangers posed by volcanic processes cannot be underestimated (Scott, 1989). By gaining an understanding of the volcanic hazards associated with past eruptions, it is possible to gain more insight into what might be expected during future eruptions.

Table 2.5. Summary of seismic swarms/volcanic unrest at Taal from AD1987 to AD2015 that did not culminate in an eruption. Source: Volcano Monitoring Division and Eruption Prediction Division (VMEPD), PHIVOLCS-DOST, 2017.

Year (AD)	Duration	Observations	Alert Status
1987	30 Oct. to 04 Nov.	Earthquakes felt at the SSW of TL	
1988	August (two-week period)	Several small-amplitude (average of 2 mm) HFVE; slight inflation (water tube tiltmeter)	
1989	June to October	Average of 6 earthquakes per day; epicenters located at MCL, NE of Taal; slight inflation at MC & Mt. Tabaro; small bubbles observed at MCL	
1991	March to July	Earthquakes up to 45 per day w/ some felt at TVI (RF adapted I-V); epicenters located at MCL to ENE of Taal; intense bubbling at MCL; lake temperature increased from 30° to 32°C; geysering at NNE wall of MCL w/ temp. from 97-100°C; more steaming vents formed due to fissuring along thermal area	
1992	14-28 February	Total of 2,550 earthquakes in 24 hours, some felt; returned to baseline level after two weeks; inflation of 20 cm; fissuring at DK (NE) about 5-50 mm wide & 20-400 m long; trending E-W & parallel to MC; 5 fissures at Pira-piraso (NE) approximately 2.6 mm wide & 1-2 m long; intense bubbling at MCL; lake temperature increased by 2°C.	Feb 14-Alert 2; Feb 17-Alert 3 (total evacuation of TVI); Feb 22- Alert 2; Feb 26- Alert 1
1993	09 April	Slight increase in seismicity; increased bubbling activity & temperature of MCL	Apr 9- Alert 2
1994	23 February	Increasing trend in seismicity; slight inflation at SW portion of TVI; increasing trend in MCL temperature & bubbling activity	Feb 23- Alert 2 reiterated
1994	11 March to 31 May	Total of1,550 earthquakes recorded within 24 hours, several felt (RF I-II) located at E & SE sides of Taal with depths of <5 km; Inflation of 16 cm at DK (NE) & 9.8 cm at Calauit (SE of Taal); two ground fissures formed at Calauit, 70 m apart (8.0 mm and 10 mm wide); pH values range from 2.18 to 2.20; intense bubbling at E & NE sector of MCL; lake temperature increased from 34°C to 39°C.	Alert Level 3 (evacuation of women, children & elderly from TVI); Jul 27-Alert 2; Feb 22'95-Alert 1; Jan 9'96-Alert 0
1999	27 July	Localized tremor at MC; occurrence of geysering activity near shoreline of Main Crater Lake	Jul 27- Alert 1; Apr 6'2000- Alert 0
2000	19 July to 31 October	Seismic swarm; 59 earthquakes plotted & located w/ epicenters in E & SE of MCL w/ depths of 2-5 km	Alert 0 maintained
2004	23 Sept. to November	Significant increase in daily seismic count; large amplitude earthquakes; epicenters plotted w/in MC near Binintiang Malaki (NNW) & near Calauit area (SSE); depths of less than 1.0 to 4.0 km beneath the volcano; slight inflation of volcanic edifice	Oct 29-Alert Level 1
2005	January to February	Series of volcanic earthquakes recorded; some felt at PEIS II-III at Volcano Island (Pira-piraso); epicenters located w/in Main Crater and SSE near Calauit; depths of less than 1.0 to 4.0 km	Jan 9-Alert Level 1; Jun 30-Alert 0
2005	21 November	Slight seismic unrest	Nov 23-Alert 1
2006	January, November	January – high level of seismicity; earthquakes clustered mainly at the east and southeast sectors of volcano island covering the MC & Calauit areas; depths of earthquakes about 2-4 km; Nov 17 - geysering activity near the shoreline of MCL; muddy water spewed 2-3 m high; sulfur stench observed; lake temp 35°C & slight increase in bubbling activity at MCL	Alert Level 1
2007	June	June – increase in seismic activity; felt at Int. II-III at Pira-piraso; felt also at Calauit; depths of 2.8-3.4 km; inflation of the volcano edifice during June survey	Alert Level 1
2008	August & September	Aug 28 (12:33 PM and 12:46 PM) – earthquakes felt at PEIS II at Pira-piraso w/ depths of 0.6 to 0.8 km.; source located at DK; Sep 30-another earthquake felt at Pira-piraso, Alas-as & Banyaga (PEIS I) located 650 m W of TVI w/ depth of 1.7 km; still inflated when compared to 2004 readings	Advisory issued about volcano's unrest; Alert Level 1 maintained
2010	8 June	Continued increase in seismicity; size increasing with LF-type recorded on June 2; further inflation detected in June precise leveling survey; lake temperature was 34°C on May 24, 2010; intensified steaming activity at N & NE side of MC sometimes accompanied by audible hissing sounds; increase in ground temperature & magnetic anomaly at DK & MC	Jun 8-Alert 2; Aug 2-Alert 1
2011	March	Increasing number of volcanic quakes	Mar-Alert Level 1

2011	April	Increased seismicity w/ shallow depths (1.0-4.0 km); increase in felt earthquakes (PEIS I-III) at TVI w/ some rumbling sounds; ground deformation results showed inflationary trend compared w/ February 2011 survey; gas measurements conducted at MCL yielded CO_2 emission flux of 1,875 t/d in February 2011 and 4,670 t/d during the last week of March 2011 w/ the increase related to its release from the magma at depth; steaming activities at N & NE of MC intensified intermittently w/ some burst accompanied by audible hissing sounds	Apr 9-Alert 2; Jul 5-Alert 1
2012	November	Increased no. of earthquakes with 10 felt (PEIS I to III) at TVI, some accompanied by rumbling sounds	Alert Level 1 reiterated
2015	Late January to early March	Increased seismicity with 39 volcanic earthquakes on 3 February with one felt at 3:26AM, PEIS II reported at Barangays Pira-Piraso & Talisay; inflationary trend in precise levelling and GPS measurements since June 2014	Still at Alert Level 1
2015	5-6 May	Sudden increase in volcanic earthquakes w/ maximum of 41 on 5 May with two 2 felt earthquakes, one w/ rumbling sounds; slight inflationary trend measured during 17 February to 2 March 2015 compared to Nov 2016 survey	Still at Alert Level 1

ACRONYMS: TL-Taal Lake; LFVE-low frequency volcanic earthquakes; HFVE-high frequency volcanic earthquake; MC- Main Crater; MCL- Main Crater Lake; TVI- Taal Volcano Island; RF(adapted)-Rossi-Forrel earthquake intensity scale used from 1935-1996; PEIS- PHIVOLCS Earthquake Intensity Scale; DK- Daang Kastila; t/d- tonnes per day; SSW-south-southwest; SSE- south-southeast; NE-northeast; NNW- north-northwest; W-west; SSE-south-southeast; E- east.

2.3.1. Processes and products from Taal eruptions

This section provides an overview of the identified processes and products of Taal and discusses one important environmental factor (climate) crucial to volcanic hazard and risk assessment and management, as well as provincial issues that have considerable influence on how a volcanic crisis might be handled by the community. This analysis is undertaken because present day landforms around Taal may not always provide evidence of the processes and products generated during historical eruptions. With the Philippines being a tropical country, eruptive deposits are generally poorly preserved, especially tephra fall deposits that are easily eroded and washed away (Collins & Dunne, 1986). However, where field data are available, interpretation of processes and products becomes more credible and consistent with the narratives from those historical accounts.

Most of the historical eruptions of Taal were hydrovolcanic. In most instances, magma interacting with external sources of water generated explosive ejection of water, steam and volcanic fragments (Fontaine et al., 2002). Some of the listed eruptions, such as AD1605-1611, AD1634, AD1635 and AD1645, I now deem uncertain. Detailed discussion of the historical eruptions and new interpretations about the processes and products are provided in Chapter 4. Some events are classified as phreatic eruptions including those in AD1591, AD1641, AD1707, AD1878, AD1904 and AD1977. Classified as *Phreatomagmatic eruptions* are the AD1709, AD1716, AD1731, AD1808, AD1874, AD1966, and AD1967 events. The AD1572, AD1715, AD1968, and AD1969 events were *Strombolian*, which are considered mild to violent eruptions of gas-charged, low viscosity basaltic magma (Carey, 2005).

Previous interpretations of the AD1749 event were that it was Phreatomagmatic with a description of the occurrence of a column-collapse pyroclastic density current. I provide an alternative interpretation of eruption style for this event and this will be discussed in Chapter 4. Further, previous studies did not identify individual eruptive phases for the AD1754 event. Where needed, new and/or additional interpretations of processes and products of the abovementioned eruptions are undertaken in this thesis, guided by newly available volcanology literature and my field experience. These new interpretations, and more detailed discussion on the mechanism, associated deposits, and impacts of the historical eruptions of Taal, are provided in Chapter 4. Appendix B summarises dates of eruptive activity, location of eruption sites, assigned VEIs, the style and nature of each eruption, eruptive processes, deposits, and impacts of the historical eruptions of Taal.

Previously identified volcanic hazards at Taal include pyroclastic density currents (pyroclastic flows and base surges), tephra fallout and ballistic projectiles, lava flows, volcanic tsunami and seiche, toxic volcanic gases, volcanic earthquakes, ground fissuring and subsidence, lahars and flooding, electrical activity, and atmospheric shock waves.

One of the deadliest products of an explosive eruption is *pyroclastic density currents* (PDCs) that are gravity-driven, ground-hugging flows moving at very high speeds consisting of volcanic ejecta and gases (Scott, 1989; Druitt, 1998). Based on textural characteristics, PDCs can either be massive, poorly-sorted and density-stratified *pyroclastic flows*, or *pyroclastic/base surge deposits* that generally consist of blocks, lapilli, and ash that are observed to be plastered on objects in their path, providing evidence that the blasted materials were mixed with water (Moore, 1967; Cas and Wright, 1987). The observed PDCs during the more explosive eruptions (e.g. AD1911) at Taal created sand blast effects on objects in their paths. Other eruptions that generated PDCs included the AD1716, AD1731, AD1749, AD1754, and AD1965 events (Appendix A). *Tephra fall* is gravitational settling of air-borne fragments of volcanic material ejected into the atmosphere during explosive eruptions (Scott, 1989; Tilling, 2005) and dispersed depending on prevalent wind strengths and directions, as well as the height of the eruption column (Scott, 1989). Emplacement of tephra deposits during eruptions causes widespread damage and disruption to lifelines, infrastructure, agriculture, health, aviation and the environment (Antos, 1984; Casadevall et al., 1996; Blong, 2003; Kuhnt et al., 2005; Horwell & Baxter, 2006; Stewart et al., 2006; Ayris & Delmelle, 2012; Carslaw et al., 2012; Wahyunto et al., 2012; Wardman et al., 2012a, 2012b; Wilson et al., 2012; Damby et al., 2013; Magill et al., 2013; Thompson et al., 2017). All of the confirmed historical eruptions of Taal generated tephra fallout deposits (Appendix B) (PHIVOLCS-DOST, 1991). The farthest reported distance reached by tephra during the AD1754 eruption was more than 60 km from the volcano, even as far as Manila. *Ballistic projectiles* are rock fragments (blocks or bombs) that are explosively hurled into the air from the erupting vent (Tilling, 2005). Based on various reports, ballistic projectiles were described during the eruptions in AD1572, AD1715, AD1731, AD1731, AD1749, AD1754, AD1904, AD1911, AD1965, AD1966 and AD1967 (Appendix B) (PHIVOLCS-DOST, 1991). *Lava flows* are defined as incandescent rivers of hot molten material from effusive eruptive phases (Tilling, 2005) that can result in burning, burial, and crushing of structures (Scott, 1989). The AD1968 and AD1969 eruptions were previously reported to have generated lava deposits (PHIVOLCS-DOST, 1991), but other eruptions, such as the AD1572, AD1715, and AD1965 events, also produced lava. The lava deposits during the AD1968 and AD1969 strombolian eruptions encroached past the shoreline at Mt. Tabaro (Figure 2.7B) into the lake (PHIVOLCS-DOST, 1991; Ruelo, 1983).

Sudden displacement of water resulting from the occurrence of large-magnitude earthquakes, subsidence of a volcano edifice, landslides and/or other types of entry of volcanic materials into bodies of water, or by shock waves occurring close to bodies of water can generate *volcanic tsunami* (Latter, 1981; Paris, 2014; Scott, 1989; Tilling, 2005). Conversely, a *seiche* is an oscillation of a landlocked body of water (such as a lake) that are generated by disturbance due to a volcanic activity (e.g.

underwater volcanic eruption) or emplacement of volcanic deposits with a duration varying from a few minutes to several hours. Volcanic tsunami during eruptions at Taal resulted in waves inundating lakeshore areas and causing damage and deaths due to inundation and drowning. Another hazard is *volcanic gases* (Scott, 1989). The most prevalent volcanic gas is water vapour, while sulfur dioxide (SO_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S), carbon monoxide (CO), chlorine and fluorine are also common toxic gases near the vents of erupting volcanoes (Scott, 1989; Williams & McBirney, 1979). Toxic gases can have global impacts during large-magnitude eruptions that may include the injection of SO_2 into the stratosphere, or reverse greenhouse effects (e.g. AD1991 eruption of Pinatubo Volcano, Philippines) (Self et al., 1996), or have local health effects including asphyxiation, respiratory tract and airway constriction, and eye irritation. Toxic gases were released during eruptions at Taal in AD1716, AD1749, AD1754, AD1874, AD1911, and AD1965 (Appendix B). *Acid rain* is commonly formed when precipitation is combined with sulfur dioxide released into the atmosphere (Christiansen, 2015). This phenomenon is known to cause burns, with acid rain recorded during the AD1716, AD1749, AD1754, AD1911 and AD1965 eruptions (PHIVOLCS, 1991) (Appendix B).

Movement of magma to the surface generates *volcanic earthquakes* (Blong, 1984; Scott, 1989). Volcanic explosions, related mass movement and/or tectonic activity near the volcano can also produce earthquakes. Precedent to and during most of the eruptions at Taal, swarms of moderate to large-magnitude volcanic earthquakes were felt and recorded (Appendix B). Seismic activity related to the AD1911 eruption was recorded by seismic monitoring equipment established during the American occupation. Some of these volcanic earthquakes were felt as far as Manila. Further, although eruption documentation for the AD1965 to AD1977 events does not specifically describe the occurrence of volcanic earthquakes, the DOST-PHIVOLCS volcano stations already installed at TVI and Buco in Talisay Municipality recorded ground shaking during the AD1965 to AD1977 events. *Ground fissuring* is produced because of the movement of magma beneath the surface or adjustments along faults in the vicinity of the volcano. The phenomenon is often accompanied by severe earthquakes. Immediately after intense earthquake shaking during the AD1749, AD1754 and AD1911 Taal eruptions, fissures and subsidence were observed (Appendix B). Lakeshore areas were subsequently inundated by lake water after the subsidence. The phenomena also resulted in damage to infrastructure (PHIVOLCS, 1991). Ground fissures and subsidence were also reported in Lemery, Batangas Province during or after the AD1911 eruption (Pratt, 1911; PHIVOLCS-DOST, 1991).

Lahars occurred during past eruptions. On 29 November AD1754, during a heavy downpour, there was notable reference to ash being washed to the ground presumably with landslides and lahars (PHIVOLCS, 1991). Flooding also occurred on the eastern and northern lakeshores with Old Lipa (now part of Mataas Na Kahoy Municipality) and Old Tanauan (now part of Talisay Municipality) cited by Saderra Masó (1911) resulting from the damming of Pansipit River by volcanic materials (Figure 2.1).

When tall eruption columns are generated, *electrical activity* may occur (McNutt & Williams, 2010; Behnke et al., 2013). The presence of fine tephra particles within the plume and the subsequent friction caused by the interaction of tephra particles, steam and other gases produces electrical discharges (Blong, 1984). Lightning may be in the form of *vent discharges* that are small and close to or directly above the vent, or *near-vent lightning* that are often one to seven kilometers in height that extents from the vent towards the tephra plume, or they may be *plume lightning* that is often found within the plume far from the vent (Behnke et al., 2013). Notable observations of electrical discharges were reported by Pratt (1911) during the AD1911 eruption. Electrical activity during the AD1749 eruption is reported in the PHIVOLCS-DOST Taal Volcano Profile (PHIVOLCS-DOST, 1991), but the other Taal eruptions with accounts reported by Saderra Masó (1911) and Worcester (1912) (e.g. AD1707, AD1754, AD1911), and those "continuous display of lightning" mentioned by Moore (1966) during the AD1965 eruption are now interpreted in this thesis as electrical activity (Appendix B). Electrical activity is found to be an important phenomenon that can confirm the occurrence of an ongoing explosive eruption (McNutt & Davis, 2000).

Atmospheric shock waves were also observed during some of the historical eruptions of Taal including the AD1707, AD1749, AD1754, AD1911 and AD1965 eruptions (Appendix B). Shock waves are formed when volcanic materials are ejected at supersonic velocity during an explosive eruption, moving rapidly along slopes, with the energy and sound dissipating as they move farther from the source (Scott, 1989). Shock waves can cause structural damage and glass breakage.

Frequently observed in saturated alluvial environments with loosely consolidated materials, liquefaction occurs when these loose materials are subjected to intense ground shaking during earthquakes (Emergeo Working Group, 2013; Liyanapathirana

& Poulos, 2004). Some of the subsidence, fissuring near the shoreline, sand boils, and changes in water courses were mostly observed near the shoreline adjacent to Taal Lake subsequent to occurrence of large-magnitude volcanic earthquakes during the AD1749, AD1754 and AD1911 eruptions (Saderra Masó, 1911) (Appendix B). More detailed discussion on the eruptive deposits produced by the historical eruptions of Taal are provided in Chapter 4.

2.3.2. Climate and rainfall as critical environmental factors contributing to hazard assessment

An important environmental factor to consider is the climatic conditions as they relate to potential dispersal and deposition of tephra fallout. The impacts of the eruption of Pinatubo in AD1991 was further aggravated by the passage of a typhoon and intense precipitation (Wolfe and Hoblitt, 1996). Likewise, the study by Ayris (2012) showed that cohesive tephra fallout deposits have higher threshold velocities especially when wet and this could result in greater impact to agriculture because wet ash is harder to wash away from agricultural crops. In the assessment of volcanic hazard and risk, specifically for prediction of dispersal of tephra fallout, wind advection plays a crucial role (Volentik et al., 2010).

Two of the four types of Philippine climate are dominant in the Province of Batangas (Figure 2.8). These include Type I, which is identified with two pronounced seasons: 1) dry from November to April; and 2) wet during the rest of the year. On the other hand, the dry season for Type III climate lasts from one to three months that may either be from December to February or March to May, while there is no pronounced wet period (PAGASA-DOST, 2017).

The prevailing wind direction (Table 2.6) is the most frequently observed direction during a given period, while average wind speed is measured in meters per second (Table 2.6) and is the arithmetic average of the observed wind speed. Wind direction is where the wind is coming from (e.g. NE winds are coming from the northeast).

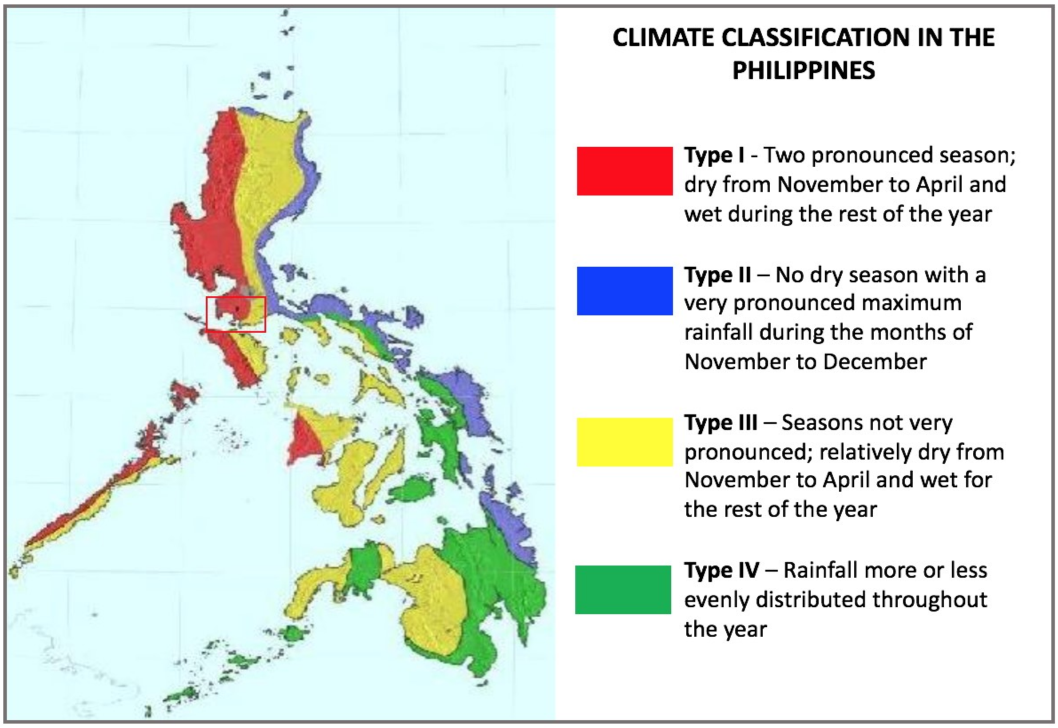


Figure 2.8. Climate classification in the Philippines. Batangas Province is straddled between Types I and III (in red box). Source: Department of Science and Technology-Philippine Atmospheric, Geophysical and Astronomical Services Administration of the (DOST-PAGASA).

Average wind speed from October to March is 2 $m{\cdot}s^{-1}$; 1 $m{\cdot}s^{-1}$ for April to July, 2 $m{\cdot}s^{-1}$ for the month of August, and 1 $m{\cdot}s^{-1}$ from September to October. Wind direction is NE from October to May and SW from June to September (Table 2.6) (PAGASA-DOST, 2014). Wind patterns have an important role during eruptions and in volcanic hazard assessment since ashfall/tephra dispersal are governed by prevailing wind patterns. The climatological information gathered here was used as initial input for wind direction and speed for numerical modelling. However, mean wind speeds used as inversion constraints were obtained from NCEP/NCAR Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, extracted from their web site at [https://climatedataguide.ucar.edu/climate-data/ncep-reanalysis-r2], the results of which are presented in Chapter 6.

Table 2.6. Climatological Normal Values for Batangas Province from AD1981 to AD2010. The prevailing wind direction most frequently observed during a given period while the average wind speed in meters per second is the arithmetic average of the observed wind speed. Wind direction is where it is coming from (e.g. NE winds is coming from the Northeast). Source: Ambulong Batangas Station of PAGASA-DOST.

MONTH	RAINFALL		WIND		NO. OF DAYS WITH	
	AMOUNT (mm)	NO. OF READINGS	DIRECTION	SPEED (m/s)	THUNDERSTORM	LIGHTNING
January	22.7	5	Northeast (NE)	2	0	0
February	16.0	3	Northeast (NE)	2	0	0
March	21.5	3	Northeast (NE)	2	1	1
April	35.0	4	Northeast (NE)	1	5	5
May	116.6	10	Northeast (NE)	1	13	14
June	228.7	16	Southwest (SW)	1	15	15
July	329.6	19	Southwest (SW)	1	17	16
August	255.0	18	Southwest (SW)	2	12	12
September	218.4	17	Southwest (SW)	1	14	14
October	218.4	15	Northeast (NE)	1	9	14
November	144.7	13	Northeast (NE)	2	2	6
December	92.0	9	Northeast (NE)	2	0	1
ANNUAL	1767.0	132	Northeast (NE)	2	88	98

2.3.3. Hazard and risk profile of Batangas Province

After focusing on the hazards posed by Taal, as narrated by eruption observers and interpreted by succeeding researchers including myself, I also reviewed all available DRR documents available from various local government units in the Province of Batangas to establish an overview of how various stakeholders in the province perceived threat of natural hazards including volcanic hazards.

Batangas Province continues to be vulnerable to various natural and man-made hazards (PPDO, 2016). Ballistic projectiles, base surge, and seiche or volcanic tsunami were identified as the main hazards related to Taal. Table 2.7 provides a summary volcanic hazard assessment list modified from the information gathered from the Provincial Disaster Risk Reduction and Management Office (PDRRMO) that identified the 14 Cities/Municipalities and 199 barangays prone to volcanic hazards that were purportedly based on the hazard maps for ballistic projectiles, base surge, and seiche or volcano tsunami generated by DOST-PHIVOLCS (2011) shown in Figures 2.9, 2.10 and 2.11, respectively. The hazard zone limits in the Taal Volcano Hazard Maps were based on data from the historical eruptions of AD1754, AD1911 and AD1965 eruptions. The basic assumption is that the eruption will occur anywhere within TVI and the likely maximum expected event scenario will be similar to the AD1754 eruption. In addition, for the PDC hazard delineation, the Energy Cone Model (ECM) was applied (Malin & Sheridan, 1982; Tierz et al., 2016). One volcanic hazard not identified in the provincial DRR documentation is tephra fallout hazard. This is because DOST-PHIVOLCS has to date, not produced a tephra fall hazard map for Taal due to an absence of detailed numerical modelling, a gap this thesis takes the initial step in addressing.

With the identified volcanic hazard of two Cities and 12 Municipalities highlighted in red as interpreted and applied by the local government of Batangas (Table 2.7), the question emerges about what preparedness measures are in place at the provincial, municipal and barangay level in order to mitigate impacts of these hazards? This study concentrates on the two cities, the City of Tanauan and Lipa City, and four municipalities, Talisay, Bauan, San Nicolas, Agoncillo and Laurel. Except for Bauan, all the municipalities and cities are generally within proximal to medial distances from Taal. I collected, collated and reviewed existing DRR plans in order to assess existence of the plans and validate their implementation in each community I have identified as part of my research (Table 2.8). Due to the extensive scope of my research, I was compelled to limit my search for DRR related documents to a selected number of local government units surrounding Taal. Figure 2.1 shows the locations of communities from which DRR information was obtained. The participation of various provincial offices in DRR and management aims at ensuring that preparation and implementation of strategies to handle crisis situations can either prevent or mitigate the impacts, reduce casualties and damage to properties, and provide prompt, safe and cost-effective rehabilitation and recovery measures. The DRRM-CCA Plan of the Province of Batangas aims to prioritize disaster prevention and mitigation through preparedness measures, not just emergency response. As I reviewed the provisions of the DRRM-CCA Plan and other DRRM related assessments, there appeared to be limited identification and analysis of volcanic hazards by the Provincial Government and the local government units.

In my vignette study, I therefore used the data I gathered from the review of the DRR documents I collected as reference (Table 2.8) when I analysed the data from the structured interviews of the Barangay Captains during my 2014, 2015 and 2016 fieldwork campaigns. The methodology of the vignette study is discussed in Section 3.4.1. The structured interview questionnaire generated for this study was intended to assess education, knowledge, eruption experiences, risk reaction and preparedness of the Barangay Captains to various volcanic hazards that may potentially impact their communities. Validation of the identified volcanic hazards that the Barangay Captains perceived may threaten their community versus actual hazard proneness based on the DOST-PHIVOLCS Volcanic Hazard Maps (Figures 2.9. 2.10 and 2.11) will be discussed in Chapter 7.

In-so-far as knowledge obtained from the literature review related to the historical eruptions of Taal is concerned, most especially regarding tephra deposits from the AD1754 eruption, validation of the dispersal, deposition and thicknesses of the tephra fallout was conducted through geologic mapping. While narrative descriptions of tephra dispersal from various eruptions of Taal were noted and documented in the past, detailed tephra accumulations from different point locations have never been mapped. Further, the detailed mapping of the tephra deposits from the AD1754 eruption was predetermined because it was one of the most explosive eruption of Taal.

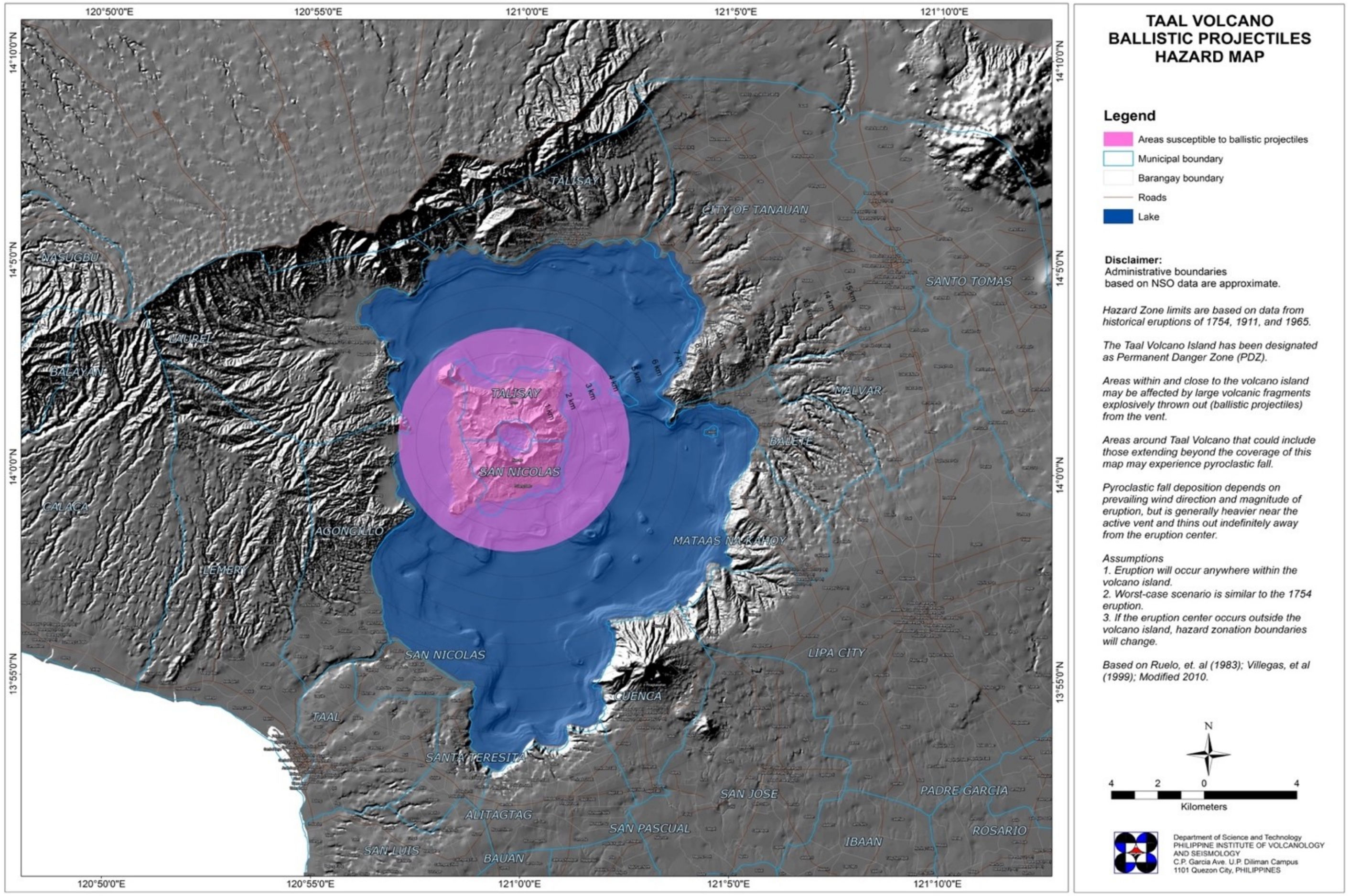


Figure 2.9. Taal Ballistic Projectiles Hazard Map. Source: PHIVOLCS (2010); modified version from Ruelo et al. (1983) and Villegas et al. (1999).

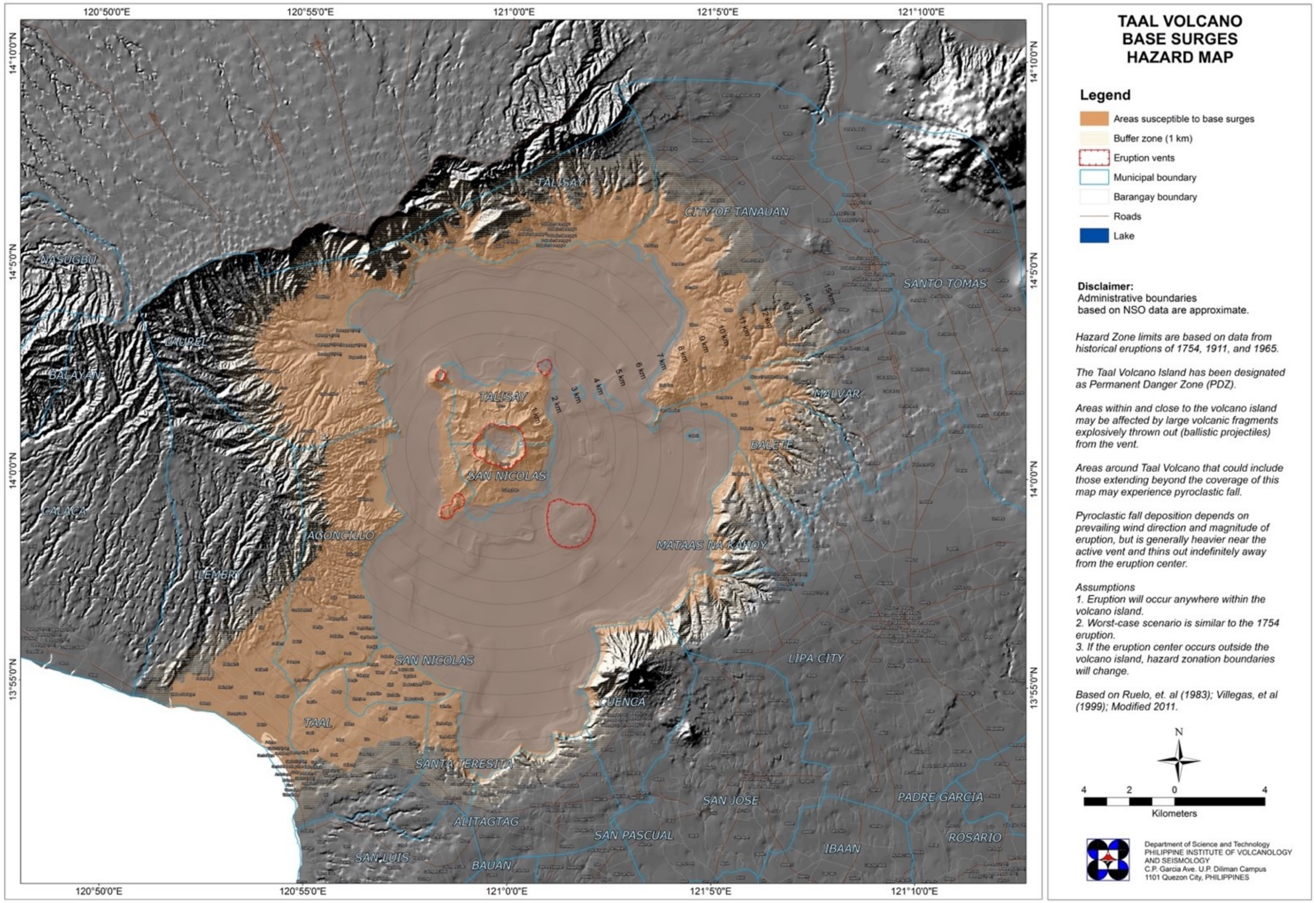


Figure 2.10. Taal Base Surge Hazard Map. Source: PHIVOLCS (2011); modified version from Ruelo et al. (1983) and Villegas et al. (1999).

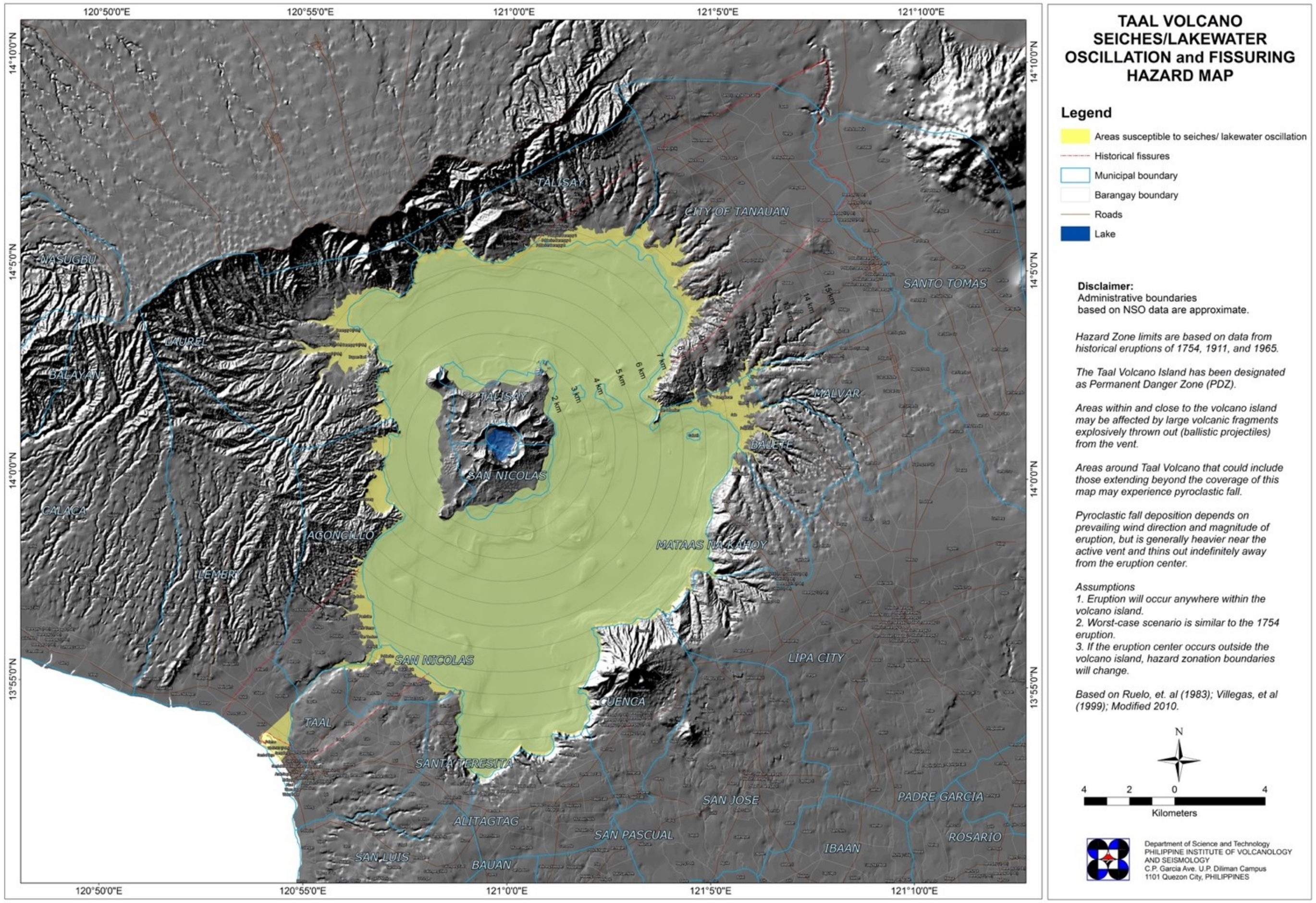


Figure 2.11. Taal Seiches/Lakewater Oscillation Hazard Map. Source: PHIVOLCS (2011); modified version from Ruelo et al. (1983) and Villegas et al. (1999).

Table 2.7. Summary volcanic hazard assessment list modified from the information provided by the Provincial Disaster Risk Reduction and Management Office (PDRRMO) of the Provincial Government of Batangas. Three cities and 12 municipalities of Batangas were identified as vulnerable to ballistic projectiles (BP), volcano tsunami/seiche (TSU/S), and/or pyroclastic density current/base surge (PDC/BS). They used the Taal hazard maps of DOST-PHIVOLCS (2011) as basis for their assessment. The cities and municipalities with identified potential impact from processes and products of an eruption at Taal as interpreted by the local government are in RED print. Estimated population at risk derived from population data from Census 2015.

MUNICIPALITY / CITY	POPULATION AT RISK	DISTRICT	BARANGAYS W/ HAZARD(S)			IDENTIFIED HAZARDS EXPOSURE OF CITY/MUNICIPALITY
			BP	TSU/S	PDC/BS	
Agoncillo	38059	3rd	3	7	11	38059
Alitagtag	7899 (partial)	3rd		5		7899 (partial)
Balayan		1st				
Balete	20186 (partial)	3rd	1	10		20186 (partial)
Batangas City		5th				
Bauan		2nd				
Calaca		1st				
Calatagan		1st				
Cuenca	5784	3rd	1	2		5784
Ibaan		4th				
Laurel	39,444	3rd	12	3	3	39,444
Lemery	56990	1st		8	24	56990
Lian		1st				
Lipa City	11008 (partial)	6th		4		11008 (partial)
Lobo		2nd				
Mabini		2nd				
Malvar	7156 (partial)	3rd			4	7156 (partial)
Mataas Na Kahoy	7308 (partial)	3rd		4		7308 (partial)
Nasugbu		1st				
Padre Garcia		4th				
Rosario		4th				
San Jose		4th				
San Juan		4th				
San Luis		2nd				
San Nicolas (Mainland)	20599	3rd	2	10	6	20599
San Pascual		2nd				
Santa Teresita	8099 (Partial)	3rd		9		8099 (Partial)
Santo Tomas		3rd				
Taal	39919 (Majority)	1st		3	31	39919 (Majority)
Talisay (Mainland)	39600	3rd		19	2	39600
City of Tanauan	173,366 (partial)	3rd	1	10	5	173,366 (partial)
Taysan		4th				
Tingloy		2nd				
Tuy		1st				

Table 2.8. List of critical agencies and community offices with Disaster Risk Reduction and Management (DRRM) related documents reviewed for this study.

OFFICE	LOCATION	CATEGORY	DOCUMENTS ACQUIRED	DRRM PROVISIONS /REMARKS
Municipal Mayor	Agoncillo Municipal Hall	Municipal	MDRRM Plan (2013-2016)	Unusual animal behaviour as signs of volcanic activity; high perceived risk for all 21 barangays; trainings conducted
Brgy Hall	Subic Ibaba, Agoncillo	Barangay	BDRRM Plan 2012	Training conducted but no volcanic eruption drill yet; existing Barangay Emergency Response Teams (BERT) & BDRRM Plan but no fixed evacuation procedure; early warning system (EWS) in place; believe within range of 12 kms at risk during eruption; needs assessment done including lack of emergency equipment and evacuation centers
Subic ES	Subic Ibaba, Agoncillo	School	DRR Management/DepEd-Region IV-A, Division of Batangas, District of Agoncillo	Have School DRR Development Plan as part of the requirement of DepEd aimed at integrating DRR activities into the daily lives of all stakeholders in the school including parents of enrolled students; have DRR coordinator in the school
PDRRMO/Provincial Assistance for LDRRMO	Provincial Office-Batangas	Provincial	Provincial Socio-Economic & Physical Profile 2016; Provincial DRRM-CCA Plan	Identified Cities/Municipalities/Barangays at risk during volcanic eruption
MDRRMO	Bauan Municipal Hall	Municipal	Bauan DRRM Contingency Plan (for all hazards); Contingency Plan for Volcanic Eruptions; Location map of Evacuation; Centers in Bauan; CLUP (2011-2020)	Volcanic eruption not identified as hazard; only identified flood, fire & dengue as hazards
Brgy Hall	Poblacion 1, Bauan	Barangay	BDRRM Plan 2012	Specified that the BDRRMO has sufficient knowledge on what to do before and after a crisis but no specific action identified; mentioned that they conduct drills related to disasters and have protocols in place related to disaster response
Leviste, Laurel	Brgy Hall	Barangay	Barangay Leviste Contingency Plan 2014; Spot Map	No discussions on volcanic eruption as a hazard and perceived vulnerability
Lipa City	Office of the Mayor	City	Lipa City DRRM Plan 2011; Lipa City Profile	Have Contingency Plan for volcanic eruption with DRR Committees with designated responsibilities, Heads and member agencies; evacuation centers identified; believe they have moderate capacity for DRR; Barangay Operation Center in place
Duhatan, Lipa City	Brgy Hall	Barangay	Brgy Duhatan Disaster Contingency Plan 2014 (Typhoon/Dengue/ Landslide/ Volcanic Eruption)	Have Contingency Plan for Typhoon/Dengue/Landslide/ Volcanic Eruption; have identified two sitios (small units of a barangay) Malabong & Hinitan as being at risk in the event of an eruption
Tanauan City Hall	MSWDO/ MDRRMMO/ City Planning & Development Office	Municipal	LDRRM Plan 2014; Contingency Planning for Volcanic Eruption/ Flood/ Landslides; CLUP 2005-2025	Existing CDRRMO Contingency Plan for volcanic eruptions with pre-, during and post-eruption activities with identified responsible persons and committees for each activity; identified schools that will serve as evacuation centers; identified vulnerable communities
Talisay Municipal Hall	MDRRMO	Municipal	CLUP 2012-2022; Talisay Profile; Municipal Socio-Economic & Physical Profile 2015; Contingency Plan draft on Volcanic Eruption; DRRM Plan 2014-2016	CLUP identifies volcanic hazards including base surge, tephra, lakeshore landslides, erosion and subsidence

Acronyms: PDRRMO- Provincial Disaster Risk Reduction & Management Office; LDRRMO- Local Disaster Risk Reduction & Management Office; MSWDO- Municipal Social Welfare & Development Office; MDRRMO- Municipal Disaster Risk Reduction & Management Office; CCA- Climate Change Adaptation; LDRRM- Local Disaster Risk Reduction & Management; CLUP-; Comprehensive Land Use Plan; BDRRM; BDRRMO- Barangay Disaster Risk Reduction & Management Office; DepEd- Department of Education; CDRRMO- City Disaster Risk Reduction & Management Office.

This specific study on tephra deposits was conducted as this hazard has the most widespread impact including the potential to affect Manila. In relation to tephra fallout, the information gathered from historical narrative accounts included: 1) identification of areas impacted by historical eruptions, specifically the AD1754 event; 2) thickness of tephra; and 3) interpreted heights of tephra column that can provide estimates of explosivity and style of the eruption (Plinian/Sub-Plinian), and provide estimates of total volume of erupted material (150 million m^3 for the AD1754 event), and the magnitude and explosivity (VEI 5). However, more detailed information on the actual eruption source parameters of the AD1754 eruption remains undetermined. Volentik et al. (2010, p. 117) emphasised the importance of eruption source parameters when they wrote, "*the determination of eruptive parameters is crucial in volcanology, not only to document past eruptions, but also for tephra fallout hazard assessments*". As it is, the field information and historical accounts for the AD1754 eruption, on their own, cannot provide adequate information that will enable the conduct of a full tephra hazard assessment. Refinement of eruption source parameters through numerical modelling has been proven to be an effective tool for volcanic hazard and impact assessment (Connor, et al., 2001; Bonadonna et al., 2005a; Barsotti et al., 2010; Bonasia et al., 2011; Biass et al., 2012, 2013) and I therefore chose to use inversion techniques to refine source parameters for the AD1754 eruption in this study.

I reviewed the available literature to gather information on tephra dispersal modelling and sought answers to some basic questions that need to be addressed prior to selection of the tephra model to be used. These include: 1) Why is there a need to conduct tephra modelling? 2) What are the different models available and how do they work? 3) How accurate are they and what are their limitations? 4) What model is best suited to replicating the AD1754 eruption? 5) What input data are required? and 6) How can they be validated?

2.4 Tephra dispersal modelling

2.4.1. Tephra fallout hazard

Perhaps the best description to justify my research focus on Taal Volcano's tephra fall hazard is given by Scott (1989, p. 17): "*Tephra fall poses the widest ranging hazard from volcanic eruptions*". During the AD1754 eruption, a translated account from Father Buencuchillo, then stationed at Old Taal, now known as San Nicolas, located southwest of the volcano (Figure 2.1), narrated a description of the observed thickness of tephra in the area when he said "*At daybreak of September 25, we found ourselves forced to abandon our dwellings for fear lest the roofs come down upon us under the weight of ashes and stones which had fallen upon them during that hapless night. In fact, some weaker buildings collapsed. The depth of the layer of ashes and stones exceeded two cuartas (45 centimeters), and the result was that there was neither tree nor other plant which it did not ruin or crush, giving to the whole region as aspect as if a devastating conflagration had swept over it*" (Saderra Masó, 1911). In the study undertaken by Spence et al. (1996), with similar results by the research findings of Blong (2003), building failures occurred with wet ash loading of 15 to 20 cm of tephra. However, there are still ongoing conflicting views on such issues as vulnerability estimates on ash loading for buildings, levels of damage from such events, issues on building resilience within specific construction types, and the limited experience of evaluators (Blong et al. (2017). As a consequence, there are large uncertainties in the assessment of potential building damage and loss associated with volcanic ash loading. Blong further recommends that future research should consider which building characteristics will be most appropriate for vulnerability assessments of buildings to ash/tephra.

Authors have seen the importance and impact of tephra fallout to agricultural crops through *acid burning and burial* (Craig et al., 2016; Cronin et al., 1998; Cronin et al., 2003; Hunn and Norton, 1984; Magill et al., 2013; Wahyunto et al., 2012; Wilson et al., 2011); *health* (Damby et al., 2013; Hickling et al., 1999; Horwell and Baxter, 2006; Horwell et al., 2010; Rose and Durant, 200;); *buildings and other infrastructure* (Blong, 1981; Blong et al., 2017; Broom, 2010; Milazzo et al., 2013; Spence et al., 1996; Spence et al., 2005; Wilson et al., 2012); *the environment* (Haeckel et al., 2001; Kuhnt et al., 2005); *critical power* (Wardman et al., 2012b), *water supply* (Stewart et al., 2006; Stewart et al., 2009), and *transportation services* (Blong, 1984; Magill et al., 2013); *corrosion of metal* (Oze et al., 2014); *disruption of communications due to interference of radio waves or direct damage to communication facilities* (Folch, 2012); *flora and fauna* (Antos, 1984; Kelfoun et al., 2000; Seymour et al., 1983; Zobel and Antos, 1997); *civil aviation* (Alexander, 2013; Armienti et al., 1988a; Casadevall, 1994; Casadevall et al., 1996; Carslaw et al., 2012; Guffanti et al., 2005; Guffanti et al., 2009; Sulpizio et al., 2012; Tupper et al., 2006; Volentik and Houghton, 2015); *manufacturing and industry* (Wilson & Cole, 2007); and more recently, *tourism* (Bird et al., 2010).

Knowing how widely tephra fall can impact people and the environment, it becomes critical that volcanic risk assessment includes consideration of tephra fallout. Numerical modelling in particular can validate historical records and field observations of tephra accumulation, as well as serve to predict dispersal and accumulation during future eruptions (Connor et al., 2001; Keating et al., 2008; Magill et al., 2015; Magill et al., 2006; Mead et al., 2016).

2.4.2. Reconstruction of the AD1754 eruption through numerical modelling

The AD1754 Plinian/Sub-Plinian event was one of the most explosive and catastrophic historical eruptions of Taal. The paucity of information available regarding eruption source parameters, accurate estimation of the total volume of erupted deposits from the eruption, and the extent of tephra dispersion and accumulation from this eruption are knowledge gaps that this research will attempt to address. Likewise, no previous attempt has been made to determine the different eruptive phases of the AD1754 event. In the course of this research, it has been possible to separate the events into various major phases that will be discussed in detail. Reconstructing the AD1754 eruption, representing the maximum expected event scenario for Taal, through numerical modelling can provide vital eruption information specifically to fill the information gaps regarding this eruption, including providing a complete picture of tephra dispersal, environmental conditions, and eruption source parameters. The limited, but valuable, descriptions of the tephra fall effects sourced from narrative accounts were utilised as starting points for geologic mapping and inputs for numerical modelling.

The following sub-sections provide a summary of different tephra models, their use, advantages and drawbacks, and more detail on the *TEPHRA2* tephra dispersal model, chosen for this research.

2.4.3. Tephra dispersal models

Numerical modelling of tephra dispersion and fallout is a computational process by which tephra advection, diffusion and accumulation are quantified (Bonadonna et al., 2005). With improved ability to quantify eruption dynamics, and to predict dispersal and accumulation, tephra hazard assessment is also improved and short-term forecasts can be provided (Connor et al., 2001; Folch et al., 2008).

Folch et al. (2008) identified the tephra model types in use, either for predicting particle transport and/or determination of deposit accumulation: 1) particle settling and deposition in a wind field; 2) advection-diffusion Eulerian models; 3) particle dispersal from umbrella clouds spreading as gravity currents; and 4) Lagrangian particle tracking.

Models simulating particle settling and deposition in a wind field in a particular trajectory generally predict mass and grain size of tephra particles as a function of distance from the vent. These particular models use known wind velocity profiles and eruption heights. Examples of models are described in the model by Shaw et al. (1974), the model by Bursik et al. (1992a), the FALLOUT Model (Carey and Sparks, 1986), and the tephra dispersal model from umbrella clouds (Koyaguchi and Ohno, 2001)(Appendix C).

Advection-diffusion models are Eulerian (simulate for fixed locations in space, as opposed to Lagrangian, which simulate for space and time) and reconstruct grain size dependent particle diffusion from an eruptive source within in a stratified atmosphere and accumulation on the ground (Bonadonna et al., 2005c; Connor et al., 2011). Some examples of advection diffusion models are provided in cited Table 2.9 that includes the Suzuki Model (Suzuki, 1983), the 3-D Model (Armienti et al., 1988b), HAZMAP (Macedonio, et al, 1988; Macedonio et al., 2005; Pfeiffer et al., 2005), the Ash dispersal model (Glaze and Self, 1991), Fall3D (Costa, et al., 2006, Macedonio et al., 2008), ASHFALL (Hurst & Smith, 2004; Hurst & Turner, 1999; Jenkins et al., 2012), TEPHRA (Bonadonna et al., 2005a), and TEPHRA2 (Biass et al., 2012; Courtland et al., 2012; Magill et al., 2015; Volentik et al., 2010).

Mushroom Cloud is a model that predicts particle dispersal from umbrella clouds transported by prevailing wind then subsequent spreading as gravity currents, with the assumption of uniform turbulent suspension (Slaughter and Hamil, 1970; Bonadonna et al., 1998; Bursik et al., 1992b; Folch et al., 2008). It is a simplified and qualitative physical model that incorporates particle aggregation to account for the presence of coarse and fine particles near source. Resulting tephra thickness maps show a single thickness with distance from the vent and my review of the literature saw limited use.

Particle-tracking models are typically Lagrangian and predict volcanic plume dispersion at a specific time. They were developed as an emergency response measure focused on providing data on dispersal mainly for aircraft flight operations (Connor et al., 2011). Various particle tracking models have been developed by concerned agencies including Volcanic Ash Advisory Centres (VAACs) throughout the world. These include: MLDPO (Modele Lagrangian de Dispersion des Particules) developed by Montreal VAAC (http://www.ssd.noaa.gov/VAAC/vaac.html), PUFF (Volcanic Ash Tracking Model) by Anchorage VAAC (Searcy et al., 1998), NAME (Numerical Atmospheric-dispersion Modelling Environment) by London VAAC (Müller et al., 2013), HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory by Washington VAAC (Draxler et al., 2005), MEDIA (Model for Dispersion in the Atmosphere) used by Toulouse VAAC, VAFTAD (Volcanic Ash Forecast Transport and Dispersion) developed by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (Heffter & Stunder, 1993), VOL-CALPUFF (Barsotti et al., 2008), and CANERM (Canadian Emergency Response Model) (D'amours, 1998). Summary descriptions of these models are provided in Appendix C. Table 2.9 provides the list of the different tephra model types as identified by Folch (2008), as well as the advantages and drawbacks of these models.

Table 2.9. Summary list of tephra fall model types, their advantages and drawbacks as identified by Folch (2008).

TEPHRA MODEL TYPES	ADVANTAGES	DRAWBACKS
Particle settling & deposition in a wind field	generally predict mass and grain size of tephra particles as a function of distance from the vent; able to infer paleowind directions & velocities and record eruption dispersal; can estimate volume and total height of eruption column	Does not consider some unknown factors such as varying eruption conditions, wind, & turbulence in the atmosphere; does not provide good results for eruption w/ fine particles (<1/2 mm) which are better studies using diffusion models
Advection-Diffusion Eulerian models	Simulate for fixed locations in space and reconstruct grain size dependent particle diffusion from an eruptive source within in a stratified atmosphere and accumulation on the ground; dispersal pattern independent of variation in total tephra mass; circular dispersion indicates low or absence of wind; good correlation of thicknesses of computed and observed measurements further from the vent; able to generate roof collapse risk; predicted geometry of tephra dispersal complements well with observed geologic data and can generate isopach maps and isomass distribution maps; automated & simplified meteorological datasets in a single-step process	Need to enhance performance & speed; requires larger computational times and resources; computed and observed near vent thicknesses do not correlate well
Particle dispersal from umbrella clouds	Simplified, qualitative physical model; incorporates particle aggregation to account for presence of coarse and fine particles near source	Ash thickness maps show single thickness
Lagrangian particle-tracking	Rapid computation results in just 2 minutes with the output ready for automatic facsimile distribution to pre-designated stakeholders	Does not compute for absolute ash concentrations or deposition; very few validations; Overestimation of surface concentration

Considering the different "families" of models, and having determined their objectives, advantages and drawbacks (Appendix C), early models classified as "particle settling and deposition in a wind field" are too simplified for my purposes as they do not consider variations in eruption conditions, wind, or turbulence in the atmosphere. Particle tracking models, on the other hand, are best suited for use during an eruption and are most appropriate for aircraft flight operations and aviation safety. Advection-diffusion models are the most appropriate for my research as they predict tephra accumulation on the ground and can be used for civil protection through generation of scenario-based hazard maps identifying areas prone to tephra fall.

While I identified various tephra models, I selected *TEPHRA2* for my research because of the model's proven ability in simulating other eruptions similar to the AD1754 Taal event (Bonadonna et al., 2005a; Fontijn et al., 2011; Johnston et al., 2012; Magill et al., 2015). Furthermore, inversion code (where iterative simulations are used to reconstruct a given deposit) has already been developed and tested utilising *TEPHRA2* (Biass & Bonadonna, 2011; Biass et al., 2012, 2013; Bonadonna et al., 2005c; Bonadonna et al., 2015; Bonasia et al., 2010; Cobeñas et al., 2012; Connor & Connor, 2005; Volentik et al., 2010), providing an ideal platform to simulate the AD1754 eruption. The succeeding section provides more detailed information about the *TEPHRA2* model and inversion methods.

2.4.4. *TEPHRA2* Model

TEPHRA2 is a public domain tephra transport and dispersal model [https://github.com/geoscience-community-codes/tephra2]. Rapid run times make the model ideal for conducting multiple simulations to predict transport and accumulation using specified eruption conditions and wind field information (Biass et al, 2012; Bonadonna et al., 2005b; Connor and Connor, 2005). The *TEPHRA2* model may also be used to simulate and reconstruct past eruptive events (Biass et al., 2017). It is an improved and optimized version of *TEPHRA* described in detail by Bonadonna et al. (1998), which is one of the many modified versions of the Suzuki Model (Suzuki, 1983).

Basic assumptions used within the *TEPHRA2* model, as provided by Bonadonna et al. (2002, 2005) and Connor and Connor (2011), include: 1) a normal grain size distribution (phi) describing the entire deposit; 2) the total mass erupted is vertically distributed within the tephra column, which is partitioned into discrete levels; 3) tephra particles are assumed to fall to a surface of uniform elevation that is considered as a reasonable approximation for many volcanoes; 4) particles are spherical and the total fall time considers particle density, grain size and atmospheric density; 5) mass is accumulated at given grid locations with results being total accumulation of tephra in mass per unit area; 6) a bivariate Gaussian probability density function is used to calculate particle diffusion in the atmosphere; and 7) varying wind speeds and directions may be applied to each atmospheric layer. Other modelling studies using *TEPHRA2* applied the same assumptions listed here (Biass et al., 2012; Cobeñas et al, 2012; Connor & Connor, 2006; Courtland et al., 2012; Fontijn, 2011; Magill et al., 2015; Volentik et al., 2010).

Tephra modelling simulation case studies utilising *TEPHRA2* include the work of Connor and Connor (2011) on the 1992 eruption of Cerro Negro in Nicaragua, the 1968 eruption of Irazu Volcano in Costa Rica, and the 2350 BP eruption of Pululagua in Ecuador, Johnston et al. (2012) on the Bronze Age eruption of Santorini in Greece, Biass et al. (2012) on Cotopaxi Volcano in Ecuador, Courtland et al. (2012) on Cerro Negro Volcano in Nicaragua, Volentik et al. (2010) on the 2450 BP Plinian eruption of Pululagua Volcano in Ecuador, and Magill et al. (2015) on the 1707 Hoei eruption of Mount Fuji in Japan.

2.4.5. Inversion using *TEPHRA2*

Using inversion techniques and field observations, one can obtain estimations of eruption source parameters for a specific eruption being studied. These parameters include total erupted mass, eruption column height, and total particle size distribution statistics, which in turn provide estimates of eruption dynamics, especially for events that have limited or incomplete field or historical information.

The inversion method developed by Connor and Connor (2005), and utilised here, involves: 1) use of field-derived mass per unit area observations for a particular deposit; 2) acceptable, user-defined ranges for eruption source parameters, e.g. column height and total erupted mass; 3) for each run, simulated tephra dispersal using a selected set of eruption source parameters by *TEPHRA2* with results compared to field-derived measurements; and 4) selected a new set of parameters for simulation using a downhill simplex method, until an acceptable best fit is found between modelled and measured mass per unit area values.

Connor and Connor (2005) successfully applied these techniques in the numerical reconstruction of the 1992 Cerro Negro eruption, Nicaragua. These approaches were later adopted by other authors including Bonasia et al. (2010) for the 472 AD Vesuvius eruption in Italy, Volentik et al. (2010) for the 2450 BP Pulugua in Ecuador, Cobeñas et al. (2012) for the c.2030 yr BP El Misti eruption in Peru, Fontijn et al. (2011) for the ~4-ka Rungwe eruption in South-Western Tanzania, Johnston et al. (2012) for the Bronze

Age eruption of Santorini, Magill et al. (2015) for the 1707 Hoei eruption of Mount Fuji, and White et al. (2017) for the 1992 Cerro Negro eruption and the 2011 Kirishima-Shinmoedake eruption in Japan.

The approach and methods used for my *TEPHRA2* inversion modelling is provided in Chapter 3, while results are provided in Chapter 6.

2.5 Exploring key aspects of the social understanding of risk as one element of social volcanology

While understanding of the eruption dynamics during past eruptions and identification of the associated hazards provides the framework for hazard assessment (Connor et al., 2001; Bonadonna et al., 2005; Bonasia et al., 2011), exploring the social understanding of volcanic hazard and risk for all stakeholders within communities located on or close to an active volcano like Taal, helps provide an initial and fundamental input for the development of a holistic strategy to mitigate and reduce harm associated with volcanic activity (Gaillard and Dibben, 2008).

2.5.1. Past studies of social volcanology

Socially-oriented work has slowly but steadily been expanding around the world. Pioneering work on the social dimension of volcanic risk was initiated in the 1960s in volcanoes in industrialised countries such as the United States (Cashman & Cronin, 2008; Lachman & Bonk, 1960; Greene et al., 1981; Gregg et al., 2004; Hodge et al., 1979;

Murton & Shinabukuro, 1974; Perry, 1990; Perry & Lindell, 1990; Perry & Lindell, 2008; Perry et al., 1982). Since then, significant contributions to the understanding of volcanic risk perception, as it relates to behaviour, adjustment and adaptation, as well as various social, institutional and cultural influences, have been conducted for volcanoes in different countries and regions such as *Africa* (Njome, 2010); *the Caribbean* (Cashman and Cronin, 2008; Haynes et al., 2008); *Greece* (Dominey-Howes & Minos-Minopoulos, 2004); *Iceland* (Bird et al., 2009, 2010, 2011, 2012; Johannesdottir & Gisladottir, 2010; Bird and Gísladóttir, 2012); *Indonesia* (Dove, 2008; Lavigne et al., 2008; Donovan, 2010); *Italy* (Barberi, et al., 2008; Carlino et al., 2008; Chester et al., 2008; Davis & Ricci, 2004, 2005; Dibben, 2008; Ricci et al., 2013); *Mexico* (Limon-Hernandez & Macias, 2009; Lopez-Vazquez, 2009; Rodríguez-VanGort & Novelo Casanova, 2015; Tobin et al., 2011); *New Zealand* (Becker et al., 2001; Johnston et al., 1999, Johnston et al., 2000; Paton et al., 2000; Paton et al., 2001a; Paton et al., 2008); *Portugal* (Dibben & Chester, 1999), and the *United States of America* (Cashman and Cronin, 2008; Leathers, 2014). Philippine-based studies on social understanding of risk include work by Carroll & Parco (1966), Oppenheimer, (1991), Saquilon & De Guzman (2005), and Tayag et al., (1988), at Taal; Bankoff (2004) at Taal and Pinatubo; Banzon-Bautista (1996), Gaillard (2008), Gaillard et al. (2001) and Tayag et al. (1996) at Pinatubo; Usamah and Haynes (2012) on Mayon; and MIA-VITA (2012) on Kanlaon. At some stage, Donovan (2010) coined the term 'social volcanology' to encompass work merging of physical hazard research on volcanoes with various societal aspects of volcanology. *Social volcanology*, as defined by Donovan (2010. p. 117) involves "*integration of social science research methods into the traditionally physical domain of volcanology*".

Numerous volcanic risk perception studies have been conducted globally that emphasises the importance of the social perception of risk as a crucial factor in the development of volcano risk reduction initiatives and public education programs (Bird, 2010; Cashman and Cronin, 2008; Dominey-Howes and Minos-Minopoulos, 2004; Dove, 2008; Haynes et al., 2008; Lavigne et al., 2008; Paton et al., 2008). Further, specific influences on people's risk perception and response to hazards include *religious traditions* (Bankoff et al., 2004; Chester, 2005; Chester & Duncan, 2010; Gaillard & Texier, 2010; Saderra Masó, 1911), *individual demographic characteristics* such as participant's ages, level of education, gender and marital status and socio-economic status (Gaillard & Dibben, 2008; Khan et al., 2012; Tobin & Montz, 1997), *past experiences of eruptions, perceived exposure and susceptibility* (Khan et al., 2012; Paton et al., 2000; Paton et al., 2008;), and *cultural influences* through ritual adaptation, especially in the face of uncertainty about vulnerabilities (Barnes, 2002; Cardona, 1997; Gregg et al., 2008; Poggie, 1980).

A summary review related to the emerging field 'social volcanology' is undertaken for global case studies (Appendices D-1). The different philosophical views, modes and topics of inquiry of previous risk perception studies helped me determine key questions I needed to ask the Barangay Captains to have a better understanding of their feelings, attitudes, beliefs, experiences, risk perception, and attitude towards DRR preparedness measures. Here, studies of volcanic risk perception are reviewed to draw out the key issues so that knowledge gaps may be identified and to find commonality of issues or factors influencing the social understanding of risk of the community leaders. How relevant is the level of education of community leaders to how they receive and respond to hazard and risk information? Do they take the risk seriously? Does knowledge and awareness of hazards and risk correspond to better preparedness? Does eruption experience provide additional motivation to be more pro-active in preparedness activities for the community? Bird and Gisladottir (2012) emphasised that the capability of each individual to recognise risks is based upon past personal experiences that provide them with greater understanding of the hazard resulting in a more positive attitude towards DRR management initiatives implemented in their communities. Importantly, I note that there are very few studies focused on community leaders and their role in DRR. Likewise, very limited research has been conducted that specifically focuses on community leaders in terms of their education, knowledge and reaction to hazards and risk, eruption experiences and preparedness in tackling volcanic emergencies. I deem it important to mention that I acknowledge bias/limitation in possibly missing some relevant articles using a non-systematic search which I conducted.

2.5.2. People's understanding of risk in a volcanic setting and its importance to risk assessment and management processes

The social and economic consequences of volcanic eruptions have not deterred communities from living close to active volcanoes (Sutton and Restrepo, 2013). Cashman and Giordano (2008, p. 407) wrote: "*history has shown that humans persist in living with* *active volcanoes despite repeated catastrophes caused by damaging eruptions*". Frequently asked questions in regards to living in hazard prone areas are why communities choose (and if indeed they actually 'choose') to live in areas where they are exposed to these hazards and why they return after a disaster has occurred (Khan et al., 2012). Leathers (2014, p. 5) defined *risk perception* as "*the way in which an individual views a situation*", and further emphasised that risk perception may vary according to social, cultural, psychological or institutional factors that can influence their actions and reactions. I interpret this to mean that perception of risk is influenced/dictated by the person's social and spiritual interaction in his or her community, culture and tradition, and economic situation. People perceive risk differently. A geographer or a geologist like myself might focus on understanding human behaviour in the face of a natural or technological hazard (Slovic, 2000). A sociologist or anthropologist would relate risk perception to social and/or cultural influences (Cardona, 1997; Chester, 2005; Chester & Duncan, 2010; Chester et al., 2008; Gaillard and Le Masson, 2007; Lachman and Bonk, 1960; Short, 1984; Swanson, 2008;). A psychologist may be more analytical and provide empirical probability assessments to their risk perception studies (Edwards, *In* Slovic, 2000). While people may have a good understanding of risk, one may choose to or be unable to take a variety of risk reduction measures because of social, cultural, political, economic or religious factors that influence their decision making (Bankoff, 2004; Gaillard, 2006; Gaillard and Texier, 2010; Hewitt, 1983; O'Keefe et al. 1976; Wisner et al., 2004). In the case of the vignette study, I wanted to examine the extent of the understanding of the volcanic hazards and risk, and identify key elements that relates to how the Barangay Captains prepare for, respond to and mitigate impacts of these hazards.

2.5.3. Paradigms of risk perception

In order for me to have a better understanding of people's perception of risk, I now provide an overview of the three major risk perception paradigms generally related to natural hazards. Three key theories or risk perception paradigms have come to dominate explanations of risk perception of natural hazards over time. A review of these should provide a framework for better understanding what factors shape local risk perceptions and behaviours around Taal.

Starr (1969) provided the initial work on risk perception developing a revealed preference methodology for weighing technological risks versus benefits. His approach concluded that "*society has arrived at an essentially optimum balance between risks and benefits associated with any activity*" (Starr, 1969, p. 1237), thereby obtaining acceptable risk-benefit trade-offs. Other authors identified two risk concepts; namely risk as a physical attribute and another as a social construct (Bradbury, 1989). The concept of risk as a social construct focuses on the social and cultural background of the risk perceiver. Armed with people-focused knowledge through dialogue and consultations, risk management and communication procedures can be more relevant and credible (Bradbury, 1989).

2.5.3.1. Psychometric method

The psychometric paradigm is one approach to examining risk perception. Pioneer work on the psychometric approach was led by Starr (1969) whose "*revealed preference*" method assumes that society gains an "*optimum balance*" between risks and benefits through "*trial and error*" and come up with "*risk-benefits trade-offs*". From Starr's "*revealed preferences*" study, he was able to develop conclusions now regarded by other researchers as "*laws of acceptable risk*" that were summarized by Fischhoff et al. (1978, p. 128) and Slovic et al. (2000, p. 282) who stated: 1) *that the acceptability of risk is roughly proportional to the third power of the benefits*; 2) *that the public seems willing to accept risks from voluntary activities roughly 1000 times greater than it would tolerate from involuntary activities that provide the same level of benefit*; 3) *that the acceptable level of risk is inversely related to the number of persons exposed to that risk*; and 4) *that the level of risk tolerated for voluntarily accepted hazard is quite similar to the level of risk from a disease*.

With this school of thought, it is believed that there is parallelism in the perception of some risk characteristics, such as voluntariness, which is associated with controllability, catastrophic potential with inequity, observability with knowledge about risk, and immediacy with novelty (Schmidt, 2004, p. 10). Relative to these correlated risk characteristics, nine identified dimensions to risk which influences perception of actual or acceptable risk include: 1) voluntariness of risk; 2) immediacy of effect; 3) knowledge about risk by persons exposed to those risks; 4) knowledge of risk by experts; 5) control over risk; 6) newness; 7) chronic-catastrophic; 8) common-dread; and 9) severity of consequence (Fischhoff et al., 1978, p. 144; Starr, 1969, p. 1237).

Fischhoff et al. (1978) conducted further work on the psychometric paradigm and provided an alternative method to Starr which utilised psychometric procedures to generate quantitative conclusions on perceived risk, acceptable risk, and perceived benefit for each of the 30 activities and technologies he examined. The alternative approach is called "*expressed preferences*" wherein he conducted quantitative research utilising questionnaire surveys in order to gauge the attitudes of respondents towards the risks and benefits from various activities (Fischhoff et al., 1978). Some of the conclusions drawn by Fischhoff el al. (1978, p.148) were: 1) most of the current risk levels for many activities included in the study were seen as unacceptably high; 2) there was little relationship between perceived existing risks and benefits of the 30 activities and technologies, and that there is no marked difference in risk at fixed levels of benefit whether they be voluntary or involuntary; 3) they found a consistent relationship between perceived benefit and acceptable level of risk, and also concluded that conflicting principles for acceptable risk not only come from voluntariness but also from perceived controls, familiarity, knowledge, and immediacy, and 4) that the nine characteristics that influence judgment of perceived and acceptable risk were highly correlated.

As more research on the psychometric paradigm was conducted, the nine characteristics of risk were narrowed down to three factors identified by Schmidt (2004, p. 10) as: 1) "*dread risk"* which includes perceived lack of control, catastrophic potential, inequitable distribution of risks and benefits, and fatal consequences; 2) "*unknown risk or familiarity"* including observability, experts' and lay people's knowledge about the risk, delayed effect of potential damage, and novelty; 3) "*people affected risk"* including those personally affected, general public affected and future generations affected. Another perspective of this paradigm shows the difference in perception and importance given to hazards from the point of view of an individual compared to a group (Slovic et al., 1982). Slovic (2000) concluded that the psychometric paradigm provides a well-established model that can assess judgements about risk quantitatively.

Marris et al. (1998) provides some criticism of the psychometric paradigm. The first argument is that the paradigm *"treated qualitative risk characteristics as inherent attributes of the hazards themselves rather than as constructs of the respondents*" (Marris et al., 1998, p. 636). The second argument was that the paradigm "*did not distinguish between different groups of respondents other than experts and laypersons*" (Marris et al, 1998, p. 636). With the realisation of the importance of the characteristics of the people who perceive the risk and the issue of trust and accountability in risk management, further psychometric studies have subsequently incorporated consideration of trust, blame and accountability (Marris et al., 1998; Slovic, 1999).

2.5.3.2. Socio-cultural approach

With importance being given to social and cultural influences in risk perception, another approach emerged known as the *cultural theoretical paradigm*. The main focus of the *cultural theory* is to study differences in how people react to risk and claims to "*provide a framework for identifying underlying patterns of world views which go beyond standard sociodemographic variables*" (Marris et al, 1998, p. 636). Another key element proposed in cultural theory is that "*individuals actively choose what to fear (and how to fear it) in order to support their way of life"* (Dake, 1991, p. 65). Two key interacting considerations ingrained in cultural theory are *cultural biases* and *social relations*. *Cultural bias* is defined as "*shared values and beliefs corresponding to different patterns of social relations*" (Dake, 1991, p. 65; Wildavsky and Dake, 1990, p. 43). *Social relations*, on the other hand, provides that there exists "*a small number of distinctive patterns of interpersonal relationships - hierarchical, egalitarian, or individualist*" (Wildavsky and Dake, 1990, pp. 43-44). Dake (1992) includes *fatalist* as one more category of interpersonal/social relationship. He conducted qualitative studies to operationalise and validate the *cultural theory*. As defined by Dake (1992, p. 29), a *hierarchical* group "*foster[s] the myth that nature is perverse or tolerant"* and assumes natural recovery and resilience following a specific command flow, and augmented by resource conservation strategies. An *egalitarian* group believes in the myth that "*nature is fragile*" and opt for "*approaches to risk policies that foster equality of outcomes*", while an *individualist "foster[s] the myth of nature as benign"* and they assume that deregulation is the inevitable risk management solution (Rayner, 1988). A *fatalist "holds the myth of nature as capricious"* and are generally excluded or opt not to be part of the abovementioned groups. The four group types were originally conceptualised by Douglas and Wildavsky (1982) using group-grid analysis. However, Dake (1992, p. 33) further elaborated that although these segregated groups exist, "*no single ideological or relational characteristic can be employed to assign individuals or institutions to cultural categories*". He further emphasised that a better understanding of the interaction of sociocultural systems and the environment is needed to better understand perception of risk. More details on *Cultural Theory* as it relates to risk perception and case studies conducted to test the theory are provided by other authors including Adams (1995), Dake (1991, 1992), Douglas (1985, 1992, 1996), Douglas & Wildavsky (1982), Kahan & Braman (2003), Lazrus (2015), Lima & Castro (2005), Marris et al. (1998), Rayner (1987, 1988, 1992), Rayner & Cantor (1987), Schwarz & Thompson (1990), Thompson et al. (1990), and Wildavsky & Dake (1990).

Some notable critics of the *Cultural Theory* are Boholm (1996) from the standpoint of anthropology, Marris et al. (1998), Oltedal and Rundmo (2007) on the issue of transport risk, and Sjöberg (1996) regarding low percentage in the variance on perception of risk. It may be prudent to say that some testing of *Cultural Theory* provided low correlation between the conceptual framework and prediction of risk perception (Sjöberg, 1995, *In* Marris, 1998).

2.5.3.3. Social amplification of risk approach

Social amplification of risk is a conceptual framework that "*denotes the phenomenon by which information processes, institutional structures, social-group behaviour, and individual responses shape the social experience of risk, thereby contributing to risk* *consequences*" (Kasperson et al., 1988, p. 181). Figure 2.12 illustrates the framework for the social amplification of risk (Kasperson et al., 1988). Based on this flowchart, information received by an individual or social group about a risk event may be amplified by personal experiences, direct communication, or indirect communication that is relayed either by individual senses, informal social networks (e.g. neighbors, relatives etc.) or through professional information brokers (e.g., barangay officials, local government representatives, church leaders, news media etc.) that serve as amplification stations. When risk information is obtained by the individual, a process of filtering, decoding, intuitive attachment to social values, consultation and evaluation is undertaken that guides the actions, responses, and/or behaviour of the individual or group in the face of the risk event. Those actions will determine the consequences or impacts associated with the risk event. Kasperson et al. (1988, p. 185) further identified four ways to trigger response mechanisms: 1) heuristics and values – "*process whereby individuals use simplifying mechanisms to evaluate risk and shape responses*" which may sometimes introduce biases that can cause distortion and errors (Kahneman et al., 1982); 2) social group relationships – "*risk issues may enter into political agenda of social and political groups"* that can and more likely influence responses of members; 3) signal value – "*seriousness and higher order impacts of a risk event are determined, in part, by what the event signals or portends*" (Slovic, 1987); and 4) stigmatisation – "*negative imagery associated with undesirable social groups or individuals*" and the stigma resulting from a risk event may result in social and policy changes (Slovic, 1987). These four mechanisms can greatly influence how people respond to an identified risk. How these mechanisms

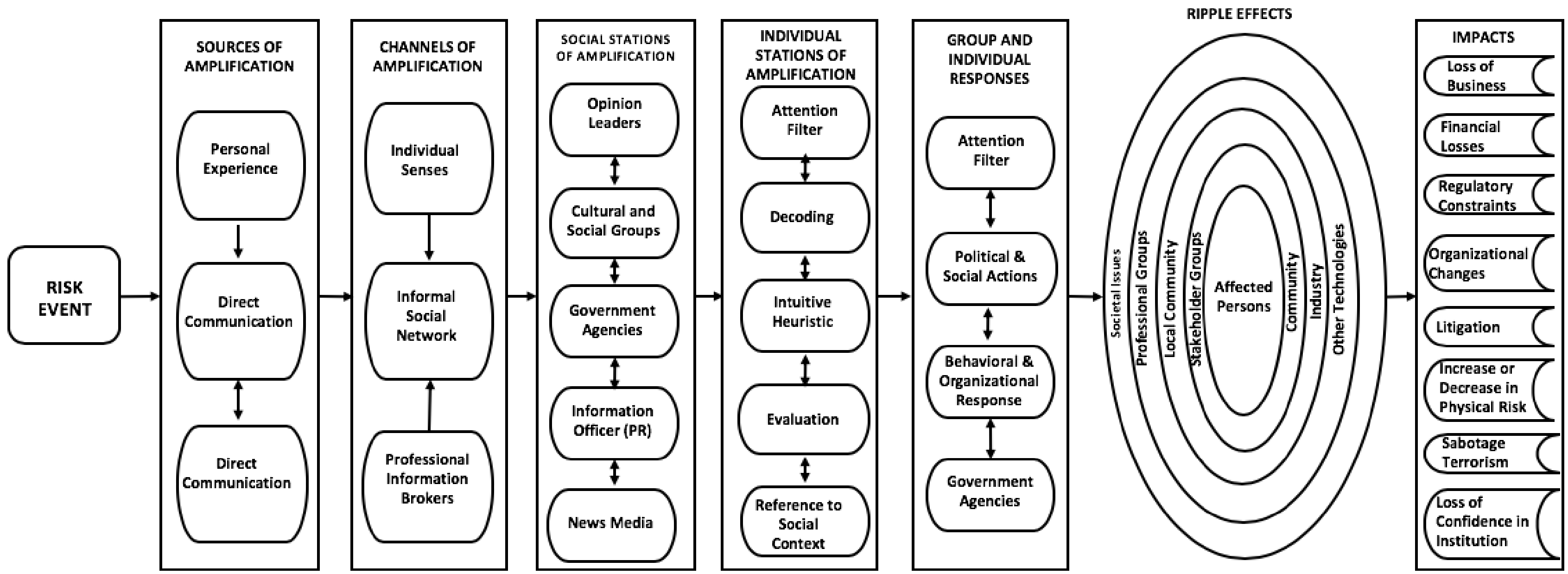


Figure 2.12. Conceptual framework of the social amplification of risk approach. Source: Kasperson et al., 1988.

can be utilised in a positive way so that we can reduce risk, as well as gain benefits would entail involvement of all stakeholders in the social process. Overviews of the three risk perception paradigms provided in the foregoing sections serve as a guide in the review of global and local risk perception research conducted.

The following section provides discussion on the progress of volcanic hazards and risk perception studies in the Philippine setting.

2.5.4. Studies on social dimension of volcanic risk in the Philippines

Volcanic risk assessment, risk perception, and risk management are relatively new fields of study in the Philippines and very limited research has been conducted on these topics. The earliest study was conducted by Carroll & Parco (1966) after the AD1965 eruption and the main objective was to describe the prevalent social organisation in the Philippines during times of natural emergencies with summary results gathered from questionnaires and interviews of '*ordinary*' informants and '*key*' informants. Results of the study showed that the family unit provides the greatest influence as far as leadership, behaviour and responses to crisis are concerned. This is because the dominant social organisation in the Philippines is family-centered with attached commitment to mutual support and loyalty (Carroll & Parco, 1966).

Oppenheimer (1991) combined a literature review of past eruptions of Taal and discussion focused on the sources of livelihood of residents living on TVI, emphasising the continuing threat to communities. From the interviews conducted, residents at TVI professed that they recognised signs of imminent eruption such as intense heat, rumbling, ground shaking, and unusual animal behaviour. Many affirm confidence in evacuation warnings being provided by PHIVOLCS-DOST. However, at the time of the interviews Oppenheimer (1991) noted that the availability of boats at TVI was only half of the required number needed for evacuation of the island dwellers.

A collaborative study by DOST-PHIVOLCS and the University of the Philippines School of Urban and Regional Planning (UP-SURP) (Tayag et al., 1988) was conducted at Taal with the objectives of: 1) assessing the development potential of the area and the constraints posed by the volcano; 2) generating a framework plan to provide insights to decision-makers on possible development directions of the planning area including policy alternatives with respect to resource utilisation, preservation or conservation; 3) sources of financing for proposed development of the area; and 4) feasible politico-administrative set-up for the efficient management of the resource area. Respondents included barangay leaders at TVI and coastal communities surrounding Taal, volcanologists, and local officials in the municipal/city and provincial levels, and methods included semi-structured and free-wheeling interviews. The number of respondents totalled 66. At the time, the total population in the island was only 3617 with 603 households. A summary of salient points of the paper and the assessments that I provided (*written in italics*) are as follows:

- Warning and evacuation – About 94% of respondent noted that DOST-PHIVOLCS efficiently provided warning information during critical periods but they were not aware of any effort by the government to assist them during evacuation. *The communities' dependence on DOST-PHIVOLCS for prompt warning places a great responsibility on the agency and sound and effective monitoring strategies must be in place that can hopefully promptly detect potential eruptions of Taal.*

- Existing community organisation – About 91% of respondents participating in organised religious-cultural type activities, noted these activities to be mostly for socialisation and cultural reasons. *This close-knit organisational set-up can be a good source for channelling hazard and warning communication and education campaigns.*
- Training needs – About 33% did not feel they needed any skill enhancement while 48% identified the need for additional skills in agricultural production such as animal husbandry and livelihood projects. *Skill enhancement on livelihood projects geared toward cottage industry would be ideal source of income so that in the event of an eruption, residents forced to evacuate the island have independent sources of income other than relief assistance.*
- Length and reason for staying in the island – A total of 91% of the 66 respondents said they have been living on the island for more than 10 years, with 88% saying they decided to stay on the island permanently, in spite of the danger of an eruption, due to economic (their basic needs are met with surplus being traded and becoming income for the family) and cultural reasons (peaceful living and sense of belonging as they have their ancestral roots on the island). *As an alternative to avoidance, prompt warning and communication of warnings, and evacuation serves an as compromise solution but this involves participatory dialogues*

between scientists, local government action officers and the community to make it function, with a community-based early warning system (EWS) as the optimum solution.

- Experience of eruption(s*)* – About 91% experienced eruptions in varying intensities, with 76% having to evacuate the island on their own, 12% with government assistance, and 12% choosing to stay in the island. Of those who evacuated, 62% returned less than a year after the eruption. *Past experience during eruptions have probably given the residents the idea that they are expected to fend for themselves during evacuation from TVI.*
- Attitude towards issue of permanent relocation – Thirty percent of the respondents said they will not relocate and believe only the island can provide them economic sufficiency and psychological fulfilment. Another 24% said yes, while 46% said they would agree if certain conditions were met including provision of employment/economic productivity (73%) and provision of a minimum of two hectares of productive land for agricultural purposes. Ranked less important, but essential, were social services such as housing, health centers, roads, markets, water and electrical facilities, and schools. *The significant number of responders who are amenable to relocation means that this alternative is viable as long as the residents are provided with the capacity to seek livelihood in the place they are relocating to.*
- Identified hazards posed by Taal Volcano – The report identified base surges, tephra falls, ballistic projectiles, acid rain and poisonous gases, lava flows, seiche/tsunami, flooding, fissuring and ground subsidence, lightning and electrical

discharges as some of the hazards that can be generated in the event of an eruption. Emphasis was given to DOST-PHIVOLCS generated hazard maps as the source for identifying areas prone to these hazardous events.

- Preparedness and response to emergencies – *Although this issue is a key element in development planning, the paper by Tayag et al. (1988) was silent on this issue. However, another point for consideration was the assessment that as a result of the government position that TVI should be listed as a Permanent Danger Zone (PDZ) or a "no man's land", the absence of recognition of the island communities as official barangays meant they do not get budgetary allotment for development and preparedness and are thus subsumed into an officially recognised barangay in the mainland. This especially poses a serious problem for disaster risk reduction and preparedness implementation considering that TVI communities are directly exposed to potential hazards from volcanic eruptions. Residents may therefore be expected to fend for themselves during future evacuation. There is a need to verify what support the local government has provided for the TVI communities in the event of a volcano crisis.*
- Some of the needs of TVI communities identified by the study:
    - The provision of primary education on the island for at least the first and second grade because at a very young age, children need to cross the Taal Lake to Batangas Mainland for schooling. Children start their education at the age of 7 or later.
    - Provision of medical and health facilities and promotion of family planning should be provided, noting that the average number of persons

per household was 6. *The Philippine and Batangas Province average has decreased to 4.4 in 2015* (PSA, 2015).

 - Provision of adequate potable water for the communities at TVI is a necessity to maintain good health of the residents.
 - Training/skills for productivity enhancement should be provided to residents in the island to ensure that they have sources of livelihood. *Alternative livelihood skills can also ensure that residents have sources of livelihood if and when they are required to evacuate TVI in the event of volcanic unrest/eruption.*
 - Roads for inter-community relations should be provided.

- Some institutional issues mentioned in the study that need further consideration:
  - Presidential Proclamation 235 declared TVI as a "no-man's land" to minimise migration of people to the island. *While the law was declared to safeguard lives in the event of an eruption, the proclamation also limited the delivery of basic services to the communities who are living at TVI.*
  - *With the prohibition of establishment of official barangay as an administrative and political entity in the island, there is no official organisation that would be responsible for coordination and planning of projects to be implemented in the area (perhaps even disaster preparedness).*
  - *There is unclear linkage between local government units and national monitoring agencies such as the Parks and Wildlife Bureau (PAWB) on the issue of control of infrastructure development on the island, and the*

Bureau of Fisheries and Aquatic Resources (BFAR) on the issue of permits to fish pen operators.

These issues identified from the work of Tayag et al., (1988) merit consideration and need to be examined further in this study in order to provide sound recommendations for the development of DRR strategies for the communities on TVI and its surroundings.

Another unpublished DOST-PHIVOLCS report by Saquilon & de Guzman (2005) sought to explore volcanic risk perception, preparedness and reaction to volcanic emergencies and to gather the latest population data and socio-economic profile of TVI. Survey respondents totalled 100. The survey responses showed that a majority consider TVI as their permanent home where they get their main source of livelihood (Saquilon & de Guzman, 2005). During the AD2005 survey, the population figure for TVI was 5,666 compared to 4,950 in AD1995, with a calculated growth rate of 1.6% per year. The high growth rate is attributed to abundant sources of livelihood at TVI. Unfortunately, there is currently no official population surveys conducted since AD2005. In one TVI community alone, the Barangay Captain mentioned that he has more than 2000 constituents. The increase in population was mostly concentrated in the northern part of TVI as a result of increased tourism activity. The AD2005 study showed that about 65% of residents have their own motorboats and about 93% of the respondents were aware of the Alert Level Scheme and knew what each level meant. Table 2.10 provides the current Alert Level Scheme for Taal, which is similar to the one used in AD2005. About 85% of the those who were aware of the Alert scheme said they would evacuate when orders are given. This action implies that they are dependent on prompt and accurate warning from authorities that would provide enough lead time for them to evacuate before the eruption. A majority of the respondents (90%) said they would be dependent on assistance from the government once they evacuated TVI.

As part of the ongoing volcanic hazard awareness and preparedness activities of DOST-PHIVOLCS, seminar-workshops are periodically conducted at communities around Taal and all active volcanoes in the Philippines. Now and in the past, I have been involved with these activities as a lecturer and facilitator for the workshops dealing with hazard awareness, community preparedness, community and livelihood continuity plans. Parallel to my PhD social research activities, DOST-PHIVOLCS is also currently conducting a Research Project for Development in collaboration with a Belgian partner institution, Université Libre de Bruxelles with the title "*Reducing the impact of volcanic disaster in the Philippines: Towards improved capacities of human communities to cope with volcanic hazards*", which commenced in March 2015. The activities of the project include: 1) socio-economic vulnerability and resilience assessment; 2) community-based disaster risk reduction planning with knowledge and information translated into community plans and actions (capacity building); 3) establishment of community-based warning and communication systems that are cost-effective, utilising indigenous, locally available materials; 4) linking

Table 2.10. Current DOST-PHIVOLCS Taal Volcano Alert Levels. All provincial governments have institutionalised recommended actions for their province related to each Alert level independent from the actions taken by DOST-PHIVOLCS. A similar Alert Level Scheme was in place in 2005. Source: DOST-PHIVOLCS (2018)

ALERT LEVEL	CRITERIA	INTERPRETATION
0	Background, quiet	No eruption in foreseeable future.

1	Low level of seismicity, fumarolic, and other activities	Magmatic, tectonic or hydrothermal disturbance; no eruption imminent
2	Low to moderate level of seismicity, persistence of local but unfelt earthquakes. Ground deformation measurements above baseline levels. Increased water and/or ground probe hole temperatures, increased bubbling at Crater Lake Possible magmatic intrusion	A) Probable magmatic intrusion; could eventually lead to an eruption. B) If trend shows further decline, volcano may soon go to level 1
3	Relatively high unrest manifested by seismic swarms including increasing occurrences of low frequency earthquakes and/or harmonic tremor (some events felt). Sudden or increasing changes in temperature or bubbling activity or radon gas emission or crater lake pH. Bulging of the edifice and fissuring may accompany seismicity.	A) If trend is one of increasing unrest, eruption is possible within days to weeks. B) If trend is one of decreasing unrest, volcano may soon go to level 2.
4	Intense unrest, continuing seismic swarms, including harmonic tremor and/or low frequency earthquakes which are usually felt, profuse steaming along existing and perhaps new vents and fissures.	Hazardous explosive eruption possible within days
5	Base surges accompanied by eruption columns or lava fountaining or lava flows.	Hazardous eruption in progress. Extreme hazards to communities west of the volcano and ashfall on downwind sectors.

community with municipal-level and provincial level-initiated corresponding actions that will be incorporated in community disaster risk reduction plans; and 5) communicating the findings to the authorities (DOST-PHIVOLCS) through small meetings and workshops, developing and communicating adequate recommendations. The project will be completed in 2020. Project activities are geared more toward capacity building of the communities around Taal. To avoid redundancy and duplication of activities, I made sure that I selected target barangays where the DOST-PHIVOLCS researchers involved in this project were not working so that our data collection complements each other.

Knowing the importance of integrating people-based and community-focused research into volcanic hazard and risk assessment and management (Bird, 2010; Bird et al., 2011; Donovan, 2010; Haynes et al., 2008), I engaged a ‘vignette approach’ using qualitative research in the field of ‘social volcanology’. It is important to understand why I am using a vignette approach in this qualitative research. Wilks (2004) attests to the successful use of vignettes to study perceptions, beliefs, attitudes and norm in the field of social science. Vignettes have been useful tool to tackle sensitive topics on health, education, social work, and social psychology (Akerlind, 2015; Alden et al. 2015Jackson et al, 2015; Langer, 2016; Wilks, 2004). Several qualitative and quantitative case studies have been conducted in volcanic settings, but unlike in other disciplines I mention earlier, I have not identified a published vignette study related to social volcanology. While my selected respondents are limited to a specific stakeholder group, the Barangay Captains, I hope their responses to situational questions will elicit useful information on their true knowledge, awareness, beliefs, reactions and preparedness in the face of a volcano emergency.

2.6 Knowledge gaps

2.6.1. Knowledge gaps related to socio-economic and governance structure

The overview of the socio-economic and governance features of Batangas Province discussed in Section 2.1 provides a better understanding of the physical, social, economic and governance structures and functions in the province. While available DRR documents include contingency plans in the event of natural disasters, these contingency plans frequently lack measures for volcanic hazards. There is also a need to confirm if existing contingency measures reach the Taal communities for whom they are designed. Knowledge about risk perception and disaster preparedness are essential to act as a starting point for developing or strengthening the risk management plans for a community (MIAVITA, 2012). There is also a need to determine if implementation of these DRR plans reach the community level. While the existing local government structure functions as the DRR chain of command, questions remain whether DRR measures are applied downwards from the top to the local Taal communities. Verification and validation of the importance and influence of socio-economic and governance issues in relation to DRR are discussed in Chapter 7.

2.6.2. Knowledge gaps from narrative accounts of historical eruptions of Taal

Fundamental to understanding the past behaviour of Taal is synthesising the complete review of all known historical data. Here, my search of the literature was mostly limited to documents written in or translated to English since I cannot read Spanish, the primary written medium of eyewitness accounts during historical eruptions. My colonial archive analysis was largely derived from second hand sources who translated the original Spanish sources.

I conducted a critical review of the translated narrative descriptions and assessed the interpretations the authors provided for each of the identified eruptions. Some of the historical eruptions have very limited narrative descriptions or no description at all. I had to determine whether the lack of knowledge about some of the eruptions is due to absence of first-hand eyewitnesses, or lack of significant eruption impacts, or simply because the event was only solfataric or hydrothermal activity that was noted by the historians but may not necessarily have culminated in full scale eruptions. If deemed necessary, new interpretations of eruptive styles were made. Proper identification of eruptive style can provide an indication of what processes and products could have been expected. For phreatic eruptions, Barberi et al. (1992) postulates that the more likely products would be fall deposits that would be confined to the area around the volcano. Particularly for Taal, where the presence of water is assumed as an inevitable ambient medium, variation in eruptive style, processes and deposits may be expected (Cas & Giordano, 2014).

2.6.3. Volcanic hazard knowledge gaps

As summarized from the archival review, I identified eruptive processes and products from past eruptions including pyroclastic density currents, tephra fall, ballistic projectiles, lava flows, volcanic tsunami, volcanic gases, acid rains, volcanic earthquakes, ground fissuring, lahars, electrical activity, atmospheric shock waves and ground subsidence. These processes and products represent key information that can be used to assess hazards and risks during future eruptions. However, although the provincial and local government in Batangas Province have identified a few of these volcanic hazards, such as base surge, ballistic projectiles and seiche and/or volcanic tsunami, that were based on the volcanic hazard maps generated by DOST-PHIVOLCS (Table 2.7), countermeasures for other identified volcanic hazards like tephra fall, emission of toxic gases, liquefaction effects, lahars along incised gullies and active river channels, and flooding, are generally not included in their disaster risk reduction plans.

2.6.4. Knowledge gaps in numerical modelling

Having chosen the *TEPHRA2* model for the hazard assessment, and having confirmed that the model was successfully used for a VEI 5 eruption (the AD1707 Hoei eruption of Mount Fuji, Japan (Magill et al., 2015)), the challenge was then to apply the model and inversion methodologies to the AD1754 eruption of Taal. Although DOST-PHIVOLCS scientists have tried to apply other models such as ASHFALL, FALL3D and Python FALL3D to eruptions from other Philippine volcanoes, the lack of complete tephra fallout information for a known eruption has meant that interpolations had to be made making the results less accurate, and validations not possible. This study will conduct inverse modelling using *TEPHRA2* in order to simulate the Plinian/Sub-Plinian AD1754 eruption in order to acquire estimation of the eruption source parameters and accumulation on the ground. This will guide input for social survey activities and contribute to the total risk assessment process to be completed for this study.

2.6.5. Knowledge gaps in social understanding of volcanic risk

I have identified gaps in knowledge that currently exist in the social understanding of risk related to Taal. While DOST-PHIVOLCS maintains state-of-the-art monitoring instrumentation at TVI and the surrounding areas, and the local government have developed volcano disaster risk reduction plans for Batangas Province, very little is known and written about the community leaders' crucial role in volcano-related emergencies.

While reviewing the two unpublished social survey studies conducted at Taal (Tayag et al., 1988; Sequilon and de Guzman, 2005), I identified gaps or issues related to disaster risk reduction. On warning and evacuation, the issue of communities' dependence on DOST-PHIVOLCS for prompt warning places a great responsibility on the agency. Have the communities developed their volcano-related DRR plans and are warning communication and evacuation system already in place? What are the positive and negative impacts of attachment to place as they relate to residents living at or near TVI? Are the barangay captains knowledgeable about the volcanic hazards and risk and do they take this risk seriously? What countermeasures have they taken to address and respond to the risk?

To answer these questions, I set out to formulated the hypothesis I wished to test/examine and that is: "*Given that the barangay captains and their communities are located on or so close to the volcano, the barangay captains will be educated, knowledgeable, experienced, take the risk seriously, and will be prepared for supporting their communities during a volcanic emergency*.

2.7 Research questions

Having identified a range of knowledge gaps, I now articulate the key questions that this thesis aims to investigate. These are:

1. What do we know, and not know, about the eruptions of Taal Volcano? What can a collation, synthesis and reinterpretation of information tell us about the past eruptions at Taal, their processes, products and hazards?

2. What is the expected distribution of tephra deposits in the event of an explosive eruption such as the AD1754 Plinian/Sub-Plinian eruption of Taal?
3. How would a major/plinian eruption affect communities around Taal?
4. Given that the Barangay Captains and their communities are located on or close to Taal, and as they are key decision makers in the community, how are the Barangay Captains responding to volcanic risk? What is the level of education, knowledge, experience, risk perception and preparedness of these specific stakeholders?
5. How can the key results obtained from this interdisciplinary study be utilised for developing or strengthening disaster risk management plans for the province?

2.8 Chapter conclusion

This chapter provided summary reviews on the different topics related to undertaking an interdisciplinary risk assessment and management research. The comprehensive review and synthesis identified knowledge gaps in the fields of study that I intended to undertake for this thesis. Subsequently I was able to formulate my research questions which is intended to be addressed by the succeeding discussions of results in Chapter 4 to Chapter 7.

CHAPTER 3
Approach and Methods

3.0 Introduction

Chapter 3 presents the approach and methods I employed to carry out my research. To develop answers to my research questions, specific information and skills were needed. Figure 3.1 provides the research process, addressing the research questions detailed in Chapter 1 (Section 1.4) and Chapter 2 (Section 2.7). Discussion of the methods that will be undertaken for the major components of my research will include: 1) comprehensive review of literature (Research Questions 1 and 2); 2) geologic mapping and field data analysis (Research Question 2); 3) numerical modelling (Research Question 2); 4) social research (Research Questions 3 and 4), and 5) integration of key results of this interdisciplinary study (Research Question 5).

With the research activities identified, the subsequent sections of this chapter are devoted to providing details of the approach and methods used, as well as outlining associated limitations.

Having identified research gaps and formulated specific research questions, it is necessary to identify methods and develop a philosophical research framework to ensure that my research approach is systematic, appropriate and, as highlighted by Kumar (2014), that outcomes are valid, verifiable, reliable, and critical. Grinnel (1993, p. 4), describes research as "*a structured inquiry that utilises acceptable*

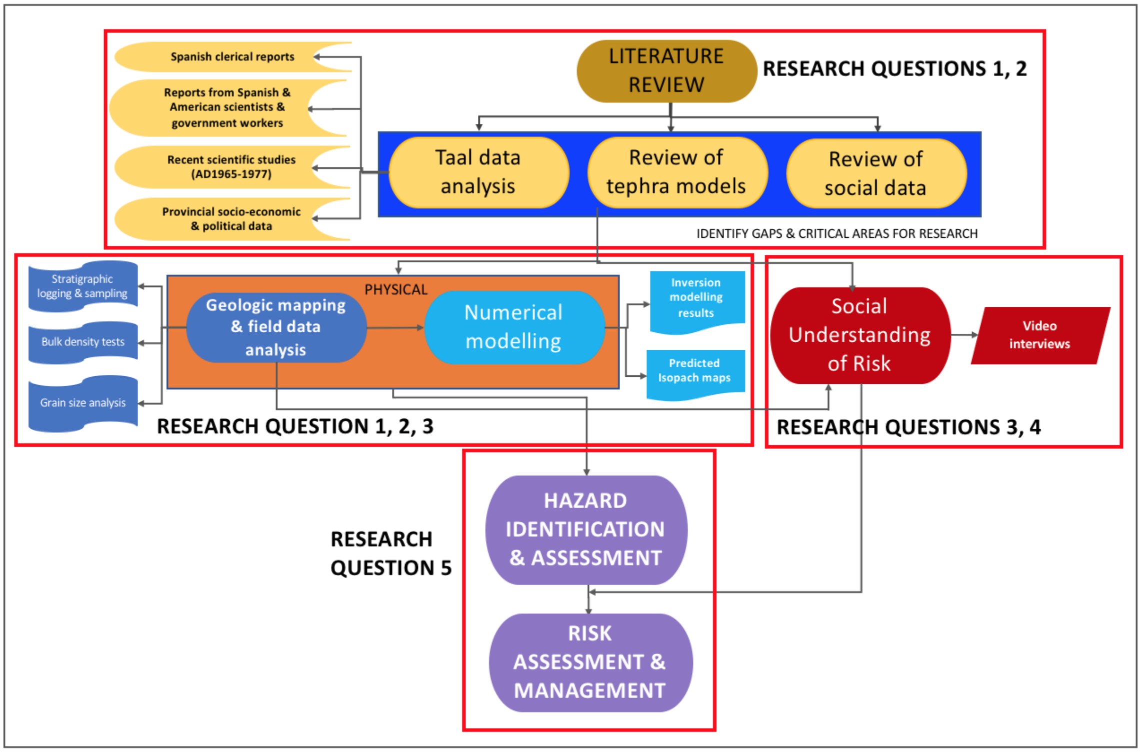


Figure 3.1. Research process for the interdisciplinary study conducted at Taal.

scientific methodology to solve problems and creates new knowledge that is generally applicable".

Kumar (2014) provides a classification of the types of research from different perspectives including applications, objectives or purposes, and mode of enquiry. He grouped the application perspective into pure and applied research. *Pure research* involves "*development, examination, verification, and refinement of research methods, procedures, techniques, and tools that form the body of research methodology*" with the aim to "*add to the existing body of knowledge of research methods*" (Kumar, 2014, p. 11). *Applied research*, on the other hand, involves application of research techniques, procedures and methods to the collection of information about various aspects of a situation, issue, problem or phenomenon so that the information gathered can be used in other ways" (Kumar, 2014, p. 13).

Kumar (2014, p. 13) also identified various objective perspectives including: 1) descriptive study to "*describes systematically a situation, problem, phenomenon, service or programme*"; 2) *correlational study* to "*discover or establish the existence of a relationship, association or interdependence between two or more aspects of a situation or phenomenon"*; 3) *explanatory research* to "*clarify why and how there is a relationship between two aspects of a situation or phenomenon*"; and 4) *exploratory research* that "*aims to explore an area where little is known or of investigating the possibilities of undertaking a particular research study*".

Table 3.1 provides an overview of the types of research I have conducted in each of the three identified perspectives. In all fields of my research, this research is *applied research* in terms of application perspective because the procedure/methods I used for my research are known and applied to each specific field. As far as the objective perspective is concerned, I found that except for numerical modelling which I perceive as not requiring descriptive study, all aspects of my research entailed descriptive, correlational, explanatory and exploratory studies. Again, in the mode of enquiry perspective, all but numerical modelling used the approaches I identified.

Table 3.1. Classification of various interdisciplinary research activities based on identified perspectives (Source: Kumar, 2014)

	MY RESEARCH ACTIVITIES:			
PERSPECTIVE (from Kumar (2014)	**Literature review**	**Geologic mapping**	**Numerical modelling**	**Social research**
A. Application				
Pure				
Applied	✔	✔	✔	✔
B. Objectives/purposes				
Descriptive	✔	✔		✔
Correlational	✔	✔	✔	✔
Explanatory	✔	✔	✔	✔
Exploratory	✔	✔	✔	✔
C. Mode of enquiry				
Qualitative				✔
Quantitative			✔	
Mixed methods	✔	✔		

During this entire research, I worked as a Filipino government worker and as a seasoned and traditionally trained geologist who has numerous field-based volcanic and earthquake crises experiences under my belt. Having dealt with both the physical aspects of volcanic and earthquake events and with communities directly or indirectly affected by events, I am confident that, I have tried to avoid any bias in data gathering and interpretation. I also know that communities living near active volcanoes that are monitored trust DOST-PHIVOLCS and I am confident that the information they have provided to me are honest and reliable. As such, my positionality affords me an entry point to communities where I am entrusted with relaying the information provided, as well as giving my insights and assessments of those findings. To begin the process of understanding knowledge, risk perception, awareness, capability and capacity, I will undertake a preliminary survey of a few Barangay Captains since they are the corner stone of good community disaster awareness and preparedness. In Book III Chapter

III Section 389 of the Republic Act 7160, otherwise known as the Local Government Code of the Philippines, the Barangay Captain is the chief executive of the barangay government who has the responsibility to "*organize and lead an emergency group whenever the same may be necessary for the maintenance of peace and order or on occasions of emergency or calamity within the barangay*" (Congress of the Philippines, 1991). Furthermore, in the National Disaster Risk Reduction Plan, in Thematic Area 2: Disaster Preparedness, the Department of Interior and Local Government (DILG) is assigned as the overall responsible agency for Disaster Preparedness, and all the local government units including the Barangay Captains are under their supervision. They are tasked with implementing activities that draw attention to community awareness and understanding of hazards and risk, preparation of contingency/emergency plans and disaster response plans, as well as the conducts of drills (NDRRMC, 2011).Republic Act 7160 is still currently in effect up to the present time.

3.1 Summary of methods and significance

3.1.1. Socio-economic and political profile of Taal and the region

Work commenced by searching for information about the Province of Batangas to create a socio-economic and political profile of the region and its people. Such information is important for understanding decision making and policy implementation, especially in relation to making suggestions about future disaster risk reduction policy and practice. Ranke (2016, p. 333) defined governance as a "*systematic approach to enable development processes associated with social,* *ecological, natural, and technological risks*". Documents were gathered from various local government offices, internet searches of websites of some national government offices and direct from communities around Taal.

3.1.2. Utilising archival records and secondary sources

I explored the geographic and tectonic settings of the region and Taal from studies published in peer reviewed international journals. The central purpose was to critically evaluate the records of the historical eruptions of Taal since AD1572, and the associated processes and products. While primary and canonical materials already provide some interpretation of significant events the original authors observed, revisiting and conducting critical reviews of these reports were necessary to provide new interpretations in light of my personal field-based experiences, and in order to add to existing knowledge (Gaillet, 2012).

In the process of conducting a review of narrative accounts related to the historical eruptions of Taal, I identified that most of the significant eruptions occurred during the Spanish occupation, and that the archival accounts were written in Spanish. Particularly important reports were compiled by Buencuchillo (1754), Centeno (1885) and Feldman (1988). In their papers on Taal eruptions between AD1572 and AD1911, Saderra Masó (1911) and Worcester (1912) often quoted Buencuchillo's descriptions of the significant eruptive events and translated these to English. No information is provided by these authors about how they translated these documents (i.e., whether they themselves could read and interpret Spanish or if they used other interpreters – both of which have various advantages and disadvantages). While knowing the limitations of Google Translate™, in that it is generally a 'quick fix' translation tool that is often only good for phrases or words (Lear et al. 2016), I used the online tool to translate some critical descriptions for some specific eruption accounts in order to cross check those English translated descriptions from Saderra Masó (1911) and Worcester (1912). I also used Google Translate™ to translate the Feldman report (1988) that is written in both English and Spanish. I found some of the literal translations incomprehensible but others were reasonably understandable. However, I concur with Rodríguez-Castro et al. (2018) when they emphasised that "*computer-generated translations cannot replace human translation*".

My critical review includes reinterpretation of some eruption styles, VEI (Newhall and Self, 1989), and volcanic processes that I deemed more appropriate for a particular narrative account. Stoler (2002, p. 87) described the importance of archival analysis as: "*scholars should view archives not as sites of knowledge retrieval, but of knowledge production*". Further, Trough (2012, p. 245) states that "*if users read them (archives) with a 'grain of salt', then they may be able to utilise them for a range of purposes never envisioned by the creators of the record*". Thus, for me, this means that new knowledge can be gained by looking more deeply and critically into what the narrative descriptions may imply with regards to the eruptive styles and processes in light of more contemporary geological understanding.

As I went into the process of reviewing archival documents and secondary data, I was critical of the narrative descriptions provided by the reports. For example, do the eruption descriptions provide confirmation that the eruptions occurred? Was there enough detail about the processes and products to establish the occurrence of an eruption or was the activity only solfataric? If it was determined that an eruption was likely, were the identified eruption styles, processed and products, and magnitude of the eruption in terms of VEI appropriate? Existing narrative descriptions of Taal's eruptions are critically reviewed following the process flow shown in Figure 3.2. In the methods process flow, an identified eruption is deemed uncertain if there is absence of sufficient descriptive accounts of the eruption and the subsequent processes and products. If the narrative account only identified solfataric events, I interpret the event as a solfataric or hydrothermal event that did not culminate into an eruption, and the eruption is therefore classified as uncertain. When the eruption details provided descriptions of eruption columns, type, extent and thickness of deposits, direction of deposition or dispersal, and impacts to communities, then that eruption is deemed confirmed. Eruption style, eruption processes and products, and VEI are either identified by secondary sources or are newly interpreted by me here.

Early first-hand eyewitness accounts provided for eruptions of Taal came from pastoral documents during the Spanish occupation, then later from Spanish, American and Filipino scientists and government workers who studied the historical records and provided further interpretations. The main objectives of the historical eruption review were to: 1) obtain better understanding of the processes, products and impacts of the 33 identified/known eruptions of Taal, specifically the AD1754 Plinian/Sub-Plinian eruption, considered as a maximum expected event scenario eruption; 2) provide alternative interpretations to eruptive processes and products, using the same clerical narratives/accounts as references for interpretations; 3) determine if all identified eruptive events actually culminated into eruptions; and 4) determine where specific eruptive products were generally deposited based on historical narratives, specifically for the AD1754 tephra fallout deposits. Significant reinterpretations on the eruption styles, and processes and products related to some of the eruptions are given in Chapter 4.

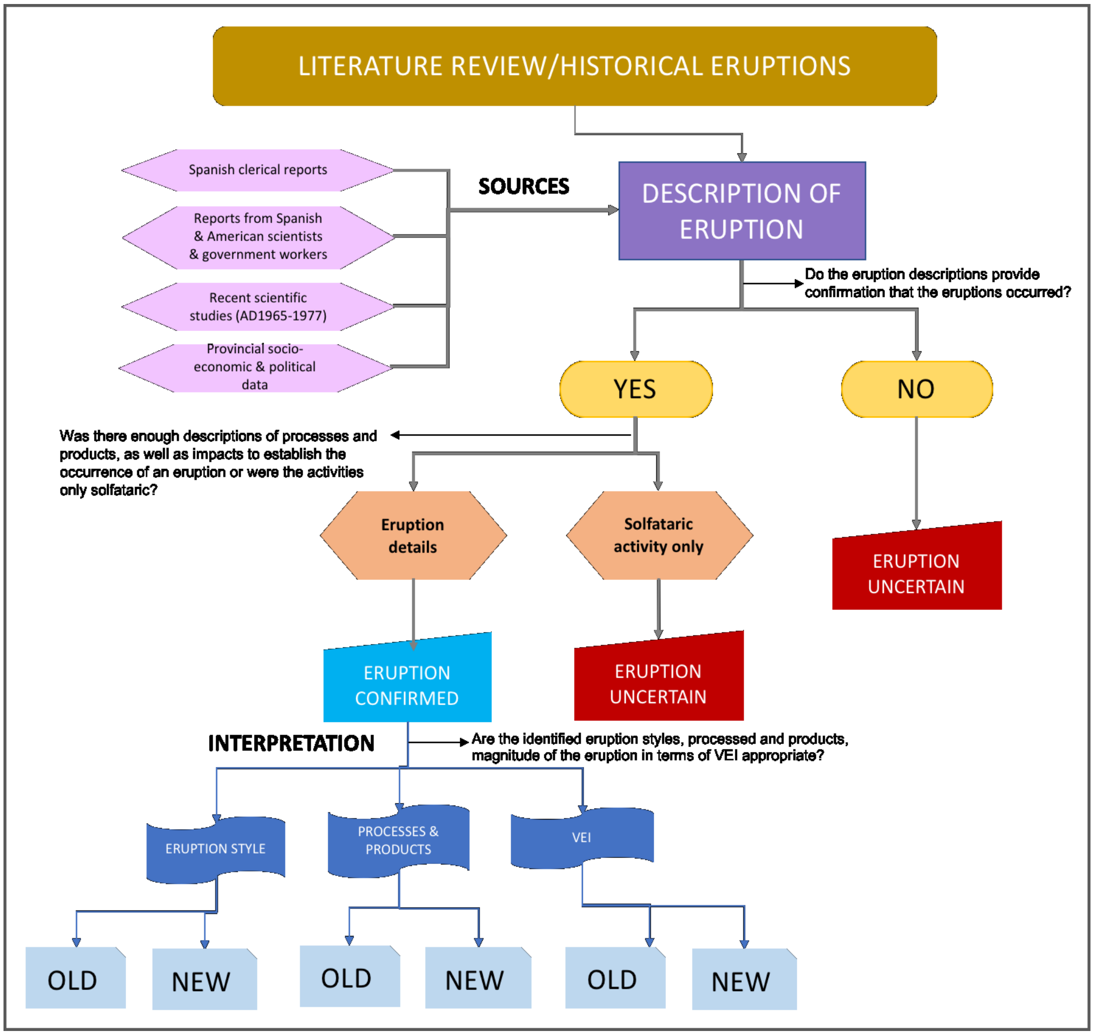


Figure 3.2. Methodology process flow utilised in the critical review of narrative accounts of the historical eruptions of Taal

3.1.3. Summary of the methods and significance

In Chapter 2, I reviewed the various types of tephra dispersal models to determine their objectives, advantages and drawbacks (Appendix C). My goal here was to identify and choose the most appropriate model and method to simulate a large multi-phased eruption such as the AD1754 eruption of Taal. The AD1754 event, with a VEI of 5 (Newhall & Self, 1982; DOST-PHIVOLCS, 1991), was one of the largest Plinian/Sub-Plinian events from Taal. Considering the significant impacts associated with the AD1754 eruption (Saderra Masó, 1911), surprisingly little information can be acquired from historical accounts regarding the magnitude or explosivity of the eruption, and the extent of tephra dispersal or the relative thickness of deposits, especially in areas where deposits have not been preserved. Through tephra modelling, I was able to acquire more information including an accurate dispersal pattern and best estimates of eruption source parameters for the event.

3.1.4. Summary of methods on social dimension of volcanic hazards and risks

Equally important to this research is an understanding of the social dimensions of risk assessment and management. As a traditional geologist, I see great benefits of and power to combining aspects of '*social volcanology*' (Donovan, 2010, 2012) with the geological mapping, archival review and analysis, and numerical modelling I have conducted to provide a richer and better assessment of risk. I adopted methods developed in areas such as human geography to this research. I conducted a comprehensive review of various concepts and theories to better understand existing paradigms and how these relate to perception of risk in a volcanic setting. Further, global volcanic risk perception case studies were critically reviewed to identify objectives, theories applied, limitations and methods utilised, and to review the knowledge, attitudes and behaviour of community leaders during volcano crisis. Considering the diversity in philosophical thinking, this allowed me to identify the appropriate concepts and methods to use in the design and implementation of my structured interviews.

Time constraints prevented me from interviewing a wide range of relevant stakeholders. Consequently, I decided to focus on one critical group - the Barangay Captains (Philippines, 1991). As such, understanding their views, experiences, knowledge, awareness, perceptions and potential behaviours was deemed a significant entry point in to understanding social aspects of risk around the volcano.

3.1.5. Methodological problems identified

While conducting the literature review, I identified some major challenges related to this research.

3.1.5.1. Challenges in Taal data gathering, review and assessment of DRR documents

During the process of data gathering, the conduct of courtesy calls to key government officials had to be conducted strategically. These courtesy calls were time consuming and involved providing briefings on the research. Since there are three (3) cities and thirty-one (31) municipalities, with 1078 barangays in the province, it was not feasible to conduct courtesy calls and data gathering for all cities and municipalities. Thus, with geologic mapping, numerical modelling, and information on where major impacts of past eruptions were concentrated, , I preselected those communities in which I wished to undertake structured interviews. The municipalities/cities selected were Talisay (north, medial), Laurel (northwest, medial), Agoncillo (west, proximal), San Nicolas (southeast, proximal), Bauan (south, distal), Lipa City (east, medial), and Tanauan City (northeast, medial) (Figure 3.3).

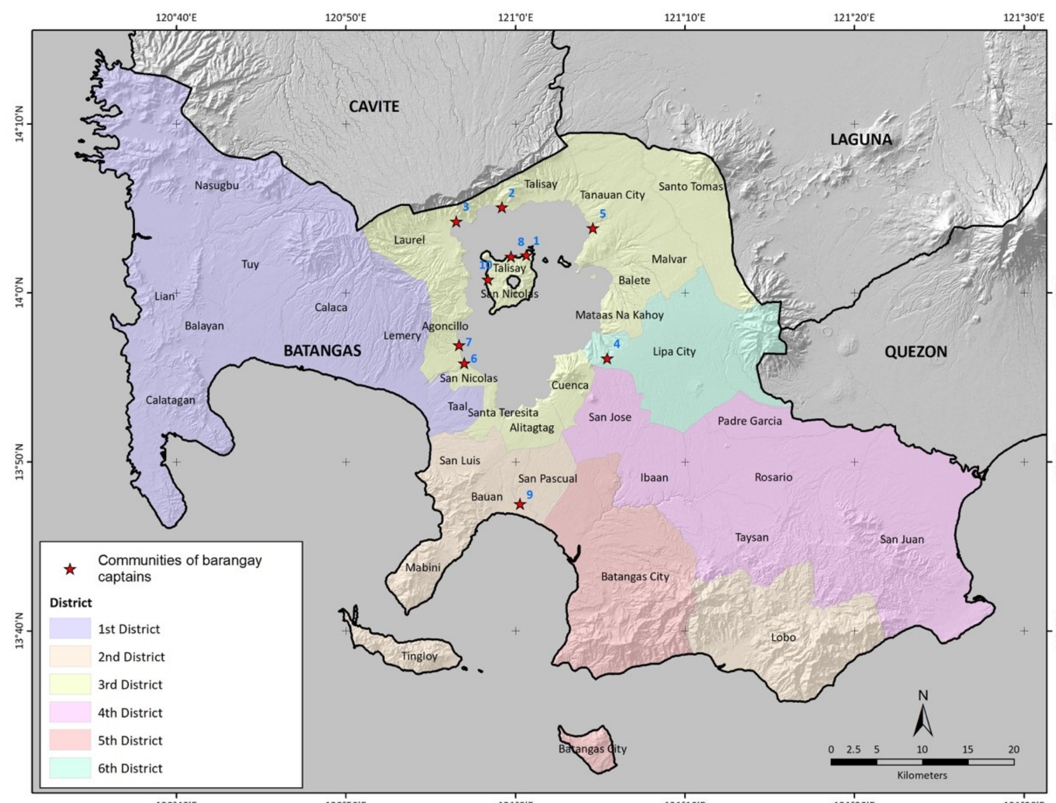


Figure 3.3. Map showing locations of cities/municipalities (red stars) in Batangas Province where specific responders, the Barangay Captains, were selected. Base map is NAMRIA IfSAR-DTM (2013) and Administrative boundaries are adopted from the PhilGIS (2011).

Another challenge to data gathering was the fact that interviews in 2015 and 2016 coincided with elections (General Elections held in May 2016 for Presidential including local government officials and originally October 2016 for Barangay level but was later moved to October 2018). As such, conducting courtesy calls and obtaining government documents was challenging. Locations of cities and municipalities where the DRR documents were obtained are shown in Figure 2.2 in Chapter 2. After collecting and collating the DRR documents, I then reviewed the documents and provided a summary list (Table 2.8) provided in Section 2.3.3 of Chapter 2. A comparison of listed versus what are actually available in the barangay level will be assessed and discussed in Chapter 7.

3.1.5.2. Challenges in archival analysis

Perhaps the most glaring methodological limitation that I have encountered while doing the historical eruption review is that posed by my lack of appropriate language skills to read archival documents written in Spanish. I had to rely mostly on interpretations provided by other authors (Saderra Masó, 1911; Worcester, 1912), making them second hand information.

3.1.6. Way forward

Notwithstanding the identified limitations in data gathering and analysis, I deem my literature review activities to be a valuable instrument in providing me with sufficient basic knowledge on the disciplines I have chosen and provided me with the direction on where I wanted to go. The exercise also made me realise that although my interdisciplinary study is an ambitious project in terms of the bulk of work that needs to be accomplished, I cannot do a holistic and relevant risk assessment for Taal and the surrounding communities if one component is missing.

3.2 Geological mapping and laboratory processing

I next set out to conduct geologic mapping to search for and validate the dispersal, deposition and thicknesses of the tephra fallout deposits from the AD1754 event. From the research process illustrated in Figure 3.2, the geologic mapping and laboratory processing activities aimed at seeking answers to Research Question 2: "*What is the predicted distribution of the tephra deposits in the event of an explosive eruption such as the AD1754 Plinian/Sub-Plinian eruption of Taal".*

I initially intended to look for tephra deposits from the major eruptions in AD1749, AD1754, AD1911 and AD1965 knowing that there are likely no preserved geologic record of the tephra deposits from smaller events (Connor et al., 2001, p. 37). The tephra deposits from minor eruptions are rarely preserved because they are thin and easily washed away by precipitation. However, during the course of my data gathering in August and October 2014, field investigations conducted in all areas surrounding Taal provided little evidence of deposits from the AD1749, AD1911 and AD1965 eruptions, and only the AD1754 deposits were prominent enough to be mapped. Accounts about the other explosive and destructive historical eruptions provided descriptions on where deposits were emplaced but there was no evidence found in the field. Furthermore, while deposits from the AD1754 eruption were found to the west of the volcano, I failed to find outcrops east of TVI. Figure 3.4 shows the locations where I conducted my initial field investigations in 2014. The previously generated isopach map for the tephra fallout from the AD1754 eruption is shown in Figure 3.5. The estimated dispersal during the eruption is based on Saderra Masó

(1911) and DOST-PHIVOLCS (1991) with an approximate bulk volume of erupted magma pegged at 150 million m^3 (DOST-PHIVOLCS, 1991). Forty-one outcrops containing AD1754 eruption deposits were identified, mapped, logged and sampled during the field investigations conducted in 2014 and 2016.

Initially, the deposit description of Torres (1989) was used as the basis for field recognition of tephra outcrops. Torres conducted stratigraphic logging, grain size analysis, morphological studies and petrology in his work but was limited to a few exposures. Torres identified seven deposit layers. The scoria lapilli and indurated base surge were identified as Layer A (A1 and A2) and Layer B (B1 and B2). On top of the surge and lapilli fall materials, he identified a layer of lapilli-supported basaltic bombs and lithic andesite fragments that he named Layer C1. He also mapped blocky lava that is found to be in gradational contact with C. He also mapped a blocky lava in gradational contact with Layer C1 identified as D (D1 and D2). Layer B2 was identified to be the topmost layer consisting of massive to bedded base surge deposits. While the deposition of Layers A, B, and C are consistent with narrations on the AD1754 eruption and field exposures, the lava flow extrusion and identification of Layers D1 and D2 as part of the AD1754 eruption are deemed not part of the AD1754 deposits.

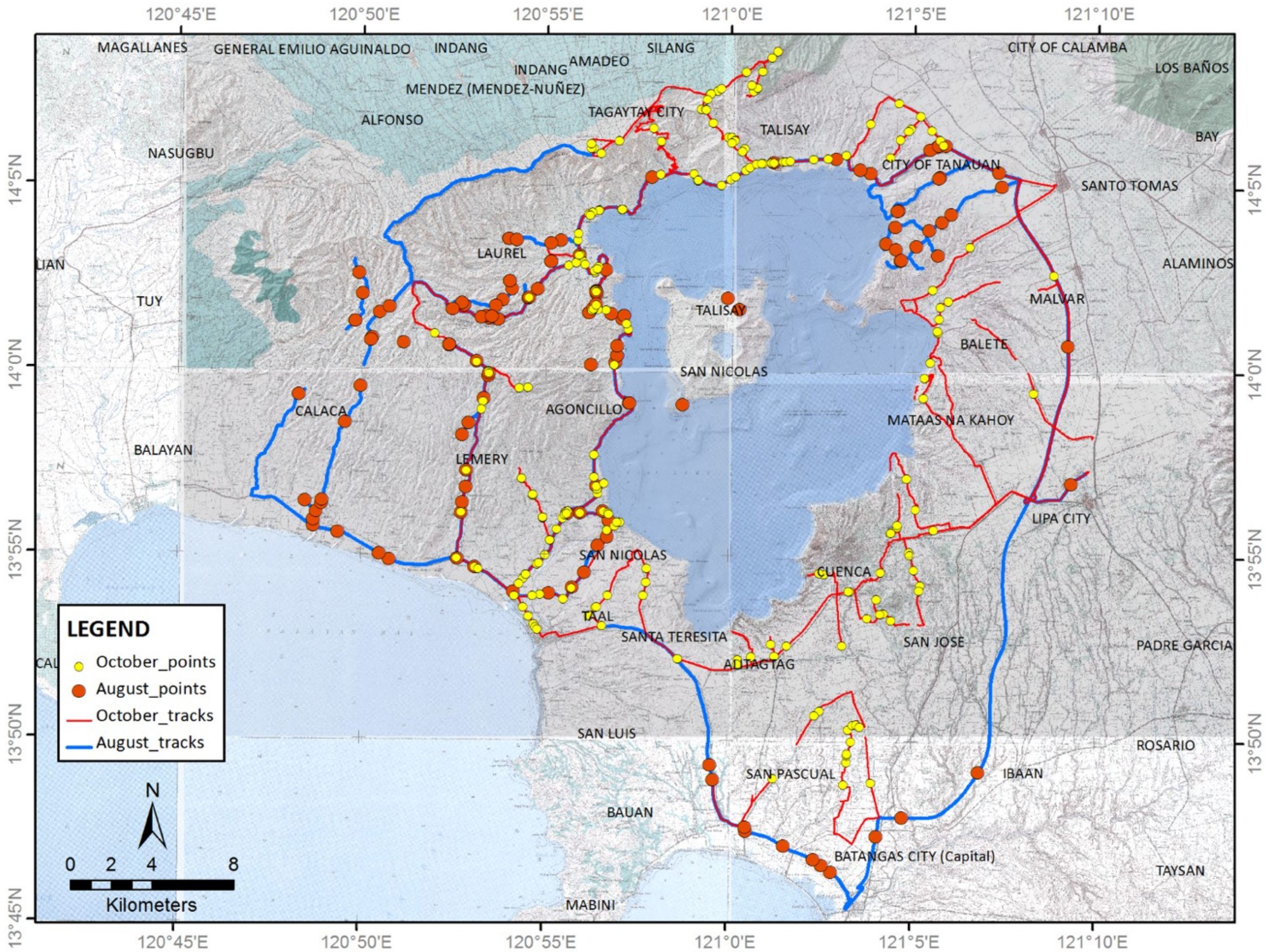


Figure 3.4. Map showing field survey tracks (red and blue lines), plots of the locations of field stops to check for Taal eruption deposit outcrops (yellow and red circles) in various cities/municipalities of Batangas Province during the 2014 field investigations. Base maps are NAMRIA 1:50,000 scale topographic maps (Series 711) reprinted 1990 and IfSAR-DTM (2013).

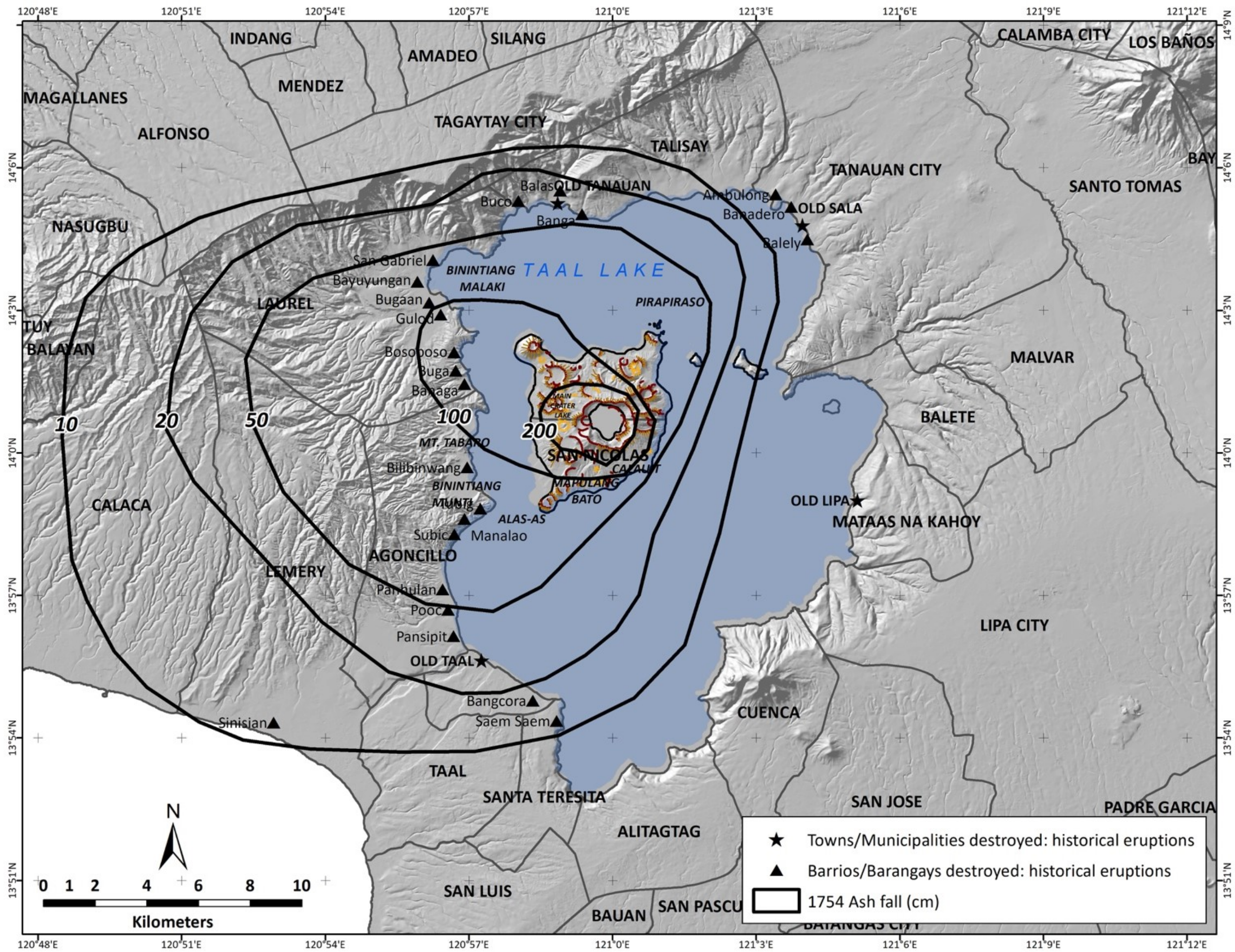


Figure 3.5. Isopach map showing estimated tephra dispersal during the AD1754 eruption based on Saderra Masó (1911) and PHIVOLCS (1991), with contour lines indicating thickness of fallout in centimeters. Brown lines and hachured lines delineate existing and active craters at TVI. Map overlain on NAMRIA IfSAR-DTM image (2013) and Administrative boundaries are adopted from PhilGIS (2011).

3.2.1. Mapping and stratigraphic logging of the AD1754 deposits

While mapping deposits from past eruptions are wrought with uncertainties due to reworking of the deposits including erosion or deposition, sectoral deposition and non-exposure (Burt et al., 2001), historical accounts provided useful information about the tephra fallout from this eruption and implied that tephra was generally dispersed to the west of the volcano (Saderra Masó, 1911; Worcester, 1912; DOST-PHIVOLCS, 1991). These accounts, along with the tephra isopach map previously generated (DOST-PHIVOLCS, 1991) (Figure 3.5), provided a guide on where to investigate the AD1754 tephra deposits.

Detailed deposit investigation included: 1) clean-up of the façade of the outcrop by removing overgrown grass and weeds that frequently covered the outcrops; 2) undertaking photo documentation of the outcrop; 3) obtaining GPS location of the deposits; 4) identification, stratigraphic logging and measurement of thickness of each stratigraphic layer, noting geologic unit descriptions that can help determine eruption dynamics and eruption styles; and 6) sampling and *in situ* bulk density tests of representative deposits (Farrel, 2014). Standard stratigraphic mapping (Doyle et al., 2001; Dellino et al., 2011; Mele et al., 2011) was done on presumed AD1754 deposits that consisted of alternating layers of pyroclastic density current (PDC) and tephra fallout (TF) deposits.

Detailed field descriptions of each outcrop included identifying lithologic classification (Cas & Wright, 1987), noting colour and composition, abundance, distribution and general particle sizes of fragments, grading and sorting, stratification, welding and induration, boundaries and/or contacts of each stratigraphic layer, as well as other characteristics of the eruptive materials which can provide information on the origin, transport, and emplacement processes related to the AD1754 eruption.

While conducting stratigraphic logging, some layers identified by Torres (e.g. Layer D) are not consistent with narrative accounts and not identified as part of the eruptive products of the AD1754 eruption. Layer C, consisting of lithic andesitic fragments in a scoria lapilli matrix and volcanic bombs (Bornas, 2016), while recognised as part of the AD1754 eruption, are limited in deposition in proximal areas including the Main Crater located in the central part of TVI (Figure 3.6).

During field investigations, only two of the four major phases of the AD1754 eruption were recognised, which I now name *TF1* (*A1* as identified by Torres) and *TF2* (*A2* as identified by Torres). The *TF1/A1* layer is identified as a deposit of the Plinian/Sub-Plinian eruptive phase that began between 9:00 and 10:00PM on 15 May, and continued up to 2 June. Layer *TF1* was found to consist of non-graded, very poorly sorted dark lapilli fall deposits. The *TF2* layer, on the other hand, consisted of thick dark lapilli fall units that were often observed to be graded that were likely ejected and likely deposited during the November Plinian/Sub-Plinian and/or Phreatomagmatic phase.

3.2.2. Bulk density sampling and computation

Bulk density is the weight of a material per unit volume with a deposit containing more irregularly shaped particles having lower bulk densities (USGS, 2015). Bulk density considers both the solids and the pore spaces in between, and therefore represents the actual density of the stratigraphic layer upon deposition. It also provides information on the porosity and compaction of the deposits being tested. Accurate determination of the

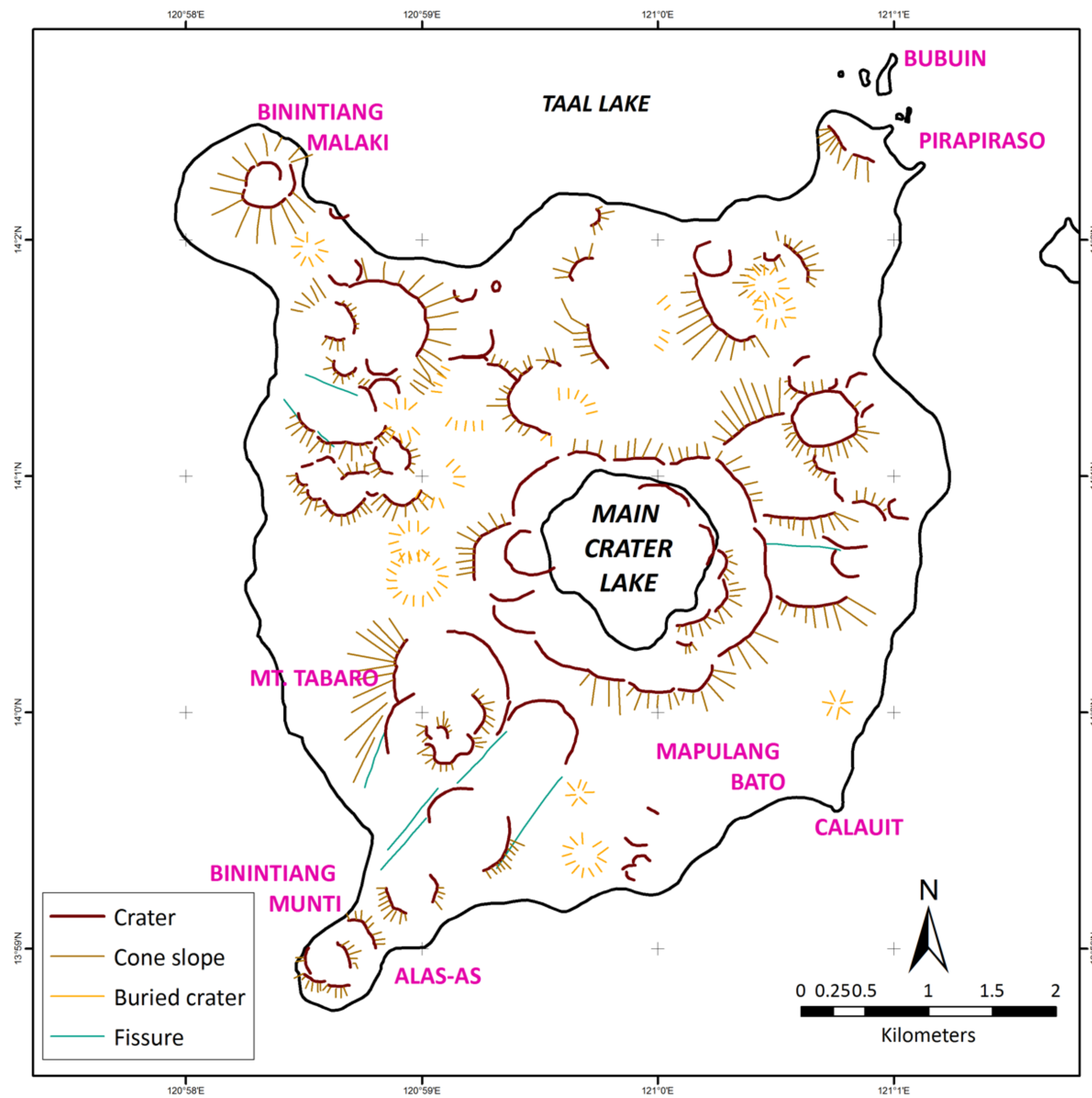


Figure 3.6. Location map of major eruption centers at TVI: Binintiang Malaki (northwest), Pira-piraso (northeast), Calauit (southeast), Binintiang Munti (southwest), Mt. Tabaro (southwest), and the Main Crater or the central caldera. Brown lines and hachured lines delineate existing craters. Map source: Modified from Ruelo (1983).

density of tephra deposits is one of the key input parameters for inversion modelling (Connor and Connor, 2011). Furthermore, precise sampling of the tephra deposits for density computation must be accurate to ensure that the sample represents the natural condition of the tephra deposit (Farrell, 2014). Here, the *in situ* bulk density test was conducted in the field following the tin can sampling method by Farrell (2014), and was performed at selected sites with identified AD1754 tephra. The method required the use of a tin can with known cylinder height and radius. Both ends of the tin can were removed. Using a shovel and scraper, the surface of the outcrop to be sampled was smoothened, removing any roots or plants present on the façade of the deposit. The tin can was then placed on the surface of the outcrop (Figure 3.7A). A square block of wood was placed on top of the can and the can was driven into the deposit by hammering on the block of wood evenly on all sides until the can was completely inside the deposit. Hammering too hard was avoided to ensure that no compaction occurred and an undisturbed sample was taken (Figure 3.7B). The deposits surrounding the buried can were removed and the surface levelled off to the edge of the rim. The can was then extracted from the deposit using a knife/scraper (Figure 3.7C). The tephra inside the tin can was removed and placed into a labelled sample bag (Figure 3.7D). Upon return to the laboratory, the tephra samples were dried and weighed according to Farrell (2014). Bulk density of the samples was then calculated as total weight of dry sample divided by the total volume of the sample through the computation of the volume of the tin can (Brown & Wherrett, 2017). The computed average density was then used to convert deposit thickness values to mass per unit area (kg m^{-2}) for use in inversion modelling.

Figure 3.7. *In situ* bulk density test using a tin can sampling method conducted in the field. (A) smooth surface of selected tephra outcrop clearing any roots or plants present and place tin can on the surface; (B) place a square block of wood on top of tin can and hammer on the block of wood evenly on all sides until tin can is completely inside the deposit; (C) excavate buried tin can and level off surface to the edge of the rim of can and extract tin can from the deposit using a knife/scraper; (D) remove the sample inside tin can into a labelled sample bag.

3.2.3. Grain size analysis

Samples were processed for grain size analyses at the DOST-PHIVOLCS laboratories in Manila to avoid the need for importing samples in to Australia through quarantine. The results of grain size and bulk density tests were subsequently utilised for numerical modelling (Connor et al., 2001; Volentik et al., 2010; Magill et al., 2015; Volentik & Houghton, 2015; Spanu et al., 2016).

Preliminary treatment of the samples prior to analysis included: 1) weighing the wet tephra samples; 2) drying in air (chosen because the tephra samples consist mostly of very brittle and highly vesiculated scoria) to avoid crushing; 3) weighing the dry samples to obtain estimated weight of erupted materials; 4) splitting samples by coning and quartering with two used for grain size analysis to avoid systematic bias (Carver, 1971). I did not use mechanical sample splitters for the sieve analysis but opted instead to manually dry sieve the samples using the Tyler Standard sieves from -6ϕ to +4.5ϕ at 1/2ϕ interval (Carver, 1971). Manual sieving was necessary for the samples because the highly vesiculated scoria fragments were too fragile and could easily be crushed if mechanical sieving was used (Figure 3.8).

For *TEPHRA2* modelling, Median phi (*Md*ϕ) and Standard Deviation or Sigma phi (σϕ) were computed at individual locations using the approach described by Boggs (2006). Standard deviation or Sigma phi (σϕ), a mathematical expression of sorting (Boggs, 2006), was computed for each of the tephra samples and likewise included to guide *TEPHRA2*

Figure 3.8. Grain size processing of the AD1754 tephra deposits included: (A) air drying of samples; (B) weighing of samples before and after drying; (C) and (D) mixing and splitting of samples using coning and quartering with two of the quarters used for grain size analysis using the Tyler Standard sieves from -6ϕ to +4.5ϕ at 1/2ϕ interval; and (E) manually sieving because the scoria fragments are too fragile and could easily be crashed if mechanical sieving were used.

input parameters. Standard deviation or Sigma phi ($\sigma\phi$) is computed using the formula from (Boggs, 2006):

$$\sigma\phi = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

The phi (ϕ) percentages are obtained from the plotted frequency curve of the grain size distribution of a particular tephra sample. The 16th and 84th percentage encompasses the central 68 percent of the area of the plotted frequency curve. Median size is the midpoint in the grain size distribution obtained from grain size analysis and represented as the 50th percentile diameter on the cumulative curve. The ranges of the median phi and sigma phi of the deposits at individual locations are noted, as well as the computed average, in order to determine the predominant grain size and sorting of the entire tephra layer, which is presumed to be the best estimate of the total grainsize distribution (TGSD) of erupted material. It is possible that this method may be overestimating the mean as I have not sampled significant number of outcrops in distal locations; however, inversion modelling will use these values as a starting point to refine the TGSD most appropriate for replicating the deposit.

3.2.4. Challenges in geologic data gathering

Absence of outcrops to the east of Taal – Although an exhaustive search for tephra deposits from the AD1754 eruption was conducted, no outcrops were found to the east of Taal. One reason for the absence may be due to poor preservation because of climatic conditions prevailing during or after the eruption (Janebo, 2016, p.66). From narrative accounts of the events, the deposits were generally concentrated to the west because of prevailing wind direction but there were still account that ashfall affected the east side and so I speculate that deposits were likely very thin to be preserved. Another likely reason for the preservation of the tephra on the west side is the fact that the deposits from the PDCs that subsequently occurred were emplaced on top of the tephra fallout materials which could be the reason why they were not eroded. This presumption is validated by the fact that most of the AD1754 tephra layers mapped on the west side of the mainland were overlain by PDC deposits.

Stratigraphic and lithologic identification – The layered stratigraphy of mapped and sampled outcrops made the identification of some of the tephra fallout deposits difficult to distinguish from ash cloud surge deposits. Ash cloud surges are defined as "*turbulent, low density flows generated in the overriding gas and ash cloud as observed above historic pyroclastic flows*" (Cas & Wright, 1987, p.119). Part of the ash cloud is elutriated and subsequently deposited as fine ashfall, which makes it difficult to distinguish these deposits from true tephra fallout deposits.

Bulk density testing and grain size analysis – Time constraints limited the number of tephra samples that could be processed. Therefore, I selected strategic sites such that they were truly representative samples of areas where the AD1754 tephra fallout deposits were identified, mapped and sampled.

3.2.5. Way forward

The discovery of new tephra outcrops from the AD1754 eruption, not previously discovered by Torres (1989), measured deposit thicknesses, processed grain size distributions, and calculated bulk densities, acted as useful inputs for inversion modelling, which ultimately provided new estimates of eruption source parameters, such as total erupted mass. This will be the first attempt to determine this critical information through numerical modelling for an eruption at Taal.

3.3 Numerical modelling

While volcanic deposits mapped in the field provide evidence of a particular eruption, stratigraphies are frequently and likely incomplete due to being buried or eroded by subsequent eruptions (Cassidy, 2014) or due to remobilisation by environmental or human processes. The information gap can be partly addressed using numerical modelling. Like geologic mapping, numerical modelling also intends to help address Research Question 2: "*What is the possible extent of tephra fallout in the event of another explosive eruption such as the AD1754 Plinian/Subplinian eruption of Taal?"*. While individual stratigraphic records can provide geologic information to constrain physical processes of past eruptions, the limited spatial extent of geological information describing the tephra fallout associated with the AD1754 eruption necessitated that I conduct numerical modelling to better understand the distribution of airfall material. In addition, inversion methods allowed me to estimate eruption source parameters such as the total erupted mass and eruption column height. Determining eruption source parameters, and dispersal extent is not only vital information to document this eruption, but can also be used for tephra hazard and risk assessment, particularly in relation to impacts of future eruptions to people, the environment, and infrastructure.

The aims of the numerical modelling were to: (1) use geological data gathered during field surveys as input data and to validate the analytical model; (2) utilise *TEPHRA2* and inversion methods in order to simulate and reconstruct the AD1754 eruption of Taal Volcano and to obtain best-fit eruption source parameters; and (3) resolve gaps in eruption information (e.g. estimate eruption source parameters and accumulation over the wider area), particularly for locations where tephra deposits were not found during field surveys.

3.3.1. Inversion using *TEPHRA2*

Recently, numerical tephra dispersal modelling has been coupled with inversion methods to look for the ideal set of eruption parameters that best fit field observations (Connor and Connor, 2005). For this study, the inversion modelling used is based on the method developed by Connor and Connor (2005), who built on the method by Nelder and Mead (1965). Rather than conducting numerical simulations using manual selection of reasonable parameter inputs one at a time until an adequate fit to field observations is obtained, inversion modelling automates this search utilising a mathematical algorithm (Connor and Connor, 2005). For the simulation results ultimately chosen to be the best-fit, modelled accumulations were extracted and plotted and regressions between measured and modelled calculated. The correlation coefficient found for these regressions determines how strong the relationship is between the two variables.

Prior to my geologic mapping in 2014, I undertook preliminary inversion simulations using estimated tephra fall accumulations of the AD1754 eruptions from PHIVOLCS (1991) and Saderra Masó (1911) (Figure 3.5). The preliminary results of these simulations served as an additional guide to where geologic investigations would be conducted and prioritised in search of AD1754 tephra deposits. Details of these simulations and their outcomes are not provided here.

After the surveys conducted in 2014 and 2016, more detailed simulations were performed. I included the new geologic information gathered from field mapping, granulometric analysis and *in situ* bulk density tests. Mass per unit area data included my new findings and 20 tephra outcrops mapped in 2013 by DOST-PHIVOLCS colleagues prior to the onset of my own thesis. I obtained permission to include the thickness and location information in the inversion modelling I conducted and identified the acquired data as *N1* to *N20*. This study is related to research on the spatio-temporal succession of major eruptive events of Taal Volcano, with particular attention to the composition and distribution of large-volume pyroclastic deposits (Bornas, 2016). With the newly acquired geologic data, I subsequently obtained much improved modelling results compared to my preliminary simulations.

3.3.2. Identified phases used for inversion modelling

In summary, the multi-phased eruption of Taal Volcano lasted from the 15 May to 2 December AD1754 and comprised: a) a Plinian/Sub-Plinian phase that commenced between 9:00 and 10:00PM on 15 May and continued to 2 June; b) a Phreatomagmatic phase from 2 June to 26 September; c) a Plinian/Sub-Plinian or Phreatomagmatic phase from 1 to 15 November; and d) a Plinian/Sub-Plinian and Phreatomagmatic phase from 28 November to 2 December. The chronology of the AD1754 eruption is shown in Appendix C (Saderra Masó, 1911; Worcester, 1912; Berninghausen, 1969; DOST-PHIVOLCS, 1991).

Two significant phases of the AD1754 eruption are represented, preserved and were mapped in 2014 and 2016. Tephra deposits from the first Plinian/Sub-Plinian phase were identified as *TF1,* while *TF2* relates to the last Plinian/Sub-Plinian and phreatomagmatic phase that occurred November AD1754. The locations and measured thicknesses of the tephra fallout deposits from the identified phases of the AD1754 eruption were discussed in Chapter 5. Considering the wide representation of *TF1* (15 May to 2 June phase) and *TF2* (November phase) in the field, these two phases were selected for simulation. Tephra modelling was also done for a single data set combining all accumulation point locations based on two data sets: initially utilising the isopach map in Figure 3.5 for modelling constraints, then with my geological field-derived data set.

3.3.3. Compilation of modelling input parameters

As inversion modelling works to find best-fit parameter values between predefine limits, acquiring truly representative and realistic ranges of eruption parameters as input is critical (Komorowski et al., 2008). With the identification of two observable major eruptive phases, and with corresponding measured thicknesses, it was necessary to determine input parameters ranges for the two distinct phases.

Eruption characteristics such as mass eruption rate, duration of eruption, plume height, and total particle size distribution, are important not only to document an eruption, but also to determine the impact of particular eruption styles and the magnitude of future eruptions (Bonadonna et al., 2015; Connor et al., 2001; Connor & Connor, 2005; Magill et al., 2015). Some of the *TEPHRA2* parameters are fixed because they pertain to the specific eruption and volcano being modelled, or to make simplifying assumptions where adding additional uncertainty is unwarranted. Fixed eruption input values for Taal simulations include volcano location, vent height based on highest elevation at Taal, Plume Model 2, lithic density based on typical density of lithic fragments, pumice density obtained from my own density tests and calculations, and the eddy coefficient. Particular assumptions of Plume Model 2 include a straight-line trajectory and this essentially means that the model do not account for rising or turning of the wind. Plume Model 2 assumes that meteorological condition is spatially uniform, contrary to actual atmospheric condition. These two assumptions then become the limitation of the model.

Limits are placed around the remaining parameters and these parameters are investigated and improved by inversion. Inversion limits used for my research (realistic minimum and maximum values that inversion code samples between) are provided for eruption column height, total erupted mass, a minimum and maximum median phi, a minimum and maximum sigma phi, fall time threshold, diffusion coefficient, wind direction at each step in the eruption column, and wind velocity at each step in the eruption column. The minimum and maximum median ($Md\phi$) and standard deviation ($\sigma\phi$) values were obtained from the grain size analysis of the AD1754 tephra samples. The main objective is to obtain an optimal set of values from within these eruption parameter ranges.

3.3.4. Determination of parameter ranges

With the inversion code developed by Connor and Connor (2006, 2011), an automatic search is performed in a parameter space for the optimal values that gave a best-fit to field observations and measurements.

To estimate the appropriate range for total erupted mass, I used previously constructed isopach maps from DOST-PHIVOLCS (1991) and from my geological investigation, and the method of Pyle (1989). The total mass equals the volume multiplied by deposit bulk density. To obtain the volume of the tephra deposits, the utilised equation (Pyle,1989, p. 13) is:

$$V = 2\pi T_o b_t^2$$

In the above equation, V is deposit volume, *pi* (π) is equal to 3.14159, T_o is the extrapolated maximum thickness and b_t is thickness half distance or average thinning rate for the whole deposit (Pyle, 1989). Tephra thickness is assumed to exponentially decrease away from the vent and it is also assumed that the isopach contours are elliptical. Based on the isopach map (Figure 3.5) generated by me for the AD1754 eruption, the value of T_o, the extrapolated maximum thickness or the point where the line crosses the y axis, was derived by plotting the square root of each isopach area against the logarithm of thickness.

For inversion modelling, the minimum potential erupted mass was assumed to be five times smaller than the estimated mass, while the maximum mass was five times larger. Plume height limits are based on historical accounts.

The range of median and standard deviation particle sizes, in phi units, were obtained from the results of the grain size analysis for tephra deposits sampled from individual locations. The four size parameters, minimum and maximum median phi ($Md\phi$) values for *TF1* and *TF2*, and the minimum and maximum the standard deviation ($\sigma\phi$) values for *TF1* and *TF2* provided in Section 3.3.3 represent the total tephra deposit of the two particular eruptive phases of the AD1754 event.

Initial parameter range for wind direction was based on dispersal shown in the isopach map generated by Ruelo et al. (1991) (Figure 3.5), and wind speed range was estimated using wind speed data from current Climatological Normal Values for Batangas Province from PAGASA for the months of May to December to best reconstruct the eruption. These limits were employed for all inversion runs.

3.3.5. Modelling workflow

Multiple inversions with narrow mass and height ranges were performed to consider inversion sensitivity and to avoid parameters converging on a false minimum (Connor and Connor, 2005; Magill et al., 2015). One hundred sets of parameters were assigned equating to 10 equal ranges of mass (log scale) and 10 ranges of column height (linear scale) segmented into 2500 m bins between the minimum and maximum limits.

Also, to avoid false minimums, multiple inversion runs were completed with 10 unique random seeds, which ensured distinct plume height, erupted mass and particle size characteristics, etc. were sampled (Connor and Connor, 2005; Magill et al., 2015). This meant that, in total, 1,000 inversion runs were completed for each simulated deposit (*TF1*, *TF2* and a combined data set).

For each parameter set, the inversion runs with the lowest root mean square error (RMSE) was selected, i.e. the simulation with the best performing random seed. This resulted in a smaller set of 100 model runs for each deposit that were analysed for RMSE and goodness-of-fit.

3.3.6. Predicted isopachs for best-fit eruption source parameters

After further analysis, the source parameters representing the best fit to measured data were simulated over a 1-km resolution grid utilising the forward solution of *TEPHRA2* and results plotted as isopach maps. To generate the isopach maps, modelled values of mass loading were converted to thickness using the deposit density obtained from the density test conducted in the field. Regressions between simulated and measured values were plotted to better visualise the spread of data, goodness-of-fit, outliers, etc.

Analysis and interpretation of inversion results will be discussed in detail in Chapter 6- Numerical Modelling.

3.4 Use of structured interviews

The social research in this thesis aims to address Research Questions 3: "*How would a major/plinian eruption affect communities around Taal Volcano?*" and Research Question 4: *Given that the Barangay Captains and their communities are located on or close to Taal, and as the key stakeholder in the community, how are the Barangay Captains responding to volcanic risk? What is the level of education, knowledge, experience, risk perception and preparedness of these specific stakeholders?*" as illustrated in Figure 3.1.

Elements of what might be considered 'social volcanology' have only been applied in the Philippines in a very limited way (Usamah & Haynes, 2012; Martinez-Villegas, 2013) and I wanted to make a modest contribution to this emerging field. While acknowledging that a complete and comprehensive survey of the whole spectrum of stakeholders would provide a better understanding of the knowledge, risk perception, awareness, attitudes and capability to address the hazards and risk, such a comprehensive social study is beyond the scope of the current thesis. Instead, I undertake a pilot survey via the process of structured interviews of selected Barangay Captains of communities on or close to Taal. Specifically, the results are presented as a vignette, or 'mini' study (Wilks, 2004; Jackson et al., 2015) of the Barangay Captains to serve as an entry point that might be expanded in future, dedicated, socially-oriented work. It is prudent to say at the outset that I am, as a classically trained field geologist, embracing the value of taking a social sciences approach to understanding aspects of risk perception and behaviour. I seek to gain some insights in to the understanding, preparedness and challenges faced by the Barangay Captains – the officials at the sharp-end of 'doing volcano disaster risk management' in the communities located around Taal.

The purpose of the vignette study and its qualitative approach is to gauge the level of education, knowledge, experience, risk perception, awareness and preparedness of the Barangay Captains for supporting their communities during a volcanic emergency considering that they are located on or very close to Taal Volcano. The abovementioned key considerations were selected based on recurring themes in the research papers I reviewed (Appendix D-1 and Appendix D-2). From the results of the vignette study, recommendations will be offered on how Barangay Captains could be supported to enhance their DRR activities and governance.

I concentrated my efforts on obtaining responses to questions pertaining to issues or problems directly related to their understanding of volcanic risk and their reaction and behaviour towards those risks. While the 'right action' for a scientist is avoidance of the hazards and risk, I wanted to understand what the 'right action' is for people who live with the risk.

The process flow of this socially-oriented research is as follows: 1) structured interview design; 2) University of Sydney Human Research Ethics Committee (HREC) application and approval of the project; 3) interviews with participants; 4) interview data processing, analysis and interpretation (Figure 3.9). Interviews were conducted over a period of three years, with interviews undertaken in between episodes of geologic mapping.

3.4.1. Structured interview design

The interview design should be such that it addresses the research questions identified in Chapter 2 (and reiterated in Section 3.4 above). A research design is defined by Thyer (1993, p. 94) as a "*blueprint or detailed plan for how a research study is to be completed-operationalizing variables so they can be measured, selecting a sample of interest to study, collecting data to be used as basis for testing hypothesis, and analysing the results*".

For my vignette study, I chose to interview selected Barangay Captains, with one participant further away from the volcano to gain a perspective of those living a considerable distance from the volcano. My sampling was purposive and my selection of respondents (Barangay Captains) was based on proximity to Taal. I utilised some of the questions in the HREC-approved questionnaire forms (Appendix E-1 and Appendix E-2) as prompts for the structured interviews and qualitative discussions I conducted with the Barangay Captains. I further expounded on each of the questions with follow-up questions. Structured interviews/questionnaires have proven to be an effective medium

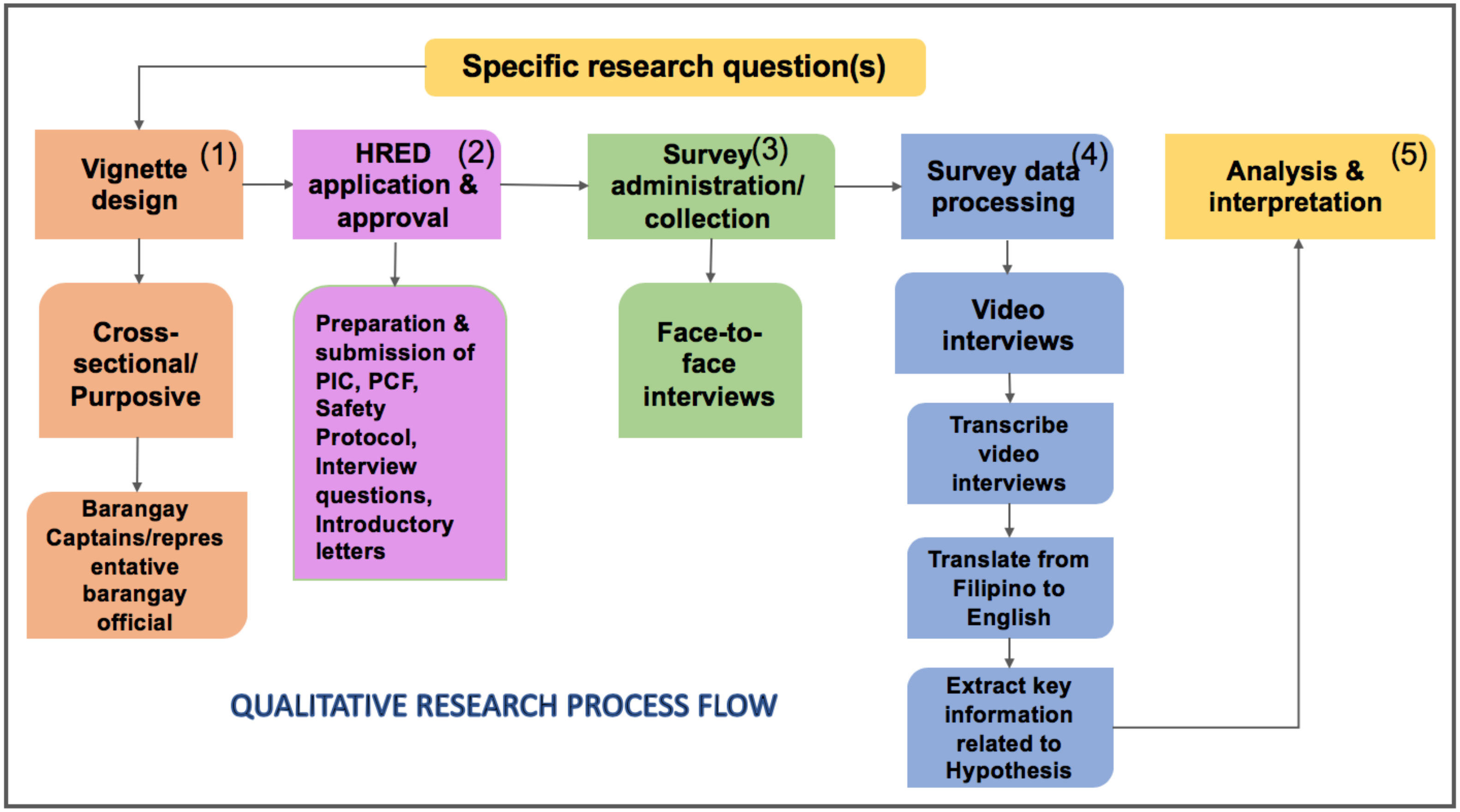


Figure 3.9. Social volcanology process flow. 1) survey design; 2) University of Sydney Human Resource Ethics Committee (HREC) application and approval; 3) survey administration; 4) survey data processing; and 5) survey analysis and interpretation.

to use to extract information on people's perception and knowledge of natural hazards including volcanic threat (Barberi et al., 2008; Bird, 2009; Gubrium & Holstein, 2001; Kvale, S., 2009, 2015; Njome et al., 2010).

3.4.1.1. Cross-sectional study design

To generate answers to the Research Questions 3 and 4, I have selected a cross-sectional study design, rather than 'before-and-after' design or a longitudinal study. Cross-sectional study design is known to be frequently used in social research (Bryman, 2006, Cresswell, 2014; Kumar, 2014; Levy & Lemeshow, 2008; Mathers et al., 2009).

Kumar described cross-sectional design (2014, p. 134) as "*one-shot or status studies, suited to studies aimed at finding out the prevalence of a phenomenon*, *situation, problem, attitude or issue, by taking a cross section of the population*". In my research, I chose a cross-section of a specific stakeholder group – the Barangay Captains (Figure 3.3). A total of ten Barangay Captains were interviewed. While the number of respondents prohibits over-generalisation, it is adequate to identify key issues related to DRR management and practice and to make recommendations for future research.

3.4.1.2. Sampling technique – probability versus non-probability or purposive sampling

By definition, *probability sampling* is a method where the sample obtained "*properly mirrors the population it is designed to represent*" (de Vaus, 2002, p. 70). Probability sampling techniques include *simple random*, *cluster*, *longitudinal* or *spatial* defined in more detail by Bird (2009). On the other hand, statistical generalisation cannot be done for *non-probability sampling*. However, non-probability sampling is used when participants are selected on the basis of known common characteristics but unknown population demographics (Patton, 1990; McGuirk & O'Niell, 2005; Bird, 2009). *Non-probability sampling* includes accidental, purposive, quota, and snowball approaches (Bird, 2009). I opted for purposive non-probability sampling rather than probability sampling because participants are selected purposively based on their community roles. Review of the historical eruptions, especially the AD1754 event, helped identify areas most likely to be affected during a future eruption similar to the AD1754 event, which then became one of the justifications for the selection of Barangay Captain respondents. The communities where the selected Barangay Captains where located, experienced the greatest impacts during historical eruptions. One Barangay Captain was selected from a more distal location in order to obtain a viewpoint of a respondent least likely to experience the direct impact of an eruption at Taal.

3.4.1.3. Measurement procedures including research tools/instruments

As far as information gathering is concerned, both primary and secondary data were collected. Primary data are information I specifically gathered in the form of interview responses that were also video recorded. Transcripts were then transcribed and translated to English with key salient points noted together with observations made by me in the field. Secondary data is defined by Payne & Payne (2004), as qualitative or quantitative information previously collected and re-analysed for current research which may have new research questions to address. I collected secondary data from some of the risk perception studies already completed at Taal (Tayag et al., 1988; Saquilon & de Guzman, 2005).

Structured interviews were chosen as the primary tool for my vignette study because a wide range of information can be gathered from the respondents using this approach, which includes personal characteristics, behaviour, attitudes, beliefs and response influences (Bird, 2009). The interviews were structured in the sense that the questions were divided into themes that provide information about extent of knowledge and awareness of the respondents to volcanic hazards and risk, behaviour in the face of a volcanic emergency, experience(s) of volcanic eruptions, and existing preparedness measures in their communities. A review of the literature on social volcanology allowed me to extract frequently discussed themes/issues pertaining to volcano related risk perception and DRR problems and strategies that became the subject of my questions. The five factors for my structured interviews identified as recurring themes included importance of the *level of education* (Barberi et al., 2008; Njome et al., 2010), knowledge and understanding of volcanic hazards and risk (Bird, 2009; Bird et al., 2010; Perry & Lindell, 2008; Saquilon & De Guzman, 2005), direct or indirect experience of an eruption (Becker et al., 2017; Gaillard et al., 2015; Johnston et al., 1999; Paton et al., 2001b; Tobin et al., 2011), influencing factors to behaviour and responses related to taking volcanic risk seriously (e.g. *family*-Carroll & Parco, 1966; *religious beliefs*- Banzon-Bautista, 1996; Bankoff, 2004; *attachment to place*- Gaillard, 2008), and influencing factors and level of preparedness (Dibben & Chester, 1999; Dominey-Howes & Minos-Minopoulos, 2004; Lindell & Perry, 2000; Paton & McClure, 2013; Paton et al., 2015; Solberg et al., 2010).

The first cluster of questions identifies the personal characteristics of the Barangay

Captains including age, gender, marital status and level of education (Question # 1 to 4 of Appendix E). Question #6 to 15 explore the respondents' sense of place or emotional attachment to the community where they reside. The next cluster of questions explore the Barangay Captains' level of education, knowledge of volcanic hazards and the possible impact of these hazards on their communities, direct or indirect experience of an eruption, as well as finding out what their reactions and preparedness measures during volcano emergencies would be (Question # 16 to 29 and 35). The free text responses were video recorded, transcribed and translated to English in order to extract the salient information I need for Research Questions 3 and 4.

3.4.2. Human Resource Ethics Committee application and approval

All relevant documents related to the socially-oriented research were submitted to the Human Resource Ethics Committee (HREC) at the University of Sydney for approval. Appendix F provides a copy of the HREC approval.

Documentation included:

1. *Participant Information Statement (PIS)* - explains the purpose of research project, who is running the project, what the study will involve for the participant, duration of the survey, the rights of the participants, contact information in the event the participant wants further clarification or wants to file a complaint. The PIS is provided to the prospective respondent for his or her information. The PIS is available in both English and Filipino.
2. *Participant Consent Form (PCF)* – consent is sought from the potential respondent for the use of his/her responses in the questionnaire and interview,

photo and video documentation. The PCF is available in both English and Filipino.

3. *Safety Protocol for Data Gathering* – provides certain constraints and to ensure that I take care of my safety during the conduct of my social research.
4. *Summary Description of the Project*
5. *Questionnaire Form* available in both English and Filipino.
6. *Interview questions* available in both English and Filipino.
7. *Draft Introductory letters* about the project for provincial, municipal/city, and barangay officials.
8. *Statutory Declaration* that the translations of the PIS, PCF, Questionnaire and the Interview questions are accurate and faithful to the said documents.

Approval of the project (Project No. 2014/560) was granted on 01 July 2014 and is valid for four years from approval.

3.4.3. Survey administration

In order to initiate administration of my social research, courtesy calls were conducted to provincial, municipal/city, and barangays officials using the introductory letters prepared as a project overview. Briefings were also held to provide them with more details about the project. Advise was also sought on their recommendation as target barangays for the interviews. The interviews generally consisted of two persons, myself as interviewer and one photo and video documenter.

At the onset, Participant Consent Forms were provided indicating permission to take photos and videos during the interview. Only one of the ten Barangay Captains opted not to have a video recording of his interview. In general, each interview took one to two hours with some divergence from the topic being discussed. Video interviews were transcribed by me - each taking approximately three hours to complete.

3.4.3.1. Face-to-face interviews

An important methodological detail in any social survey is the identification of response format (Bird, 2009). The structured interviews were administered face-to-face by the researcher (de Vaus, 2002). The respondents preferred to be interviewed on the topics in the questionnaire, by answering verbally to the questions being read to them and the interviewer writing down their responses on the questionnaire because some do not feel comfortable reading the questionnaire while others feel they are more able to inquire and understand better if the questions were read by the interviewer before they answer the questions. While reading through the transcribed video interviews, I noted key information that addressed specific themes I defined in Section 3.4.1.3.

3.4.4. Interview data processing and analysis

In the process of analysing responses, one must visualise how the findings will be communicated. Ideally, this should be done in the planning stage when creating the research instrument (Kumar, 2014). Information gathered from the interviews is identified as 'raw data' and is being identified as qualitative and descriptive (Kumar, 2014). The nine transcribed interviews were translated to English to allow for easier dissection of the responses but important direct quotes were also noted. While quantitative and categorical responses can easily be translated into numerical values known as 'codes', descriptive responses must be analysed to identify to which key issues in my vignette study the responses of the Barangay Captains will be most appropriate. In general, all respondents answered the key questions in the interviews, as well as additional supplementary questions that emerged and seemed relevant during each interview.

Having gathered the qualitative raw data (i.e. education, knowledge, experience in volcanic emergencies, reaction/behaviour to risk, and preparedness) from the transcribed interviews, I generated a table of responses that I deemed appropriate to analyse the interview responses. Subsequently, I determined if the Barangay Captains provided positive or negative responses to the identified issues assessed by me as 'positive' or 'negative' responses. The results of the vignette analysis is provided in Chapter 7.

CHAPTER 4:
Historical descriptions of eruptions of Taal

4.0 Introduction

This chapter presents new data to address Research Question 1: "*What do we know and do not know about the eruptions of Taal Volcano? What can a collation, synthesis and reinterpretation of information tell us about the record of past eruptions at Taal, their processes, products and hazards?*" and Research Question 2: "*What is the expected distribution of tephra deposits in the event of an explosive eruption such as the AD1754 Plinian/Sub-Plinian eruption of Taal*". While the summaries and interpretations of Spanish colonial documents on the historical eruptions of Taal from AD1572 to AD1911 serve as outstanding contributions, reinterpretation is deemed necessary in some cases and the results of these new interpretations are provided in this chapter. With the benefit of drawing upon a more extensive volcanology literature and my field experiences after the Mayon eruptions in AD1984, AD1993 and AD2000, and the AD1991 Pinatubo eruptions, I have newer insights and a greater knowledge of likely products and processes than were available to previous researchers. A change of classification of eruption styles and eruptive products suggested for some of the eruptive events is based on a critical re-examination of the narrative accounts.

In Chapter 2, I provided a summary of the regional and local tectonic setting of Taal, the prehistoric eruptions and evolution of Taal Caldera, and a discussion of various geologic and historical database utilised for this research. An introductory summary of the thirty-three identified historical eruptions of Taal from AD1572 to AD1977

(Section 2.2.4) was also provided, with the eruptions subdivided into series based on locations of the eruption centers and repose periods. The comprehensive summaries of the historical eruptions are herein discussed in this chapter, with the original eruption information sourced from documents written by various authors. The methodology on the process of critical literature review was presented in Chapter 3, Section 3.1.2.

The summaries generated from my literature review now serve as a single detailed comprehensive synthesis of all known information on the historical eruption record of Taal and were published in *Earth Science Reviews* (Delos Reyes et al., 2018) (Appendix A). Appendix B provides the list of the eruptions and some salient details on eruption styles, processes and products. A summary of my suggested changes for the classification of eruption style and re-interpretation of processes and products shall be provided in this chapter.

4.1 Reinterpretation of narrative accounts

The rationale for the reinterpretation of the historical eruptions as confirmed or uncertain is based on availability of eruption information that describes processes and products that can authenticate the occurrence of each event. In this chapter, I examine and summarise narrative accounts of each historical eruption in order to provide a complete chronological eruption profile of Taal. Where necessary, a change of classification of eruption styles and eruptive products is undertaken for some of the eruptive events following the process flow shown in Figure 4.1. In the process flow, all available sources for each identified eruption are critically reviewed. With the absence of sufficient details to confirm an eruption or event, identified eruptions are automatically downgraded to "uncertain" (Figure 4.1). When narrative accounts are available, these accounts are filtered if they only identify solfataric events or, alternatively, if they have detailed eruption descriptions including eruption columns, intensity, processes and products, extent and thicknesses of deposition and/or dispersal, or impacts to communities (Figure 4.1). A solfataric event is also classified "uncertain" and it is presumed that the event did not culminate into an eruption (Figure 4.1). The eruption is confirmed when detailed descriptions of eruptive activity is provided. Further, where I agree with previous interpretations of narrative descriptions of eruption style, processes and products, and/or the VEI values provided (Newhall & Self, 1982) by secondary sources, then eruption classification is authenticated. Where interpretations are deemed inaccurate, a change of classification is newly interpreted with adequate support and justification.

At least nine reported eruptions were deemed uncertain including the AD1605-AD1611 event, AD1634, AD1635, AD1645, AD1790, AD1825, AD1842, AD1873 and AD1903 events. Details on their proposed reclassification is discussed in the following subsections. Furthermore, some VEI values, processes and products identified in previous studies about Taal are reclassified.

4.1.1. Background on prehistoric and historical eruptions of Taal

A summary of the evolution and prehistoric eruptive activity of Taal, specifically Taal Caldera, was previously provided in Chapter 2, Section 2.2.3. The four caldera-forming events identified by Listanco (1994) are represented by four major ignimbrite deposits identified from oldest to youngest as: 1) the silicic Alitagtag (ALI) pumice flow deposits; 2) the Caloocan (CAL) pumice flow deposits; 3) the dacitic Sambong Ignimbrite (SAM); and 4) the basaltic-andesitic scoria flow originally named Taal

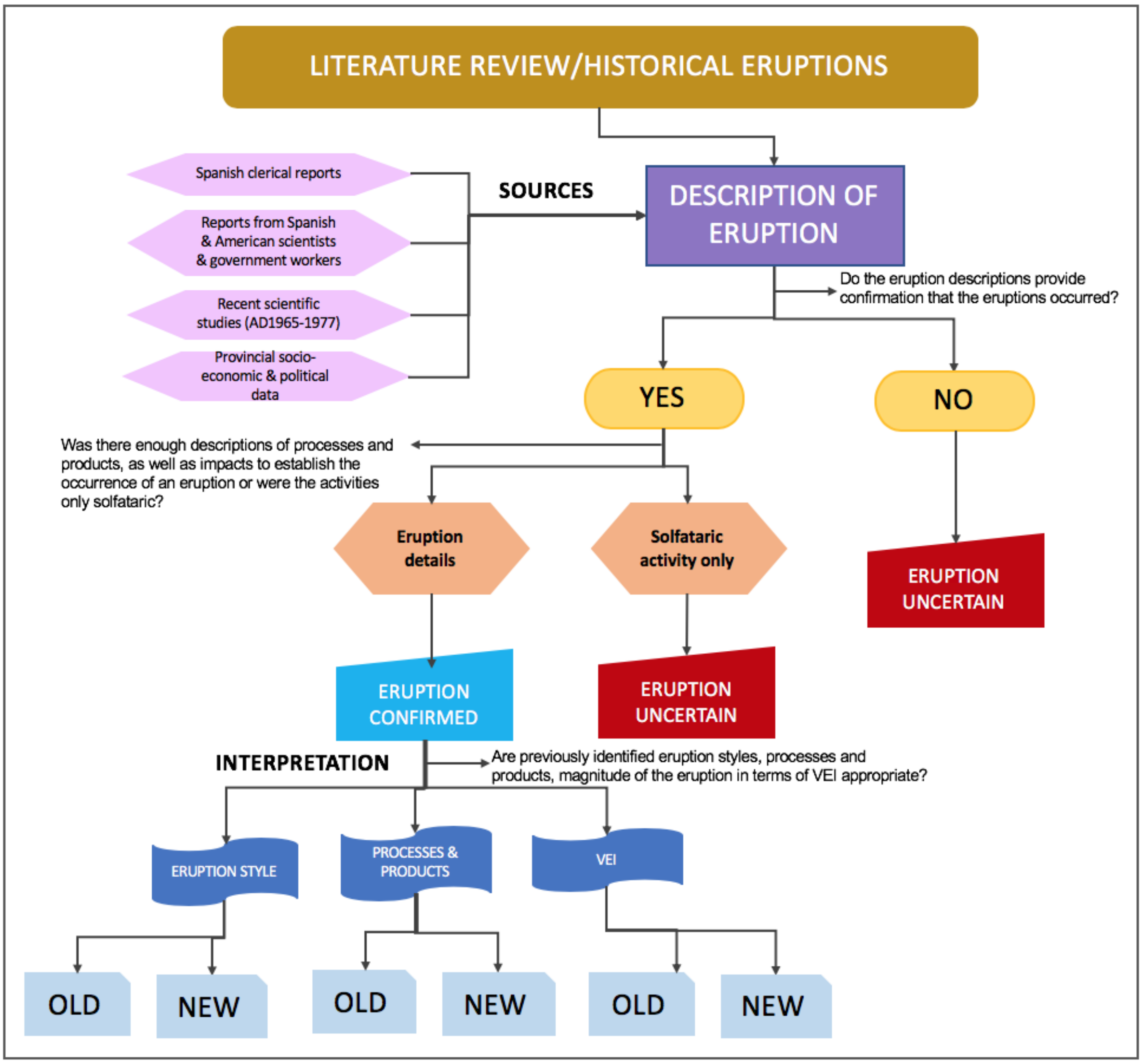


Figure 4.1. Methodology process flow utilised in the critical review of narrative accounts of the historical eruptions of Taal.

Scoria Flow (SFL) by Listanco (1994), then subsequently renamed Scoria Pyroclastic Flow (SPF) by Martinez and Williams (1999). Of the four prehistoric ignimbrite deposits, the uppermost and best-studied SPF is the only deposit that is dated, with ^{14}C dating age of 5380 ± 70 to 6830 ± 80 BP (Martinez & Williams, 1999). Data on the older Quaternary caldera-forming eruptions of Taal are limited. More research needs to be undertaken in refining likely eruption dates, to approximate the extent of deposition and other diagnostic characteristics of the products of these eruptions. This is especially important since they produced large-volume pyroclastic density currents that are extensively distributed and exposed in highly urbanised areas in the provinces of Batangas, Laguna and Cavite (Martinez & Williams, 1999).

A total of 33 historical eruptions of Taal were previously identified (DOST-PHIVOLCS, 1991, 1995) (Table 4.1). Four of these eruptions were considered violent with VEIs ranging from 3 to 5 (Newhall & Self, 1982; DOST-PHIVOLCS, 1991): the AD1749, AD1754, AD1911 and AD1965 eruptions. The 33 eruptive events are divided into four series based on the locations of the eruption centers and eruption repose periods (DOST-PHIVOLCS, 1991). *Series A* includes eruptions centered at the Main Crater (Figure 4.2). *Series B* eruptions were alternately centered between the flank craters located around the volcano. *Series C* grouped the eruptions centered again at the Main Crater. Finally, *Series D*, last series of eruptions, were centered at Mt. Tabaro located on the southwestern flank of TVI. Discussion on the reassessment and proposed changes of events will be provided here, series by series.

4.1.2. Comprehensive summary of the historical eruptions of Taal

4.1.2.1. Series A

Series A includes the eruptions from AD1572 to AD1645 that were centered at the Main Crater (Figure 4.2). Three eruptions (AD1572, AD1591 and AD1641) are confirmed while four eruptions (AD1605-AD1611, AD1634, AD1635 and AD1645) are considered uncertain.

AD1572

Following the assessment process flow in Figure 4.1, confirmation of an eruption is provided by Father Gaspar de San Agustin in his report (1699, *In* Saderra Masó, 1911, p. 6; *In* Worcester, 1912, p. 313) where he wrote that *"there is a volcano of fire which is wont to spit forth many and very large rocks, which are glowing and destroy the crops of the native"*. The previous interpretation for the AD1572 eruption was phreatomagmatic (DOST-PHIVOLCS, 1991) (Table 4.1). However, an alternative interpretation of the phenomena is that it was a Strombolian style event with lava fountaining and/or lava flow. The description more likely relates to a Strombolian eruption with ejection of scoria and incandescent lava spatters (Cas & Wright, 1987). Previous classification for this eruption was phreatomagmatic (DOST-PHIVOLCS, 1991). Secondary sources like DOST-PHIVOLCS (1991) also did not ascribe any description insofar as processes and products related to the AD1572 eruption is concerned. However, the abovementioned description implies that likely eruptive processes are lava fountaining and/or lava flows with ballistic projectiles and tephra fall deposits. While there are no mapped and dated deposits from this eruption, the description of Father Gaspar de San Agustin (*In* Saderra Masó, 1911; Worcester, 1912) that clearly indicated the eruptive process and products, means that confirmation of the occurrence of this eruption is unquestionable and the previously assigned default VEI of 3 is maintained. The proposed changes in eruption description for the AD1572 eruption are summarised in Table 4.1.

Table 4.1. Reinterpretation of eruption styles of Taal and related eruptive processes and products. Old and new interpretations of VEIs, eruptive style and processes and products are provided in the table. New interpretations are in BLUE. Hachured lines separate the four identified eruption series. Sources of past interpretations came from Adams (1910), Pratt (1911), Saderra Masó (1911), Worcester (1911), DOST-PHIVOLCS (1991, 1995). VEI sourced from DOST-PHIVOLCS (1991) and Smithsonian Global Volcano Program (GVP)** (2018). Number headings correspond to abbreviations in Legend located at the bottom of the Table.

ERUPTION NO.	DATE(S) OF ERUPTION (AD)	VEI (1)	NEW PROPOSED VEI (1)	PREVIOUS DESCRIPTIONS OF ERUPTIVE ACTIVITY (2)	NEW ERUPTION STYLE INTERPRETATION (2)	PREVIOUS IDENTIFIED PROCESSES/ PRODUCTS (3)	NEW IDENTIFIED PROCESSES/DEPOSITS (3)	ERUPTION CONFIRMED/ UNCERTAIN
1	1572	Default 3	No change	PM	More likely ST	No description	LVFO with BP, TF	Confirmed
2	1591	Default 3	2	PH	Minor PH	No description	TF	Confirmed
3	1605 - 1611	3*/2**	0	Not specified	SA	No description	RS, VE	Uncertain
4	1634	Default 3	0	Not specified	SA or minor PH	No description	No change	Uncertain
5	1635	Default 3	0	Not specified	SA or minor PH	No description	No change	Uncertain
6	1641	Default 3	2	PH	No change	TF	TF	Confirmed
7	1645	Default 3	0	Not specified	SA	No description	No change	Uncertain
8	1707	Default 2	No change	PH	No change	SW	VE, TF, EA	Confirmed
9	1709	Default 2	No change	PM	No change; insufficient data	No description	VE, RS, TF	Confirmed
10	1715	Default 2	No change	Not specified	More likely ST	No description	LVFO with BP, LVF	Confirmed
11	1716 24-27 Sep	2*/4**	3	PM	Violent subaqueous PM with tephra columns w/ heights of 100 to 150m; multi-phased	VE, TF, PDC, VT, G	VE, TF, PDC, VT, G, AR	Confirmed
12	1729	Default 2	1	Not specified	PH	No description	TF	Confirmed
13	1731	Default 2	No change	PM	Violent subaqueous PM with large tephra column accompanied by volcanic earthquakes	TF, BP, VE, PDC, VT	TF, BP, VE, PDC, VT	Confirmed

14	1749 11 Aug to Sep	3*/4**	4	PM	Eruption series more likely PL or a very violent PM, with column-collapse pyroclastic density current	TF, BP, VE, PDC, SU, F, EA, SW	TF, BP, VE, PDC, VT, AR, SU, F, EA, SW, LIQ, G	Confirmed
15	1754 1) 15 May to 02 June phase	3/4/5	5	PM (Different eruptive phase not classified)	PL/SP with column collapse leading to generation of pyroclastic flows/base surges	TF, BP, PDC, VE, F, GE, SW, VT, AR	TF, BP, VE, PDC	Confirmed
	2) 02 June to 25 Sep phase				PM		TF, PDC, VE, EA	
	3) 1-15 Nov				PL/SP or PM		TF, PDC, VE, VT	
	4) 28 Nov to 02 Dec				PL/SP and PM		TF, PDC, VE, EA, SW, VT, FL, AR, F, G, LIQ	
16	1790	Default 2	0	Not specified	SA	No description	Not determined	Uncertain
17	1808	Default 2	3	PM	Moderate PM	No description	TF, GE	Confirmed
18	1825	Default 2	0	Not specified	SA	No description	Not determined	Uncertain
19	1842	Default 2	0	Not specified	SA	No description	Not determined	Uncertain
20	1873	Default 2	0	Not specified	SA	No description	Not determined	Uncertain
21	1874 19 Jul	Default 2	No change	PM	Moderate PM	TF, G	TF, G	Confirmed
22	1878 12 to 15 Nov	Default 2	No change	PH	Moderate PH	TF	TF	Confirmed
23	1903	Default 2	0	Not specified	SA	No description	Not determined	Uncertain
24	1904 Apr to 5 Jul	2*/1**	2	PH	Minor PH	TF, BP	TF, BP, G	Confirmed
25	1911 27 Jan	4*/3**	4	PH *(Different eruptive phases not classified)*	PM and/or PP	VE, SU, F, S, EA, SW, VT, AR, TF, PDC, BP	VE, TF, BP, RS	Confirmed
	28 Jan				PM		VE, TF, EA	
	29 Jan				PM		VE, TF, EA, F, SU, SW, RS	

	30 Jan.				PM or PP		VE, TF, EA, SU, AR, PDC, SW, VT, G, LIQ	
26	1965 28 to 30 Sep	4	No change	PM *(Different eruptive phases not classified)*		S, SW, VT, AR, TF, PDC, BP		Confirmed
	28 Sep (2:00AM)				Strombolian		TF, LVFO, LVF, VE	
	2:40-3:30AM				PM		TF, BP, PDC, SW, VT, EA, G, RS	
	9:20AM 28 Sep to 6:00AM 30 Sep				Minor PM		TF	
27	1966 5 Jul to 4 Aug	3	No change	PM	Moderate PM	TF, BP	TF, BP, VE	Confirmed
28	1967 16 to 18 Aug	1	No change	PM	Minor PM	TF, PDC, BP	TF, BP, VE	Confirmed
29	1968 31 Jan to 01 Feb	2	No change	Strombolian *(Different eruptive phases not classified)*	Minor PM	TF, LV	TF, VE	Confirmed
	02 Feb to 28 Mar				Moderate ST		LVF, LVFO	
	29 Mar to 02 Apr				Minor PM		TF	
30	1969 29 Oct	2	2	Strombolian (Oppenheimer, 1991)	PM	TF, LV	TF, VE	Confirmed
	30 Oct to 22 Nov				Moderate ST		LVF, LVFO	
	22 Nov to 10 Dec				PM		PDC	
31	1970 9 to 13 Nov	1	1	PM	PH or PM	No description	TF, VE	Confirmed
32	1976 3 Sep to 22 Oct	2	No change	Minor PH	No change	TF	TF, VE	Confirmed

33	1977 3 to 4 Oct	1[*]/2[**]	1	Minor PH	No change	TF	TF, VE	Confirmed

LEGEND:

(1) Volcano Explosivity Index – VEI

(2) Nature of eruptive activity: SA- solfataric activity; PH- Phreatic; PM- Phreatomagmatic; ST- Strombolian; PP- Phreatoplinian; SP-Sub-Plinian; PL- Plinian

(3) Eruptive processes/deposits: AR- acid rain; BP- ballistic projectiles; EA- electrical activity (e.g. vent discharges, near-vent lightning, plume lightning); F-fissuring; FL- flooding; G- toxic gases; GE- geysering; LIQ- liquefaction effects; LV- lava deposit; LVF- lava flow; LVFO-lava fountaining; PDC- pyroclastic density current (e.g. pyroclastic flows, base surge); TF- tephra fall; RS- rumbling sounds; S- solfatara; SU- subsidence; SW- shock waves; VE- volcanic earthquakes; VT – volcanic tsunami/seiche.

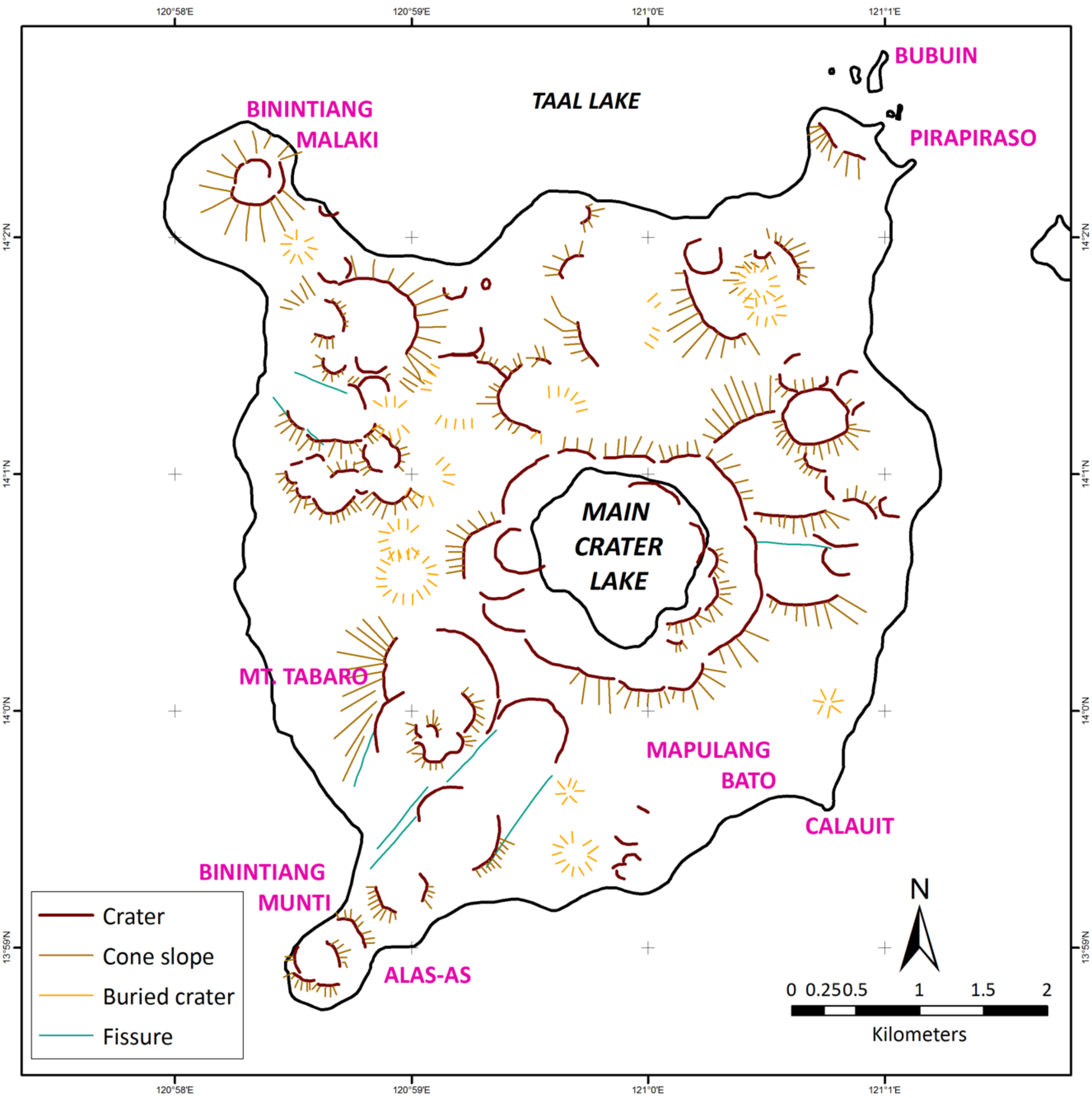


Figure 4.2. Location map of the eruption vents at Taal. 1) *Series A* include eruptions from AD1572 to AD1645 centered at the Main Crater; 2) *Series B* include eruptions from AD1707 to AD1731 with eruption vents alternately located in various flank craters; 3) *Series C* include eruptions from AD1749 to AD1911 centered again at the Main Crater; and 4) *Series D* include eruptions from AD1965 to AD1977 centered at Mt. Tabaro. Source: Delos Reyes et al. (2018); modified from Ruelo (1983).

AD1591

Perhaps the most significant new information for this eruption was the identification of the possible occurrence of minor tephra fall described by Saderra Masó (1911, p. 6) and Worcester (1912, p. 313) when they mentioned that "*Fr. B. de Alcantara repeated* *the ceremony performed by Fr. Alburquerque for the reason that the volcano had begun to belch forth extraordinary masses of smoke"*. The "*belch forth*" is expected to have produced a significant tephra column to be observable from the mainland, where the parish churches are generally located, and to have generated tephra fall. The previous eruption style classification was Phreatic and this is maintained. The VEI previously assigned was a default VEI 3 (Newhall & Self, 1982; DOST-PHIVOLCS, 1991; Smithsonian GVP, 2018). Barberi et al. (1992, p. 232) defined a Phreatic eruption or explosion as "*all cases of explosion of a confined pocket of steam and gas with no direct involvement of magma, independent of the source of the steam and the involvement or not of juvenile fluids*". The "*extraordinary masses of smoke*" implied that an eruption did occur and more likely a Phreatic one. Newhall & Self (1982) assigned a default VEI of 3 when an eruption is confirmed but no additional information is available for that eruption. With the current interpretation of eruption style being a minor Phreatic eruption, the VEI of 2 is deemed more appropriate for the AD1591 eruption (Table 4.1).

Between AD1605 and AD1611

The only significant account for this eruption is provided by Saderra Masó (1911, p. 7) and reads *"frequent rumbling which terrified the inhabitants of the neighboring villages"*. The description implies that seismic swarms occurred. Further confirmation of a seismic swarm and occurrence of rumbling sounds was provided by Worcester (1912, p. 313) when he described the action of Father Tomas de Abreu of performing a mass and placing a cross on the rim of Taal Main Crater "*for the reason that from the crater there had come frequent subterranean rumblings which greatly terrified the inhabitants of neighboring villages*". Whilst earthquake swarms may occur, they do not always culminate in an eruption (Kilgore et al., 2011). Table 2.5 lists more recent seismic unrests at Taal Volcano that did not culminate in eruptions. The DOST-PHIVOLCS Earthquake Intensity Scale (PEIS), the current intensity scale used in the Philippines that measures the relative effects of an earthquake to people, objects and infrastructures is also used for volcanic earthquakes (DOST-PHIVOLCS, 2018). The lack of any additional narrative description of eruptive activity other than that which described the earthquake swarm, makes the identification of an eruption between AD1605 and AD1611 uncertain and may simply be solfataric activity. The default classification of VEI 3 assigned by DOST-PHIVOLCS (1991) was based on criteria set by Newhall and Self (1982), while Smithsonian GVP (2018) listed the eruption as AD1608 ± 3 years and assigned a VEI of 2, specifying sources of information from historical observations. Both assigned VEIs seem inappropriate and a better estimation based on Newhall and Self *(1982)* would be VEI 0. The proposed changes in eruption description are summarised in Table 4.1.

AD1634 and AD1635

Written sources for these eruptions provide only vague and ambiguous accounts of volcanic eruptions in AD1634 and AD1635 (Worcester, 1912; Masigla and Ruelo, 1987; Hargrove, 1991; DOST-PHIVOLCS, 1991) while Saderra Masó (1911) ascribed the two eruptions as being in AD1634 and AD1645 but more authors ascribed dates of AD1634 and AD1635. Cited as the source of information was a naturalist named Semper who was quoted as saying that "*in several chronicles are found vague statements concerning two eruptions of the volcano which took place during these years*" (Saderra Masó, 1911, p. 313). While no description of eruptive activity was assigned, I now interpret the activity as being either a very minor

Phreatic or simply solfataric activity (Table 4.1). Using the criteria for estimation of VEI by Newhall and Self (1982), a VEI of 0 seems more reasonable rather than the VEI 3 previously assigned by DOST-PHIVOLCS (1991), and Smithsonian GVP (2018) (Table 4.1). Overall, the AD1634 and AD1635 events are considered uncertain.

AD1641

This eruption was not mentioned in the accounts of Saderra Masó (1911) or Worcester (1912) but was mentioned as "*the first eruption of historical importance*" by Foreman (1890). Furthermore, the change (e.g. formation of two craters within the Main Crater) observed and narrated by San Agustin (1699, *In* DOST-PHIVOLCS, 1991) confirms that an eruption did occur that resulted in the observation of newly formed Yellow and Green Lakes. While previous accounts did not clearly identify any specific eruptive style for this event, it is now proposed that the eruptive activity is more likely Phreatic (Cas & Wright, 1987). Further, it is also recommended that the VEI be lowered to 2 compared to the previously assigned VEI of 3 (DOST-PHIVOLCS, 1991; Smithsonian GVP, 2018). This is because the eruption was explosive enough to create new craters within the Main Crater, but not big enough to generate a tephra column 3,000 to 15,000 m high or last more than 12 hours. The recommended changes to eruption characteristics are shown in Table 4.1.

AD1645

While the eruption was mentioned by Saderra Masó (1911) and listed in DOST-PHIVOLCS (1991) and Smithsonian GVP (2018), and assigned a default VEI of 3, the limited description of the event imply that the activity might simply be solfataric in nature that did not culminate in an eruption. Therefore, the eruption is classified as uncertain and a VEI of 0 is proposed. The proposed changes in eruption description are summarised in Table 4.1.

4.1.2.2. Series B

The eruptions from AD1707 to AD1731 are grouped together as *Series B*. Eruptive activity alternated between the flank craters located around the volcano (Figure 4.2). The flank craters include Binintiang Malaki (e.g. AD1707 and AD1715 eruptions), Pira-Piraso (e.g. AD1731), Binintiang Munti (e.g. AD1709 and AD1729), and near Calauit (e.g. AD1716). All the eruptions in Series B are confirmed. An alternative interpretation of eruption style is provided for the AD1715 eruption, while a new interpretation of eruptive style is provided for the AD1729 eruption where past authors did not classify style due to limited narrative descriptions. The following subsections describe each identified eruption, as well as new interpretations arising from this research.

AD1707

Saderra Masó (1911, p. 7), Worcester (1912, p. 313) and DOST-PHIVOLCS (1991, p. 32) cited a man named Arce as saying *"the cone called Binintiang Malaqui burst forth with tremendous display of thunder and lightning; but aside from fear and trembling, no damage was done in the towns situated on the shores of Lake Bombon"*. While only atmospheric shock waves were identified as a product of this eruption (DOST-PHIVOLCS, 1991), the one sentence description provides a multitude of useful information about the eruption characteristics. The occurrences of thunder and lightning are now newly interpreted as electrical activity that may have occurred in the form of volcanic lightning storm or a handful of lightning discharges (Behnke et al., 2013). In general, volcanic lightning causes minimal impact on communities but may affect the global atmospheric electrical circuit (Mather & Harrison, 2006). While volcanic lightning is more frequently observed in large tephra columns (Mather & Harrison, 2006; Behnke et al., 2013), eruptions with a VEI 1 or 2 can also generate electrical activity (McNutt & Williams, 2010). Another apparent eruption product during the AD1707 event is tephra fall that has not been previously identified in written accounts. Electrical discharges form within a tephra column, and with the existence of a column, tephra fallout must have occurred, controlled by the height of the column and prevailing wind patterns during the time of eruption (Cas & Wright, 1987). There were no reports of damage in adjacent Taal communities related to tephra fall deposition.

Atmospheric shock waves were previously reported during the AD1707 eruption (DOST-PHIVOLCS, 1991). In general, atmospheric shock waves are pressure disturbances caused by explosive volcanic eruptions (Donn & Balachandran, 1981; Mauk, 1983; Medici et al., 2014; Morrissey & Chouet, 1997; Simkin and Fiske, 1983). While Saderra Masó (1911) recognised shock waves as a product of some eruptions at Taal (e.g. AD1749, AD1754, and AD1911), the lack of a more detailed description of the AD1707 eruption implies that this eruption was not explosive enough to have generated such shock waves. Consequently, based upon the preceding description and hazard interpretation, I am confident that the AD1707 event did culminate in an eruption and I believe that the previous classification of eruption style as Phreatic should be maintained. However, while only shock waves were previously interpreted from the narrative accounts, I now make additional interpretations of the eruptive processes and products, including the existence of volcanic earthquakes, tephra fall deposits and electrical activity (Table 4.1). Further, the previously assigned default VEI of 2 (DOST-PHIVOLCS, 1991) is maintained.

AD1709

The AD1709 eruption was not cited in the summaries of Saderra Masó (1911) or Worcester (1912). While DOST-PHIVOLCS (1991) listed the eruption, no ascribed eruption style was provided. However, Foreman (1890, *In* DOST-PHIVOLCS, 1991, p. 32) described the volcano as having *"vomited forth a deafening noise*". The eruptive activity was centered at Binintiang Munti (Figure 4.2) and a phreatomagmatic eruption style was previously assigned because of the Foreman narrative (DOST-PHIVOLCS, 1991). Such a sound, most likely associated with an explosive eruption, can be generated because of dissolved magmatic volatiles (Cas & Wright, 1987). Phreatic, Phreatomagmatic, or Phreatoplinian, all highly volatile eruptions (Cas & Wright, 1987), are possible styles for the AD1709 event. DOST-PHIVOLCS (1991, 1995) and the Smithsonian GVP (2018) previously assigned a default VEI of 2. With such a limited narrative description of observed eruptive processes and behaviour, an alternative interpretation of eruptive style and VEI was not possible and the default VEI is maintained. However, occurrences of volcanic earthquakes, rumbling sounds and tephra fallout deposits are to be expected from the explosions heard by the observers, confirming that an eruption did occur and these eruptive products were most likely present at the time of the eruption (Table 4.1).

AD1715

While the AD1715 eruption has no narrative description of processes and products and was not included in the papers by Saderra Masó (1911) and Worcester (1912), DOST-PHIVOLCS (1991, 1995), and the Smithsonian GVP (2018) listed the eruption and gave it a default VEI 2. Eruptive activity was briefly described as *"loud explosions and threw out incandescent materials, giving an impression of a river of fire"* (DOST-PHIVOLCS, 1995, p. 49). The eruptive style was previously not identified in the DOST-PHIVOLCS paper (1991). However, the abovementioned description is now ascribed as being Strombolian activity, with lava fountaining, ballistic projectiles and lava flows (Table 4.1).

AD1716

The AD1716 eruption is the first Taal eruption with a more detailed narrative description of the activity because of better observation. The eruption commenced on 24 September at 6PM and lasted for four days. An account that states "*a great number of detonations were heard in the air*" (Saderra Masó, 1911, p. 7; Worcester, 1912, p. 314) marked the onset of a series of explosions observed in Calauit, located to the southeast of TVI (Saderra Masó, 1911; Worcester, 1912; DOST-PHIVOLCS, 1991, 1995), which is now interpreted as a sub-lacustrine Phreatomagmatic flank eruption (Table 4.1). Further, from the narrative description of tephra columns described as "*great masses of smoke, water, and ashes rushed out of the lake, high up into the air, looking like towers*" (Saderra Masó, 1911, p. 7; Worcester, 1912, p. 314), I interpreted the height of the tephra column to be about 100 to 150 m and likely less than one kilometer based on typical heights of church towers during the Spanish era. Such low tephra column height is not surprising since fragmentation and dispersal in sub-lacustrine eruptions are expected to decrease with increasing confining pressure or water depth (Graettinger et al., 2013; Zimanowski & Büttner, 2013), and are likely to be less than those generated by a magmatic explosive eruption (Cas and Wright, 1987). Subsequent collapse of the tephra columns is presumed to have generated pyroclastic density currents and volcanic tsunami. Pyroclastic materials in the form of density currents are typical products of a Phreatomagmatic eruption (Cas & Wright, 1987). Movement of water due to the eruptive deposits resulted in volcanic tsunami that inundated adjacent communities located in the south and southwestern side of the mainland. Horizontal inundation was estimated to be about 17 m (Saderra Masó, 1911; Worcester, 1912; Berninghausen, 1969; DOST-PHIVOLCS, 1991, 1995).

Volcanic gases are interpreted to be another product of the AD1716 eruption since they are known to be released into the atmosphere during eruptions or prior to eruptions when magma is at, or near the surface of the volcano (Scott, 1989). Acid rain is also expected to be generated when a large quantity of ash and sulfuric acid are injected into the air during an explosive eruption (Costa et al., 2012). The heated lake water, gases and ejecta released during the sub-lacustrine phreatomagmatic eruption resulted in fish kill described by Father Manuel de Arce as "*killed all fishes, large and small, the waves casting them ashore in a state as if they had been cooked, since the water had been heated to a degree that it appeared to have been taken from a boiling caldron*" (Worcester, 1912, p. 314)

DOST-PHIVOLCS (1991) assigned a default VEI of 2 for the AD1716 eruption while the Smithsonian GVP (2018) assigned a VEI of 4. While the tephra column height was small, with most of the erupted materials emplaced within the lake, the duration of the eruption, lasting almost a week, and the amount and force of the erupted deposits towards the lake resulted in the generation of a volcanic tsunami. I therefore newly interpret the VEI to be more like 3 (Table 4.1).

AD1729

No additional eruption description is available for this eruption other than the eruptive activity being described by Saderra Masó (1911, p. 7) as *"a new outburst of the volcano*", which confirms the occurrence of an eruption centered at Binintiang Munti (Table 4.1) (DOST-PHIVOLCS, 1991). No ascribed eruptive style was provided from available written accounts but eruptive activity may be considered minor in magnitude and likely Phreatic, simply involving ejection of steam and minor ejecta (Cas & Wright, 1987). Likewise, with the above quoted statement, eruption column and tephra fallout deposits are now interpreted to have been generated during the AD1729 eruption. Tephra fall is gravitational settling of air-borne fragments of volcanic material ejected into the atmosphere during explosive eruptions (Scott, 1989; Tilling, 2005). A default VEI 2 (Newhall & Self, 1982; DOST-PHIVOLCS, 1991; Smithsonian GVP, 2018) is assigned for the AD1729 eruption. With such limited details of the event and in light of the previous discussion, it is more likely the AD1729 eruption was a minor Phreatic event and a downgrading of the VEI to 1 seems reasonable.

AD1731

The AD1731 event was another sub-lacustrine Phreatomagmatic eruption previously assigned a default VEI of 2 (Smithsonian GVP, 2018; DOST-PHIVOLCS, 1991). In Saderra Masó (1911, p. 7) and Worcester (1912, p. 315), Father Torrubia did not specify when the exact eruption commenced but wrote "*With terror we heard during one of the nights a continuous fire of heavy artillery*" which provides information that the onset of the eruption was at night and described continuous explosions even though his observation point was located in Los Baños, Laguna, about 25 km northeast of Taal Volcano. The account given by Father Torrubia cited by Saderra Masó (1911, p. 7) of "*vast and towering obelisks of earth and sand rose out of the water*" aptly describes a tephra column of a sublacustrine Phreatomagmatic event (Sheridan & Wohletz, 1983) that occurred at the present location of the island of Bubuin (Figure 4.1). The presence of a tall tephra column is interpreted from the description by Father Torrubia of "*a frightful and all-devouring conflagration that the whole region was panic-stricken*" (Saderra Masó, 1911, p. 8). The tephra column generated by a phreatomagmatic eruption is expected to be much lower than a magmatic eruption because most of the heat that could have been used to forcefully convect a tephra column upward from the vent is used instead to convert water to steam (Cas & Wright, 1987). The *"subterranean rumblings which caused the entire region to tremble"* (Saderra Masó, 1911, p. 8) means that the eruptive event was also accompanied by volcanic earthquakes. In addition, Father Torrubia described "*surrounded by sulphurous flames and pestilential smoke, enormous boulders, which built up an island from the bottom of the deep lake, said island having a diameter of one mile, more or less*" (Saderra Masó, 1911, p. 8) that means incandescent ballistic projectiles were ejected that resulted in the formation of a new islet (Bubuin) measuring 1.8 km in diameter, as well as emission of sulfuric gases.

The above descriptions confirm that the AD1731 eruption was considered violent and a moderate-sized sublacustrine phreatomagmatic eruption, but there were no significant reports of damage to communities adjacent to Taal Volcano that would warrant a change in the previously assigned default VEI of 2 (DOST-PHIVOLCS, 1991) (Table 4.1).

4.1.2.3. Series C

The identified twelve eruptions from AD1749 to AD1911 are classified under *Series C* that were again centered at the Main Crater (DOST-PHIVOLCS, 1991). Some of the eruptions in this series (e.g. AD1749, AD1754 and AD1911) were explosive and destructive, resulting in severe devastation to TVI and adjacent communities. Because of the devastation brought about by these three eruptions, detailed narrative descriptions were written and are now available as secondary sources for my research. Separating the eruptive phases for these three eruptions is undertaken, where possible, but I did not attempt to identify possible reasons for transition in phases. There is an absence of detailed historical documentation for the eruptions identified in AD1790, AD1825, AD1842, AD1873 and AD1903. A critical review of these eruptions was conducted to assess whether they were indeed, fully-fledged eruptions. The results of the reanalysis and reinterpretation of the identified eruptions from AD1749 to AD1911 are discussed in the subsequent sections.

AD1749

A series of eruptions commenced on 11 August AD1749 and lasted for three months (Smithsonian GVP, 2018). The towns of Old Sala, Old Taal, and Old Tanauan (Figure 4.3) were severely affected (Saderra Masó, 1911).

During the AD1749 eruption, Father Buencuchillo, parish priest of Old Sala, now a part of Talisay, Batangas, described the onset of the event as "*During the night of that* day (11 August) *the top of the mountain burst out with tremendous force from the same crater which since ancient times used to emit fire and rocks*." (Saderra Masó, 1911, p. 8; Worcester, 1912, p. 317). Further, Father Buencuchillo compared the series of explosions he observed around 3AM the next day to "*heavy artillery fire*" that usually signifies the arrival of ships and entry to Balayan Bay as homage to Our Lady of Caysasay (Saderra Masó, 1911). He also described two eruption centers, one sourced at the Main Crater described as "*immense column of smoke which rose from the summit of the island*" (Saderra Masó, 1911, p. 8) (Figure 4.2**)**, and another that started at dawn and was observed at the northeast quadrant of Taal with the eruption column rising from the lake indicating that it was a sub-lacustrine eruption (DOST-PHIVOLCS, 1991). The sub-lacustrine eruption was written as follows: "*from the water there arose enormous columns of sand and ashes, which ascended in the shape of pyramids to marvellous heights and then fell back into the lake like illuminated fountains*" (Saderra Masó, 1911, p. 8; Worcester, 1912, p. 317)) that aptly describes the generation of enormous tephra columns that subsequently collapsed and generated pyroclastic density currents either in the form of pyroclastic flows and/or surges (Francis, 1993) that may have crossed the lake in the north and eastern direction and continued until 9AM on 12 August. Large magnitude volcanic earthquakes were felt at intensities VII-VIII (PEIS) (DOST-PHIVOLCS, 2018) based on the descriptions of damage written by Father Buencuchillo. As a result of the occurrence of large-magnitude volcanic earthquakes, subsidence and extensive fissuring were observed in Old Tanauan and Old Sala (Figure 4.3) and as far away as Calamba to the north of Batangas Province. While some of the fissuring resulted as a consequence of large

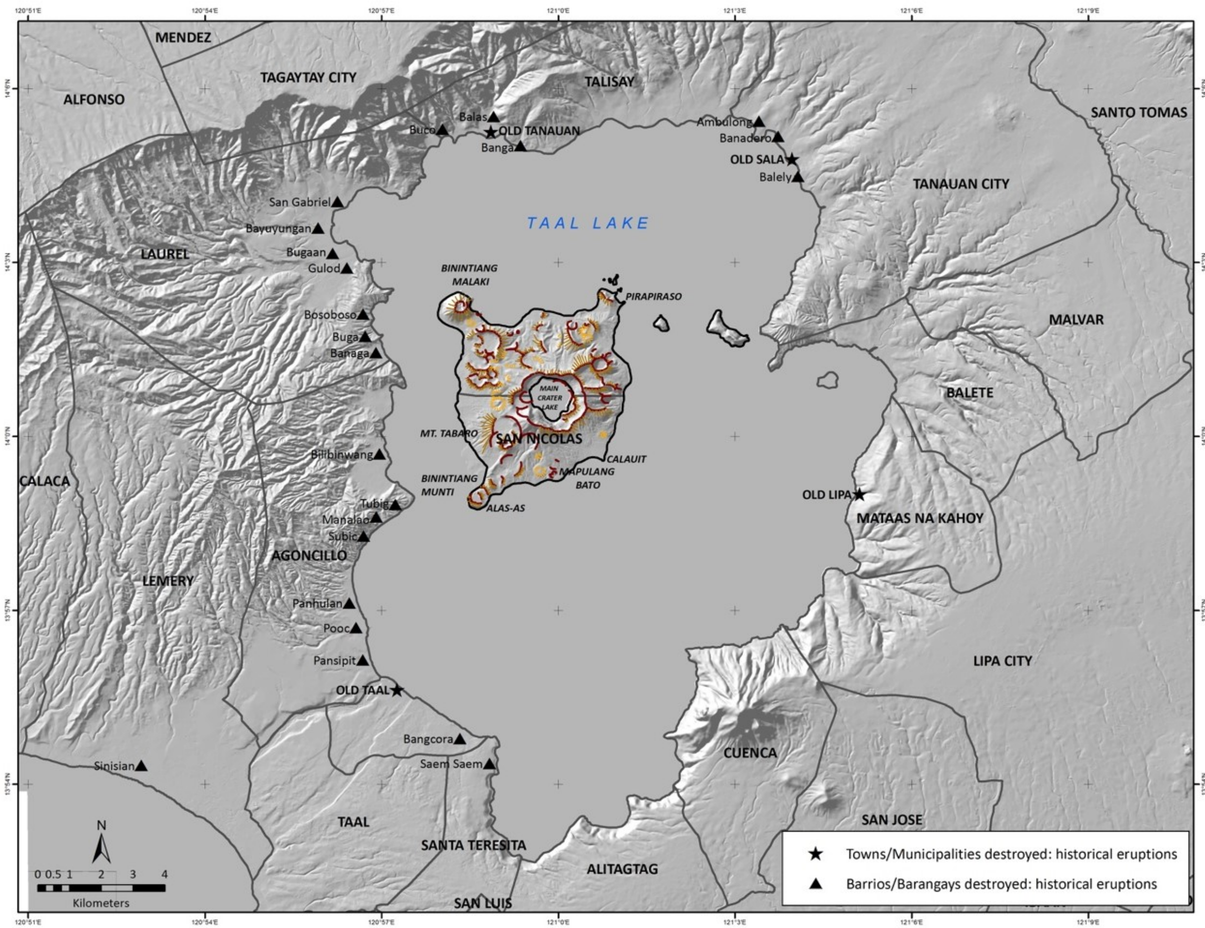


Figure 4.3. Map showing locations of Old Sala (northeast), Old Taal (southwest) and Old Tanauan (north) that were greatly affected by the AD1749 and AD1754 eruptions of Taal. Identified eruption centers at TVI indicated by brown hachured lines. Map overlain on NAMRIA 2013 Interferometric Synthetic Aperture Radar - Digital Terrain Model (IfSAR-DTM) and Administrative boundaries are adopted from PhilGIS (2011). Source: Delos Reyes et al., 2018.

magmatic intrusion accompanied by ground deformation, especially those aligned along a north-northeast trend line up to Calamba (DOST-PHIVOLCS, 1995; Torres et al., 1995), I interpreted the fissures and subsidence close to the Taal Lake shore areas as liquefaction effect and were likely lateral spreading and ground settlements, respectively (Dixit et al., 2012). As further proof of the occurrence of liquefaction phenomenon, Father Buencuchillo also wrote that "*the water courses have been altered, former springs have ceased to flow and new ones made their appearances*" (Saderra Masó, 1911, p. 8). During strong earthquakes, loose saturated granular sediments are usually prone to liquefaction because the strong ground shaking decreases the pore space, allowing the sediments to settle (Győri et al., 2015). Győri et. al. (2015) concluded that a Peak Ground Acceleration (PGA) ranging from 0.2 to 0.3 g were found in areas where liquefaction occurred. This is roughly equivalent to a MMI Intensity VII to VIII or the same PEIS (DOST-PHIVOLCS, 2018) equivalent to a VII-VIII intensity event (M.L.P. Bautista, personal communication, 18 September 2016). This is the first time that the abovementioned phenomena are being interpreted as liquefaction effects.

The magnitude of the volcanic earthquakes is also supported by Father Murillo situated in Antipolo, > 50 km due east from Manila who noted that "*during the eruption, felt three to four earthquakes of such violence that the roof tiles of the tower were thrown to a distance of more than 10 meters*" and also felt "*less intense shocks there were more than one hundred*" (Saderra Masó, 1911, p. 9). The intensity of the earthquake based on the abovementioned description is PEIS VI-VII (DOST-PHIVOLCS, 2018).

Tephra fallout and dispersal was also observed and documented during the AD1749 eruption with one description written as follows: *"It rained ashes in considerable quantity and that part of them which remained suspended in the air, formed a vast cloud which grew so dense as to cause real darkness during the hours of broad daylight."* (Saderra Masó, 1911, p. 8; Worcester, 1912, p. 319). The description that while evacuating from Sala, Father Buencuchillo "*saw a great many tall trees, such as coconut and betel nut-nut palms, either miserably fallen, or so deeply buried that their tops were within reach of my hands*" provides an estimate of the deposition of erupted materials (e.g. heights of coconut trees usually 2 or 3 times a man's height and the average height of a Filipino is about 1.5 m). However, it cannot be determined if the deposits were tephra fall and/or surge deposits nor where the impacted area was located. Another significant eruption hazard described was electrical activity in the form of volcanic lightning that Father Buencuchillo described as "*fierce thunderstorms during many days*" (Saderra Masó, 1911, p. 9).

The reported total bulk volume of eruptive products during the AD1749 events was previously estimated at 50-100 million m^3 (DOST-PHIVOLCS, 1991). In terms of the eruptive style for the AD1749 event, while previous interpretations classified the eruption as simply Phreatomagmatic, based on the above observations, my current reassessment indicates that the eruption could either be a very violent Phreatomagmatic and/or a Plinian eruption with tall tephra columns that subsequently generated collapse-type pyroclastic density currents (Francis, 1993). Distinction between individual phases of the eruption could not be made because of a lack of detailed time-bound descriptions. A VEI of 3 assigned by DOST-PHIVOLCS (1991) while the Smithsonian GVP (2018) classified the eruption as having a VEI of 4, indicating a review of historical observations as source. Based on the classification of Newhall and Self (1982), the more reasonable VEI would be 4. While the eruption did not result in casualties, impact and damage to the communities of Old Sala and portions of Tanauan (Figure 4.3) was so severe that residents left the towns and the two towns were subsequently merged (Saderra Masó, 1911; Delos Reyes et al., 2018). Previous interpretations of the AD1749 event was that it was Phreatomagmatic with a description of the occurrence of a column-collapse pyroclastic density current. I provide alternative interpretation that the eruption style is more likely Plinian considering the volume of ejecta, the newly interpreted VEI of 4, and the magnitude and impact of the eruption. The changes in interpreted eruption characteristics for the AD1749 event is shown in Table 4.1.

AD1754

Previous studies did not identify individual eruptive phases for the AD1754 event and I note that the eruptive activity transitioned from Plinian to Phreatomagmatic is implied from the narrated accounts and the subsequent deposits.

In the past, no attempt was made to determine the different eruptive phases of the AD1754 eruption. However, in the course of my research, at least four major phases have been identified: 1) the 15 May to 02 June phase; 2) the 02 June to 26 September phase; 3) the 1 to 15 November phase; and 4) the 28 November to 02 December phase. Eruptive styles for each of the phases is determined based on detailed descriptions provided in historical accounts. During the course of the eruption the style of eruption changed (Cas & Wright, 1987). However, the controls for the transition from one eruptive style to another will not be discussed in this research.

Previous studies identified the eruption style as phreatomagmatic (DOST-PHIVOLCS, 1991) but did not make attempts to identify individual phases of the eruption. Oppenheimer (1991) assigned a VEI of 3, the Smithsonian GVP (2018) assigned a VEI 4, while DOST-PHIVOLCS (1991) gave a VEI of 5. With the estimated volume of erupted deposits and the column height, the VEI assigned by DOST-PHIVOLCS is deemed more appropriate. Moreover, the current detailed research on the AD1754 eruption being conducted by Bornas et al. (personal communication) shows possible greater extent and volume of pyroclastic density current deposits erupted during the AD1754 eruption and the VEI may even be greater than 5. Figure 4.4A shows the extent of the AD1754 base surge modified from that mapped by DOST-PHIVOLCS in 1991.

Based on the narrative descriptions, the 15 May to 02 June phase is classified as a Plinian/Sub-Plinian event associated with the generation of tall tephra columns as high as 40,000 m, that subsequently collapsed resulting in pyroclastic flows and/or base surges (Francis, 1993). Father Buencuchillo described the first phase as follows: "*the volcano quite unexpectedly commenced to roar and emit, sky-high, formidable flames intermixed with glowing rocks which, falling back upon the island and rolling down the slopes of the mountain, created the impression of a large river of fire*" (Saderra Masó, 1911, p.9; Worcester, 1912, p. 319). Plinian eruptions produce large volumes of pyroclastic materials and widely dispersed tephra fall deposits (Cas & Wright, 1987). Subplinian eruptions can be described as scaled down plinian but their eruption mechanisms are basically the same (Cas & Wright, 1987). The observed eruptive products during the first eruptive phase include tephra fallout deposits, ballistic projectiles, pyroclastic density currents, and large-magnitude earthquakes.

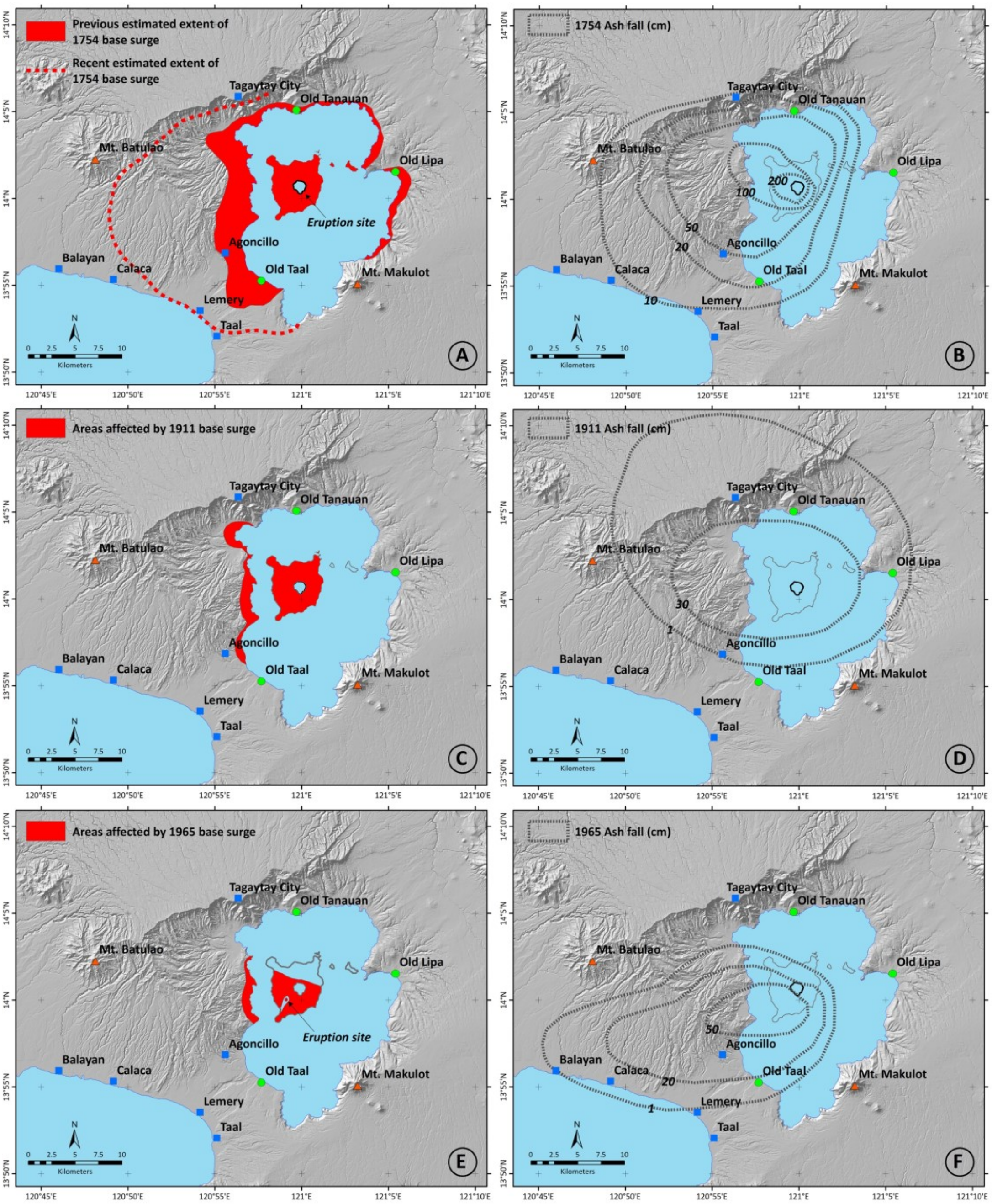


Figure 4.4. Deposit maps of major eruptions of Taal. (A) Map showing extent of the base surge deposits during the AD1754 plinian eruptions centered at the Main Crater. Previously delineated extent of the 1754 base surge shown as red shaded area sourced from DOST-PHIVOLCS (1991) modified from Saderra Masó (1911), while the dashed line approximate extent from ongoing mapping by Bornas et al. with distal run-out of more than 16 km. (B) Isopach map showing the estimated tephra fall dispersal during the AD1754 eruptions based on DOST-PHIVOLCS (1991) and Saderra Masó (1911). (C) Map showing extent of the base surge deposits during the AD1911 phreatomagmatic eruption centered at the Main Crater. (D) Isopach map showing the tephra fall dispersal during the AD1911 eruptions. (E) Map showing extent of the base surge deposits during the AD1965 eruptions centered at Mt. Tabaro. (F) Isopach map showing the tephra fall dispersal during the AD1965 eruptions. Isopach units are in centimeters. Modified from DOST-PHIVOLCS (1991) with map overlain on NAMRIA IfSAR-DTM (2013). Source: Delos Reyes et al., 2018.

Documents indicate that impacts of these eruptive products reached as far as 8 km northwest of the volcano and completely destroyed the community of Bayuyungan, a barrio now located within the barangay boundaries if Balaquilong, Laurel (Figure 4.3).

The 02 June to 31 October phase is determined as a phreatomagmatic eruption since written accounts of Father Buencuchillo note the occurrence of continuous explosions with formation of tephra columns that were not thought to be tall or enormous as he described that "*the volcano never ceased to eject fire and mud of such bad character that the best ink does not cause so black a stain*" (Saderra Masó, 1911, p. 9). Further, the tephra fallout deposits, more than 45 centimeters thick, consisted of ash and rock fragments, that caused collapse of some buildings, and destroyed or crushed trees and plants (Saderra Masó, 1911). Coincident with formation of the tephra columns, the occurrence of electrical activity was also observed within the plumes during this phase, with Father Buencuchillo narrating "*within the black column of smoke issuing from the volcano ever since June 2, there frequently formed thunderstorms, and it happened that the huge tempest cloud would scarcely ever disappear during two months*" (Saderra Masó, 1911, p. 9). From 26 September to 31 October, the volcano quietened considerably but eruptive activity did not cease (Saderra Masó, 1911).

The 1-15 November phase likely transitioned to a plinian/subplinian eruptive episode characterised by greater magnitude explosions. On 15 November, Father Buencuchillo wrote "*it vomited enormous bowlders which rolling down the slopes of the island, fell into the lake and caused huge waves*" (Saderra Masó, 1911, p. 9), which is interpreted as pyroclastic density currents invading the lake and subsequently generating volcanic tsunami. The explosive eruptions were accompanied by felt earthquakes that greatly shook houses with Father Buencuchillo writing that "*these paroxysms were accompanied by swaying motions of the ground which caused all the houses of the town to totter*" (Saderra Masó, 1911, p. 9). His description places the intensity of the volcanic earthquakes at PEIS V or more (DOST-PHIVOLCS, 2018). Father Buencuchillo compelled residents of Old Taal to leave their place and seek refuge in the Sanctuary of Caysasay located 20 km southwest of the volcano in the location of the present town of Taal (Figure 4.3) (Saderra Masó, 1911).

The 28 November to 02 December phase is also classified as a Plinian/Subplinian episode with Father Buencuchillo indicating that the volume of erupted materials was greater than all the past eruptive episodes combined. Collapse-type pyroclastic density currents occurred and were documented. Tephra columns rose higher than before with Taal Volcano Island appearing to be on fire, due perhaps to the deposition of incandescent materials that were accompanied by volcanic earthquakes and electrical activity (Saderra Masó, 1911). The tephra was described as being dispersed to the west and south (with stones) towards the location of Old Taal (Figure 4.3). While Father Buencuchillo was in the convent in Old Taal with the intention of checking the condition of the church, he observed the occurrence of volcanic tsunami that had already inundated shoreline communities prior to their evacuation. After a lull in activity on 29 September lasting several hours, eruptive activity resumed again at 8AM and again Father Buencuchillo described the phenomenon as follows: "*I noticed smoke was rising from the point of the island which looks towards east*" (Saderra Masó, 1911, p. 10; Worcester, 1912, p. 320) which possibly points to an eruption center other than the Main Crater, or a secondary explosion resulting from the contact of hot pyroclastic density current with water when entering the lake. By 3-4PM, the tephra fall consisting of wet-mud and ashes, reached the Convent of Caysasay located at the current position of Taal Municipality and lasted three days (Saderra Masó, 1911). Even at ~20 km distance, Father Buencuchillo still observed lightning flashes that intermittently illuminated the otherwise dark surroundings due to the tephra clouds that hovered about and turned day into night. By 30 November, in surrounding areas near the convent, houses had collapsed due to the weight of the tephra deposits (Saderra Masó, 1911). Approximately 6 km southwest of Taal Volcano, the ash and mud were observed to be 1.1 m thick.

After all eruptive activities ceased and upon return to Old Taal, Father Buencuchillo observed that the tephra fall deposits were more than 2 m thick and that the shoreline communities had been inundated or washed away by volcanic tsunami (Saderra Masó, 1911). The observation of several cracks and extensive landslides are now attributed to liquefaction effects (Dixit et al., 2012). The mouth of the Pansipit River was blocked by eruptive deposits but it is not possible to determine if they were from pyroclastic density currents or tephra fall. The clogging resulted in a rise of lake water levels and subsequent flooding of Old Lipa and Old Tanauan, the lowest level in the surrounding lake shore areas (Figure 4.3) (Saderra Masó, 1911). All livestock either got buried, drowned or starved to death because there were no plants remaining in the whole town (Saderra Masó, 1911). Similar impacts at Old Lipa, Old Tanauan, and Sala were observed. As a result of the AD1754 eruptions, the official locations of Taal, Lipa and Tanauan were permanently moved to their present sites (Figure 4.3) (Saderra Masó, 1911). The extent of deposition of the pyroclastic density currents in the form of base surges is shown in Figure 4.4A. A major modification of the approximate extent of the AD1754 base surge illustrated as red dashed line in Figure

4.4A was based on ongoing mapping being conducted by Bornas et al. (personal communication). The previously estimated extent of tephra fallout with corresponding average thicknesses is shown in Figure 4.4B (DOST-PHIVOLCS, 1991). This research will present separate isopach maps based on geologic mapping conducted in 2014 and 2016 that represents the tephra deposits from the two identified eruptive phases, and are discussed in Chapter 5 and Chapter 6. Changes in interpretation of eruption style and processes and deposits for this eruption are listed in Table 4.1.

AD1790

Saderra Masó (1911) and Worcester (1912) did not identify the AD1790 eruption in their respective papers while DOST-PHIVOLCS (1991) and the Smithsonian GVP (2018) listed the eruption as confirmed but provided no descriptive account due to an absence of retrievable records. No explanation was provided as to why the AD1790 eruption was identified as confirmed. A default VEI of 2 was assigned (DOST-PHIVOLCS, 1991; Smithsonian GVP, 2018). Although this eruption was previously identified as confirmed, the present study interprets the absence of further description other than the default VEI to mean that the occurrence of the eruption is considered questionable and uncertain and recommends that the VEI be downgraded to 0 (Table 4.1).

AD1808

The AD1808 eruption commenced mid-March and consisted of a series of explosions that generated tephra columns resulting in deposition of tephra fall deposits on Taal Volcano Island as thick as 84 cm described by Saderra Masó (1911) as consisting of ashes and pumice. There was also a major change in the configuration of the Main

Crater Lake (Figure 4.2) (Saderra Masó, 1911; Worcester 1912). The Main Crater Lake is interpreted to be previously quite deep based on Saderra Masó's (1911, p. 11) description of the change narrated by an unidentified author: "*Formerly the depth seemed immense and unfathomable, and the bottom was seen a liquid mass in continual ebullition. After the eruption the whole aspect was changed; the crater had widened, the pond within it had been reduced to one-third and the rest of the crater floor is dry enough to walk over it.*" The former Yellow and Green lakes that were formed during the AD1641 eruption were again amalgamated into one (Saderra Masó, 1911). The *'continual ebullition'* presumably describes geysering that can still be observed to the present day. Geysers are types of hot springs that produce explosively discharged columns of hot water at intervals that may reach altitudes of up to 100 m (Bell, 1999). This eruption was categorised as phreatomagmatic with a VEI of 2 (DOST-PHIVOLCS, 1991; Smithsonian GVP, 2018). The description of prolonged and continuous explosions with generally high composition of fine ash and pumice showing degree of fragmentation resulting in damage to nearby communities confirms the classification that the eruption was Phreatomagmatic (Francis, 1993) but with the notable modification of the Main Crater and the duration of the eruption. An alternative VEI of 3 is proposed (Table 4.1). While DOST-PHIVOLCS (1991) provided no description of processes and products for this eruption, the widening of the Main Crater confirms the eruption and it is certain that tephra columns and tephra deposits were generated (Table 4.1).

AD1825, AD1842 and AD1873

These eruptions do not have associated eruptive style classifications but were assigned a default VEI of 2 without reference to any source (Smithsonian GVP, 2018;

DOST-PHIVOLCS, 1991). Both Saderra Masó (1911) and Worcester's (1912) original sources did not contain any descriptions for these eruptions. The lack of available details of these eruptions preclude determination of their occurrence indicating uncertainty that the eruptions happened. *The observed events could possibly indicate solfataric activities that may not have culminated into eruptions.* Further, if these eruptions did occur, they could have been minor eruptions and *the VEI would be more likely 0 rather than VEI 2* (Table 4.1).

AD1874

Previous interpretation of the eruption style for the 19 July AD1874 eruption was phreatomagmatic with a description of "*an eruption of gases and ashes"* (Worcester, 1912, p. 328) (Table 4.1). The presence of emitted toxic gases cannot be eliminated because animals were killed and the entire vegetation on the western slopes of the Main Crater dried up or was burnt (Worcester, 1912). Saderra Masó (1911, p. 11) and Worcester (1912, p. 328) both described "*an eruption of gases and ashes which killed all the livestock on Volcano Island and withered or burned the vegetation on the western slopes of the crater*". Gases, including hydrogen chloride and sulphurous gases, depending on their concentration in the air, can be toxic to plants and animals (Bell, 1999). The previously assigned eruption style (Phreatomagmatic) is maintained and no change is recommended to the assigned default VEI of 2.

AD1878

The AD1878 eruption occurred between 12 and 15 of November and was previously classified as a Phreatic event with a VEI of 2 (Smithsonian GVP, 2018; DOST-PHIVOLCS, 1991). The explosions were accompanied by detonations indicating that they were forceful ejections that generated tephra fall deposits that covered the entire volcano island (Saderra Masó, 1911). The limited but significant descriptions confirm that an eruption did occur and that it was a moderate Phreatic event. Therefore, the assigned VEI of 2 is appropriate (Table 4.1).

AD1903

No details of the AD1903 eruption could be obtained but it is currently listed as one of the 33 eruptions of Taal with an assigned VEI of 2 (Smithsonian GVP, 2018; DOST-PHIVOLCS, 1991). While Saderra Masó (1904) identified an eruption occurring in April AD1903, the eruption was not mentioned in the Saderra Masó (1911) or Worcester (1912) accounts. I believe the April AD1903 eruption previously mentioned in Saderra Masó (1904) is the same eruption identified as occurring in April AD1904. Because of the lack of narrative accounts, the occurrence of the AD1903 eruption seems uncertain (Table 4.1).

AD1904

The AD1904 eruptive activity occurred from April to July (Smithsonian GVP, 2018) and was mostly concentrated on a newly formed funnel-shaped crater located in the southeast sector of the Main Crater (Saderra Masó, 1911; Worcester, 1912). The explosions occurred at intervals and the generated tephra columns were about 200 meters high and the ejecta fell back inside the Main Crater since there was no wind at the time of the eruption (Worcester, 1912). The subsequent tephra fallout deposits were saturated and described as causing a burning sensation. Steam produced by volcanic explosions generally contain carbon dioxide and hydrogen sulfide (Bell, 1999). The eruption was previously classified as Phreatic with an assigned default

VEI of 2 by DOST-PHIVOLCS (1991) while the Smithsonian GVP (2018) assigned a VEI of 1 citing review of historical observations as a basis but original sources were not provided. The eruption was explosive enough to have resulted in the formation of a funnel shaped crater inside of the Main Crater. Therefore, the default VEI of 2 seems appropriate for the AD1904 eruption (Table 4.1).

AD1911

The 27 to 30 January AD1911 eruption was the last large-scale eruptive event in *Series C*. Similar to the AD1754 eruption, detailed narrative descriptions make it possible to identify four distinct phases for the AD1911 eruption that are generally classified as phreatomagmatic (DOST-PHIVOLCS, 1991) but I now provide individual eruptive styles with varying eruptive products for the four identified phases: 1) the 27 January phase identified as either phreatomagmatic or Phreatoplinian; 2) the 28 January event identified as Phreatomagmatic; 3) the 29 January event also identified as Phreatomagmatic; and lastly, 4) the 30 January phase identified as Phreatomagmatic or Phreatoplinian (Table 4.1).

The 27 January eruptive activity commenced at 8:20PM with the recording of pre-eruption volcanic earthquakes by the Manila Observatory seismographs (Saderra Masó, 1911) and was felt at Intensity III when intensity is converted to the current PEIS (DOST-PHIVOLCS, 2018) in Metro Manila. The eruption that started at 11PM most likely generated tephra columns and subsequent tephra fallout deposits described as follows: "*during the night of Friday the volcano had been ejecting mud, ashes, and some rocks*" (Saderra Maso, 1911, p. 12). Based on narrative accounts, processes and products observed during the 27 January event included volcanic earthquakes, tephra fallout deposits, ballistic projectiles and rumbling sounds heard by Mr. J.D. Ward at TVI (Saderra Masó, 1911).

The 28 January event was written as follows: "*since the early morning a huge column of black smoke was rising from it and that in the nearest towns sinister rumblings could be heard at intervals*" (Saderra Masó, 1911, p. 12), and interpreted as a tall eruption column ejected from the volcano accompanied by rumbling sounds. With the forceful ejection of an eruption plume, ballistic projectiles and tephra fall deposits are expected to have been dispersed and deposited in surrounding areas (Cas & Wright, 1987). Tephra was carried southward as observed from a camp located in Bayuyungan, now part of the town of Laurel, within 6 to 8 km northwest of Taal Main Crater and about 400 m from the lake shoreline (Figure 4.2) (Worcester, 1912). Tephra fall was experienced the whole day over a distance of more than 20 km, with the west side from the vent experiencing 80 cm of tephra deposition. Electrical activity was observed within the tephra column (Saderra Masó, 1911; Worcester, 1912) and was most likely *plume lightning* from the description that lightning was sky-high and not near the vent (Behnke et al., 2013). A total of 197 volcanic earthquakes were recorded by the seismograph at the Manila Observatory in Metro Manila (Saderra Masó, 1911; Worcester, 1912). Ten were described as severe and caused panic to residents in Metro Manila before they found out the epicenters were located at Taal Volcano. Again, when intensities of volcanic earthquakes are converted to the current PEIS, the earthquakes felt in Metro Manila at that time could have been in the range of PEIS IV to VI (DOST-PHIVOLCS, 2018), and are expected to have been greater in the Taal area.

More volcanic earthquakes were recorded at the Manila Observatory on 29 January with 113 having greater intensities than those felt on 28 January. An eyewitness named Mr. Charles Martin, a government photographer tasked to document the activity of Taal, arrived at the rim of the Main Crater at 8PM and started to observe the eruption which he described as follows: "*There rolled an enormous column of vapour, which towered skyward until caught by the morning breeze, and was then swept, black and threatening, westward over the neighboring province of Cavite*" (Worcester, 1912, p. 339). Figure 4.4D shows the isopach map delineating the estimated tephra fallout dispersal (DOST-PHIVOLCS, 1991). Within the enormous tephra columns, electrical activity was noted, with Pratt (1911, p. 65) describing the phenomenon as follows: "*clouds above the volcano was frequently crossed and streaked with lightning, and often showed flashes or sheets of light*". The lightning flashes are now interpreted as either near-vent or plume lightning (Behnke et al., 2013). Extensive fissures were also observed at around 3PM in Lemery and Taal, located on the northeastern shores of Balayan Bay and in Talisay that was observed coincident with the occurrence of earthquakes (Figure 4.3) (Pratt, 1911). Smaller fissures were reported on the northern shores in Talisay (Figure 4.2), assumed by Pratt (1911) to have taken place at the same time as the Lemery and Taal fissures, and likewise accompanied and/or preceded by volcanic earthquakes.

The 30 January event commenced at 1PM with the occurrence of a large-magnitude earthquake followed by a violent explosion with an enormous tephra column streaked with lightning flashes (Saderra Masó, 1911; Pratt, 1911; Worcester, 1912). The tephra columns generated during the 2:20AM event were described as having the shape of "*an umbrella or a giant cauliflower*" (Pratt, 1911, p. 65). This event could have been

Phreatoplinian, a hydrovolcanic eruption which is the equivalent of a Sub-Plinian and Plinian eruption (Francis, 1993). The eruption was accompanied by detonations heard as far away as Metro Manila (Saderra Masó, 1911; DOST-PHIVOLCS, 1995). The tephra fallout was experienced twelve minutes after the eruption at the new location of Tanauan, 17 km northeast of the Main Crater (Worcester, 1912) (Figure 4.2). Continuous explosions generating tephra columns, lightning flashes, and earthquakes were observed throughout the day of 30 January, resulting in total darkness in the areas surrounding Taal. Pyroclastic density currents in the form of base surges (Lacroix, 1903) impacted at least 15 km to the west and 5 to 6 km to the east of the Main Crater (Figure 4.4C) (DOST-PHIVOLCS, 1995). Base surges impacted communities at TVI and the western side of Taal during the 30 January AD1911 eruption. On the western portion of TVI, trees were shredded and broken 0.3 to 0.5 m from the ground. A wave front generated by the advancing base surges detached roofing approximately 10 km from the volcano (Saderra Masó, 1911).

Additional hazard impacts during the 30 January eruptions included the occurrence of shock waves, and the presence of toxic gases, volcanic tsunami, fissures, landslides, and subsidence, some related to liquefaction effects. Shock waves/atmospheric pressure (Magill et al., 2013; Oswalt et al., 1996) were reported in Talisay (north of the volcano and former location of Old Tanauan) and San Nicolas. Toxic gases were also noted and acid burns were reported to have affected people and vegetation (DOST-PHIVOLCS, 1995). Some residents in Guillot and Bugaan, part of the municipality of Laurel located on the northwest shores (Figure 4.2) died in the absence of any scorching or burning and this is attributed to toxic gases (Saderra Masó, 1911). The presence of gases was also observed in Talisay with the occurrence of an explosion that propelled metal roofing to a distance of some 18 m at a time when the eruption had dissipated (Saderra Masó, 1911). Possible presence of soluble acidic salts in ash-laden plants and trees may have affected plant foliage (Cook et al., 1981; Wilson et al., 2011) such as the observed discoloration noted during the 30 January event (Saderra Masó, 1911). Volcanic tsunami completely destroyed the villages of Bosoboso, Bañaga, Bilibinang (now known as Bilibinwang), and Manalao, located on the western shore of Taal Lake, and now part of the Municipality of Agoncillo (Figure 4.2). Houses, livestock and residents were washed away by waves 2.3 to 3 m high (Saderra Masó, 1911; Berninghausen, 1969). The northeast-southwest fissure zones were reactivated extending from Lemery to Calamba (DOST-PHIVOLCS, 1995). Fissures along the shoreline, including those observed near Sinisian could be interpreted as lateral spreading, and reported mud cones and explosion pits, presumably sand boils are related to liquefaction generated by severe ground shaking due to the large-magnitude volcanic earthquakes (Figure 4.2). A three-meter subsidence occurred at TVI and the level of water at Taal Lake was lowered by about one meter. The eruption also brought significant changes in crater floor morphology, with the three small lakes previously existing inside the Main Crater fused into one (DOST-PHIVOLCS, 1995).

The total bulk volume of ejecta from the AD1911 eruption is estimated to have been about 80 million m^3 (DOST-PHIVOLCS, 1991). The estimated extent of the pyroclastic density current that were observed to be predominantly base surge is shown in Figure 4.4C, with estimated run-out distance approximately 9 km. The total thickness of tephra fall deposits was estimated at 25 cm covering and damaging an area of around 230 km^2, and greater than 80 cm within 8 km west of the Main Crater

(DOST-PHIVOLCS, 1991). An isopach map delineating dispersal and cumulative thickness of tephra fall deposits during the AD1911 eruption is shown in (Figure 4.4D). The AD1911 eruption was assigned a VEI of 4 (DOST-PHIVOLCS, 1991) but the Smithsonian GVP (2018) assigned a VEI 3. Considering the magnitude of the eruption and the related impacts and eruptive hazards and using the VEI classification of Newhall & Self (1982), a *VEI of 4 seems more reasonable and appropriate* (Table 4.1).

4.1.2.4. Series D

Finally, *Series D* consists of eight eruptions from AD1965 to AD1977 that were centered at the Mt. Tabaro eruption site located on the southwestern flank of TVI (Figure 4.1, Figure 4.5 and Figure 4.6). One of the most the most explosive eruptions during this series is the AD1965 event. All eruptions from this series are confirmed.

AD1965

Being the most explosive eruption of this series, a significant number of narrative accounts were available, examined and reinterpreted. With the availability of time-bound descriptions of the eruptive activity, the three-day eruption was subdivided into three phases, with eruption styles transitioning from a Strombolian, to a moderate Phreatomagmatic, then to a minor Phreatomagmatic phase (Table 4.1). Prior to the AD1965 eruption, the Commission on Volcanology (COMVOL), the predecessor to DOST-PHIVOLCS, established a manned volcano observatory located on the west-central part of TVI. Visual observations, 24/7 seismic monitoring, periodic lake temperature measurements, and geochemical and geotechnical measurements were conducted. An increase in lake temperature was noted at the Main Crater, from an average reading of 30-33 degrees centigrade (°C) in AD1964 to 45°C on 21 July AD1965. Further, short seismic swarms were noted that in hindsight were precursory signals to the eruption.

The eruptive activity occurred from 28 to 30 September AD1965 and transitioned from an initial Strombolian phase to a Phreatomagmatic phase based on the described eruption behaviour (Alcaraz & Datuin, 1977) (Table 4.1; Appendix B). The Strombolian phase commenced after 2AM on 28 September and consisted of lava fountaining and lava flows (DOST-PHIVOLCS, 1991, 1995) described by Moore et al. (1966, p. 955) as follows: "*incandescent material shooting high in the air from the general vicinity of the newly formed cinder cone*". The eruption was accompanied by large-magnitude volcanic earthquakes, recorded and felt at the COMVOL observatory located at TVI. These volcanic earthquakes were accompanied by rumbling sounds that immediately alarmed and compelled the volcano observers to check the seismograph. Sand-sized tephra fallout (was experienced at 2:13AM) and the COMVOL observer then evacuated the island together with 19 residents.

From 2:40 to 3:30AM, electrical activity (Behnke et al., 2013) was observed within the eruption plume reported by a resident from the northwest sector of TVI that described "*a continuous display of lightning in the eruption cloud*" (Moore et al., 1966, p. 955). This was the predicted onset of the Phreatomagmatic phase. The activity peaked between 3:25AM and 9:20AM, with eruption column height estimated at 15 to 20 km, reported as being visible from the Metro Manila area (Moore et al., 1966). Column collapse pyroclastic density currents in the form of base surges were described by Moore et al. (1966) that sandblasted and coated trees with fine eruption deposits. Multiple base surge events occurred during this phase (Moore et al., 1966).

The extent of base surge deposition is shown in Figure 4.4E, with an estimated run-out distance of 4.5 km, causing devastation to the southern part of TVI from Balantoc in the west to Calauit in the east, and the lakeshore barrios west of TVI, from Barangay Gulod in the Municipality of Laurel to Barangay Bilibinwang in the Municipality of Agoncillo. In addition, volcanic bombs, possibly ejected as ballistic projectiles, were seen up to a distance of one kilometer from the vent with average diameters of 50 cm, but with a maximum size of about three meters (Moore et al., 1966). The tephra column was dispersed southwest by prevailing winds to a distance of more than 80 km west from the vent (Moore et al., 1966). Tephra fall deposits ranged from 20 to 50 cm thick within a 60 km^2 area (DOST-PHIVOLCS, 1991) (Figure 4.4F). Other observed and reported phenomena were shock waves/atmospheric waves (Moore et al., 1966). Volcanic tsunami were generated that not only resulted in deaths of some of the evacuating islanders but also devastated communities on the western shoreline (Moore et al., 1966). The wave run-up was estimated at 4.7 m above the lake level and inundated areas up to about 80 m from the shore (Moore et al., 1966; Berninghausen, 1969). This paroxysmal phase subsequently created a new 1.5 km by 0.3 km explosion crater with an average depth of approximately 25 m (Figure 4.5).

The eruptive activity from 9:20AM on 28 September to 6AM on 30 September, marked the decline in the intensity of the Phreatomagmatic activity, with reduced height of the tephra columns observed within the newly formed explosion crater (Figure 4.5A). Only tephra fallout deposits are expected to have impacted communities during this phase. The last explosion occurred at 3:50PM on 30 September.

The AD1965 eruption claimed at least 200 lives. At the time of the eruption, the population on TVI was approximately 4,000. The total bulk volume of ejecta from the AD1965 eruption was estimated at 90 million m^3 spread over TVI, Taal Lake, and the western shoreline. Damage to vegetation resulting from tephra deposition was observed (Moore, 1966, p.960). Only a dusting of tephra fall was experienced by residents in the north, northeast and east lakeshore areas. With tephra columns ranging in height from 15 to 20 km and the bulk volume of volcanic ejecta, the VEI 4 assigned (DOST-PHIVOLCS, 1991; Smithsonian GVP, 2018) seems reasonable and appropriate, and should be retained (Table 4.1). Newly interpreted processes are lava fountaining and lava flows, volcanic earthquakes that preceded the eruptions and continually occurred during the subsequent three-day eruptions, electrical activity, gases and rumbling sounds (Table 4.1).

AD1966

The 5 July to 4 August AD1966 event was described as a Phreatomagmatic eruption (Alcaraz & Datuin, 1977; Ruelo, 1983; DOST-PHIVOLCS, 1991) with an assigned VEI of 3 (DOST-PHIVOLCS, 1991; Smithsonian GVP, 2018). A series of minor eruptions centered on the southwest side of the AD1965 cinder cone produced a *"122-meter high ellipsoidal tuff cone measuring 500x400 meters at its base"* (DOST-PHIVOLCS, 1991, p. 53) (Figure 4.5C). Tephra fallout deposition resulted in damage to houses and vegetation. Although volcanic earthquakes were not mentioned in narrative accounts (Alcaraz & Datuin, 1977; DOST-PHIVOLCS, 1991, 1995; Ruelo, 1983), similar to other past eruptive events, volcanic earthquakes are presumed to have occurred during this eruption (Table 4.1). Considering the explosiveness of the eruptions that produced a mix of juvenile and lithic fragments exploded from the walls of the existing crater, the assigned eruption style and VEI are herein affirmed and reiterated.

AD1967

The 16 to 18 August AD1967 eruption was classified as a Phreatomagmatic event centered at the AD1966 cone lake (Figure 4.5D). The assigned VEI was 1 (DOST-PHIVOLCS, 1991; Smithsonian GVP, 2018). The eruptive activity and the products of the eruption created *"a small doughnut-shaped cinder cone"* with an outer diameter of 40 m and inner diameter of 22 m (DOST-PHIVOLCS, 1995, p. 51). Steam laden clouds with dark fine basaltic ash were ejected from the cone as high as 400 m (Ruelo, 1983; DOST-PHIVOLCS, 1991). Volcanic earthquakes are thought to have occurred during this eruption (Table 4.1). The assigned eruption style and VEI are likewise affirmed and reiterated.

AD1968

During the 31 January to 2 April AD1968 activity, the eruption style was simply classified as Strombolian centered within the AD1966 eruption cone lake, a few meters from the AD1967 conelet (DOST-PHIVOLCS, 1991; Ruelo, 1983) (Figure 4.5E). Different eruptive phases were not determined by past authors. The default VEI of 2 was assigned to this eruption (DOST-PHIVOLCS, 1991) (Table 4.1).

In this research, three eruptive phases were identified and some newly interpreted eruptive processes and products were discerned from the available narrative accounts. The initial phase was Phreatomagmatic from 31 January to 1 February, with the generation of tephra columns, and tephra fallout deposits. Volcanic earthquakes are also predicted to have occurred and were instrumentally monitored by COMVOL. The Phreatomagmatic phase transitioned to a Strombolian phase from 2 February to 28 March, with lava fountaining and lava flows directed towards the western base of a cinder cone formed during the eruption (Figure 4.5E) (Ruelo, 1983). After 28 March and until 2 April, eruptive activity reverted back to a minor Phreatomagmatic eruptive phase, with ejection of pyroclastic materials in the form of fall deposits (DOST-PHIVOLCS, 1991). The default VEI of 2 is reaffirmed for this eruption (Table 4.1).

AD1969

The AD1969 activity consisted of three distinct eruptive phases with the initial phase being Phreatomagmatic that commenced on 29 October AD1969 (Ruelo, 1983; DOST-PHIVOLCS, 1991). The eruptive activity was centered on the southeastern upper slope of the AD1968 scoria cone and the new explosion formed a pit about five meters wide (Figure 4.6A and Figure 4.6B) (Ruelo, 1983). The volcanic ejecta consisted of ash, steam and incandescent material. At 7:30PM on 30 October, the eruption transitioned to a Strombolian eruptive phase with lava flows directed towards the eastern base of the 1968 scoria cone. These subsequently overtopped and exceeded the extent of those from the AD1968 eruption (Ruelo, 1983; DOST-PHIVOLCS, 1991). Lava fountaining was also observed forming a new scoria cone (Figure 4.6B).

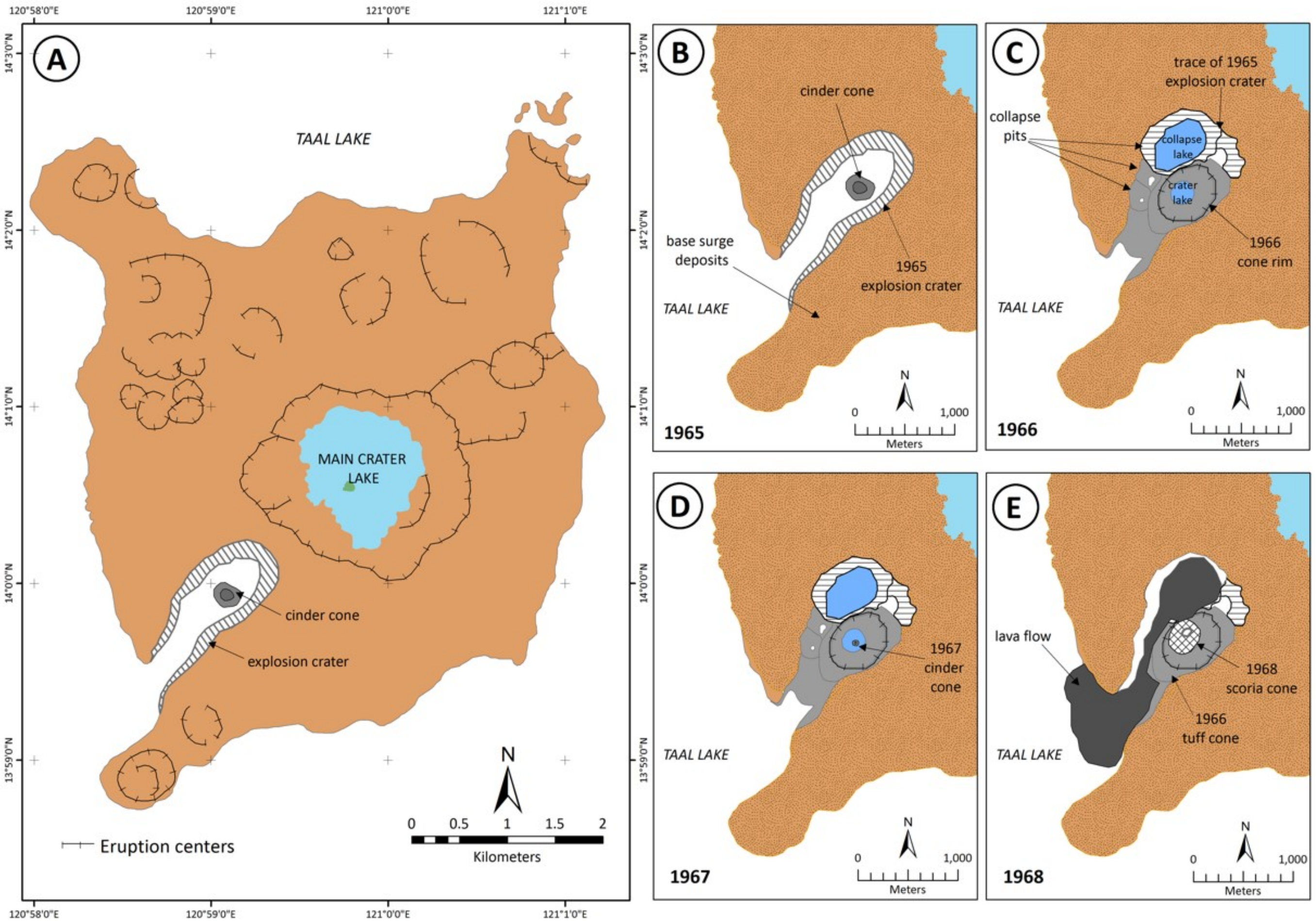


Figure 4.5. (A) Physiographic map showing features following the AD1965 eruptions of Taal. (B) Close-up view of the post-AD1965 eruption morphological features of Mt. Tabaro eruption crater. Morphological features of Mt. Tabaro eruption crater following: (C) the AD1966 eruption; (D) the 1967 eruption; (E) the AD1968 eruption. Source: Delos Reyes et al. (2018); modified from Ruelo (1983) and DOST-PHIVOLCS (1991).

The Strombolian phase continued until 22 November with eruptive activity shifting towards the northeast sector (20 November). Lava subsequently flowed into a creek until it reached the river mouth towards Taal Lake, with an estimated speed of four meters per minute (Figure 4.6B) (DOST-PHIVOLCS, 1991; Ruelo, 1983). Eruptive activity subsequently transitioned to minor Phreatomagmatic eruptions after 4:20PM on 22 November, lasting until 10 December AD1969, with the ejection of volcanic materials centered at the AD1969 scoria cone (Figure 4.6B) (DOST-PHIVOLCS, 1991). The VEI assigned by Oppenheimer (1991) was 1 while DOST-PHIVOLCS (1991) and the Smithsonian GVP (2018) assigned a default VEI 2 for this eruption. Considering that the eruptive phases consisted of Phreatomagmatic and moderate Strombolian activity, a VEI of 2 seems more appropriate for the AD1969 eruption (Table 4.1).

AD1970

The 9 to 13 November AD1970 eruption was previously classified as Phreatic (DOST-PHIVOLCS, 1991; Ruelo, 1983). A VEI of 2 was assigned by Oppenheimer (1991), while DOST-PHIVOLCS (1991) and the Smithsonian GVP (2018) assigned a VEI of 1. The eruptive activity was initially centered at the eastern section of the AD1969 cone and formed a five-meter diameter explosion pit within the cone (Figure 4.6C) (Ruelo, 1983). Alcaraz & Datuin (1974, p. 37) provided a description of "*weak and short-lived eruptions*" for the AD1967 and AD1970 eruptions and while there is limited narrative accounts on the AD1970 event, a VEI of 1 seems appropriate for this eruption (Table 4.1).

AD1976

The eruptive activity commenced at 4:00AM on 3 September and lasted until 22 October AD1976 (Masigla & Ruelo, 1987; Ruelo, 1983). The event was classified as a mild Phreatic eruption consisting of a series of minor ash ejections (Masigla & Ruelo, 1987). The assigned VEI was 2 (DOST-PHIVOLCS, 1991; Smithsonian GVP, 2018). An explosion resulted in the generation of an eruption column about 1.5 km high that drifted to the southwest and a northeast-southwest elongated explosion crater was formed with two collapse craters found in the north and southeast section of the AD1968-1969 eruption cones (Figure 4.6D) (DOST-PHIVOLCS, 1995; Ruelo, 1983). No change in VEI and eruptive style classification are deemed necessary (Table 4.1).

AD1977

The latest recorded eruption of Taal was observed from 3 to 4 October AD1977. The activity was classified as a minor Phreatic eruption. The VEI assigned by DOST-PHIVOLCS (1991) was 1 while the Smithsonian GVP (2018) assigned a VEI of 2. Ejection of steam and ash took place on 3 October with the center of activity located in the northeast sector of the AD1976 elongated explosion crater. The tephra column reached a height of 500 m (Ruelo, 1983). A new conelet was formed and observed on4 October estimated to be about five meters above the base and ten meters in diameter, with an estimated volume of 1.6 x 10 m^3 (DOST-PHIVOLCS, 1991; Ruelo, 1983). Considering that the eruptive activity only produced a 500-meter high tephra column and no significant change occurred in the morphology of the eruptive centers,

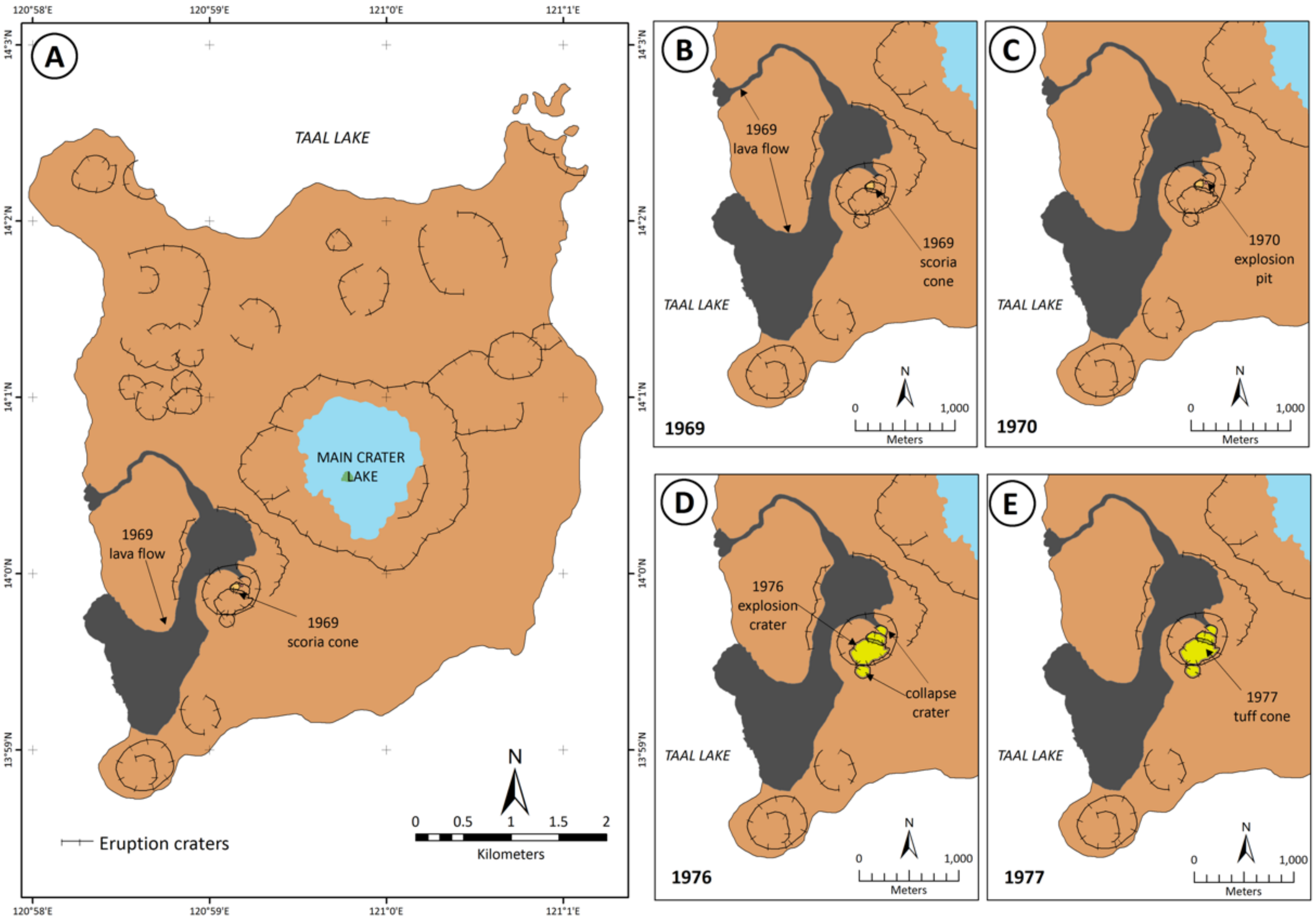


Figure 4.6. (A) Physiographic map following the AD1969 eruptions of Taal. (B) Close-up view of the post-AD1969 eruption. Morphological features of Mt. Tabaro eruption crater following: (C) the AD1970 eruption; (D) the AD1976 eruption; and (E) the AD1977 eruption. All eruptive activities centered at the Mt. Tabaro area. Source: Delos Reyes et al. (2018); modified from Ruelo (1983) and DOST-PHIVOLCS (1991).

a VEI of 1 seems more appropriate but the eruption style is affirmed to be minor Phreatic eruption (Table 4.1).

After the AD1977 eruption, Taal was quiet but sporadically manifested unrest with at least 22 significant episodes of seismic swarms recorded (Table 2.5).

4.2 Discussion

This chapter sought to address Research Question 1 and Research Question 2. I first presented an overview of the methodology utilised in the critical re-examination of narrative accounts of the historical eruptions of Taal, then provided new insights and interpretations of the processes and products of the eruptions from AD1572 to AD1977, as well as descriptive extents of tephra dispersal and accumulation whenever possible based on the narrative accounts of all available published and unpublished literature. The new interpretations were drawn from the more extensive volcanology literature search and mapping conducted in this research, as well as diverse personal experience dealing with past eruptions. The summary table (Table 4.1) provides a list of the 33 identified eruptions of Taal and the recommended changes in interpretation of event characteristics.

4.2.1. Salient changes in interpretations

The most important re-interpretations provided in this research are:

1. *Classification of eruptions being certain or unconfirmed*. At least nine (9) previously identified eruptions were deemed as uncertain. Seismic swarms do not always culminate in eruptions. The identified eruptions in AD1605-AD1611 are now considered uncertain with the recorded activity being deemed more likely to

correspond to seismic swarms or solfataric activity only. Likewise, solfataric activities were also interpreted for the AD1634, AD1635, and AD1645 events in *Series A*, with occurrence of eruptions uncertain. Further, the previously identified eruptions in AD1790, AD1825, AD1842, AD1873 and AD1903 in *Series C* are likewise considered uncertain due to lack of descriptions and no ascribed reference that can support or confirm their occurrence (Table 4.1). All previously identified eruptions in *Series B* and *Series D* were confirmed and supported by narrative descriptions.

2. *Re-interpretations of eruption styles*
    - The eruption style of the AD1572 eruption was re-interpreted as more likely Strombolian rather than Phreatomagmatic. Lava fountaining was observed and became the main basis for change in the interpretation.
    - There was no previously specified eruptive style for the AD1715 event and it was newly classified as Strombolian with lava fountaining and lava flows.
    - Eruptive style for the AD1729 event was newly classified as Phreatic. No specified eruption classification was provided by other authors.
    - The AD1749 event could not be classified by one single eruptive style throughout the duration of the eruptive activity and the lack of time-bound narrative descriptions for the eruption prevented identification of different eruptive phases. However, the eruption likely included Plinian or very violent sub-lacustrine Phreatomagmatic activity with column-collapse pyroclastic density currents.

3. *Re-interpretations of eruption phases*

   - The eruptions in AD1754, AD1911 and AD1965 were previously not classified into eruptive phases but critical review of the same narrative accounts allowed the determination of individual phases for these eruptions.
   - The AD1754 eruption was initially Plinian/Sub-Plinian (15 May to 02 June), then transitioned to a Phreatomagmatic eruption (02 June to 25 September). A lull in the eruptive activity occurred from 26 September to 31 October. The next phase from 1 to 15 November is now interpreted as likely being Plinian/Sub-Plinian or Phreatomagmatic. The eruptive styles during the last phase from 28 November to 2 December may have been Plinian/Sub-Plinian and Phreatomagmatic.
   - Four eruptive phases are now recognised for the 27 to 30 January AD1911 eruption. These were likely Phreatomagmatic but with different eruptive processes and products to those previously described.
   - The AD1965 eruption transitioned from Strombolian (28 September at 2AM) to Phreatomagmatic (between 2:40AM to 3:30AM on 28 September), and finally to minor Phreatic (between 9:20AM on 28 September to 6AM on 30 September).
   - The AD1968 eruptions transitioned from Phreatomagmatic (31 January to 1 February) then became Strombolian (2 February to 28 March), and finally minor Phreatomagmatic (29 March to 2 April).
   - Two eruptive phases are now identified for the AD1969 event: Phreatomagmatic phase (29 October) and Strombolian phase (30 October to 10 December).

4. *Re-interpretation of processes and products*

- Notable occurrences of electrical activities accompanied most of the large-magnitude eruptions of Taal such as the AD1707, AD1749, AD1754, AD1911 and AD1965 events. A more significant observation is that with the newly interpreted occurrence of lightning flashes for the AD1707 eruption, and a confirmed default VEI of 2, there is confirmation that lightning can be generated within a sub 5 km high tephra plume.
- New interpretation of liquefaction effects is provided in this research associated with the AD1749, AD1754, and AD1911 eruptions that are attributed to the occurrence of large-magnitude volcanic earthquakes that resulted in severe ground shaking. Sand boils, lateral spreading, and settlement in lakeshore areas were interpreted from the narrative accounts.
- Compared to previously mapped and delineated extents of pyroclastic surges from the AD1754 eruption, current mapping confirmed that the surges travelled significantly farther than previously known, and alarmingly into areas that are now densely populated.

5. *Hazard and risk implications*
    - *Tephra dispersal and implication to aviation operation* – A critical narrative of tephra fall reaching Manila during the AD1754 eruption has implications for tephra hazard impact to aviation operation. A major hazardous eruption occurring with the same or greater magnitude as the AD1754 event could result in an aviation crisis, similar to the ash encounters experienced during the AD1991 eruption of Pinatubo Volcano and the aviation crisis resulting from the AD2010 eruption of Eyjafjallajökull Volcano in Iceland. Part of this research also attempts

to provide tephra hazard modelling results that will provide more details on likely dispersal and thickness of tephra falls, specifically from a AD1754-type eruption at Taal. This work will be discussed in Chapter 6.

- *Electrical activity* – accompanying most of the large-magnitude eruptions of Taal, including the AD1707, AD1749, AD1754, AD1911 and AD1965 events. Volcanic lightning can provide warning of the presence of a tephra plume in the vicinity of a volcano.
- *Liquefaction effects* – are a newly identified hazard related to Taal and interpreted to have occurred during the AD1749, AD1754, and AD1911 eruptions. With growing industrial and commercial development in the Taal region, consideration of this hazard should be included in applications for building permits in the vicinity of Taal, especially in areas close to shallow ground water or close to water bodies such as lakes and bays.
- *Pyroclastic density currents (PDCs): pyroclastic flows and base surges* – The occurrence of PDCs during the AD1716, AD1731, AD1749, AD1754, AD1911 and AD1965 eruptions, at a time when TVI was not as populated as today, resulted in minimal casualties. Should another hazardous eruption at Taal occur and PDCs be generated, how devastating will the consequences be, especially with more than 5,000 people now residing on TVI?
- *Volcanic tsunami and seiche* – The AD1716, AD1731, AD1749, AD1754, AD1911 and AD1965 eruptions generated volcanic tsunami that devastated several Taal communities and resulted in numerous casualties. With more people now living along the shorelines of Taal Lake, the hazard continues to exist and

risk is now greater than they were during past eruptions with more people living at TVI and Taal Lake shoreline.

- *Toxic volcanic gases* – The Taal eruptions with recorded toxic gases released were those in AD1716, AD1749, AD1754, AD1874, AD1911, and AD1965. This hazard resulted in casualties, and impact to flora and fauna.
- *Volcanic earthquakes* – The eruptions with narrative descriptions of ground shaking due to volcanic earthquakes include AD1605-AD1611, AD1707, AD1709, AD1716, AD1731, AD1749, AD1754, AD1911, AD1965, AD1966, AD1967, AD1968, AD1969, AD1970, AD1976 and AD1977. However, based on current seismic monitoring conducted around Taal, it is presumed that all confirmed eruptions of Taal were accompanied by volcanic earthquakes.
- *Lahars and flooding* – Perhaps two of the least considered hazards from an explosive eruption at Taal are occurrence of lahars and flooding. Although past lahar activity at Taal Volcano were not as frequent or as devastating as those which occurred at Mayon Volcano in the Bicol area, or Pinatubo Volcano in Central Luzon, there was notable reference to ash being washed to the ground presumably with landslides and lahars occurring after emplacement of tephra deposits during the 29 November AD1754 eruption, which was followed by heavy downpour. Furthermore, with more communities living at the foot of TVI, and adjacent to steep ridges that form the Taal Caldera wall, the study of potential occurrence of future lahars becomes more important. Flooding was also experienced during past eruptions of Taal. The damming of the Pansipit River by

volcanic materials during the AD1754 eruption resulted in flooding on the southeast and eastern lakeshores.

- *Atmospheric shock waves* – Shock waves were reported during the AD1707, AD1749, AD1754, AD1911 and AD1965 eruptions of Taal.

Identification of the volcanic hazards, and consideration of the consequences and impacts of these hazards, can be utilised for designing and developing more sustainable disaster risk reduction strategies for Taal communities.

Furthermore, most of the eruptions with default VEIs were generally unclassified eruption styles. This is likely because there is limited documentation of those eruptions. Most of these default VEIs have now been downgraded to VEI 0 because either the identified eruption was reinterpreted as merely solfataric activity or as very minor Phreatic eruptions (Figure 4.7). Those eruptions prior to AD1904 that have more detailed written accounts indicate that they are significantly larger eruptions. From AD1904 onwards, eruptions have been well-documented and the reinterpretation of originally assigned VEIs and eruption styles are rarely changed. However, for larger eruptions, the more extensive and more detailed descriptions of the eruptions allowed me to separate the eruptive events into phases with transition of eruptive styles.

4.2.2. Recommendations for future work related to this research

After conducting a more critical and comprehensive review of the narrative accounts of the historical eruptions of Taal, I was able to identify gaps in knowledge related to these eruptions. Drawing from an extensive volcanology literature provided me with new

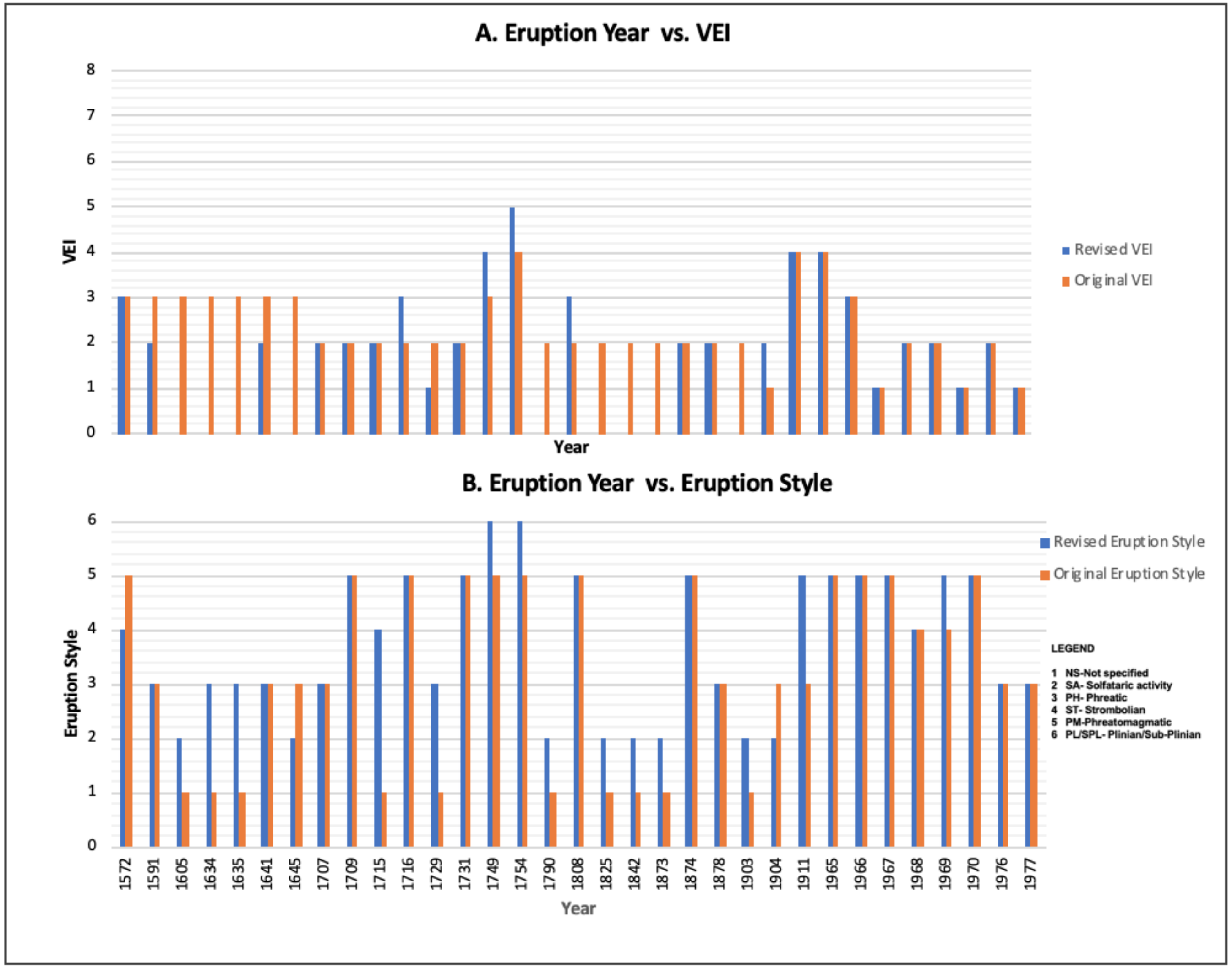


Figure 4.7. Comparison of original and revised interpretations related to the 33 identified historical eruptions of Taal Volcano. (A) plot of Volcano Explosivity Index (VEI) versus eruption year; and (B) plot of eruption styles versus eruption year. The eruption styles are numbered: 1) Not specified (NS); 2) Solfataric activity; 3) Phreatic; 4) Strombolian; 5) Phreatomagmatic; and 6) Plinian/Sub-Plinian.

insights and a greater knowledge of likely products and processes, I was able to provide new interpretations of eruptive styles, processes, products and VEIs for the Taal eruptions. I can now make a number of recommendations for further work:

1. Most of the extensively distributed older Quaternary caldera-forming eruption deposits are currently not dated and more research is critically needed on these caldera-forming events in order to build a better picture of the early evolution of Taal, as well as to provide an estimate of the recurrence rate of large eruptions from Taal Caldera.
2. More research into the potential for large explosive eruptions, such as that of c. 5,700 BP, growing from small eruptions; knowledge of any precursory eruptions (or absence thereof) is important for anticipating a future caldera-forming event. There is also a need to look for analogous, preferably well-studied calderagenic volcanoes for better understanding of the volcanic processes involved in their formation.
3. This research identified nine previously listed eruptions that were deemed uncertain and may have only been solfataric activity. These eruptions need further investigation and potential reclassification. This has important implications for hazard identification including determination of recurrence intervals, magnitude frequency relationships and so forth.
4. The sand blast effects from PDCs created devastating impact on objects in their paths on TVI and at some communities on the mainland. Further mapping of the distal extent of the PDCs could shed light on the magnitude of this hazard and the risk that these hazards pose to Taal communities.

5. Tephra fallout deposits are the most widespread and distal products of eruptions from Taal Volcano. Estimation of dispersal and thickness of deposition can be conducted through numerical modelling. Utilising the results of modelling, combined with the results from the other fields of this interdisciplinary research, critical hazard information can be provided to stakeholders from the agricultural, engineering, tourism, aviation, and emergency management sectors in regard to future events. However, prediction of dispersal and accumulation using tephra modelling excludes conditions where there is potential climate variations during large eruptions such as the AD1991 eruption of Pinatubo.
6. While there were only limited accounts of lahar occurrence, potential exposure to this hazard exists and further investigation of lahar hazard and risk should be undertaken, especially with increasing numbers of residents at the foot of the slopes of Taal.
7. Whilst I have provided a summary review and re-interpretation of all known historical eruptions of Taal, more work is needed to understand the changes in eruptive styles and the processes and products they generate.
8. Finally, the VEIs for the confirmed eruptions may still be further reviewed so that they truly reflect the magnitude and explosivity of these eruptions.

4.3 Conclusion

The results of the critical review, including new insights and interpretations of the processes and products of historical eruptions of Taal between AD1572 and AD1977, provide important knowledge from these past eruptions. Better understanding of the dynamics and mechanism of processes and products of past hazardous eruptions at Taal could provide important information for estimating volcanic hazards and risk, and for preparing and managing this risk.

CHAPTER 5:
Geological mapping of the suspected AD1754 Taal deposits

5.0 Introduction

This chapter presents new information to address Research Question 2: "*What is the expected distribution of tephra deposits in the event of an explosive eruption such as the AD1754 Plinian/Sub-Plinian eruption of Taal?*" and a part of Research Question 3: *"How would a major/plinian eruption affect communities around Taal Volcano"*.

Having provided summary descriptions and reinterpretations of processes and products of historical eruptions of Taal, this chapter presents and discusses the results of new geologic investigations to map the extent and thicknesses of suspected tephra deposits from the AD1754 eruption. As mentioned in Chapter 3 Section 3.2, I originally set out to conduct mapping of tephra deposits from the AD1749, AD1754, AD1911 and AD1965 eruptions. However, the results of my 2014 field investigations showed that only the tephra deposits from the AD1754 eruptions were widely exposed. The AD1754 eruption was one of the largest historical eruptions and it devastated the towns of Old Taal, Old Tanauan, Old Sala and Old Lipa, and forced survivors to evacuate and resettle elsewhere (Figure 5.1) (DOST-PHIVOLCS, 1991; Saderra Masó 1911; Worcester, 1912). While dating and geochemical analysis of deposits were not undertaken in this project, mapping and identification of the AD1754 deposits were completed using the narrative descriptions provided by the translated work of Buencuchillo (1754) and Centeno (1885), and subsequent papers by Saderra Masó (1904, 1911), Worcester (1912), Masigla &

Ruelo (1987), Hargrove (1991), Oppenheimer (1991), DOST-PHIVOLCS (1991, 1995), Torres et al., (1995), del Barrio Muñoz (2015), and Delos Reyes et al. (2018). Information from these studies was combined with stratigraphic descriptions of the AD1754 tephra characteristics provided by Torres (1989), and the tephra isopach map generated by Masigla & Ruelo (1987) and DOST-PHIVOLCS (1991) (Figure 3.5). Geological investigations were conducted in 2014 and 2016.

The following sections provide details of the geological investigations conducted for the AD1754 tephra fallout deposits that included stratigraphic logging, deposit characterisation, thickness measurement, *in situ* bulk density testing, sampling and grain size processing and analysis.

5.1 Mapping and stratigraphic logging of the deposits

Mapping of the suspected AD1754 tephra deposits was undertaken to determine how extensive the tephra fall was for this event, and to establish a maximum expected event scenario for Taal, as caldera forming eruptions are likely improbable at this stage. This was achieved by identifying point locations where tephra fallout deposits are exposed, as well as determining the deposit thicknesses of each exposure. Geological information gathered in the field was collected with the purpose of informing tephra modelling, which in turn will create a better understanding of likely tephra dispersal and eruption source parameters.

Further, stratigraphic logging is necessary to study and interpret the characteristics and succession of the lithologic units, including identifying various phases of the eruption.

Doyle & Bennet (1998, p. 1) defined stratigraphy as "*the study of rock units and the interpretation of rock successions as a series of events in the history of the earth*". Stratigraphic mapping entails studying the sorting and grading, particle sizes and abundance of fragments, stratification, welding and induration, and thickness of each lithologic layer. By conducting stratigraphic mapping of each outcrop, I may correlate the eyewitness narrative descriptions provided for the eruption with deposits to determine eruptive processes and validate the characteristics of eruptions that took place. Further, by correlating the tephra deposits from each identified phase of the AD1754 eruption, the extent of dispersal could be estimated and new and best-fit tephra isopach maps could be generated that are representative of the true tephra dispersal. Isopach maps constructed from the field mapping and analysis may then be compared with the best-fit results of the tephra modelling reported in Chapter 6.

From the review of historical eruptions, it was determined that the AD1754 eruption was a multi-phased eruptive event with at least four distinct phases. The eruption spanned from 15 May to 2 December, and the four main phases included: a) a Plinian/Sub-Plinian phase that started on 15 May and lasted until 2 June; b) a Phreatomagmatic phase from 2 June until 26 September; c) a Plinian/Sub-Plinian or Phreatomagmatic phase from 1 to 15 November; and d) a Plinian/Sub-Plinian and Phreatomagmatic phase that commenced on 28 November and lasted until 2 December. Detailed summary descriptions of the AD1754 eruption are provided in Chapter 4 and Appendix A and Appendix G.

5.1.1. Establishing the eruption sequence in the field

While the multi-phased eruption was separated into four distinct phases through descriptive accounts, it was more challenging to identify the tephra fallout products from each phase in the field. Guided by the AD1754 tephra isopach map generated by DOST-PHIVOLCS (1991), existing roads were traversed to search for possible outcrops. In general, exposures were found where past and present quarrying and road cutting was being undertaken at the time of the surveys (Figure 5.1A). Another challenge to mapping the AD1754 deposits is that the local government engineering offices and regional offices of the Department of Public Works and Highways (DPWH) conduct riprapping of roadcuts to reduce landslide potential, subsequently covering valuable exposures (Figure 5.1B). Consequently, validation and follow-up investigations of some of the previously mapped outcrops could not be undertaken in this study because the exposures were subsequently covered with cement.

Only two phases were deemed to be represented by exposed deposits: the 15 May to 2 June phase tephra deposit identified as *TF1* in this study, and the tephra deposit identified as *TF2* correlated to the November phase. Fr. Buencuchillo of Taal provided a narrative description of the 15 May to 2 June AD1754 eruptive phase in Chapter 4 as translated by Saderra Masó (1911) and Worcester (1912) that indicated that the first phase of the eruption was a Plinian/Sub-Plinian phase with tephra fall deposits and column collapse leading to the generation of pyroclastic density currents. I identified the tephra from this phase as *TF1*, likely associated with the *A1* layer of Torres (1989). The tephra deposit

Figure 5.1. Limitations in mapping the AD1754 eruption deposits. A) Photo of outcrop exposed through quarrying a activities in Barangay Banyaga in Agoncillo taken on 21 Sept 2016. B) Riprapping activities along roadcuts in Barangay Bilibinwang, Agoncillo undertaken by local government engineering offices and regional offices of the Department of Public Works and Highways (DPWH) to reduce landslide potential that subsequently covered valuable AD1754 exposures. Photo from Bornas et al., 2018.

consists of a thick layer of highly vesiculated juvenile fragments that was dispersed westward and affected the barrio of Bayuyungan, now known as Barangay Balakilong, in the Municipality of Laurel (Figure 3.5). Although rare, similar basaltic scoria-fall deposits with plinian dispersal patterns have been erupted from other volcanoes in the past (Costantini et al., 2008; Schauroth et al., 2016; Walker, et al., 1984; Williams, 1983). Constantini et al. (2008) successfully predicted the eruption source parameters for the Pleistocene Plinian eruption near Masaya Volcano in Nicaragua through numerical modelling and the results were validated by mapped exposures, grain size analysis and use of distal marine core information.

Continuous ejection of volcanic materials was observed during the second Phreatomagmatic phase from 2 June to 26 September AD1754 that subsequently resulted in the darkening of the lake waters. Tephra clouds were continuously generated but the heights of these clouds could not be determined due to a lack of detailed narrative descriptions. The eruptive deposits from this phase could not be recognised in the field due to insufficient narrative description of the deposits, either because the eruptive phase impacts were minor and/or the deposits were not preserved. A lull in activity occurred from 26 September to 30 October, followed by a resumption of eruptive activity that was described to have "*resumed its former fury, ejecting fire, rocks, sand, and mud*" (Saderra Masó, 1911, p. 9; Worcester, 1912, p. 319). The tephra fallout unit identified as *TF2* here, was more likely deposited during this November phase, where the eruptive styles transitioned between Plinian/Sub-Plinian and Phreatomagmatic (Appendix A and Appendix G).

5.1.2. Stratigraphic mapping of the inferred AD1754 tephra deposits

During the entire mapping activity conducted in 2014 and 2016, 41 new tephra exposures considered to be from the AD1754 eruption were identified and stratigraphic logging was conducted at each. The locations of these outcrops are plotted in Figure 5.2. The black lines are isopach contour lines that represent average thicknesses of the AD1754 tephra deposits generated by previous authors (DOST-PHIVOLCS, 1991; Masigla & Ruelo, 1987) (Figure 5.2). The tephra fallout from the two eruptive phases comprised the main bulk of the tephra ejected during the AD1754 event. The tephra from the other phases were difficult to identify, were lost through erosion, or may have been inadvertently included in the thickness measurements of the two major phases. Although investigations were conducted east of the volcano, no tephra deposits from the AD1754 eruption were found. The absence of identified tephra outcrops east of Taal may be due to low preservation and/or very thin tephra accumulation. Figure 5.2 identifies the 41 exposures, either with the *TF1* deposits only (blue triangle symbol), the exposures with *TF2* only (orange circle), and 25 of the 41 exposures with both *TF1* and *TF2* tephra deposits present (yellow square). Eight outcrops only had *TF1* and eight outcrops only had *TF2*. The very thin key bed unit (*K*) is generally found underlying *TF2*. Keybeds or marker beds, are chronostratigraphic markers readily recognisable because of their distinct physical characteristics and are generally found over a large area (Davies et al., 2016). The mapped tephra unit *TF1* was assumed to be from the initial phase of the AD1754 eruption based on past accounts that provided description of where tephra fallout deposits were dispersed and deposited (e.g. Saderra Masó, Worcester etc.) and from outcrop descriptions by Torres (1989). The *TF1* tephra deposit generally consists of dark, brittle, non-graded, very poorly sorted and highly vesiculated lapilli. However, it also consists of fine ash to fine sand-sized in some layers that seems consistent with narrated descriptions (Figure 5.3). In contrast, graded beds are characterised with pronounced vertical

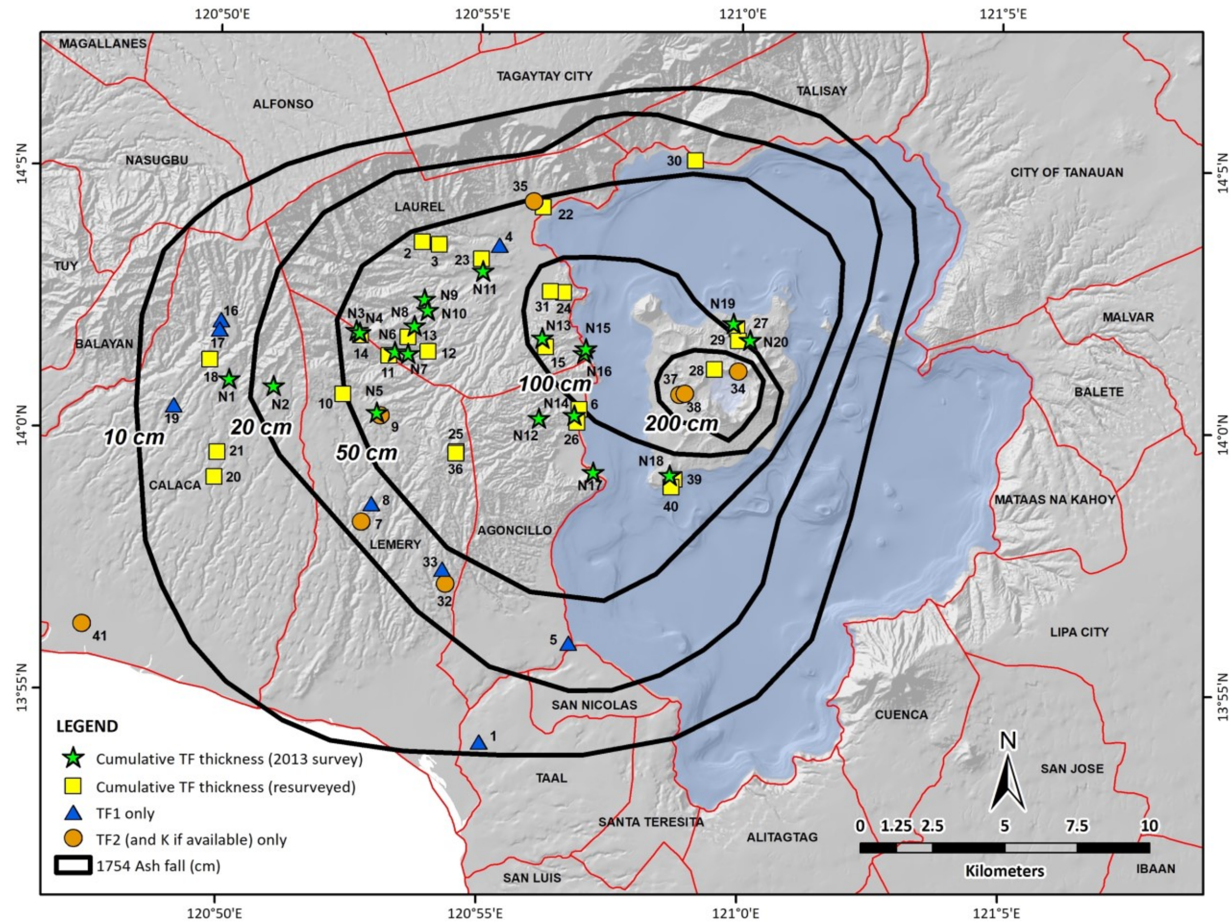


Figure 5.2. Map showing locations of identified and mapped AD1754 tephra fallout deposits during the 2014 and 2016 field surveys. *TF1* are tephra deposits assumed to be from the 15 May to 2 June Plinian/Sub-Plinian phase, *TF2* from the November phase including the key bed layer (*K*) underlying *TF2*. Red lines identify municipal boundaries. The outcrops with green star symbols are deposits mapped prior this study but are included as model input. The isopach lines shown in the map were modified sourced from the isopach map generated by DOST-PHIVOLCS (1991) in order to correlate with location points of the tephra outcrops. Base map is NAMRIA IfSAR-DTM (2013) and Administrative boundaries are adopted from the PhilGIS (2011).

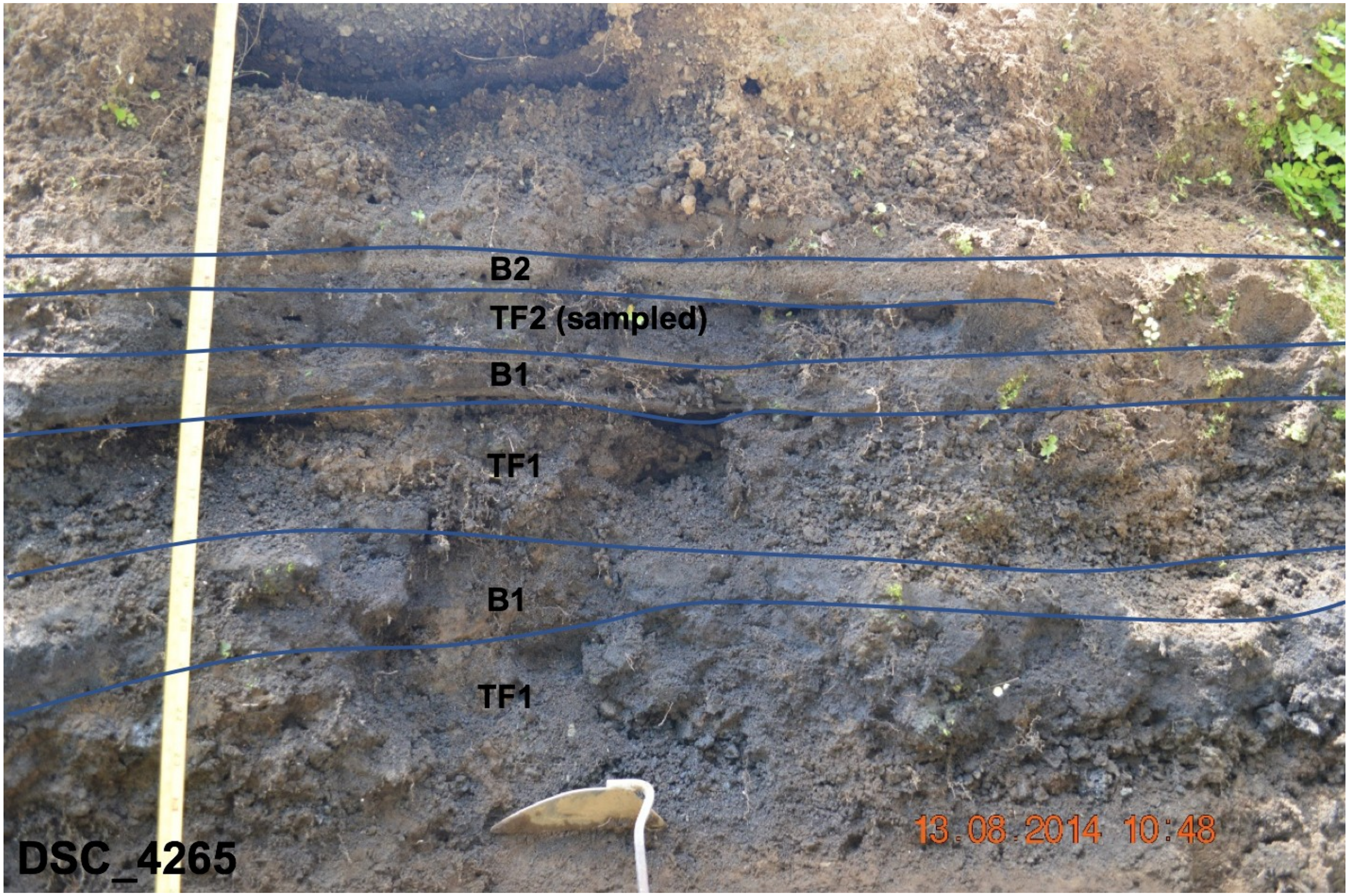


Figure 5.3. Typical alternating layers of tephra (*TF1* and *TF2*) and pyroclastic density current deposits that were mainly base surges (*B1* and *B2*) of the AD1754 eruption found in Barangay As-is, Laurel. The *B1* and *B2* layers appeared as massive to bedded units intercalated with the *TF1* and *TF2* units. The *TF1* deposits are generally non-graded, very poorly sorted dark lapilli fall, while *TF2* are thick, often graded, dark lapilli fall.

gradation in the size of fragments (Boggs, 2006).

Stratigraphic mapping of the deposits helps establish the relative chronology and sequence of erupted materials (Doyle et al., 2001). Here, stratigraphic mapping of the suspected tephra deposits from the AD1754 eruption was undertaken to provide the relative chronology of the events. Detailed interpretation of the different lithologic units for each outcrop makes it possible to identify and measure thicknesses of accumulation of the tephra, allowing estimation of the total bulk volume of the tephra deposits.

Stratigraphic logging of the 41 suspected AD1754 deposit exposures (Table 5.1) was undertaken that comprised deposit characterisation including: observations of composition, shape and sizes of fragments, sorting, grading, induration and stratification.

Detailed measurement of thicknesses was completed for each tephra layer at each outcrop. Measurement and characterisation techniques were discussed in more detail in Chapter 3, Section 3.2.1. While the scope of the geological investigation for this study was mainly to concentrate on the tephra fallout deposit, the stratigraphic logging included identification and measurement of the PDC deposits (Scott, 1989; Thompson et al., 2017), mainly base surge and co-ignimbrite surge deposits found alternating with the tephra units (Figure 5.3). Base surges are typical phenomena at Taal and are associated with hydrovolcanic eruptions and generally involve the collapse of a vertical tephra column (Francis, 1993). The Plinian/Sub-Plinian and Phreatomagmatic phases of the AD1754 eruptions generated PDCs that swept over and devastated parts of TVI and the shorelines of Taal Lake and subsequently generated volcanic tsunami.

Table 5.1. Summary list of thickness measurements of the mapped and suspected AD1754 tephra deposits of Taal (in centimeters). *TF1* identifies tephra deposits from the 15 May to 2 June AD1754 plinian/sub-plinian eruptive phase, and *TF2* are from the other major phase that occurred during November AD1754. The key bed layer (*K*) consists of fine-grained tephra fallout deposits that forms as a bed layer found underlying *TF2* and is presumed to be part of the tephra fallout from that phase.

Outcrop No.	Location	Latitude	Longitude	Measured Thickness		
				TF1 (cm)	TF2+K (cm)	Total/Combined Thickness TF1 +TF2 (cm)
1	Cawit, Taal	13.89913	120.91885	5	0	5
2	As-is, Laurel	14.0581	120.89947	24	25	49
3	As-is, Laurel	14.05725	120.90483	23	24	47
4	As-is, Laurel	14.0571	120.9242	27	0	27
5	Pansipit, San Nicolas	13.9308	120.94722	16	0	16
6	Banyaga, Agoncillo	14.0052	120.95006	190	124	314
7	Masalisi, Lemery	13.96894	120.88065	0	33	33
8	Masalisi, Lemery	13.97461	120.88383	17.5	0	17.5
9	Payapa, Lemery	14.0028	120.8865	0	19	19
10	Niogan, Lemery	14.00951	120.87444	33	16.5	49.5
11	Ticub, Laurel	14.02187	120.88909	21	16	37
12	Matandang Gubat, Ticub, Laurel	14.02327	120.90159	51	34	85
13	Culit, San Gregorio, Laurel	14.02782	120.89513	33.5	21	54.5
14	Culit, San Gregorio, Laurel	14.02825	120.88	21	14	35
15	Busobuso-Gulod Boundary, Laurel	14.02504	120.93913	92	62	154
16	Cahil, Calaca	14.03267	120.83529	35	0	35
17	Sitio Matala, Cahil, Calaca	14.02969	120.8348	17	0	17
18	Cahil, Calaca	14.02011	120.83183	12	10	22
19	Loma, Calaca	14.00552	120.82036	10	0	10
20	Madalunot, Calaca	13.98282	120.83347	15	12	27
21	Matipok, Calaca	13.99072	120.83438	15	4.5	19.5
22	Leviste, Laurel	14.06944	120.93803	24	9	33
23	As-is, Laurel	14.0528	120.91846	27	9	36
24	As-is, Laurel	14.04231	120.94479	10	9	19
25	Barigon, Agoncillo	13.99139	120.9109	69	102	171
26	Bilibinwang, Agoncillo	14.00103	120.94939	57	130	187
27	Daang Kastila, TVI	14.03125	121.00032	53	103	156
28	Daang Kastila, TVI	14.01829	120.9932	32	21	53
29	Daang Kastila, TVI	14.02734	121.00084	7	33	40

30	Taal Volcano Observatory (TVO), Buco, Talisay	14.08462	120.98657	10	3	13
31	Bugaan East, Laurel	14.04263	120.94062	24	69	93
32	San Jacinto, Agoncillo	13.94942	120.90768	0	20	20
33	San Jacinto, Agoncillo	13.95398	120.90664	35	0	35
34	Daang Kastila, TVI	14.01765	121.0008	0	41	41
35	Balaquilong, Laurel	14.0712	120.93502	0	6.5+10	16.5
36	Barigon, Agoncillo	13.99098	120.91078	7	7.0+7.0	21
37	Alas-as, San Nicolas	14.01153	120.98072	0	200+	200+
38	Alas-as, San Nicolas	14.01189	120.98238	0	450+	450+
39	Alas-as, San Nicolas	13.98315	120.98058	51	75+36	162
40	Alas-as, San Nicolas	13.98076	120.97964	49	64+34	147
41	San Rafael, Calaca	13.93594	120.79146	0	11.5	11.5

On top of *TF1*, a massive and indurated to cross-bedded base surge layer were logged and correlated with the *B1* layer in Torres (1989) (Figure 5.3). The massive *B1* beds appear to have no internal structure and stands out as one coherent single unit (Boggs, 2006). The observed cross bedding in the base surge layers of the AD1754 exposures are more likely small-scale trough bedding that were inclined when compared to base or top of the bed (Boggs, 2006). The *TF2* unit that consisted of thick, often graded, dark lapilli fall units were likely ejected and deposited during the November plinian/sub-plinian phase (Figure 5.3). The total thickness for the November phase combines *TF2* and *K* (hereafter, referred to as simply *TF2*), as it is assumed that they were ejected and emplaced during the same eruptive phase. The uppermost unit, *B2*, is a plane-bedded to massive base surge layer that is likely the eruptive product of a phreatomagmatic eruptive phase of the AD1754 event.

The AD1754 eruptive deposits may be considered as one of the largest post-caldera deposits. They are frequently found in basal contact with Taal Caldera ignimbrites. The thick and loose scoria fall deposits were likely preserved by the highly indurated base surge deposits that overlie the scoria fall unit. The subsequent emplacement of the surge deposits more likely degraded the fall deposit and actual thicknesses measured during mapping surveys might not be the actual deposition thickness. As such, where both tephra fallout and base surge deposits are noted and mapped, thicknesses vary rapidly - even across short distances.

The complete sequence of *TF1*, *B1*, *TF2*, *B2* was mapped in Brgy. Banyaga (Outcrop #6) and in Brgy. Barigon (Outcrop #25) in the Municipality of Agoncillo. They served as reference sections for correlations of *TF1* and *TF2.*

TF1 layer consists of a thin bed of fine to coarse dark brownish gray ash that were observed to be cohesive and laminated and often with some organic materials and there is an absence of a sharp contact with the pre-AD1754 surface. On top of the fine ash were thick interbedded layers of inversely graded ash and scoria fall units. The scoria fall unit consists of highly vesiculated, vitric and well sorted juvenile basaltic andesite scoria fragments. The *TF1* scoria fragments are distinctly larger and vesicle sizes are larger than *TF2* scoria fall clasts. Due to the presence of larger vesicles, *TF1* scoria fragments also have a greater tendency to crumble. Color of scoria fragments were also observed to be darker and luster is more distinct in *TF1* layer. On the other hand, the vesicles in the scoria fall fragments in the TF2 layer are finer and clasts are smaller than those in the *TF1* layer. More distinctive distinguishing characteristic in *TF2* layer is that the *TF2* scoria fall fragments appear to be sub-rounded and hydrothermally-altered yellowish lapilli fragments are intermixed within the *TF2* layer.

The stratigraphic sections of the AD1754 exposures are divided into proximal, medial and distal depositional zones based on distance from the vent. I considered proximal depositional zones as those closest or nearest to the vent, within the range of one to four kilometers from the vent, including the entire TVI. Medial zones are areas between four to six kilometers from the vent including those mainland areas closest to the shorelines of Taal Lake. Distal zones are areas between six to twenty kilometers from the vent. The farthest mapped tephra deposit, identified as *TF2*, with a thickness of 12 cm is located at Barangay San Rafael, Calaca, Batangas, more than 20 km from Taal (Outcrop #41 in Figure 5.2). The farthest *TF1* deposit was mapped more than 18 km from the vent in Barangay Loma, Calaca, Batangas (Outcrop #19 in Figure 5.2). The currently mapped maximum total thickness of tephra fall deposits from the AD1754 eruption was 314 centimeters at Barangay Banyaga, Agoncillo, a medial exposure approximately 6 km west of the volcano (Outcrop #15 in Figure 5.2 and Table 5.1).

Figure 5.4 illustrates a typical example of an AD1754 eruption outcrop (Outcrop #15, found in Barangay Buso-buso, Municipality of Laurel, Batangas, 6.5 km from the volcano, highlighted by a blue circle in Figure 5.4A). Stratigraphic logging of the deposit at this location showed a total thickness of 154 cm consisting of *TF1* (92 cm) and *TF2* (62 cm) (Figure 5.4B and Figure 5.4C). Detailed mapping information for the 38 of the 41 outcrops mapped for this research (excluding Outcrop #27, #28 and #38) are provided in Appendix H-1 to Appendix H-38. This is because some outcrops are poorly exposed or because previously identified exposures had been covered over by local government engineering offices and regional offices of the Department of Public Works and Highways (DPWH) to reduce landslide potential.

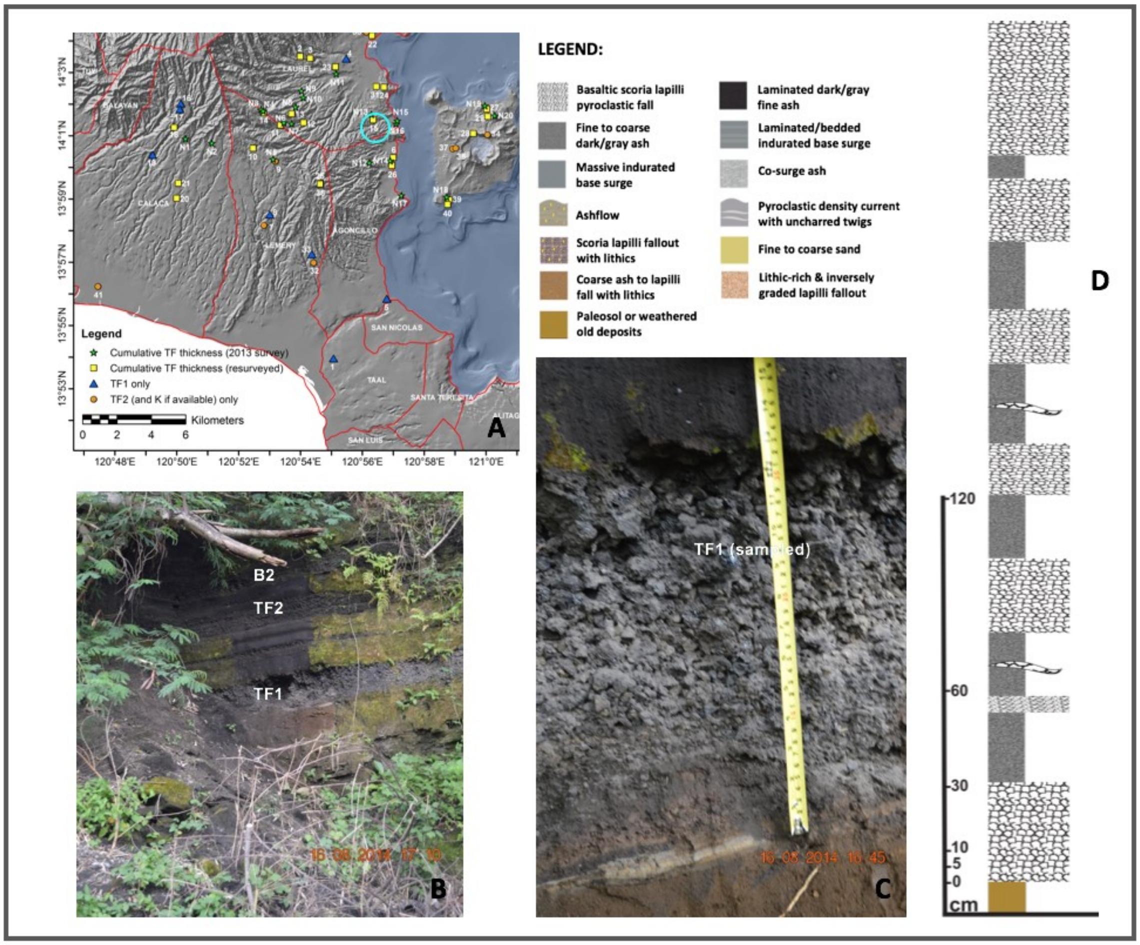


Figure 5.4. Stratigraphy of a AD1754 exposure located to the west of Taal. A) map showing location of Outcrop #15 found in Barangay Buso-buso, Municipality of Laurel, Batangas, 6.5 km from the volcano, highlighted by a blue circle (See Table 5.1); B) close-up picture of the outcrop with alternating layers of co-ignimbrite surge ash, massive to bedded base surge (*B1* and *B2*) and dark, brittle and vesiculated tephra fallout (*TF1* and *TF2*); C) profile picture of the outcrop; and D) detailed stratigraphy of Outcrop #15 showing thicknesses of 92 cm for *TF1* and 62 cm for *TF2*.

5.1.3. Stratigraphic correlation of field exposures

An attempt was made to conduct stratigraphic correlation between 29 selected outcrops that preserve the 15 May to 2 June phase tephra deposits (*TF1*) and the November phase tephra deposits (*TF2*), as shown in Figure 5.5 and Figure 5.6, respectively, from proximal to distal deposits (left to right of the figure). While the other 12 exposures were mapped and sampled, with thicknesses measured, a good stratigraphic log could not be generated due to poor exposure. Thus, they were not included in the stratigraphic correlation. The outcrops included in the correlations are listed in Table 5.2. Twenty of the 29 exposures chosen for stratigraphic correlation have both the *TF1* phase and the *TF2* phase tephra deposits.

For proximal locations within 4 km of the Main Crater, *TF1* has a maximum measured thickness of about 50 cm or less mapped at Daang Kastila (Outcrop #27, 29) located northeast from the Main Crater and at Barangay Alas-as, San Nicolas (Outcrop #39 and 40) (Table 5.2, Figure 5.2). On the other hand, the maximum thickness measured for *TF2* in the proximal location was about 450 cm found at Barangay Alas-as, San Nicolas. While the correlation of *TF1* and *TF2* are generally consistent with the assumption that there is a decrease in thickness with distance from the vent (Francis, 1993; Pyle, 1989) (Figure 5.5 and Figure 5.6), there are *TF1* tephra deposits in proximal locations that are relatively thinner than in medial locations. Coarser particles are assumed to have faster settling velocities (a function of particle size and density) (Bonadonna et al., 1998). As such, the coarser ejecta would be expected to fall much earlier and closer to the vent giving rise to the steep plot of thicknesses in the proximal-medial zone. However, older tephra deposits in near-vent locations may not always be representative of actual eruption accumulation because of post-eruption reworking activities. The unusual thinning of the tephra deposition in near-vent location were noted in the thickness plot for TF1 (Figure 5.5, Table 5.2), then abruptly thickening in medial locations. For Figure 5.6, the tephra outcrops with significant thickness were located in the southwest section of TVI that could have been preserved due to the fact that there were no major eruptions following their deposition that could resulted in their preservation. However, in both Figure 5.5 and

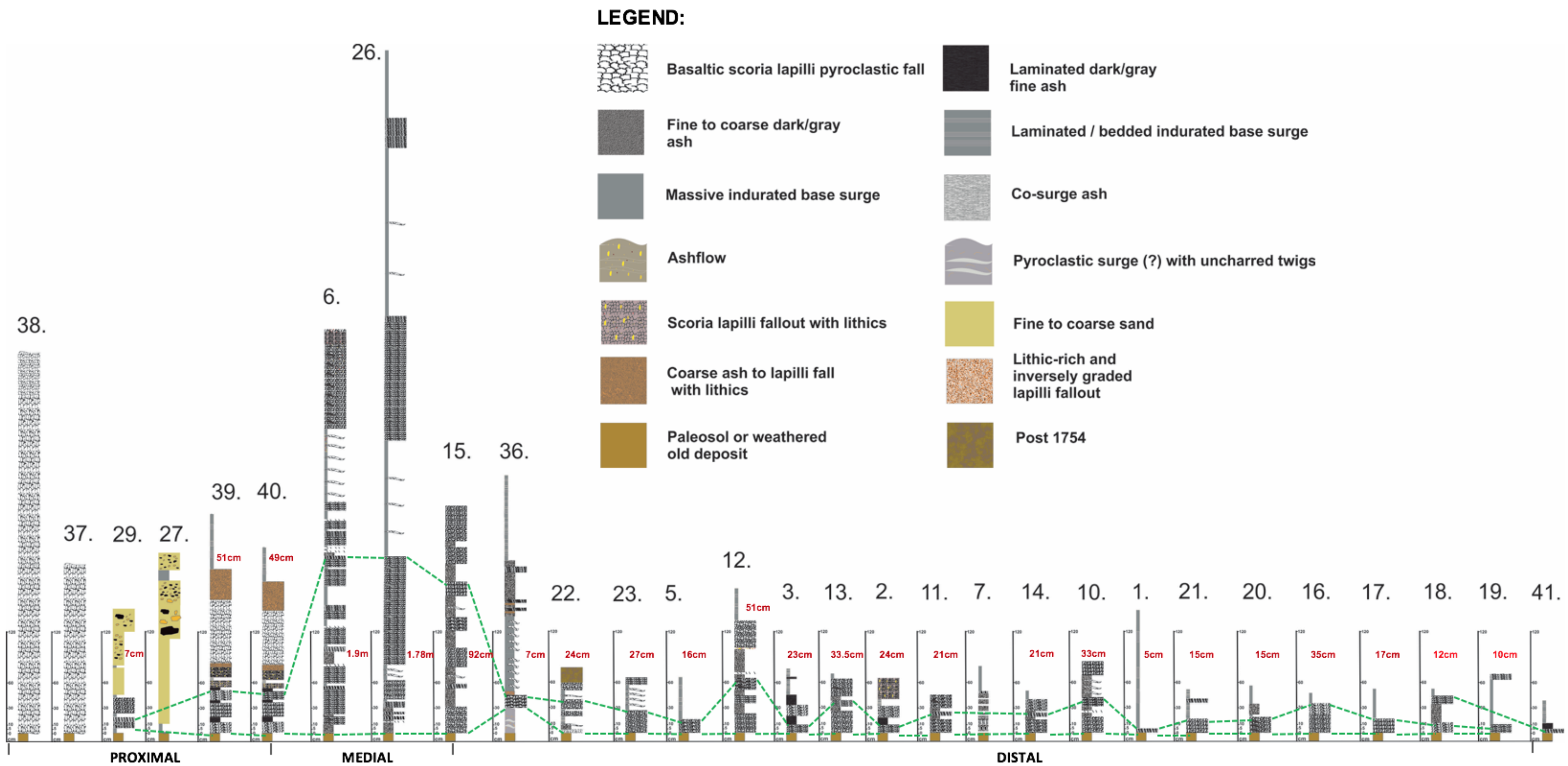


Figure 5.5. Stratigraphic correlation of selected 15 May to 2 June AD1754 eruption deposits (*TF1*) of Taal from proximal to distal locations from the vent (from left to right of the figure). Total thicknesses for *TF1* tephra deposits are indicated per outcrop in red. Distance from the volcano listed in Table 5.2. Numbers (in gray) correspond to the outcrop numbers as shown in Table 5.2. The green running line shows the relative thickness of TF1 from proximal to distal zones away from the vent. A general exponential thinning of the tephra fallout deposits is observed.

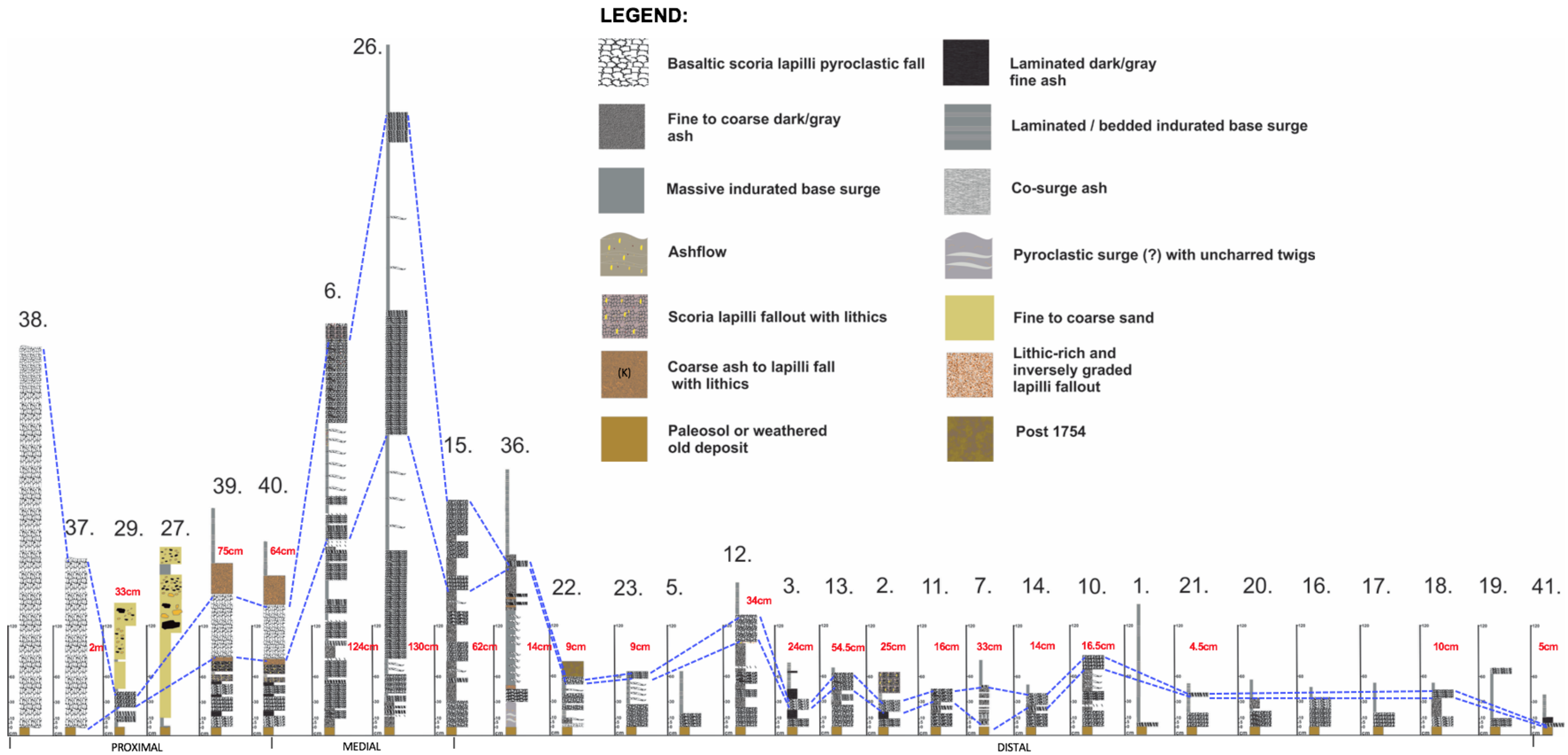


Figure 5.6. Stratigraphic correlation of selected November AD1754 eruption deposits (*TF2*) of Taal from proximal to distal locations from the vent (from left to right of the figure). Total thicknesses for the TF2 tephra deposits are indicated per outcrop. Distance from the volcano listed in Table 5.2. Numbers (in gray) correspond to the outcrop numbers as shown in Table 5.2. The blue running line shows the relative thickness of TF1 from proximal to distal zones away from the vent. Thickness of the tephra fallout deposits are generally thinning further away from the vent.

Table 5.2. List of the 29 AD1754 outcrops chosen for stratigraphic correlation in the downwind direction. Listing of outcrops based on sequence in the stratigraphic correlation plotted in Figures 5.6 and 5.7. The proximal zone includes outcrops within 0 - 4 km of the vent, including TVI. The medial zone is between 4 - 6 km, and the distal zone is between 6 - 20 km. Locations of the outcrops are shown in Figure 5.1. Distance from the vent and the thicknesses of the 15 May to 2 June (*TF1*) and November (*TF2*) tephra deposits are listed. The key bed layer (*K*), consisting of fine-grained tephra fallout deposits found underlying *TF2*, are presumed to be tephra fallout from the November phase and are therefore combined with *TF2*. While the other 12 exposures were mapped and sampled, with thicknesses measured, a good stratigraphic log could not be generated due to poor exposure.

Distance From vent	No.	Location (Barangay, City/ Municipality	Distance from the volcano	Longitude	Latitude	TF1 (cm)	TF2+K (cm)	Combined TF1 & TF2 (cm)
Proximal	38	Alas-as, San Nicolas, TVI	~2 km	120.98238	14.01189	0	450+	450+
	37	Alas-as, San Nicolas, TVI	~2 km	120.98072	14.01153	0	200+	200+
	29	Daang Kastila, TVI	~2 km	121.00084	14.02734	7	33	40
	27	Daang Kastila, TVI	~2 km	121.00032	14.03125	53	103	156
	39	Alas-as, San Nicolas, TVI	~4 km	120.98058	13.98315	51	75+36	162
	40	Alas-as, San Nicolas, TVI	~4 km	120.97964	13.98076	49	64+34	147
Medial	6	Banyaga, Agoncillo	~6 km	120.95006	14.0052	190	124	314
	26	Bilibinwang, Agoncillo	~6 km	120.94939	14.00103	57	130	187
	15	Busobuso-Gulod Boundary, Laurel	~6.5 km	120.93913	14.02504	92	62	154
Distal	36	Barigon, Agoncillo	~9 km	120.91078	13.99098	7	7.0+7.0	21
	22	Leviste, Laurel	~9 km	120.93803	14.06944	24	9	33
	23	As-is, Laurel	10 km	120.91846	14.0528	27	9	36
	5	Pansipit, San Nicolas	~10.5 km	120.94722	13.9308	16	0	16
	12	Matandang Gubat, Ticub, Laurel	~10.5 km	120.90159	14.02327	51	34	85
	3	As-is, Laurel	~12 km	120.90483	14.05725	23	24	47
	13	Culit, San Gregorio, Laurel	12 km	120.89513	14.02782	33.5	21	54.5
	2	As-is, Laurel	12 km	120.89947	14.0581	24	25	49
	11	Ticub, Laurel	12 km	120.88909	14.02187	21	16	37
	7	Masalisi, Lemery	~13.5 km	120.88065	13.96894	0	33	33
	14	Culit, San Gregorio, Laurel	~13.5 km	120.88	14.02825	21	14	35
	10	Niogan, Lemery	~13.5 km	120.87444	14.00951	33	16.5	49.5
	1	Cawit, Taal	15 km	120.91885	13.89913	5	0	5
	21	Matipok, Calaca	18 km	120.83438	13.99072	15	4.5	19.5
	20	Madalunot, Calaca	18 km	120.83347	13.98282	15	12	27
	16	Cahil, Calaca	18 km	120.83529	14.03267	35	0	35
	17	Sitio Matala, Cahil, Calaca	18 km	120.8348	14.02969	17	0	17
	18	Cahil, Calaca	18 km	120.83183	14.02011	12	10	22
	19	Loma, Calaca	~18.5	120.82036	14.00552	10	0	10
	41	San Rafael, Calaca	24 km	120.79146	13.93594	0	11.5	11.5

Figure 5.6, there is consistent thick deposition of tephra fallout materials with maximum thickness of 190 cm for *TF1* and 130 cm for *TF2* (Table 5.2). In distal locations, general exponential thinning of the tephra fallout deposits was observed with increasing distance from the vent (Figure 5.7). Figure 5.8 also plots thicknesses with distance from the vent

and the plot shows that the tephra accumulation of *TF2* is comparable to the thicknesses of the *TF1* tephra deposits. The sudden drop in thicknesses in distal locations for both *TF1* and *TF2* is further investigated through correlation with grain size results that will be discussed later in the chapter.

5.1.4. Distribution and isopach plots of the depositional units

After formation of an eruption column, tephra particles fall back to the ground and are dispersed to varying distances from the vent under the influence of gravity and the prevailing wind (Cas & Wright, 1987; Glaze et al., 1991; Bonadonna et al., 1998; Hurst & Turner, 1999; Hurst & Smith, 2004; Bonadonna et al., 2005). The size and density of each tephra particle determines the *terminal fall velocity*, defined as the "*velocity at which the force of gravity and aerodynamic drag forces are in a state of balance*" (Cas & Wright, 1987). Estimation of terminal velocity considers gravitational acceleration, the particle density, the air density and the diameter of particles (Bonadonna et al., 1998).

While terminal velocity and prevailing wind are major components to determine dispersion and accumulation, other factors such as precipitation and a more extreme case of passage of a typhoon (e.g. Pinatubo eruption in June 1991) could play havoc with dispersal patterns.

The AD1754 tephra fall deposits mapped during the 2014 and 2016 field surveys were dispersed predominantly to the west. While I conducted field investigations on the eastern side of Taal Volcano, the geologic campaign to map deposits focused on locations to the west of the volcano because of the details provided by the historical accounts by Saderra Masó (1911) and Worcester (1912), with additional input from the studies

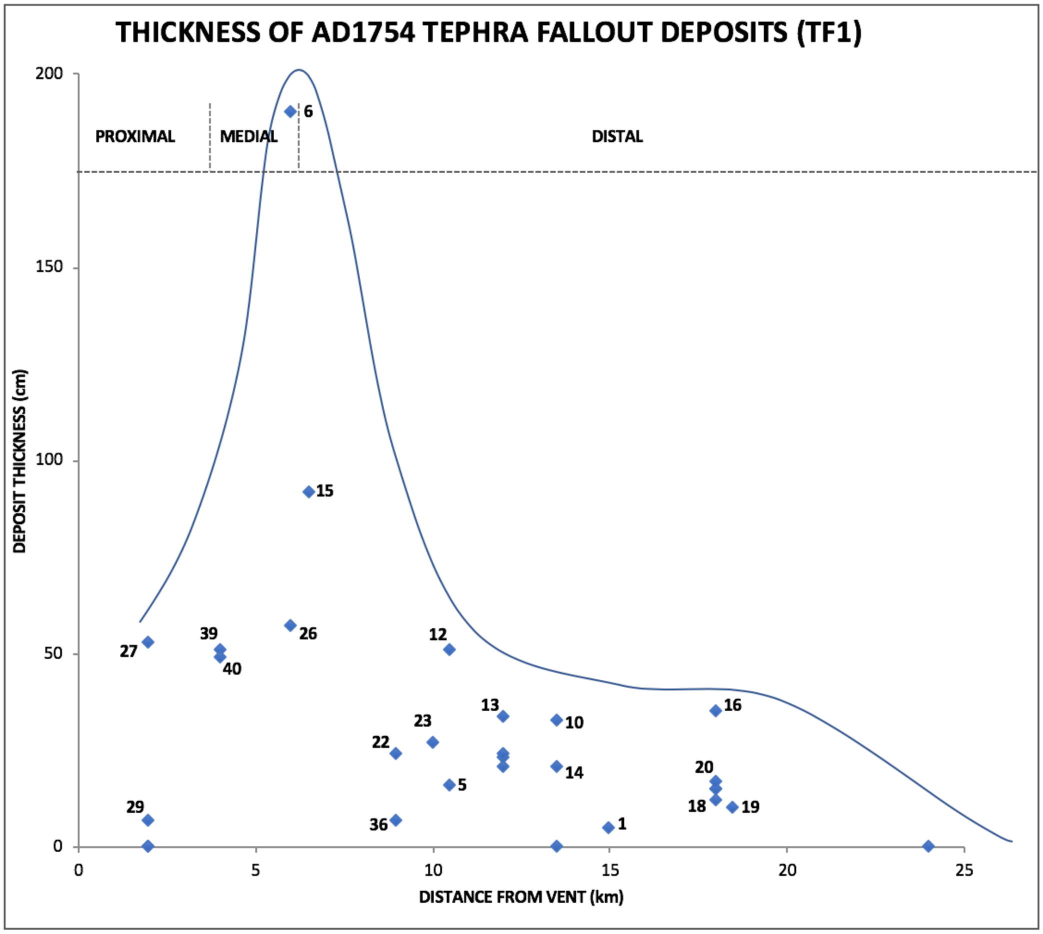


Figure 5.7. Thickness of the *TF1* tephra with distance from the vent. Proximal outcrops are within the range of 0 - 4 km, which include the entire TVI, medial between 4 - 6 km, and distal between 6 - 20 km. The most significant observation in the plot is that the maximum thickness of the tephra deposits can be observed in the proximal-medial areas from the vent, then suddenly thinning about nine kilometers from the vent. The numbers provided represent the outcrop numbers listed in Table 5.2.

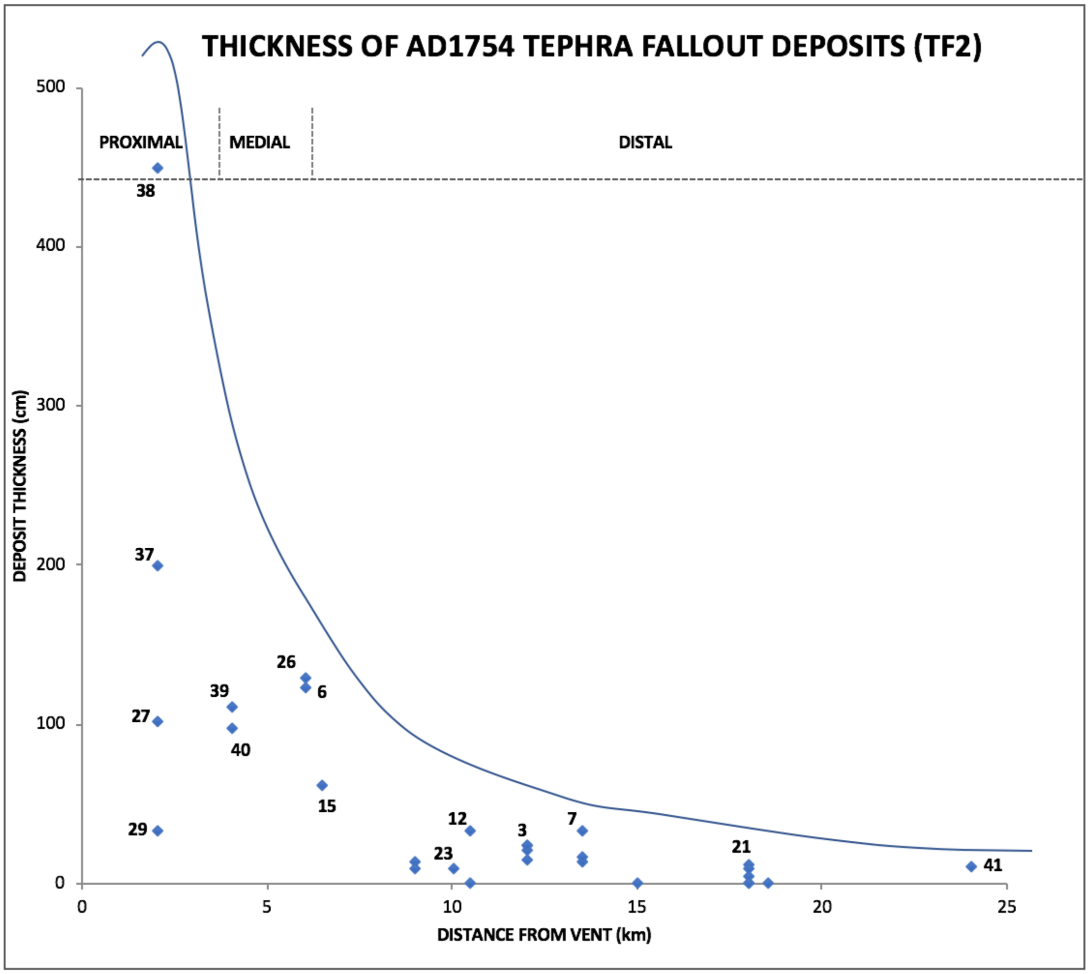


Figure 5.8. Plot of thicknesses of the *TF2* with distance from the vent. Proximal outcrops are within the range of 0 - 4 km, which includes the entire TVI, with average thickness of approximately 100 cm, but with maximum thickness of more than 400 cm in the southwest sector from the volcano. Tephra from the medial zone between 4 - 6 km from source has an average thickness of 130 cm, while in the distal zone between 6 - 20 km tephra is 15 cm or less. The maximum thickness of the *TF2* tephra deposits can be observed in the proximal-medial areas from the vent, then suddenly thinning about nine kilometers from the vent. The numbers provided represent the outcrop numbers listed in Table 5.2.

conducted by Masigla & Ruelo (1987) and DOST-PHIVOLCS (1991). Previous study generated an isopach map that showed the extent of dispersal and thicknesses of the tephra deposits and provided information on the total erupted deposits that included tephra and PDC deposits from the AD1754 eruption, but did not attempt to distinguish the deposits from the four eruptive phases (Figure 5.2). The field investigations conducted for my research validated the westerly direction of tephra dispersal related to the AD1754 tephra fallout. Utilising the thickness measurements from mapped exposures listed in Table 5.1, new isopach maps were generated separating the dispersal of *TF1* tephra (Figure 5.9) and *TF2* tephra (Figure 5.10). The assumed dispersal of the *TF1* fallout, as evidenced by outcrop exposures, maintained a slightly northwest direction while *TF2* was noted to be dispersed slightly more to the southwest (Figure 5.9 and Figure 5.10). The distribution of both tephra fallout deposits from the two identified phases are consistent with information interpreted from narrative accounts discussed in Chapter 4, Section 4.1.2.3. Further discussion of field derived isopach maps with results of modelling simulations are undertaken in Chapter 6, Section 6.3.4. The delineated contour lines for *TF1*, indicating the maximum thickness for a particular isoline, are 100 cm, 35 cm, 15 cm, and 10 cm (Figure 5.9). Volume calculations for field derived thicknesses for the *TF1* and *TF2* tephra deposits were computer generated using Geographic Information System (GIS). The thickness point data gathered from the field were interpolated applying the Kriging Method that provides autocorrelation of sample points, with ArcGIS as the platform, generating the contour lines. After this process, I manually edited smoothness of the contour lines that best reflect field thickness correlation. The area within each contour is then generated and total erupted volume is calculated. Estimated bulk volume for field-derived data for *TF1* deposit is 2.21×10^8 m^3. In Figure 5.10, the delineated contour lines for *TF2* are 200 cm, 50 cm, 25 cm, 15 cm, and 10 cm. Estimated bulk volume for field-derived data for *TF2* deposit is 1.85×10^8 m^3.

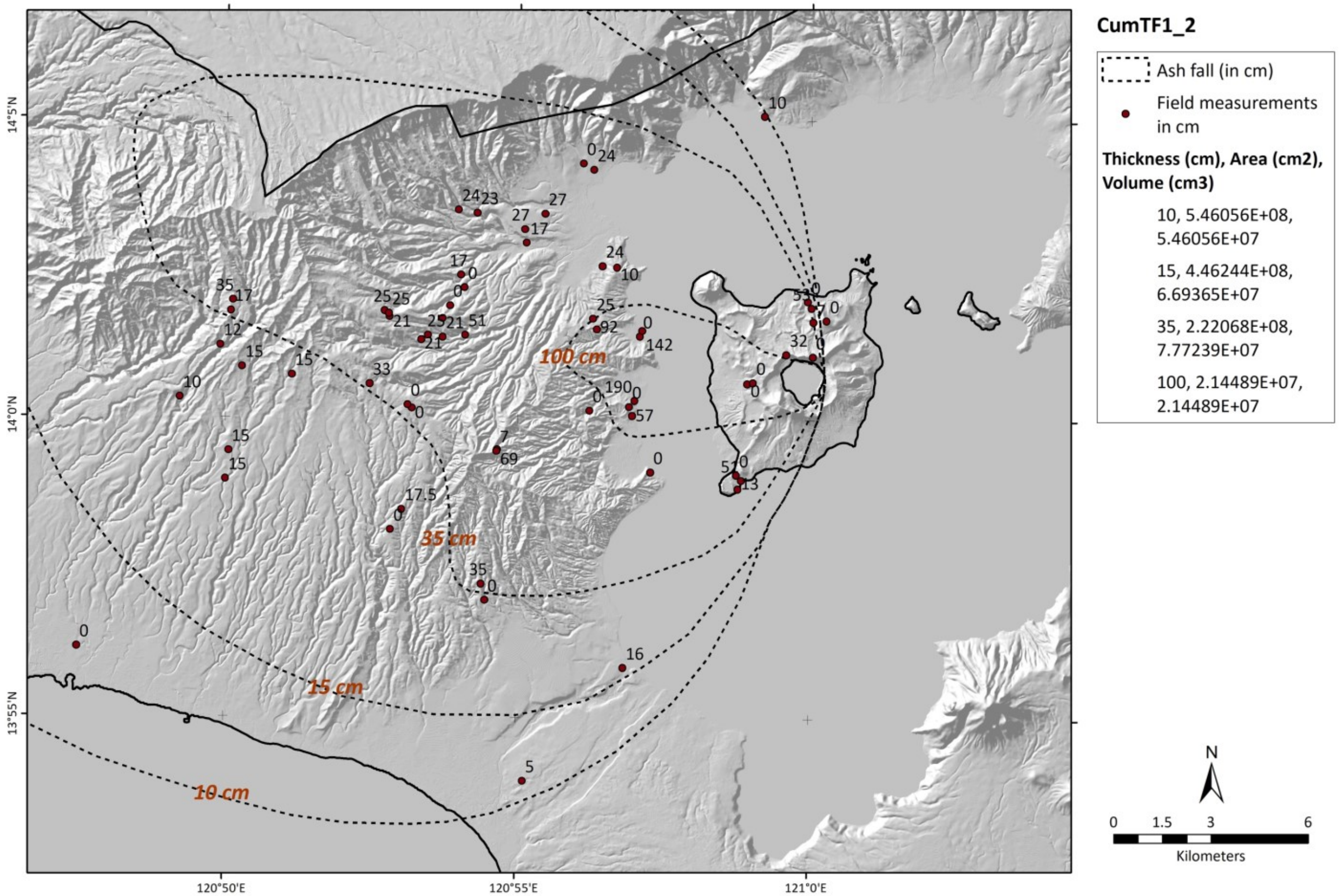


Figure 5.9. Isopach map of the identified *TF1* unit of the AD1754 eruption of Taal. Each contour represents the maximum thicknesses in centimeters for the area contained within. The isopach map of the identified *TF1* unit shows a slightly northwesterly dispersal pattern. The delineated contour lines are 100 cm, 35 cm, 15 cm, and 10 cm. The most significant observation is that the maximum thickness of the tephra in the proximal zone is less than a meter. Details of the outcrops are shown in Table 5.1. Base map is NAMRIA IfSAR-DTM (2013).

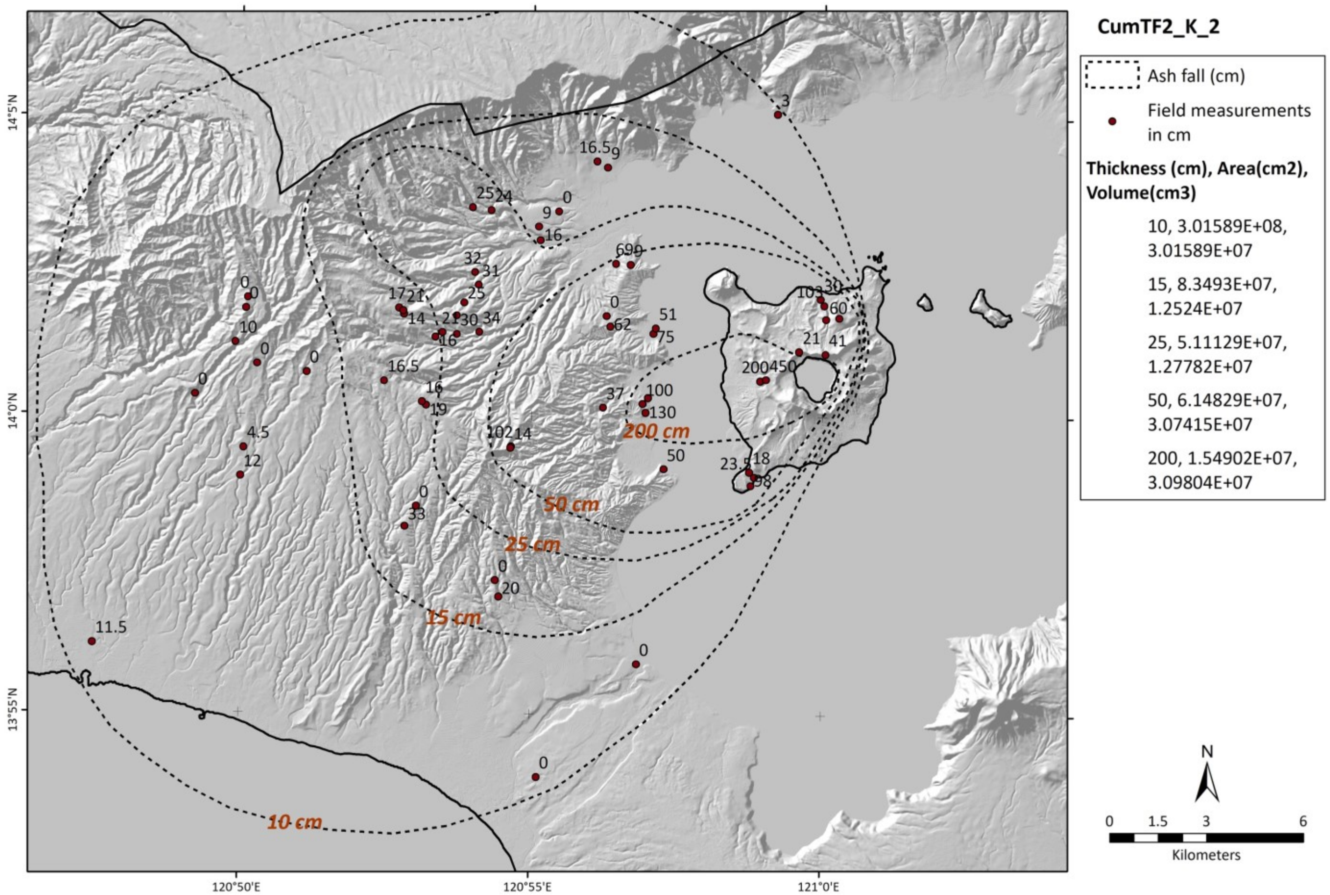


Figure 5.10. Isopach map of the identified *TF2* unit of the AD1754 tephra deposits of Taal. Each contour line represents the maximum thicknesses in centimeters for the area contained within. The isopach map of the identified *TF2* unit shows a westerly dispersal pattern. The delineated contour lines are 200 cm, 50 cm, 25 cm, 15 cm, and 10 cm. The most significant observation is that the maximum thickness of the tephra deposit can be observed in medial areas from the vent, generally about 130 cm thick. Details of the outcrops are shown in Table 5.1. Base map is NAMRIA IfSAR-DTM (2013).

In Chapter 6, a comparison of the isopachs from field derived data and from inversion modelling shall be discussed. Further comparison of field derived volumes for *TF1* and *TF2* with those from numerical modelling are presented in Chapter 6, Section 6.3.2. In both cases, the most significant observation in the isopach maps is that the maximum thickness of the tephra deposits can be observed in proximal and medial distances from the vent, with contour lines suddenly dropping from 100 cm to 35 cm for the *TF1* phase and from 200 cm to 50 cm for *TF2* phase. As previously observed in the stratigraphic correlation illustrated in Figure 5.5 and Figure 5.6, the sudden drop in thickness was observed at a distance of ~6.5 km from the vent, both for *TF1* and *TF2*.

I also conducted *in situ* bulk density tests in the field, processed the samples in the laboratory and calculated the density of these tephra samples which are discussed in Section 5.2.1. Further, grainsize analysis was also conducted in the laboratory for selected tephra samples and this analysis is discussed in Section 5.2.2.

5.1.5. Summary of deposit mapping, stratigraphic logging and distribution of the depositional units

From the deposit mapping and stratigraphic logging undertaken, I was able to obtain significant results. First, I was able to correlate eyewitness narrative descriptions of the AD1754 eruption to the actual deposit exposures in the field. Furthermore, while previous studies (DOST-PHIVOLCS, 1991; Masigla & Ruelo, 1987) collated and provided detailed descriptions of the eruption, there was no attempt to distinguish the deposits from the four eruptive phases or provide isopach maps and volume calculations for these separate phases. I have been able to establish the eruption sequence and was able to determine and separate the deposits from the different phases using detailed stratigraphic logging and other deposit characterisation. The distribution of the *TF1* and *TF2* tephra enabled me to generate isopach maps for the two identified phases and I was subsequently able to compute the total volume of *TF1* and *TF2* tephra fallout deposits.

From the isopach maps generated using field derived thickness and point locations shown in Figure 5.9 and Figure 5.10, the AD1754 eruption deposited tephra fall materials covered an estimated area of about 123,000 m^2 for *TF1* phase and about 94,000 m^2 for *TF2* phase, mostly in the north-northwest-west-southwest direction. The maximum thickness mapped was about 450 cm in proximal distances and more than 11 cm at a distance of 18 km from the volcano (Table 5.2). Identified Taal communities within the tephra isopach contours include the whole TVI, the municipalities of Taal, San Nicolas, Lemery, Calaca, Laurel, Agoncillo, Talisay, Balayan, and Nasugbu in Batangas Province and some municipalities of Cavite, north of Batangas. The latest available listing of the total population for these identified municipalities is estimated at more than 600,000 people (PSA, 2015). Thus, if an AD1754 style eruption were repeated today, this many people will likely be affected by tephra fall hazard. Furthermore, the mapped thicknesses shown in Table 5.1 provide us with the expected tephra accumulation if the eruptions were to occur during the same months (from May to December) as the AD1754 event.

While the results from the geologic mapping already provided key information on the possible extent and impacts of an AD1754 type eruption, some of the results were also used as input parameters for the numerical modelling (Chapter 6).

5.2 Results of laboratory processing of the suspected AD1754 tephra deposits

As noted in Chapters 2 and 3, physical analysis of volcanic deposits, including grain size, particle shape, sorting, thickness and other properties were utilised to better understand the physical processes that control their formation and deposition. These properties are important in supporting numerical modelling (Chapter 6). The following sub-sections provide the results of field and laboratory analysis conducted on selected tephra deposits from the AD1754 eruption of Taal.

5.2.1. *In situ* bulk density tests and processed particle density

The methodology employed in the in situ bulk density tests was discussed in detail in Chapter 3, Section 3.2.2 (Figure 3.7). Every effort was made to ensure that there was at least one bulk density test from each community where inferred AD1754 tephra outcrop were identified and mapped to account for changes with distance from source. Bulk density testing was conducted for seven out of 41 outcrops. However, only five were then used for further computation of bulk and particle densities due to time constraints (Table 5.3). By strategically selecting locations for the bulk density tests, I was able to reduce or avoid any sampling bias such that the computed average density of the tephra samples truly represents the density at the time of deposition. However, it must be noted that the deposits were likely subjected to post-eruption compaction. Even with limited processed samples, the computed results of the five particle density computations correlate well with known densities for pumice fragments (Table 5.3). Locations of the tephra outcrops where bulk density tests were conducted are plotted in Figure 5.11. In general, the tephra

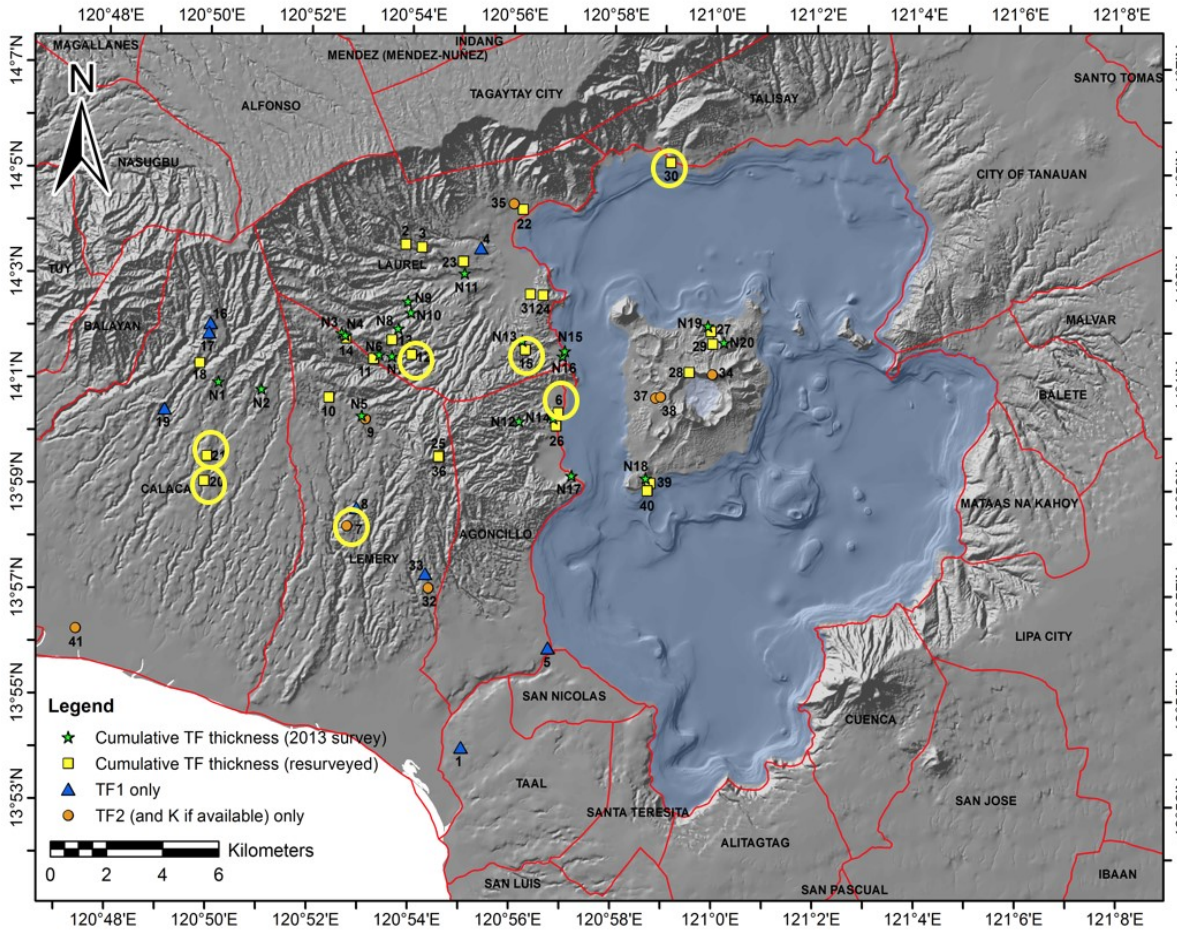


Figure 5.11. Map showing locations of tephra outcrops (yellow circles) from the AD1754 eruption where bulk density tests were conducted. Test site locations generally represent the medial and distal locations of the tephra samples. Map was overlain on NAMRIA IfSAR-DTM (2013) and Administrative boundaries are adopted from PhilGIS (2011).

Table 5.3. Bulk and particle density computations for five out of ten *in situ* field tests conducted for the selected AD1754 tephra outcrops.

LOCATION	LATITUDE	LONGITUDE	CYLINDER RADIUS (cm)	CYLINDER HEIGHT (cm)	r^2	VOLUME (cm^3)	DEPOSIT TYPE	DEPOSIT THICKNESS (cm)	WT OF SED	BULK DENSITY (g cm^{-3})	PARTICLE DENSITY (g cm^{-3})
Ticub, Laurel	14.02327	120.9016	5	12	25	942.478	TF1/A1	23	594.7	0.631198	0.631028
Buso-buso, Laurel	14.02504	120.9391	4.25	9	18.06	510.705	TF1/A1	31	304.98	0.595334	0.597174
Matipok, Calaca	13.99072	120.8344	4.25	9	18.06	510.705	TF1/A1	10	342.98	0.475891	0.671581
Masalisi, Lemery	13.96894	120.8807	4.25	9	18.06	510.705	TF2/A2	10	334.83	0.658756	0.655623
TVO, Buco, Talisay	14.08462	120.9866	4.25	9	18.06	510.705	TF1/A1	10	382.63	0.748115	0.749219

Acronyms: r-radius; WT OF SED- weight of sediment.

samples predominantly consisted of clast-supported, poorly sorted, and highly vesiculated juvenile fragments (*TF1* and *TF2* in Figure 5.3). Average particle density calculated from density testing was 0.66 g·cm^{-3}, and now rounded off to 0.7 g·cm^{-3} or 700 kg·m^{-3} that will now be the constant value for particle density of the tephra deposits. This agrees with expected densities for pumice fragments that is generally between 0.7 and 1.2 g·cm^{-3} (Shipley & Sarna-Wojcicki, 1982). While physical segregation of pumice and lithics was not undertaken, it was noted that there were negligible amounts of lithic fragments in the processed tephra samples. The voids or vesicles are formed by the removal of dissolved gases of molten rock material during the eruptive process, and by the time the erupted fragments are deposited, the gases have escaped and numerous voids are formed in the fragments making the density of the fragments very low (Shipley & Sarna-Wojcicki, 1982). Further, while the particle density results could be compared to standard results for pumice fragments, the absence of any bulk density testing for the AD1754 tephra deposits negate the possibility of any comparison with other field-derived data. The computed particle density value derived from field-based data was utilised as *TEPHRA2* input parameter rather than using standard values.

5.2.2. Grain size analysis of the tephra samples

Another important factor that controls particle settling velocity is grain size (Cas & Wright, 1987). During an eruption, coarser particles are expected to be deposited first and the finer fragments are generally dispersed farther and deposited later (Doyle et al., 2001).

Details for the grain size procedures were provided in Chapter 3, Section 3.2.3. Due to time constraints, I was only able to process and analyse 13 tephra samples, ten samples representing the tephra deposits from the May to June phase of the AD 1754 eruption (*TF1*) plotted as yellow squares, and three samples of the tephra deposits, likely from the 1 to 15 November eruptive phase (*TF2*), that are plotted as blue stars (Figure 5.12). These 13 sampling sites represent proximal, medial and distal locations.

5.2.2.1. Grain size characteristics

Improved understanding of particle dispersal and deposition can be obtained through grain size analysis using key mathematical measures: mode, mean, median size ($Md\phi$), standard deviation, and skewness (Boggs, 2006). Definitions of these terms were provided in Chapter 3, Section 3.2.3. Logarithmic phi scale (ϕ), modified from the Udden-Wentworth grain size scale, provides an expression of grain size into units of equal values in order to be able to undertake graphical plotting and statistical calculations where phi size (ϕ) is equal to $-log_2 d$ with d representing the grain diameter in millimeters (Krumbein, 1934). Formulas for calculating grain size statistical parameters by graphical methods were derived from Boggs (2006) (Figure 5.13).

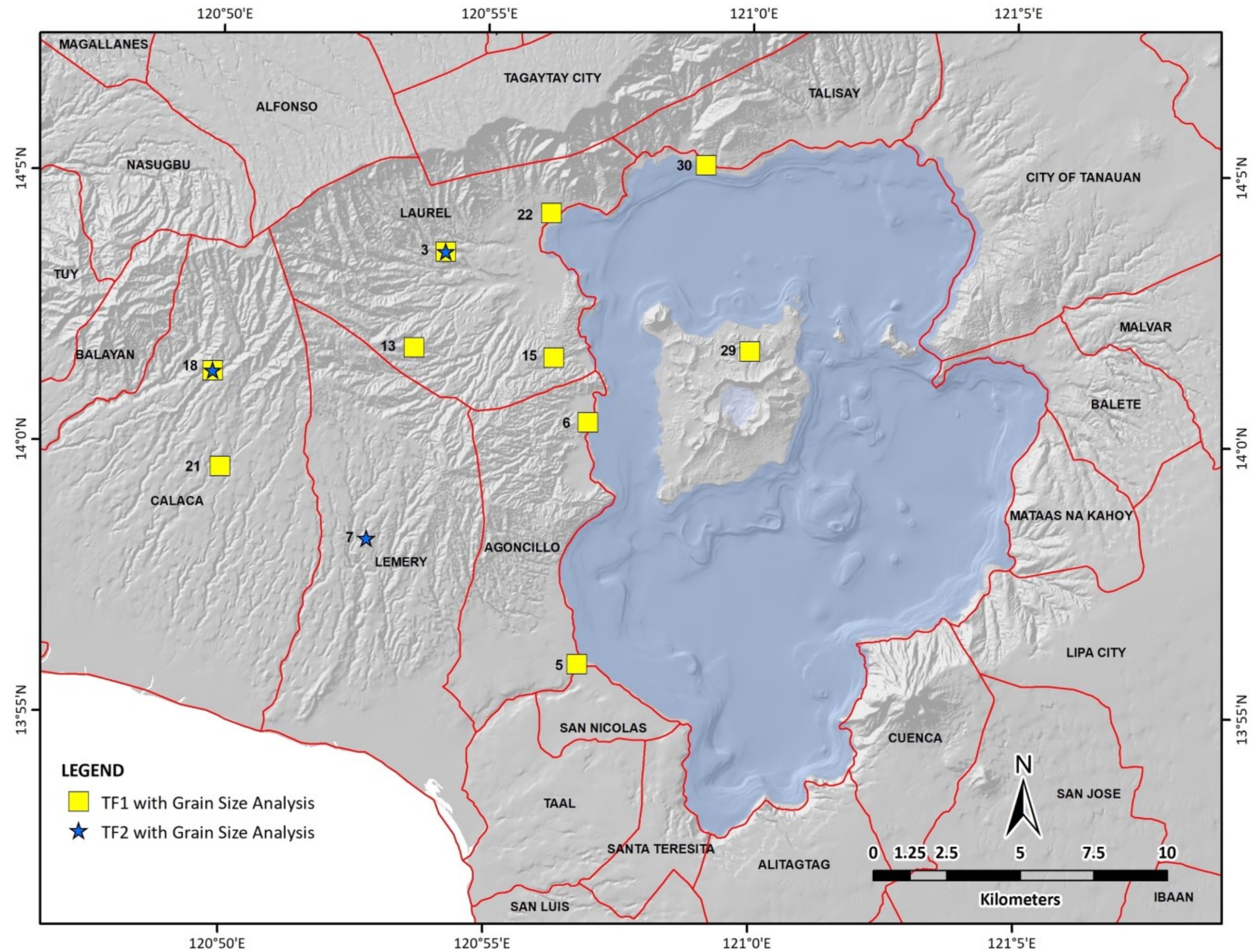


Figure 5.12. Location map of the AD1754 tephra samples selected for grain size analysis. The locations of 13 samples for processing nearly represented all municipalities where AD1754 outcrops were identified and mapped. Map was overlain on NAMRIA IfSAR-DTM (2013) and Administrative boundaries are adopted from the PhilGIS (2011).

Graphical Mean

$$Mz = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \quad (1)$$

Inclusive graphic standard deviation

$$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_{5}}{6.6} \quad (2)$$

Inclusive graphic skewness

$$SK_I = \frac{(\phi_{84} + \phi_{16} - 2\,\phi_{50})}{2\,(\phi_{84} - \phi_{16})} + \frac{(\phi_{95} + \phi_{5} - 2\,\phi_{50})}{2\,(\phi_{95} - \phi_{5})} \quad (3)$$

Graphic kurtosis skewness

$$K_G = \frac{(\phi_{95} - \phi_{5})}{2.44(\phi_{75} - \phi_{25})} \quad (4)$$

Figure 5.13. Formulas for calculating grain size statistical parameters by graphical methods derived from Boggs (2006). *Mz*=graphical mean; σ_I=inclusive graphic standard deviation; SK_I= inclusive graphic skewness; K_G=graphic kurtosis skewness.

Table 5.4 provides the results for the computation of mode, median, mean, standard deviation and skewness. Laboratory analysis showed that the median grain size (*Md*ϕ), the 50th percentile diameter for the processed tephra samples, varied from -3.5ϕ to 0.5ϕ, while standard deviation (σϕ) varied from 1.0ϕ to 2.8ϕ. Twelve of the 13 processed samples had median ϕ less than 0, while sigma ϕ values for 9 samples varied from 1.0ϕ to 2.0ϕ indicating that the samples were generally poorly sorted and the rest of the samples were very poorly sorted (Boggs, 2006).

I then compared my grain size results with those of Torres (1989). For tephra outcrops sampled from the northeastern side of TVI, grain size results undertaken for the sole TVI sample processed showed that median ϕ value of -3.0 while the standard deviation value calculated was 2.24 (Table 5.4). On the other hand, Torres' tephra samples located in the same general vicinity (Barangay Pira-piraso) provided median ϕ values ranging from 0 to -3.0 and standard deviation values between 1.3 to 2.69 (Table 5.5). The grain size results I obtained were well within the range of results obtained by Torres (1989). Furthermore, based on computed skewness, both our tephra samples can be described as very poorly sorted and strongly fine skewed, having an excess of the grain size population dominantly consisting of fine particles (Boggs, 2006). All grain size distribution results from this study and those from Torres (1989) showed consistently poorly sorted tephra deposits at proximal as well as distal locations.

The median phi (Mdϕ) and sigma phi (σϕ) values of the processed tephra samples were averaged and utilised as input parameters for numerical modelling. Further, the grain size results will be correlated with numerical modelling results.

Graphical plots of median phi (*Md*ϕ) sizes of the suspected AD1754 processed tephra samples against distance was also undertaken to compare the results from my research (Figure 5.14A) to that of Torres (1989) (Figure 5.14B). The numbers in Figure 5.14A represent the outcrop numbers listed in Table 5.1 and plotted in Figure 5.2 and identified samples as *TF1* or *TF2*. The plot in Figure 5.14A shows that the grain sizes generally follow exponential thinning, and the median grain sizes of the samples generally become finer with distance from the vent. The *Md*ϕ for Outcrop #29 in Figure 5.14A, sampled from TVI and identified as *TF1* deposit is within the range of the *Md*ϕ sizes processed by Torres. The plot of the *Md*ϕ sizes in Figure 5.14B were generally located at TVI, with only one sample located in the mainland, north of TVI. Due to a lack of processed samples from any distal location in the research conducted by Torres, correlation of *Md*ϕ sizes of my processed samples and that of Torres research (1989) could not be undertaken.

Table 5.4. Grain size analysis results for selected AD1754 tephra fallout samples. Formulas to compute Median phi (Mdϕ) and Standard Deviation or Sigma phi ($\sigma\phi$) are based on Boggs (2006). Verbal description of sorting corresponding to various values of standard deviation and skewness was sourced from (Folk, 1974). Grain size is expressed as logarithmic phi (ϕ) in order to be able to undertake graphical plotting and statistical calculations. Formulas for mode, median, mean, standard deviation and skewness are provided in Figure 5.12. *TF1* and *TF2* samples are listed from proximal to distal locations. Proximal distance: 0 - 4 km of the vent; medial distance: 4 - 6 km; distal distance: 6 - 20 km. Locations of the outcrops are shown in Figure 5.1.

OUTCROP #/SAMPLE CODE	TYPE	LAT	LONG	ϕ_5	ϕ_{16}	ϕ_{50}	ϕ_{84}	ϕ_{95}	MODE	MEDIAN (Mdϕ)	MEAN (Mϕ)	STANDARD DEVIATION ($\sigma\phi$)	SKEWNESS (SKG)	REMARKS	DISTANCE FROM THE VENT (km)
#29/TV-TAL-TVI-TF1S1-101814	TF1	13.99072	120.83438	-5.0	-4.0	-3.0	-0.5	4.0	-2.5	-3.0	-2.50	2.2386364	0.4920635	very poorly sorted; strongly fine skewed	~2/Proximal
#6/TV-AGO-04-TF1E4-81514	TF1	14.0052	120.95006	-4.0	-4.0	-3.0	-1.5	0.5	-3.5	-3	-0.83	1.306818	0.377778	very poorly sorted; strongly fine skewed/positively skewed	~6/Medial
#15/TV-LAU-10-TF1-81614	TF1	14.02504	120.93913	-5.5	-4.5	-3.5	-3.0	0.0	-0.5	-3.5	-1.33	1.208333	-0.0303	very poorly sorted; strongly coarse skewed	~6.5/distal
#30/TV-TAL-23-TF1S2-102014	TF1	14.02504	120.93913	-4.0	-3.5	-2.5	2.0	3.5	-0.5	-2.5	0.33	2.511364	0.618182	very poorly sorted; strongly fine skewed	~9/distal
#22/TV-LAU-16-TF1-101414	TF1	14.06944	120.93803	-4.0	-3.5	-3.0	-0.5	2.5	-2.5	-3.0	-2.33	1.7348485	0.6794872	poorly sorted; strongly fine skewed	~9/distal
#5/TV-SNI-03-TF1-81314	TF1	13.9308	120.94722	-4.0	-3.5	-2.0	1.0	3.0	-2.5	-2.0	-1.50	2.1856061	0.3809524	poorly sorted; strongly fine skewed	~10.5/distal
#3/TV-LAU-02-TF1-81314	TF1	14.0052	120.95006	-4.0	-4.5	-2.0	2.0	4.0	-4.0	-2	-0.17	2.837121	0.365385	very poorly sorted; strongly fine or positively skewed	~12/distal
#3/TV-LAU-02-TF2-81314	TF2	14.0052	120.95006	-4.0	-3.0	-1.5	0.0	2.0	-1.5	-1.5	-0.50	1.659091	0.083333	very poorly sorted; nearly symmetrical/ positively skewed	~12/distal
#13/TV-LAU-09-TF1-81614	TF1	14.02782	120.89513	-4.0	-3.5	-3.0	-2.0	1.0	-3.0	-3	-0.83	1.132576	0.466667	very poorly sorted; strongly fine skewed	~12/distal
#21/TV-CAL-15-TF1-81814	TF1	13.99072	120.83438	-4.0	-3.0	-2.0	0.0	3.0	-1.5	-2	-0.33	1.810606	0.380952	very poorly sorted; strongly fine skewed	~12/distal
#7/TV-LEM-05-TF2-81514	TF2	14.02504	120.93913	-4.0	-3.5	-2.5	-0.5	3.0	-2.5	-2.5	-0.50	1.810606	0.452381	very poorly sorted; strongly coarse skewed	~13.5/distal
#18/TV-CAL-12-TF1-81814	TF1	14.02011	120.83183	-3.5	-3.0	-2.0	-0.5	2.0	-0.5	-2	-0.50	1.458333	0.327273	very poorly sorted; strongly fine skewed/positively skewed	~18/distal
#18/TV-CAL-12-TF2-81814	TF2	14.02011	120.83183	-1.5	-0.5	0.5	1.5	2.0	1	0.5	0.17	1.030303	-0.07143	very poorly sorted; nearly symmetrical	~18/distal

Table 5.5. Grain size analysis results for the AD1754 tephra fallout deposits sampled by Torres (1989). The median ϕ, mean ϕ, standard deviation and skewness values were obtained from Appendix B of his paper.

SAMPLE #	SAMPLE NO.	LOCATION	TYPE	MEDIAN (Mdϕ)	MEAN (Mz)	STD DEVIATION (σϕ)	SKEWNESS (SKG)	REMARKS
B1	03311/PO-006	Bignay, Pira-Piraso, TVI	TF	-2.5	-2.00	1.3	2.04	poorly sorted; strongly fine or positively skewed
B3	03313/PO-006	Bignay, Pira-Piraso, TVI	TF	-2.0	-1.54	1.97	1.52	poorly sorted; strongly fine skewed
B4	03314/PO-006	Bignay, Pira-Piraso, TVI	TF	-2.5	-2.41	1.84	2.21	poorly sorted; strongly fine skewed
B5	03315/PO-015	Ibaba, Pira-Piraso, TVI	TF	-3.0	-2.85	1.96	1.22	poorly sorted; strongly fine skewed
B7	03317/PO-015	Ibaba, Pira-Piraso, TVI	TF	-3.0	-3.40	1.39	0.24	poorly sorted; fine skewed
B10	10282/BK-015	Balantok, TVI	TF	-1.0	-0.82	2.25	0.93	very poorly sorted; strongly fine skewed
B12	10284/BK-015	Balantok, TVI	TF	-1.0	-0.80	1.6	1.36	very poorly sorted; strongly fine skewed
B13	10285/BK-015	Balantok, TVI	TF	-3.5	-3.1	1.4	2.69	very poorly sorted; strongly fine skewed
B14	10286/BK-015	Balantok, TVI	TF	-3.5	-3.23	2.44	1.28	very poorly sorted; strongly fine skewed
B16	10288/PO-020	Bugahan Site, Pira-Piraso, TVI	TF	0.0	0.1	2.2	0.40	very poorly sorted; strongly fine skewed
B17	10289/PO-020	Bugahan Site, Pira-Piraso, TVI	TF	-1.0	-0.85	2.14	0.98	very poorly sorted; strongly fine skewed
B19	102811/PO-020	Bugahan Site, Pira-Piraso, TVI	TF	-2.5	-2.33	1.77	1.53	poorly sorted; strongly fine skewed
B20	10291/SN-020	Saluyan, TVI	TF	-2.5	-2.13	1.66	1.40	poorly sorted; strongly fine skewed
B22	10293/SN-020	Saluyan, TVI	TF	-3.0	-2.55	2.04	1.63	poorly sorted; strongly fine skewed
B24	10296/SN-020	Saluyan, TVI	TF	0.0	0.66	2.18	1.08	very poorly sorted; strongly fine skewed
B25	10297/SN-020	Saluyan, TVI	TF	-2.0	-1.67	1.67	1.73	poorly sorted; strongly fine skewed
B28	11021/CT-140	East Main Crater wall, TVI	TF	-2.5	-1.89	2.32	0.86	very poorly sorted; strongly fine skewed
B29	11022/CT-140	East Main Crater wall, TVI	TF	-3.0	-2.74	1.96	1.58	poorly sorted; strongly fine skewed
B31	11152/CN-024	Caloocan, Talisay	TF	-2.0	-1.6	2.4	1.3	very poorly sorted; strongly fine skewed

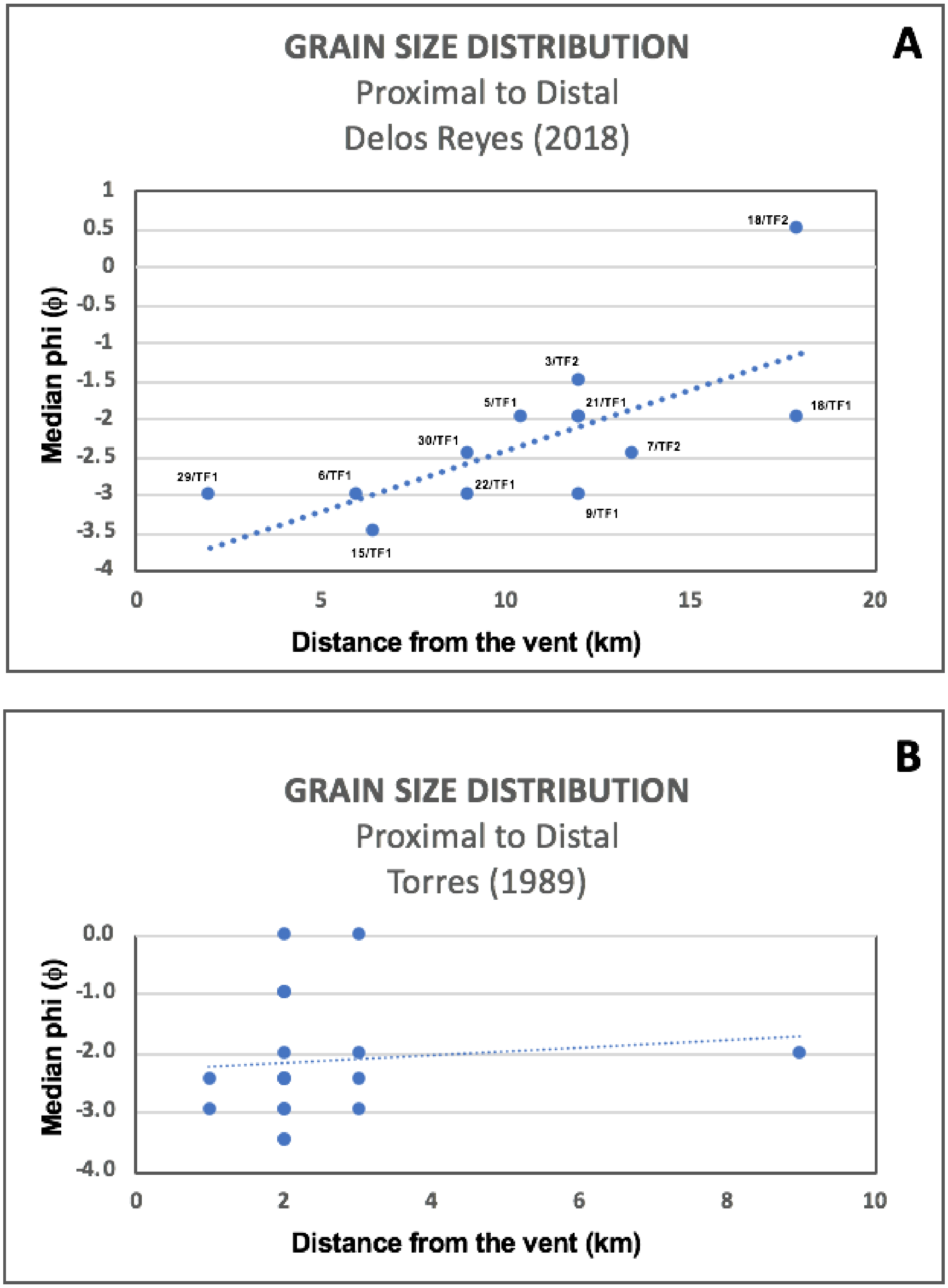


Figure 5.14. Plots of grain sizes of the tephra against distance. A) Plots of median phi (ϕ) sizes for the processed tephra deposits from the AD1754 eruption. The numbers represent the outcrop numbers listed in Table 5.1 and plotted in Figure 5.2 and identified as *TF1* or *TF2* sample. The median for Outcrop #29, sampled from TVI and identified as TF1 deposit is within the range of the median phi sizes processed by Torres. B) Plot of the median ϕ sizes of the tephra samples of Torres (1989). The tephra deposits sampled were generally located at TVI, with only one sample located in the mainland, north of TVI.

5.2.2.2. Total grain size distribution

After calculating the grain size distribution for a specific tephra sample at a specific location, total grain size distribution of tephra deposits, representing the distribution of tephra erupted from the vent, can then be calculated by integrating deposit grain size at different locations. The total grain size distribution can provide basic information about eruption dynamics as it is representative of eruption style and fragmentation mechanisms. The total grain size distribution also controls the distribution of mass within the eruption column and sedimentation processes (Costa et al., 2016, p. 90 particular sample identified by Torres (1989) as a surge deposit shows a bell-shaped curve typical of tephra fallout deposits.

The plots of cumulative weight percent versus grain size for tephra fallout deposits sampled and analysed for my research (Figure 5.15) showed the same sudden shift in the cumulative curves toward negative phi values. The plots for *TF1* (Figure 5.15A) provide a more distinct and uniform pattern. Likewise, while only three plots were generated for the *TF2* tephra deposits (Figure 5.15B), they are consistent with the S-shape curves generated for the *TF1* tephra deposits (Figure 5.15A) and in Torres (1989) (Figure 5.16). The plots for tephra deposits in Torres (1989) (Figure 5.16A) seem to be compatible with the general cumulative curves I obtained for my tephra fallout samples (Figure 5.15). In the plot of surge deposits in Torres (Figure 5.16B), one outlier is determined (orange line) that has an S-shape curve similar to the plots for tephra deposits (Figure 5.15A, Figure 5.15B and Figure 5.16A). Perhaps that particular sample was airfall tephra deposit and not a surge Figure 5.17 provides the results of the grain size analyses of a *TF1* tephra sample from Barangay Banyaga in the Municipality of Agoncillo, Batangas Province.

Figure 5.17A is the grain size data table with the summary of individual weights of tephra particles for various phi sieve sizes. Figure 5.17B shows the frequency curve plotted from the data in A. Figure 5.17C plots the cumulative curve for the tephra sample that shows a generally normal grain size distribution with an almost bell-shaped curve. The *Md*ϕ was calculated as -3.0ϕ and the Standard deviation or sigma phi (σϕ) is equal to 1.31 and described as being poorly sorted (Folk, 1974). Graphical plots for the results of the grain size analysis for all the thirteen processed tephra samples are provided in Appendices I-1 to I-13. Similar to Figure 5.17, the frequency plots in Appendices I-1 to I-13 are also bell-shaped, which signifies normal grain size distributions. One single outlier is shown in Figure 5.18 and Appendix I-7 (Outcrop #3), where the *TF1* tephra layer is bimodal with two plotted modes, the steepest or inflection points in the frequency curve. This indicates that there are two different groups of grain sizes sourced from two different phases. One inflection is in the coarser side while the other inflection is in the finer side of the grain size plot. One possible reason for the distinct bimodal plot could be that different types of eruptive products were deposited at the same time (e.g. lapilli tephra fallout deposits coinciding with the emplacement of co-ignimbrite ash) or two tephra fall events that may have occurred one after the other such that the fall and accumulate at the same time. This may provide an explanation for the difficulty in identifying the two events during the conduct of stratigraphic logging. Comparing mode, median, and standard deviation of the tephra samples relative to distance from the vent (Table 5.4), I saw no marked trend in terms of relative abundance of coarser of finer fractions.

5.2.3. Summary on the results of laboratory processing of the suspected AD1754 tephra samples

Past studies of Taal have not provided information on particle and bulk densities of eruptive products, including those for the tephra fallout. In this research, I conducted *in situ* bulk density tests and was able to compute bulk and particles densities (Table 5.3). The average bulk density calculated from density testing undertaken was 0.62 g· cm^{-3}. On the other hand, the calculated particle density is 0.66 g·cm^{-3}, and now rounded off to 0.7 g·cm^{-3} or 700 kg·m^{-3}.

The size distribution for the AD1754 tephra fallout deposits collected and analysed for this research was compared with previously published data using plots of cumulative weight percent versus grain size. Figure 5.16 shows the results of grain size analysis conducted by Torres (1989) on the tephra characteristics of the scoria deposits from the AD1754 eruption. I obtained the grain size distribution for each of his tephra and base surge samples and undertook a replot of cumulative curve. The plot of cumulative weight percent versus grain size for tephra fallout deposits show a consistent sudden shift toward the negative phi values (Figure 5.16A). In contrast, the plot for the surge samples shows a sharply increasing trend towards the finer phi sizes (Figure 5.16B). Further, the histogram plot (Appendix B8 *in* Torres, 1989) for a 0.62 g·cm^{-3} or 620 kg·m^{-3} but was rounded to 0.7 g·cm^{-3} or 700 kg·m^{-3} and subsequently utilised to compute for the mass of the tephra deposits for each point location that was needed as input parameters for the tephra modelling performed presented in Chapter 6.

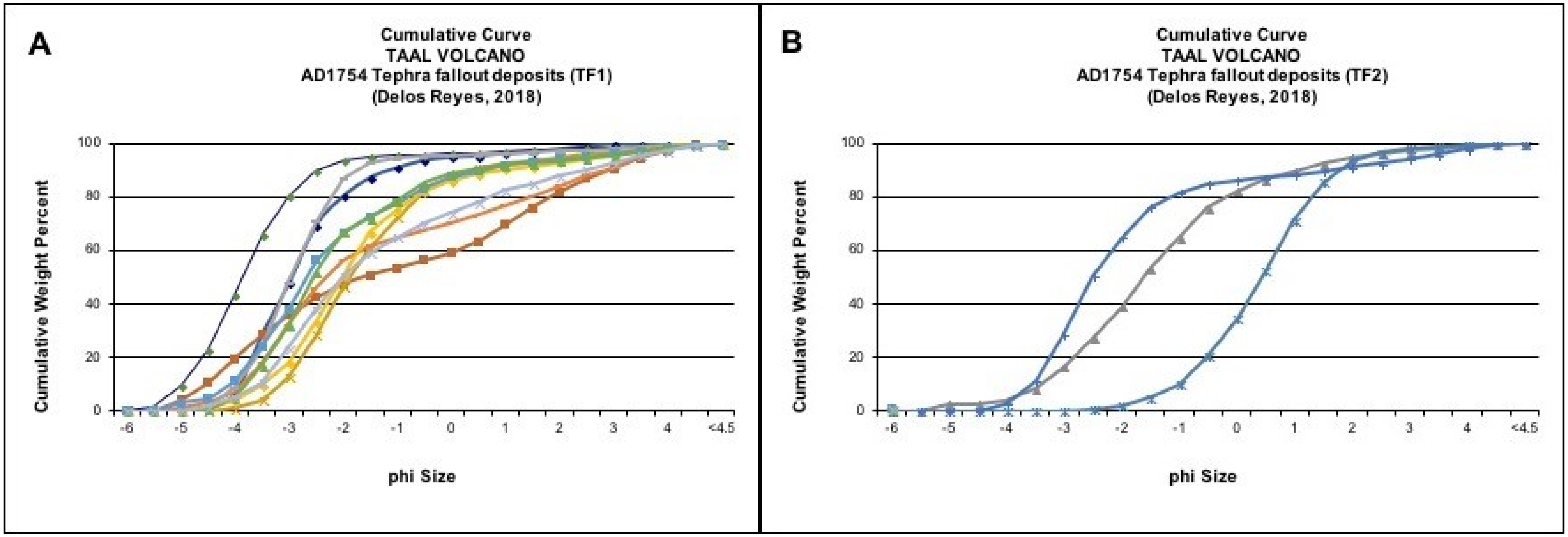


Figure 5.15. Plot of cumulative weight percent versus grain size of tephra fall (*TF1* and *TF2*) deposits related to the AD1754 eruptive deposits analysed for my research. The plots are color coded in order to distinguish each tephra sample result.

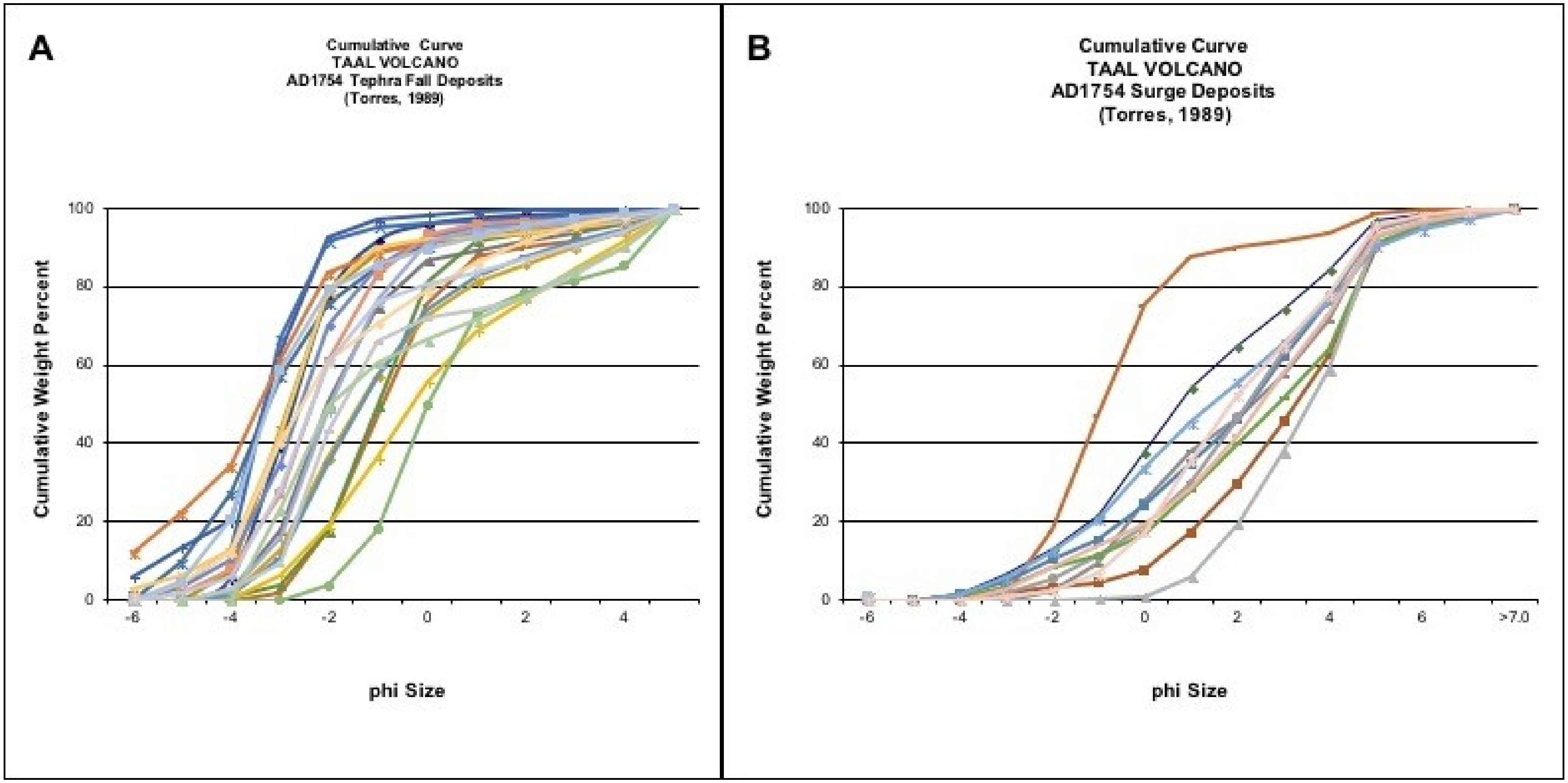
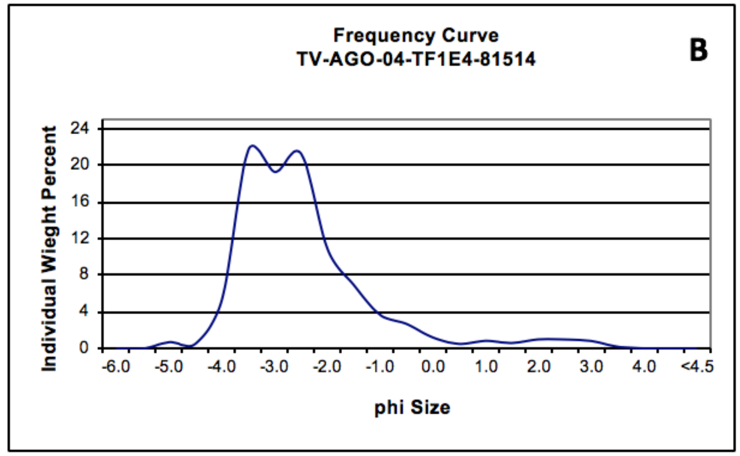


Figure 5.16. Plot of cumulative weight percent versus grain size for (A) tephra fall and (B) surge deposits related to the AD1754 eruptive deposits by Torres (1989), reconstructed for this research. The X-axis plots phi units of the samples and the Y-axis plots cumulative weight percent per sample on an arithmetic scale. The plots are color coded in order to distinguish each sample result.

Figure 5.18.
Sample Name: TV-AGO-04-TF1E4-81314
Outcrop #6/Waypoint No. 451
Location: Brgy. Banyaga, Municipality of Agoncillo
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~6km (MEDIAL REACH)
Mode phi size: -3.5
Median phi size: -3.0
Mean phi size: -2.83
Standard Deviation: 1.306818182 (POORLY SORTED)
Skewness: 0.377777778 (STRONGLY FINE-SKEWED)

A

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
6.5	-5.0	0.71	-5.0	0.71
5.19	-4.5	0.57	-4.5	1.28
50.04	-4.0	5.49	-4.0	6.77
198.9	-3.5	21.83	-3.5	28.60
176.49	-3.0	19.37	-3.0	47.97
194.6	-2.5	21.36	-2.5	69.33
99.7	-2.0	10.94	-2.0	80.27
63.51	-1.5	6.97	-1.5	87.24
33.82	-1.0	3.71	-1.0	90.96
24.69	-0.5	2.71	-0.5	93.67
11.18	0.0	1.23	0.0	94.89
4.71	0.5	0.52	0.5	95.41
7.81	1.0	0.86	1.0	96.27
5.62	1.5	0.62	1.5	96.88
9.22	2.0	1.01	2.0	97.89
9.14	2.5	1.00	2.5	98.90
7.72	3.0	0.85	3.0	99.75
2.01	3.5	0.22	3.5	99.97
0.3	4.0	0.03	4.0	100.00
0.01	4.5	0.00	4.5	100.00
0	>4.5	0.00	>4.5	100.00
911.16		100.00		



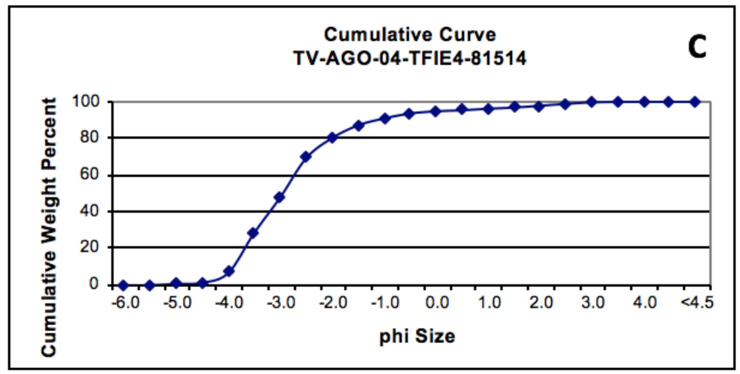
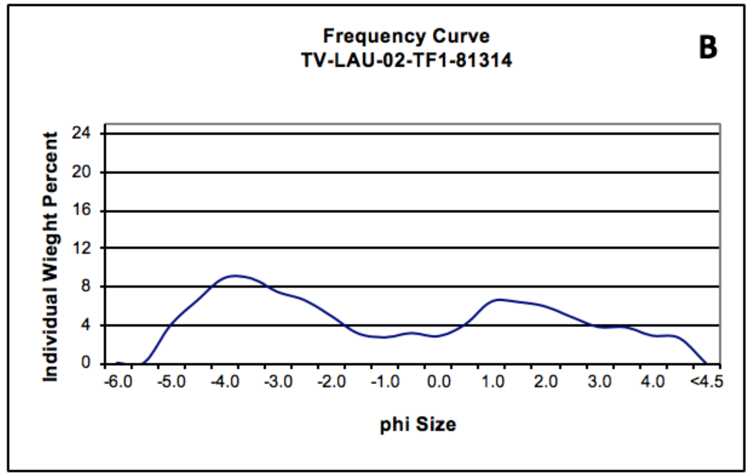


Figure 5.17. Graphical plots of grain size of the AD1754 tephra fallout deposit (*TF1*) identified as Outcrop #6 (WP 451) located in Barangay Banyaga, Agoncillo, Batangas Province with Sample No. TV-AGO-04-TF1E4-81314. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve. Median ϕ, mean ϕ, sigma ϕ and skewness are also listed. There is relative abundance of coarser fractions.

Figure 5.19.
Sample Name: TV-LAU-02-TF1-81314
Outcrop #3/Waypoint No. 444
Location: Brgy. As-is, Municipality of Laurel
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~12km (DISTAL REACH)
Mode phi size:-4.0
Median phi size: -2.0
Mean phi size: -1.5
Standard deviation: 2.83712121 (POORLY SORTED)
Skewness: 0.36538462 (STRONGLY FINE SKEWED)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
23.33	-5.0	3.98	-5.0	3.98
38.69	-4.5	6.60	-4.5	10.57
52.47	-4.0	8.94	-4.0	19.52
52.37	-3.5	8.93	-3.5	28.45
43.93	-3.0	7.49	-3.0	35.93
38.86	-2.5	6.62	-2.5	42.56
29.07	-2.0	4.96	-2.0	47.52
18.28	-1.5	3.12	-1.5	50.63
15.72	-1.0	2.68	-1.0	53.31
18.4	-0.5	3.14	-0.5	56.45
16.46	0.0	2.81	0.0	59.25
23.65	0.5	4.03	0.5	63.29
37.95	1.0	6.47	1.0	69.76
37.66	1.5	6.42	1.5	76.18
34.89	2.0	5.95	2.0	82.12
28.31	2.5	4.83	2.5	86.95
22.2	3.0	3.78	3.0	90.73
22.08	3.5	3.76	3.5	94.50
16.81	4.0	2.87	4.0	97.36
15.46	4.5	2.64	4.5	100.00
	>4.5	0.00	>4.5	100.00
586.59		100.00		

A



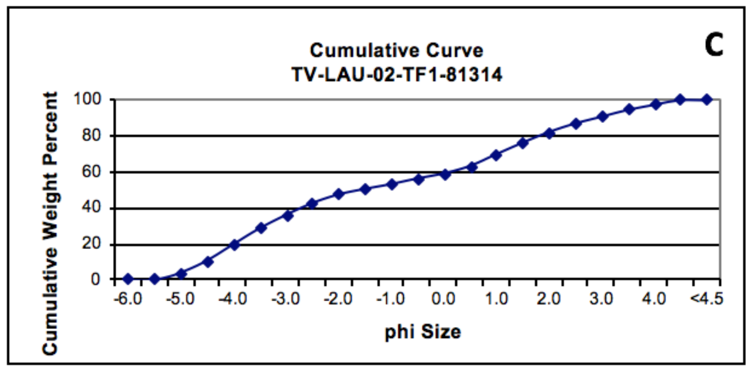


Figure 5.18. Graphical plots of grain size of the AD1754 tephra fallout deposit (*TF1*) identified as Outcrop #3 (WP 451) located in Barangay As-is, Municipality of Laurel, Batangas Province with Sample No. TV-LAU-02-TF1-81314. (A) grain size data table providing results of grain size processing with sieves used ranging from -6.0 to +4.5+ phi; (B) frequency curve plotted from the data in (A); and (C) cumulative curve. Median ϕ, mean ϕ, sigma ϕ (standard deviation) that provide relative sorting of the sample, and skewness are also listed. Relative abundance of coarser fractions

The grain size analysis I conducted shows that most of the tephra deposits followed a bell-shape form in the frequency plots signifying normal grain size distributions. The confirmation of normal grain size distribution for the processed tephra samples and the good correlation with past studies on tephra fallout deposits in general and in particular as it relates to Taal tephra means that the results are reliable. The bimodal frequency plot shown in Figure 5.18 and Appendix I-7 (Outcrop #3) is the single outlier for the processed AD1754 tephra deposits. There were two different groups of grain sizes, one inflection is in the coarser side and the other inflection is in the finer side of the grain size plot. Two plausible explanations are: 1) there were two different types of eruptive products deposited at the same time (e.g. lapilli tephra fallout deposits coinciding with the emplacement of co-ignimbrite ash), or 2) there were two tephra fall events that may have occurred one after the other such that the fall and accumulate occurred at the same time. Almost simultaneous deposition of deposits from two events could hinder identification of different episodes due to lack of gradational or sharp contacts between the two deposits. Additional deposit mapping and stratigraphic logging of the anomalous

outcrop could be undertaken in the future that might shed light on the reason for the anomaly.

5.3 Discussion

In addressing Research Question 2 and Research Question 3, I draw the following observations:

1. The *comprehensive literature review of historical eruptions* provided fundamental information on tephra dispersal, deposition and impact of tephra fallout materials ejected during the AD1754 eruption that made it easier to search for potential exposures. The detailed narrative descriptions made it possible to identify the different phases of the event and to determine eruptive styles.

2. *Identified TF1 and TF2 exposures in the field.* During my geological investigations, I was able to identify exposures of AD1754 tephra deposits. I identified, mapped, sampled and analysed deposits of the AD1754 event. I identified 41 new tephra fallout deposits in the municipalities of Talisay, Laurel, Agoncillo, San Nicolas, Lemery and Calaca, in the Province of Batangas. In the field, at least two distinct phases were identified in the outcrops mapped during field investigations: a) 15 May to 2 June (*TF1*); and b) November phase (*TF2*). The two phases were identified based on composition, shape and sizes of fragments, sorting, grading, induration, stratification and other lithologic characteristics, following the descriptions of the past narrative accounts. The thicknesses for each distinct stratigraphic layer, including tephra and pyroclastic density current deposits were mapped, logged, and sampled, with the farthest tephra outcrop found more than 20 km southwest from the volcano in Barangay San Rafael, Calaca with a thickness of 11.5 cm. The maximum thickness of the tephra fallout was found 5 km from the volcano at Barangay Banyaga, Municipality of Agoncillo in Batangas Province with a total thickness of 314 cm.

3. *Absence of AD1754 tephra outcrops to the east of Taal.* Tephra deposits from the AD1754 eruption were noticeably absent to the east of Taal, although there were

descriptions of eruption devastation in Old Tanauan (presently located in present day Talisay), and in Old Lipa (presently part of Mataas na Kahoy). This may be due to low preservation and possibly very thin tephra accumulation.

4. *Generation and correlation of stratigraphic logs.* Stratigraphic columns were generated for 29 of the 41 tephra outcrops. While the other 12 exposures were mapped and samples and thicknesses measured, good stratigraphic logs could not be generated due to poor exposure. As such, they were not included in the stratigraphic correlation. The stratigraphic correlation of the *TF1* and *TF2* tephra fallout units showed thick accumulation of tephra at proximal to medial distances then abrupt thinning approximately 6 km away from the vent. The observed thinner deposition in some proximal locations may be due to poor preservation. Older tephra deposits in near-vent locations may not always be representative of actual eruption thickness. Erosion may have occurred, either by syn-eruptive erosion by PDCs or during subsequent eruptions or during intervening periods. The stratigraphic logging and deposit characterisation including thicknesses, particle sizes, stratification, grading, sorting, induration and other characteristics generally provide an overview of the origin, transport and emplacement processes. It allowed for the identification of various phases of the AD1754 event and estimate the extent of their aerial deposition

5. *Generation of isopach maps and volume estimations of the TF1 and TF2 AD1754 tephra deposits.* Mass eruption and eruption volumes can be estimated using isopach maps (Bonadonna et al., 2015). With the field-derived thicknesses and point locations of each tephra outcrop, I was able to generate isopach maps for the *TF1* and *TF2* tephra deposits. In previous studies (DOST-PHIVOLCS, 1991; Masigla &

Ruelo, 1987), researchers collated and provided detailed descriptions of the AD1754 eruption and generated an isopach map for the whole eruption but there was no attempt to produce isopach maps for each eruptive phase. Further, volume calculations for each phase have not been undertaken. In this research, I was able to establish the eruption sequence and was able to determine and separate the deposits from the different phases using detailed stratigraphic logging and other deposit characterisation. The distribution of the *TF1* and *TF2* tephra enabled me to generate isopach maps for the two identified phases and I was subsequently able to compute the total volume of *TF1* and *TF2* tephra fallout deposits. The field-derived volumes for *TF1* and *TF2* tephra are 2.21×10^8 m^3 and 1.85×10^8 m^3, respectively. Comparison of these field derived volumes with simulated results will be discussed in Chapter 6. From the results of the mapping, should an AD1754 type eruption were to occur today, extent of dispersal and accumulation could likely impact the same areas where the tephra fallout deposits were exposed during field mapping and based on the dispersal pattern resulting from tephra modelling simulations. As it is today, those municipalities are now highly populated and more infrastructures and critical facilities are located in those areas.

6. *Importance of results of the laboratory processing.* Past studies have not provided specific particle and bulk density information for tephra fallout deposits. In this study, field-derived bulk densities and particle densities were calculated for the tephra deposits at Taal Volcano (Table 5.3). In general, the computed bulk densities were less that than the particle densities of the pumice fragments because bulk densities include pore spaces. The calculated average bulk density was 0.62 $g \cdot cm^{-3}$ or

620 $kg \cdot m^{-3}$ but was rounded off to 0.7 $g \cdot cm^{-3}$ or 700 $kg \cdot m^{-3}$ when used as input parameter to calculate the mass for each. Likewise, the computed average particle density was 0.66 $g \cdot m^{-3}$ or 660 $kg \cdot m^{-3}$. This agrees with expected densities for pumice fragments that is generally between 0.7 and 1.2 $g \cdot cm^{-3}$ (Shipley & Sarna-Wojcicki, 1982). This is the first time that the bulk densities and particle densities have been obtained for the tephra deposits from the AD1754 eruption. As far as grain size distribution is concerned, the processed tephra samples from this reseach are a good fit with general and Taal related studies as far as correlating graphical plots of frequency curves and cumulative curves are concerned. Individual weight percent versus grain size generally showed an almost bell-shaped form for 12 of the 13 processed samples, indicating a normal grain size distribution. Further, cumulative weight percent versus grain size showed a consistent sudden shift toward negative phi values consistent with the results of Torres. The results from the grain size analysis of 13 out of 41 samples are also important input parameters for *TEPHRA2* modelling. The model assumes a normal distribution of particles present in the tephra deposit. Therefore, accurate input of median phi and a normal grain size distribution consistent with the modelling assumptions will provide good modelling results that would be able to reconstruct the AD1754 eruptive phases.

While I have mapped, identified and provided my interpretations of field exposures of inferred deposits assumed to be from the different phases of the AD1754 eruption based on anecdotal recognition, the limited field gathering phase, lack of dating of the deposits and geochemical analysis are recognised as study limitations and challenges. Future research on the deposits is therefore recommended that should elucidate more geologic information than available at the time of my field surveys.

5.4 Conclusion

From the mapping conducted, point locations of the newly discovered tephra deposits from the AD1754 eruptions of Taal and the measured thicknesses of the *TF1* and *TF2* phases were obtained. This in turn allowed me to delineate and generate isopach maps that provided estimated volumes of erupted materials for each phase and identified areas likely to be affected if an AD1754 type eruption were to occur today. The dispersal of tephra from the AD1754 eruption covered an estimated area of about 123,000 m^2 for *TF1* phase and about 94,000 m^2 for *TF2* phase, mostly in the north-northwest-west-southwest direction. The maximum thickness mapped was about 450 cm in proximal locations and more than 11 cm at a distance of 18 km from the volcano (Table 5.2). The reconstruction of AD1754 event provided field derived estimation of the extent of dispersal and accumulation of tephra fallout deposits as discussed in this chapter that addressed *Research Question 2*.

Furthermore, the field derived geologic information also identified the Taal communities that are within the tephra isopach contours generated from the mapped point locations and thickness measurements undertaken for this study. Areas affected included the whole of TVI, the municipalities of Taal, San Nicolas, Lemery, Calaca, Laurel, Agoncillo, Talisay, Balayan, and Nasugbu in Batangas Province and some municipalities in Cavite, north of Batangas. If an AD1754 style eruption were repeated today, and impact the same areas, more than 600,000 people will be affected by tephra fall hazard (PSA, 2015). Tephra fall dispersal and accumulation can cause widespread damage and disruption to lifelines including transportation and communication, power lines and water sources, infrastructure, agriculture and aqua-culture, health, flora and fauna, aviation and the environment. Furthermore, the mapped thicknesses shown in Table 5.1 provide estimates of the potential tephra accumulation likely to be expected in proximal, medial and distal areas if and when a plinian/subplinian eruption were to occur (during the same months - May to December - as the AD1754 events). The prevailing wind directions in the vicinity of Taal shifts from the northeast to the southwest direction from October to May and then from southwest to the northeast from June to September, consistent with the distribution of tephra fallout deposits reported in various narrative records and mapped during field investigations related to this study. While areas likely to be affected by a similar eruption as the AD1754 event were identified in this chapter, more communities may be impacted if such an eruption occurred in the alternate season and/or the predominant wind direction changes. The latter of which happened during the AD1991 eruption of Pinatubo, when the passage of a typhoon in the Philippine Area of Responsibility subsequently affected Central Luzon. This data addresses *Research Question 3*.

Information on basaltic Plinian deposits are limited in the geologic record (Houghton et al., 2004). The new data gathered in this research have provided diagnostic characteristics for confirming the interpretations of the various eruptive phases of the AD1754 event. Further, determining similar diagnostic characteristics with other well studied mafic volcanoes can provide additional information that may be lacking in terms of evolution and eruptive behaviour of Taal. Similar to the Masaya Caldera Complex in Nicaragua (Williams, 1983), the Plinian eruptive phase of Taal generated tall eruption columns as estimated from historical accounts and the modelling results that will be discussed in Chapter 6. The deposits had similarly highly vesiculated juvenile pyroclastic materials, with grain size plots generally within the normal range of median grain sizes. Masaya was also determined to have a high volume eruption rate, and this might also be true for Taal Volcano. Due to the high vesicularity of Taal scoria fall deposits, lower bulk and particle density were confirmed through bulk density tests conducted in the field, unlike the AD1886 Plinian tephra fall deposits of Tarawera Volcano in New Zealand (Walker et al., 1984). The Tarawera tephra fall deposits were relatively poorly vesiculated than average basaltic scoria deposits and had higher density indicating higher viscosity of the erupting magma.

The results derived from this research will hopefully provide additional information that can be further improved with future geochemical and petrological study in order to better correlate the tephra fallout deposits and to have a better understanding of mafic Plinian eruptions. Basaltic Plinian eruptions can be highly explosive with corresponding rapid ascent rates. Consequently, there might be enough warning due to shorter lead time from the onset of unrest to actual eruption. The consequence of a shorter lead time may be more devastating for the TVI communities. In addition, a similar eruption duration scenario must be given consideration for future volcanic activity at Taal and must be incorporated in the volcano related DRR activities of the Province.

CHAPTER 6
Reconstruction of the AD1754 eruption of Taal using numerical modelling

6.0 Introduction

Tephra dispersal modelling discussed in this chapter builds on geological and laboratory investigations discussed in Chapter 5. Tephra dispersal modelling provides information to address Research Question 1: "*What do we know and not know about the eruptions of Taal Volcano?*" and Research Question 2: "*What is the expected distribution of tephra deposits in the event of an explosive eruption such as the AD1754 Plinian/Sub-Plinian eruption of Taal?*". This leads to Research Question 3: "*How would a major/plinian eruption affect communities around Taal Volcano?*"

Reconstruction of eruptions using numerical simulation can constrain eruption source parameters (i.e. eruption column height, erupted mass, total grain size distribution, eruption duration, etc.) that were not measured or observed at the time of eruption. These source parameters can in turn be utilised in further modelling to assist in volcanic hazard assessment. Here, numerical modelling using the *TEPHRA2* model and inversion methodologies (Chapter 3) are used to determine best-fit eruption source parameters and model coefficients, including maximum plume height, total mass ejected, median and standard deviation grain sizes for the total deposit, diffusion coefficient and fall time threshold (Figure 6.1). *TEHPRA2*, as previously discussed in Chapter 2, is a public domain tephra transport and dispersal model that is an improved and optimized version of *TEPHRA* (Bonadonna et al., 2005; Connor & Connor, 2005). The model was utilised in my research to simulate and reconstruct the AD1754 eruptive events of Taal Volcano. In my modelling, all basic assumptions used within the *TEPHRA2* model is applied (See Section 2.4.4). The best-fit parameters and coefficients result in a simulated deposit (footprint and associated accumulation) that best reconstruct the deposit created in AD1754 . In order to obtain such estimates, I utilised historical (Chapter 4) and field-derived (Chapter 5) data that served as initial constraints and validation for tephra dispersal modelling. Numerical tephra dispersal modelling must always be combined with geological investigations in order to accurately reconstruct eruption dynamics and deposits (e.g. Biass & Bonadonna, 2011; Bonasia et al., 2011; Magill, et al., 2015; Volentik et al, 2010) (Figure 6.1). While my review of historical accounts and field investigations provided important data regarding the AD1754 eruption, there is an absence of some information, including the full dispersal pattern, eruption source parameters (in particular, total erupted mass, eruption column height and total particle size distribution) and environmental conditions (wind speed and direction with height) during the eruption.

As far as Taal is concerned, although previous geological studies have been conducted on the AD1754 eruption deposits (Torres, 1989), no published accounts of analysis of tephra dispersal through modelling are available for the AD1754 eruption.

Section 6.1 will provide a brief overview of the collection of data for numerical modelling, including climatological information extracted from review of pertinent

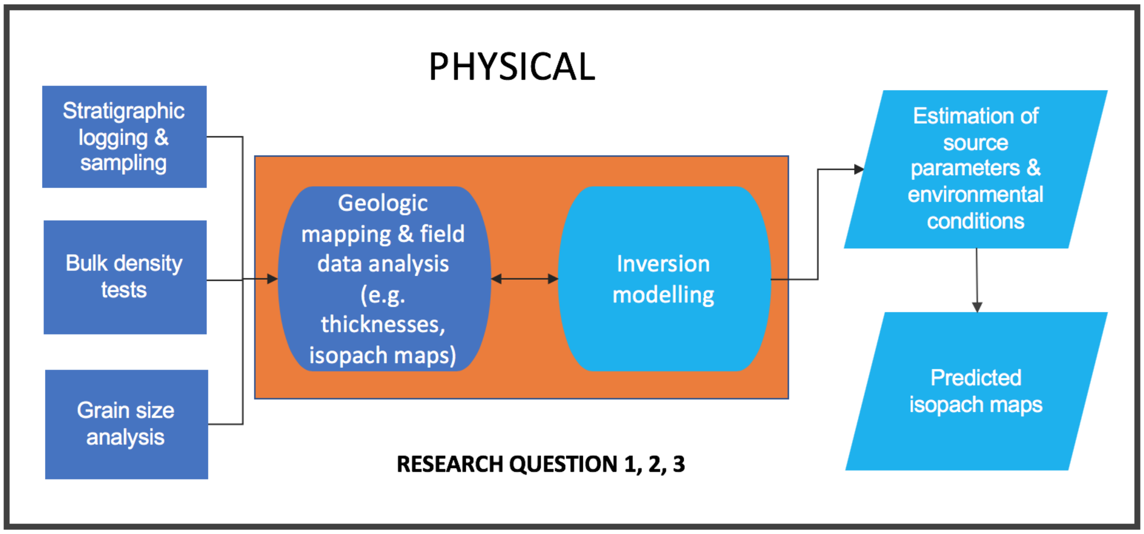


Figure 6.1. The process flow related to geologic mapping and numerical modelling conducted at Taal

documents related to the Province of Batangas. The climatological data was not used as model input but was used to validate results.

6.1 Important field-derived data for numerical modelling

As discussed in Chapters 2 and 3, the AD1754 eruption was selected for further investigation because I wanted to determine the likely extent of dispersal of tephra fallout in the event of another explosive eruption from Taal, and to better determine volume estimates and eruption source parameters for a plinian/sub-plinian type event that could be used in future hazard assessments. Narrative accounts for AD1754 provided important information on where tephra was dispersed, the thicknesses of tephra deposits, and the impacts to people and places. These accounts guided me in my identification of the AD1754 tephra deposit in the field.

The geological investigations conducted for this research described 41outcrops for the AD1754 eruption (Figure 5.1), which were discussed in Chapter 5. Tephra thickness information and tephra outcrop locations were obtained from detailed stratigraphic mapping and logging (Table 5.1). Average bulk density values and grain size distributions were also obtained during geological investigations. Details of the laboratory procedures applied to tephra samples were provided in Chapter 3, Section 3.2.2 and Section 3.2.3. The results of bulk density computations and grain size analyses were provided in Chapter 5, Section 5.2. Point locations, tephra thicknesses, bulk density values, and grain size information were utilised as inversion modelling input parameters.

For inversion modelling, both median and standard deviation phi ranges (minimum and maximum constraints) were utilised as initial constraints. Minimum and maximum median phi ($Md\phi$) ranges for *TF1* and *TF2* were obtained from information in Chapter 5, Table 5.4, extracting the finest measured particle size to the largest. On the other hand, standard deviation or sigma phi ($\sigma\phi$) values were computed using formula in Figure 5.14 with the results listed in Table 5.4. The bulk density of five tephra deposits (Chapter 5, Section 5.2.1, Table 5.3) was computed and rounded to 700 $kg{\cdot}m^{-3}$. Isopach maps were first generated by doing interpolation applying the Kriging Method that autocorrelated sample points, using ArcGIS as the platform. The resulting contour lines were manually smoothened that best reflects field thicknesses.

These maps were later compared with the isopach maps generated from the results of the *TEPHRA2* inversion modelling using gridded output and interpolation within Generic Mapping Tools (GMT) (https://www.soest.hawaii.edu/gmt/). While regressions between measured and modelled results were done using accumulated mass ($kg \cdot m^{-2}$), mass values were converted back to thicknesses after forward modelling so that isopach maps could be easily compared.

Climatological information at various heights during the duration of an eruption are key factors in the dispersal and accumulation of tephra (Bonadonna et al., 2005; Bonasia et al., 2010; Connor and Connor, 2005; Costa et al., 2006; Engwell et al., 2013; Folch and Felpeto, 2005; Glaze and Self, 1991; Klawonn et al., 2012; Magill et al., 2015; Pfeiffer et al., 2005; Rolandi et al., 1993; Scollo et al., 2007; Scollo et al., 2008; Sparks, 1986; Volentik et al., 2010). Wind speeds used as inversion constraints were obtained from NCEP/NCAR Reanalysis data, likewise providing a minimum and maximum range (https://climatedataguide.ucar.edu/climate-data/ncep-reanalysis-r2). The collection of climatological information was presented in Chapter 2. Looking at the timeframe of the eruptions, both the *TF1* (May) phase and *TF2* (November) phase occurred during times when the wind direction was most likely coming from the northeast. Therefore, I constrained the directions of wind data towards the observed direction of the observed tephra dispersal.

6.2 Inversion modelling using *TEPHRA2*

In Chapter 2, I reviewed various tephra dispersal models and provided a summary overview (Appendix C) in order to determine the most appropriate model to use for my research. I ultimately chose *TEPHRA2* because it has been successfully utilised to reconstruct large-magnitude multi-phased eruptions and because it has been successfully integrated with inversion code.

A good correlation between measured and modelled tephra fallout means that the AD1754 eruption scenario is accurately reconstructed, and results (provided on a 1,000 m grid) will provide estimates of tephra accumulation for areas where tephra deposits were not found during field investigations. The specific objectives of the tephra dispersal modelling for this study were: 1) to obtain best-fit eruption source parameters and environmental conditions using inversion techniques; and 2) validate and compare the results of inversion modelling with empirical data gathered during geological investigations.

6.2.1. Inversion input parameters

The 100 sets of parameters assigned to 10 equal ranges of mass (log scale) and 10 ranges of column height (linear scale) that were segmented into 2500 m bins between the minimum and maximum limits are listed in Table 6.1. These values are the input data for the individual configuration files used for inversion modelling. In total, 1,000 inversion runs were completed for each simulated deposit (*TF1*, *TF2* and a combined data set).

Inversion runs were performed for the two identified eruptive phases. While I also performed numerical simulations for one data set in an attempt to reconstruct the entire deposit, I do not believe the predicted the eruption source parameters are

Table 6.1. Process of dividing simulations into 100 configurations. Tephra column heights are in meters (m). Minimum and maximum mass are in kilograms (kg).

Minimum Height	Maximum Height										
15000	17500	1	2	3	4	5	6	7	8	9	10
17500	20000	11	12	13	14	15	16	17	18	19	20
20000	22500	21	22	23	24	25	26	27	28	29	30
22500	25000	31	32	33	34	35	36	37	38	39	40
25000	27500	41	42	43	44	45	46	47	48	49	50
27500	30000	51	52	53	54	55	56	57	58	59	60
30000	32500	61	62	63	64	65	66	67	68	69	70
32500	35000	71	72	73	74	75	76	77	78	79	80
35000	37500	81	82	83	84	85	86	87	88	89	90
37500	40000	91	92	93	94	95	96	97	98	99	100

Log minimum mass	10.3	10.44	10.58	10.72	10.86	11	11.14	11.28	11.42	11.56
Log maximum mass	10.44	10.58	10.72	10.86	11	11.14	11.28	11.42	11.56	11.7
Minimum mass	2.0E+10	2.8E+10	3.8E+10	5.2E+10	7.2E+10	1.0E+11	1.4E+11	1.9E+11	2.6E+11	3.6E+11
Maximum mass	2.8E+10	3.8E+10	5.2E+10	7.2E+10	1.0E+11	1.4E+11	1.9E+11	2.6E+11	3.6E+11	5.0E+11

NOTE: INITIAL ASSUMPTIONS: Plume (min-max) = 15,000 to 40,000 m; Density= 700 kg/m3; Volume (km3) = 0.129; Volume (m3)= 1.29E+08; initial mass= density x volume=9.03E+08; initial minimum mass = initial mass/5=1.81E+10; initial maximum mass = mass*5 =4.5E+11; LOG min mass =10.25671775 rounded off to 10.3; LOG max mass =11.65465775 rounded off to 11.7.

accurate. There is much uncertainty in the total thickness used for the entire duration of the AD1754 eruption due to the absence of identifiable tephra deposits from additional phases of the eruptive event. Nevertheless, I also presented the results for the simulation for a single data set for the entire AD1754 eruptive event that was mainly comprised of *TF1* and *TF2* thicknesses.

Included in the fixed eruption input values for *TEPHRA2* simulations are volcano location (UTM Zone 51, Luzon 1548837, 282360) and vent height (300 m), Plume Model 2 determined to be the uniform distribution where alpha and beta phi are equal to 1, lithic density value of 2600 $kg \cdot m^{-3}$), pumice density calculated at 700 $kg \cdot m^{-3}$ obtained from my own density tests, and the eddy coefficient value of 0.04.

The other remaining parameters with inversion limits are realistic minimum and maximum values that inversion code samples between. The determined inversion limits for: 1) eruption column height ranged from15,000 to 40,000 m; 2) total erupted mass between 3.62×10^{11} to 9.0×10^{11} kg; 3) the minimum and maximum median phi from -4ϕ and -1.5ϕ for *TF1* and -2.5ϕ and 1.0ϕ for *TF2*; 4) a minimum and maximum sigma phi from 1.0ϕ and 3.0ϕ for *TF1* and 1.0ϕ and 3.0ϕ for *TF2*, both obtained from grain size analysis; 5) fall time threshold from 1 to 250 seconds; 6) diffusion coefficient from 1 to 1000 $m^2 \cdot s^{-1}$; 7) wind direction at each step in the eruption column ranging from 210° to 315°; and wind velocity at each step in the eruption column from 1 to 20 $m^2 \cdot s^{-1}$ for both *TF1* and *TF2* (Table 6.2). Input parameters are improved with each inversion. Diffusion coefficient not only considers atmospheric diffusion but also gravitational spreading, as well as other sedimentation processes considered important inputs to tephra modelling (Magill et al., 2015).

Based on the isopach map (Figure 3.5) generated by me for the AD1754 eruption, the value of *To*, the extrapolated maximum thickness or the point where the line crosses the y axis, was derived by plotting the square root of each isopach area against the logarithm of thickness. This was estimated to be 290.77 cm (Figure 6.2). The thickness half distance (b_t), or average thinning rate, generated for the deposit was 2.61 km.

The computed total volume using this method (*TF1* and *TF2*) for the entire AD1754 event is 0.259 km^3 or 2.59×10^8 m^3 each. I postulated that half the total volume be assigned to *TF1* and half to *TF2,* which comes to 1.29×10^8 m^3 each. Using the formula above to obtain total mass, the estimated volume for each phase *TF1* and *TF2* are multiplied by deposit bulk density estimated at 700 $kg \cdot m^{-3}$. The resulting total erupted mass was therefore estimated using this method to be 9.03×10^{10} kg.

The minimum potential erupted mass, assumed to be five times smaller than the estimated mass, was calculated at 1.81×10^{10} kg, while the maximum mass, assumed to be five times larger than estimated mass was calculated at 4.5×10^{11} kg. Plume height limits are assumed to be between 15 and 40 km, based on historical accounts.

Wind direction was sampled between 210° to 315 ° based on the dispersion tephra fallout shown in Figure 5.2. Wind speed is estimated to be between 1 to 20 $m \cdot s^{-1}$ that best simulated the wind speed during the months of the eruption duration and these limits were employed for all inversion runs.

Table 6.2. The inversion parameters using *TEPHRA2*. Parameters listed in A and B are fixed and C and D are ranges simulated by the inversion method.

PARAMETER	DESCRIPTION	INPUT VALUES	
A. Volcano Location			
Vent_Easting	Easting location of vent (UTM coordinates)	282360	
Vent_Northing	Northing location of vent (UTM coordinates)	1548837	
B. Type of plume			
Plume model	Describes the diffusion of particles in the eruption column based on mass	2	
Lithic density	Density of small particles ejected from the vent (in kg m^{-3})	2600	
Pumice density	Density of large particles ejected from the vent (in kg m^{-3})	700	
Vent elevation	Elevation of vent (unit in meters)	300	
Phi range	Assume a minimum and maximum particle size (phi units)	7 to -7	
C. Inversion parameters		**MINIMUM**	**MAXIMUM**
Max_Plume_Elevation	Maximum height of tephra cloud in meters above sea level	15000 (TF1 & TF2)	40000 (TF1 & TF2)
Plume ratio	Describes where in the column most mass resides	0.4	0.4
Diffusion coefficient	Describes advection and diffusion of particles through the atmosphere; values may range from 1 to 10,000 m^2s^{-1}	1.0	1000
Eddy constant	Describes atmospheric diffusion (Fickian diffusion parameter, Earth value = 0.04)	0.04	0.04
Total mass	Total mass of tephra erupted from the volcano (in kg)	Minimum mass divided into 10 ranges from 4.0e+10 to 7.2e+11;	maximum mass range from 5.5e+10 to 1.0e+12
Median phi	Median particle size erupted from the volcano (in phi)	-4.0 (TF1) -2.5 (TF2)	-1.5 (TF1) 1.0 (TF2)
Sigma phi	Standard deviation of particle size of tephra erupted from the volcano (in phi)	1.0 (TF1) 1.0 (TF2)	3.0 (TF1) 2.0 (TF2)
Alpha phi	In phi	1.0	1.0
Beta phi	In phi	1.0	1.0
Fall time threshold	Fall time at which diffusion model changes from linear to power law diffusion	1.0	250
D. Wind file			
Wind speed	Estimated prevailing wind speed at the time of eruption (in m·s^{-1})	1.0 (TF1 & TF2)	20.0 (TF1 & TF2)
Wind direction	direction refers to the direction the wind is blowing toward (in degrees)	210^{o} (TF1) 225^{o} (TF2)	315^{o} (TF1) 315^{o} (TF2)

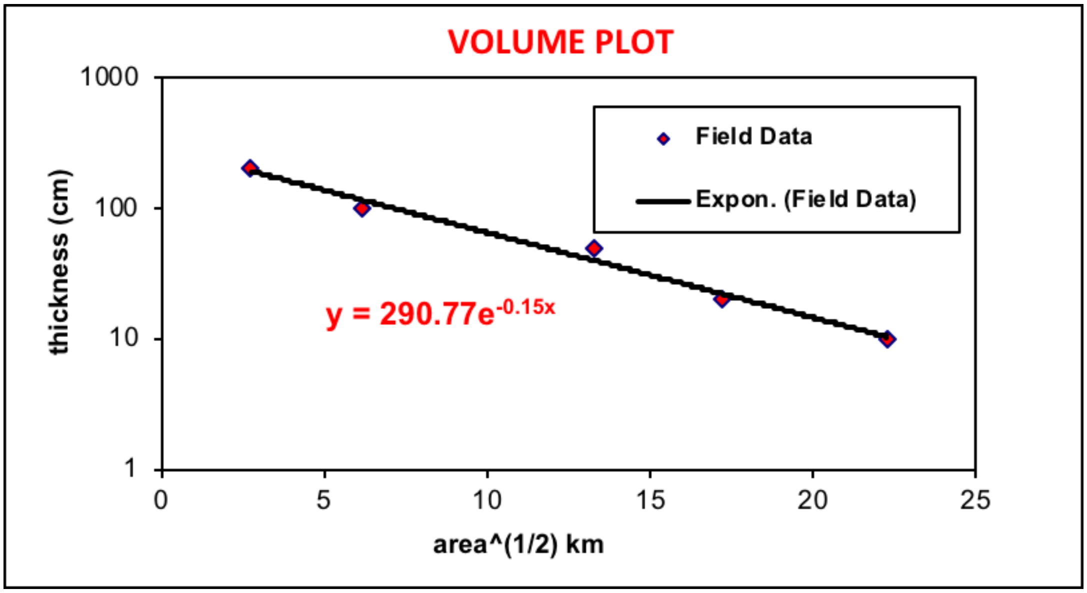


Figure 6.2. Plot of the square root of each isopach area against the logarithm of thickness for each isopleth. The extrapolated maximum deposit thickness *To* value equal to 290.77.

6.2.2. Analysis of inversion results

A summary of the steps in analysing results from the inversion modelling are:

1) find the best combination of eruption and environmental parameters that provide the lowest root mean square error (RMSE) value for each of the two identified eruptive phases of the AD1754 event;

2) extract simulated accumulation and perform regression analysis with measured accumulation to find the correlation coefficient – the highest correlation coefficient that indicates the best fit to measured data;

3) performed forward solutions utilising the best fit eruption and wind information then convert results to thickness using bulk density information; and

4) generate isopach maps that can be compared to field derived isopach maps to further compare methodologies.

The inversion results with the lowest RMSE for each plume height and total eruption mass combination from multiple seeds, were selected for both the *TF1* May to June phase (Figure 6.3A) and the *TF2* November phase (Figure 6.3B). The input parameters are listed in Table 6.1. The grid plots were intended to see convergence of plots based on RMSE values (Connor & Connor, 2005). In Figure 6.3A, the three lowest RMSE values (plotted as red diamonds) for *TF1* were noted to be clustered at heights 37,500 to 40,000 m, while in Figure 6.3B, the low RMSE values for *TF2* were noted at heights between 20,000 to 30,000 m. Of these 100 results for each eruptive phase, the best fit results selected from the combination of eruption parameters were identified by a red circle. In Figure 6.3B, it was noted that the two best fit results have very different column height values and that there is significant variation in modelled heights of the eruption column. Column heights, combined with grain sizes and wind speeds, interact in different ways and can provide the same simulated deposits. Other case studies (Connor & Connor, 2005; Volentik et al., 2010; Magill et al., 2015) also encountered this inherent problem in inversion. Column heights are not well constrained in *TEPHRA2*. However, inversion constrained erupted mass well and very similar values are clustered together with low RMSE.

These selected best-fit accumulations were then plotted against measured accumulations for *TF1* and *TF2* at each measured location and the regressions shown in Figure 6.4. For *TF1* the correlation coefficients were closer to 1 (orange line), with a value of 0.9832, while for *TF2*, the value is 0.7833. This indicates that our best-fit simulation for *TF1* fall below the line representing a correlation of 1, suggesting that in general simulated accumulation is lower than measured accumulation. I also plotted the selected best-fit regression plots for *TF1* and *TF2* on a logarithmic scale in order to better identify outliers (Figure 6.5). In general, both for *TF1* and *TF2*, identified outliers generally came from proximal/near-vent locations, including on TVI where measured thicknesses may not truly represent the thicknesses during the eruption. Thick accumulations in near-vent locations may have been particularly prone to erosion, either during succeeding eruptions, or by precipitation after emplacement. Some outliers that I identified also came from outcrops that were mapped prior to my research (2013) or were mapped during the timeframe of my research but measurements were not as detailed as in subsequent stratigraphic mapping and logging. Reinvestigation of these suspected AD1754 eruptive deposits could not be undertaken because the outcrops were subsequently covered by local engineering works intended to protect roads from landslides and rockfall as mentioned in Chapter 5, Section 5.1.1. Comparing *TF1* and *TF2* regression plots, there were more outliers in *TF2* (8) than *TF1* (6) perhaps because the grain size range in *TF2* is not well constrained due to the limited samples processed compared to *TF1*.

A similar grid plot of inversion results with lowest RSME for each parameter combination was performed for one single data set combining *TF1* and *TF2* (Figure 6.6). In the plot, the lowest RMSE simulation was not selected as the best fit inversion result. Based on the plot of simulated versus measured accumulation, the correlation coefficient value obtained was 0.6614. Linear plot of best-fit simulated

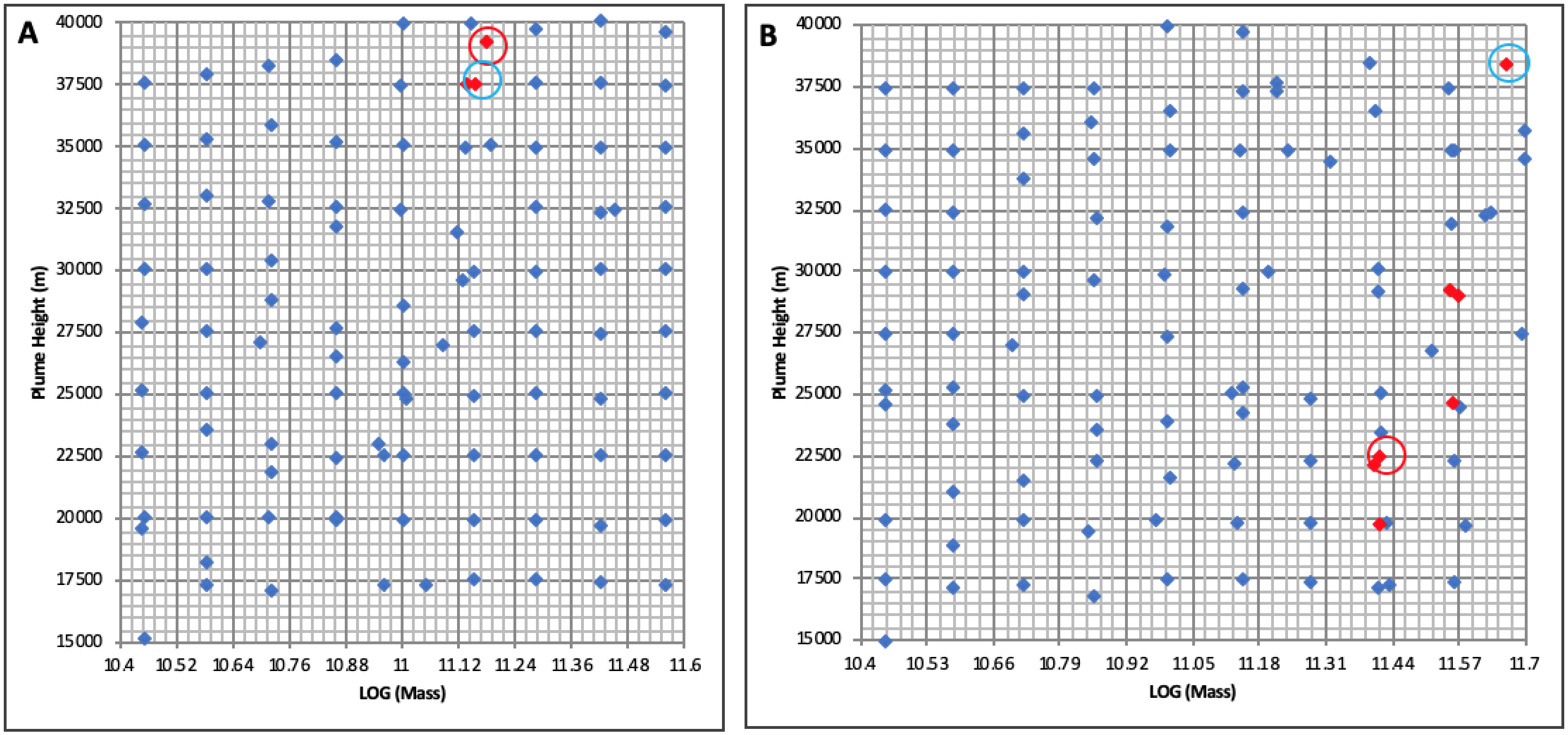


Figure 6.3. Grid plot of *TEPHRA2* inversion results with lowest root mean square error (RSME) for each plume height and total eruption mass combination. A) *TF1* phase lasting from May to June and B) *TF2* November phase. The simulations with the lowest RMSEs that provided a good fit in terms of correlation coefficients of plots of simulated and measured accumulations are identified as red diamonds and the best fits are in red circles. The second lowest fits are indicated by blue circle.

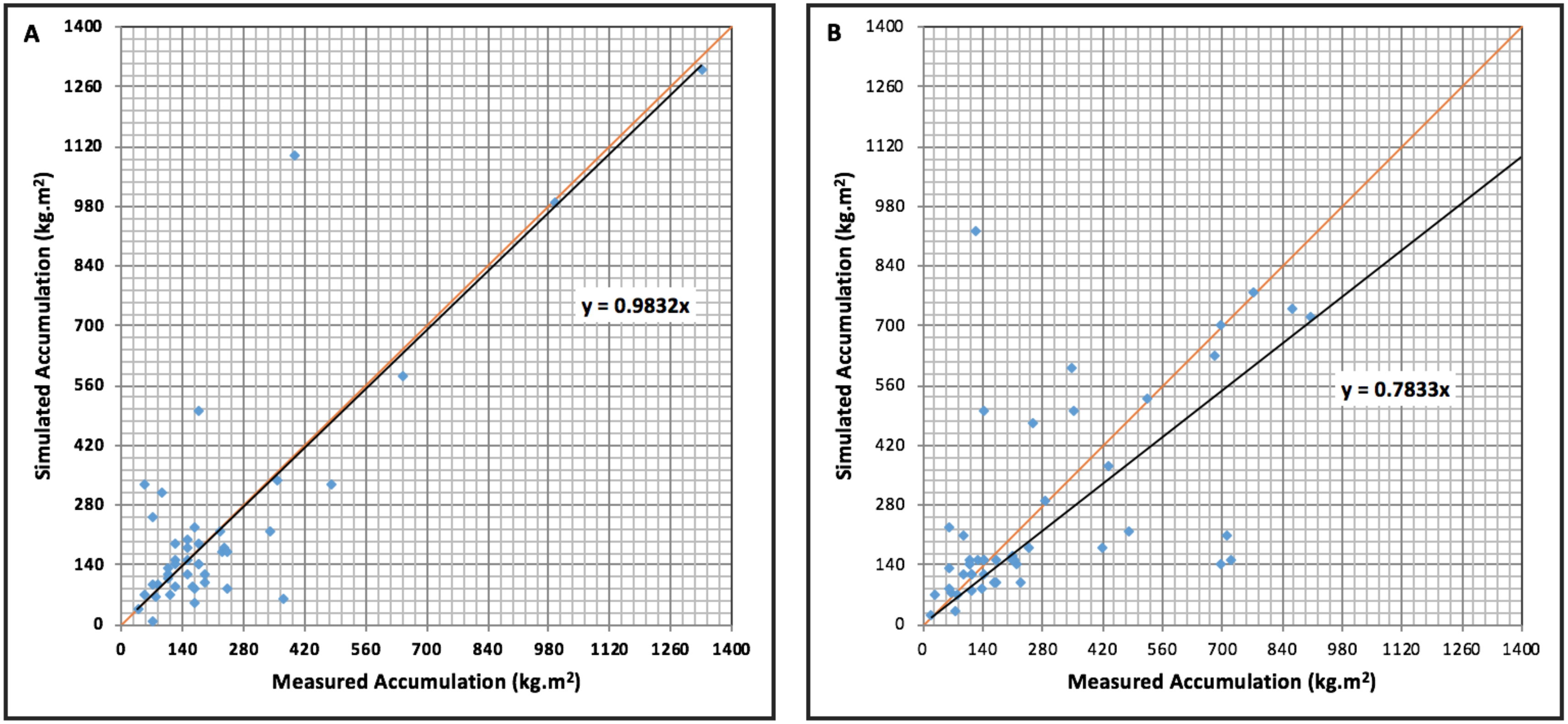


Figure 6.4. Linear plot of best-fit simulated accumulation and measured accumulation (kg·m^{-2}) for *TF1* (A) and *TF2* (B). *TF1*, represents a good fit since the linear trendline (orange) that represents a correlation of 1 and the best fit line (y) are the same and the correlation coefficient is close to 1 (value of 0.9832). For *TF2*, the correlation of measured against simulated accumulation is not as good as in TF1, with a correlation coefficient value of 0.7833.

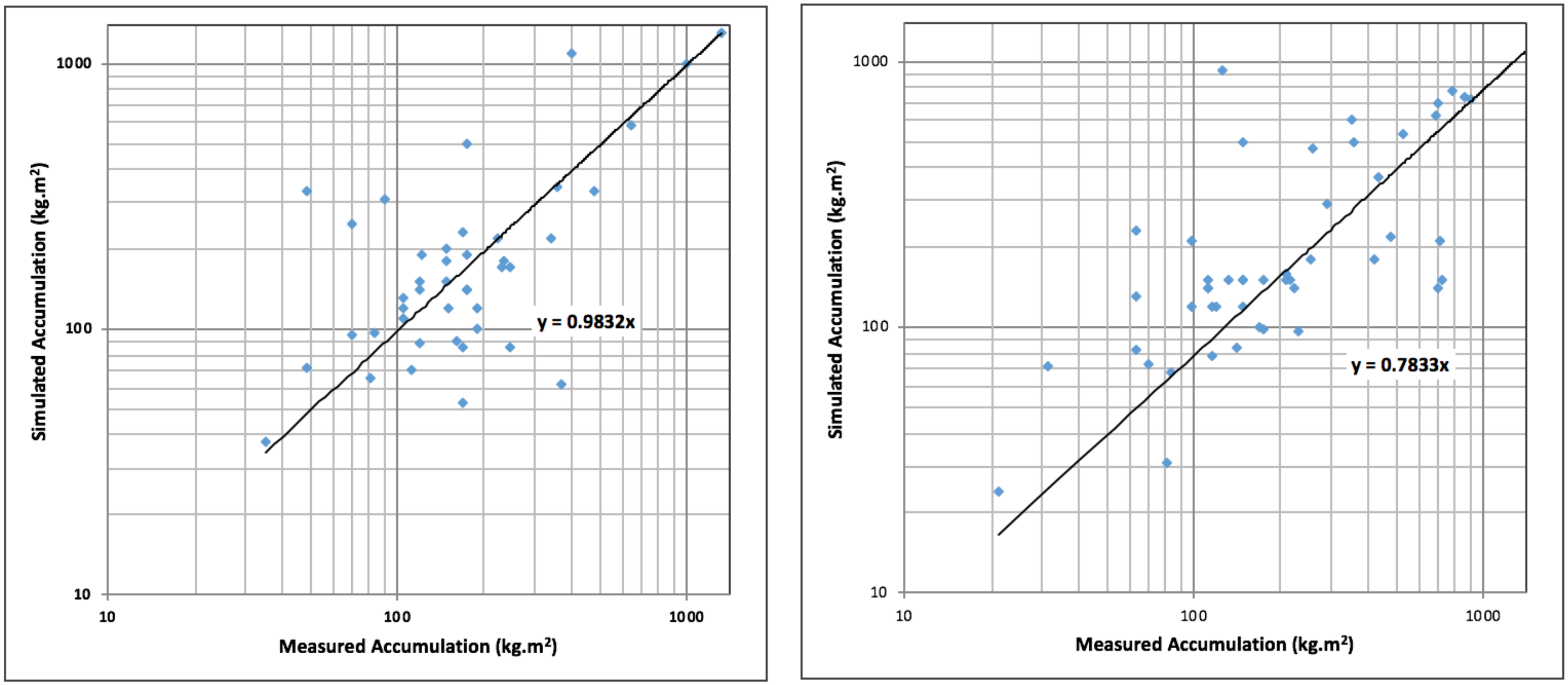


Figure 6.5. The regression for the best-fit simulated accumulation against measured accumulation (kg·m^{-2}) were plotted on a logarithmic scale to identify outliers for *TF1* (A) and *TF2* (B). A total of six outliers were identified for *TF1* and eight for *TF2*. Most of these outliers were located at TVI where measured thicknesses may not necessarily be actual thickness during eruption emplacement, either as a result of erosion during subsequent eruptions or by intense precipitation.

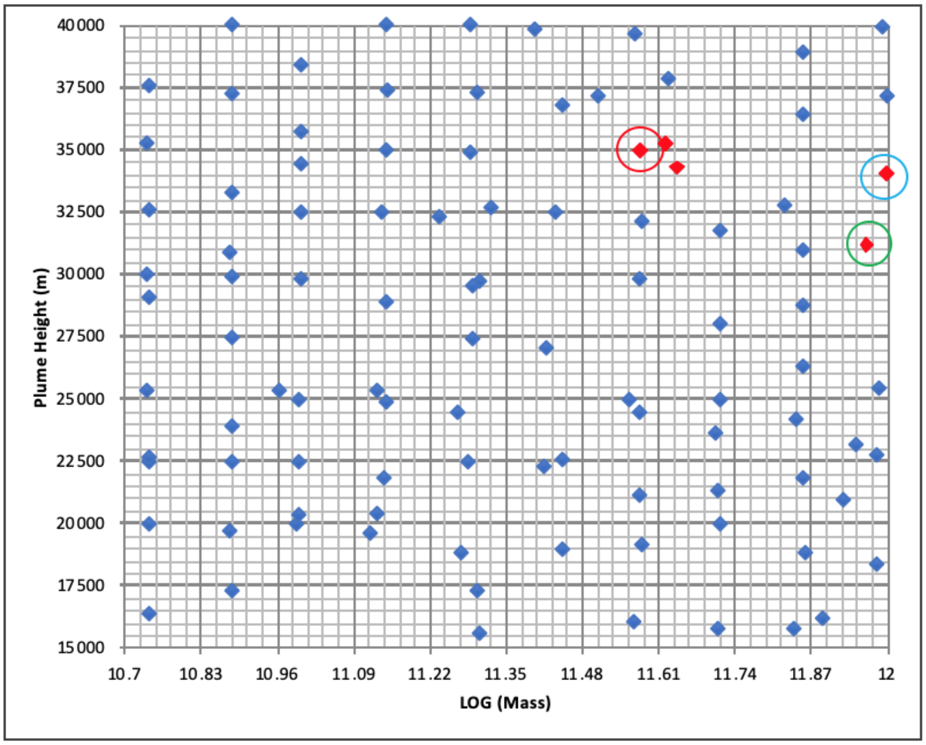


Figure 6.6. Grid plot of *TEPHRA2* inversion result for a single data set describing the entire AD1754 event with lowest root mean square error (RSME) for each plume height and total eruption mass combination. The grid plot represents the combined thicknesses of the *TF1* phase lasting from May to June, the *TF2* November phase and likely the other phases of the AD1754 event. The runs with low RMSEs that provided a good fit in terms of correlation coefficients of plots of simulated and measured accumulations are identified as red diamonds. The lowest fit value is in green circle and the second lowest fit value is in blue circle. The best fit for the single data set for the entire eruption is in red circle.

accumulation and measured accumulation for one single data set combining *TF1* and *TF2* had a correlation value of 0.7894 (Figure 6.7A). The regression between measured and simulated accumulation was again plotted on a logarithmic scale in order to identify outliers (Figure 6.7B). A total of 12 outliers were identified for this single data set. The outliers were likewise either located at TVI or were DOST-PHIVOLCS thicknesses data gathered in 2013 prior to the commencement of my research. However, the outcrops were not reinvestigated and mapped in detail due to engineering works.

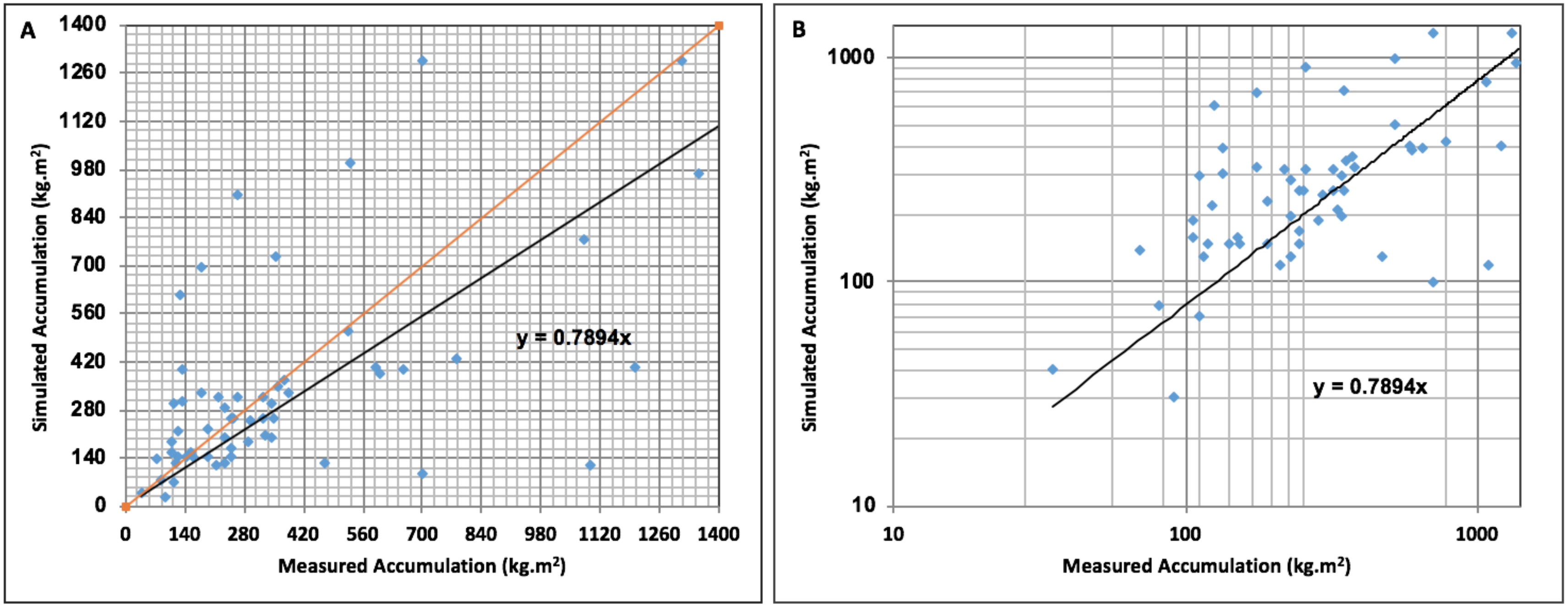


Figure 6.7. Regression plots for a single data set for the entire AD1754 eruptive event. A) Linear plot of best-fit simulated accumulation and measured accumulation (kg·m^{-2}) for one single data set combining *TF1* and *TF2*. The correlation of the linear trendline (orange) and the deposit plot and the correlation value is only 0.7894. B) Regression for the best-fit simulated accumulation against measured accumulation (kg·m^{-2}) plotted on a logarithmic scale to identify outliers. A total of 12 outliers were identified for the single data set. Most of these outliers were located at TVI where measured thicknesses may not necessarily be actual thickness during eruption emplacement, either as a result of erosion during subsequent eruptions or by intense precipitation. Five of the outliers were thickness data from the 2013 surveys conducted prior to my research that were not reinvestigated due to the coverup of the outcrop through engineering works.

6.3 Determined eruption source parameters for an AD1754 style eruption

Using the regression plots and correlation coefficients, the best-fit simulations and associated eruption source parameters for the two phases were determined (Table 6.3). The following sections provide discussion on each of the major source parameters identified from inversion.

Table 6.3. Inversion modelling results providing best-fit eruption source parameters for the two identified phases of the AD1754 eruption, *TF1* and *TF2*, and a data set representing the entire eruption.

ERUPTION SOURCE PARAMETERS	*TF1* RESULTS	*TF2* RESULTS	SINGLE DATA SET
Maximum plume height (*in meters*) above sea level	39,283	37,423	34989
Total mass ejected (*in kg*)	1.52×10^{11}	1.63×10^{11}	3.78×10^{11}
Estimated volume (*in* m^3)	2.17×10^{8}	2.34×10^{8}	5.40×10^{8}
Median Grain size (*in phi units*)	-1.5	-0.5	1.2
Standard Grain size (*in phi units*)	1.0	2.4	2.2
Diffusion coefficient (*in* $m^2 \cdot s^{-1}$)	964.7	955.9	929.1
Fall time threshold (*in seconds*)	249.8	15.7	49.1
Eddy constant (*in* $m^2 \cdot s^{-1}$)	0.04	0.04	0.04
Wind speed (*in* $m \cdot s^{-1}$)	1.0 to 20.0	1.0 to 20.0	1.0 to 20.0
Wind direction (*in degrees*)	210 to 315	210 to 315	210 to 315
Correlation coefficient of measured versus simulated accumulation	0.9832	0.7833	0.7894

6.3.1. Predicted column heights for an AD1754 style eruption

Narrative accounts of the Plinian/Sub-Plinian phase that occurred from 15 May to 2 June described tall tephra columns, with some estimated to be about 40,000 m in height. I constrained column height between 15,000 and 40,000 m in my inversion modelling. Best-fit results from the inversion suggested maximum column heights of 39,283 m for *TF1* and 37,423 m for *TF2*, an excellent replication of the interpreted narrative accounts for the AD1754 eruption. On the other hand, the predicted column height for a single data set provided a 34,989 m height, much lower than the *TF1* and *TF2* phases. This lower height is not unexpected, as the model may have required tephra to be released at a lower level in order to better explain the complexity of the entire eruption. The good correlation of simulated results with previously predicted column heights confirms that the AD1754 Plinian type eruption produced a strong enough tephra column to equal a VEI of 5 (Newhall & Self, 1982). Future eruptions may reach this explosivity, or more.

6.3.2. Predicted total erupted mass and volumes for the simulated AD1754 eruption

I now provide comparisons of total erupted mass and volume of the eruption as estimated directly from field data and inferred from inversion modelling.

Field derived data for erupted mass for *TF1* is 1.547×10^{11} kg and 1.295×10^{11} kg for *TF2*. On the other hand, field-derived data for bulk volume for *TF1* deposit is estimated at 2.21×10^{8} m^3 and 1.85×10^{8} m^3 for *TF2* tephra deposit using isopachs. Combined field derived volumes of *TF1* and *TF2* gives a total erupted volume of 4.06×10^{8} m^3.

The best-fit simulated eruption mass for *TF1* was found to be 1.52×10^{11} kg, equivalent to a volume of approximately 2.17×10^{8} m^3 using a deposit density of 700 $kg \cdot m^{-3}$. The total simulated mass calculated for *TF2* was 1.63×10^{11} kg, equivalent to a volume of more than 2.33×10^{8} m^3 using the same assumed density. Combining the volumes for *TF1* and *TF2* gives a total simulated erupted volume of more than 4.50×10^{8} m^3. The best-fit results based on a single data set for the entire AD1754 event found a total mass of 3.78×10^{11} kg or volume of 5.40×10^{8} m^3. The higher values compared to solely field derived computed volumes is reasonable considering the fact that some *TF1* and *TF2* tephra deposits might have been lost through erosion and because much thinner distal portions of the deposit were considered in my early calculations and in the calculation of mass using inversion.

The previously estimated total volume of erupted deposits for the entire duration of the AD1754 eruption was only 1.50×10^8 m^3 (DOST-PHIVOLCS, 1991), significantly lower than my estimates. At that time, calculation of volume was undertaken manually based on isopach maps alone. At the time of writing this chapter, no available thickness measurements for specific point locations were retrieved related to this previous study. With volumes calculated based solely on the size of isopachs, distal volumes were, as far as I can tell, not included in the calculations. For this research, using the Pyle (1989) exponential thinning method, distal volumes were included in my initial calculations. These values are much closer to results obtained via inversion, giving credibility to both approaches. Further, the greater volume inferred from inversion is believed to be reasonable because historical descriptions of dispersal are far more widespread than what was observed and mapped in the field. In DOST-PHIVOLCS (1991, p. 37), it was mentioned that tephra dispersal reached Manila, which forced people to "*dine with lighted candles at midday*". While it is difficult to determine the thickness of ash that could cause darkness in a particular ash-impacted area, it is presumed that ashfall affected Metro Manila at the time of the AD1754 eruption. The tephra fallout more likely occurred during the *TF1* phase from 15 May to 02 June based on the dispersal direction (west-northwest) of the measured and simulated tephra cloud (Section 6.3.4 and Figure 6.8). Likewise, based on modelling results shown in Figure 6.8, it can be estimated that the tephra thickness was more likely less than 1 cm. Correlation of the direction and extent of the dispersal of tephra using the simulated isopach map showed a good fit with the point locations of the tephra exposures and the field-derived isopach map both for *TF1* (west northwest direction) and *TF2* (westerly). The comparison between measured and simulated thicknesses will be discussed in Section 6.3.5 and is listed in Table 6.3 and Table 6.4.

6.3.3. Grain size correlation between measured and simulated results

Next I undertook grain size comparisons between measured (through grain size analysis) and modelled median phi (*Md*ϕ) and standard deviation phi (σϕ) for the two phases.

Grain size processing conducted for the AD1754 tephra samples was discussed in detail in Chapter 3, Section 3.2.3, while the results of the grain size analysis was discussed in Chapter 5, Section 5.2.2.1. The *Md*ϕ for *TF1* obtained from the grain size analysis of 10 tephra samples (Chapter 5, Table 5.4) ranged from -3.0ϕ to -1.5ϕ described to be in the size range of "*medium lapilli to fine lapilli*" (White & Houghton, 2006), while the best-fit *Md*ϕ calculated by inverse modelling was -1.5ϕ with grain size class of "*fine lapilli*" (White & Houghton, 2006). The *Md*ϕ for *TF2* obtained from the grain size results for three tephra samples (Table 5.4) ranged from -2.5ϕ to 0.5ϕ with grain size range of "*medium lapilli to coarse ash*", while *Md*ϕ obtained from modelling was -0.5ϕ with grain size of "*very coarse ash*" (White & Houghton, 2006).

Further, using the best-fit inversion results, I compared median particles sizes from grain size analysis and those from inversion for selected individual point locations listed in Table 6.3. The median particle size for each phi unit was extracted from inversion results, while mass percentage for each phi unit was found for the same point locations where total grain size distribution was determined. Simulated *Md*ϕ values were determined by plotting a cumulative curve with an arithmetic ordinate scale similar to those performed in the grain size analysis of the thirteen tephra samples (Appendices I-1 to I-13). Almost all of the simulated median sizes for *TF1* and *TF2* were in the -2.0ϕ to greater than -1.0ϕ range, with the simulated median particle size generally finer or equal in size to that measured. The simulated *Md*ϕ values were generally observed to underestimate the amount of coarser tephra in the proximal and medial point locations. While in distal reaches, *Md*ϕ values were equal or finer than simulated results. The coarser *Md*ϕ for field-derived grain size for both *TF1* and *TF2* is most likely due to the limited mapped point locations in distal areas that could have resulted in the bias towards coarser particles (Volentik et al., 2010). The *Md*ϕ values from inversion were less affected by this bias because the simulation results were based on a physical model of tephra dispersion and sedimentation (Volentik et al., 2010, p. 128). Diffusion of tephra is also grain size-dependent with *Md*ϕ being related to distance from the vent (Volentik et al., 2010). The physical model considers grain size, particle density, settling velocity, and considers a stratified atmosphere and particle diffusion time within the trajectory of the tephra column (Bonadonna et al., 2005).

The standard deviation for measured *TF1* samples ranged from 1.13 to 2.84ϕ with Wentworth size class range of "*medium ash to fine ash"* (White & Houghton, 2006). The average simulated σϕ is 1.84 with size description of "*medium ash*" (White & Houghton, 2006). The σϕ for measured results for *TF2* range from 1.03 to 1.81 with size description of "*medium ash*" (White & Houghton, 2006). The average simulated σϕ is 1.5 with size class of "*medium ash*" (White & Houghton, 2006). Similar to *Md*ϕ values, there is also a very good correlation between measured and simulated σϕ. Measured and simulated *TF2* both show generally finer particle sizes than those from *TF1*.

Table 6.4. Comparison of median particle sizes (in phi) obtained grain size analysis for selected AD1754 tephra fallout samples and those obtained from the *TEPHRA2* simulations. Median phi (Mdϕ) is the 50th percentile diameter obtained from the cumulative curve of the total tephra mass accumulation. Locations of tephra outcrop sampled and processed are based on sample number with reference to Figure 5.1. The processed samples ae listed according to distance from the vent. Distance from the vent described as proximal (0 – 4 km), medial (4 – 6 km), and C) distal (6 – 20 km).

No.	Sample Identification	Location (Barangay/ Municipality)	Tephra Type	Median (Mdϕ) Measured	Median (Mdϕ) Simulated	Distance from vent
29	TV-TAL-TVI-TF1S1-101814	Daang Kastila, Talisay, TVI	TF1	-3.0	-2 to >-1	~2km
6	TV-AGO-04-TF1E4-81514	Brgy. Banyaga, Agoncillo	TF1	-3.0	-2 to >-1	~6km
15	TV-LAU-10-TF1-81614	Brgy. Buso-buso, Laurel	TF1	-3.5	-2 to >-1	~6.5km
30	TV-TAL-23-TF1S2-102014	TVO, Brgy Buco, Talisay	TF1	-2.5	-2.5	~9km
22	TV-LAU-16-TF1-101414	Brgy Leviste, Laurel	TF1	-2.5	-2 to >-1	~9km
5	TV-SNI-03-TF1-81314	Brgy. Pansipit, San Nicolas	TF1	-2.0	-2 to >-1	~10.5
3	TV-LAU-02-TF1-81314	Brgy. As-is, Laurel	TF1	-2.0	-2 to >-1	~12km
3	TV-LAU-02-TF2-81314	Brgy. As-is, Laurel	TF2	-1.50	-2 to >-1	~12km
13	TV-LAU-09-TF1-81614	Sitio Culit, Brgy. San Gregorio, Laurel	TF1	-3.0	-3.0	~12km
21	TV-CAL-15-TF1-81814	Brgy. Matipok, Calaca	TF1	-2.0	-2 to >-1	~12km
7	TV-LEM-05-TF2-81514	Brgy. Masalisi, Lemery	TF2	-2.5	-3 to >-2	~13.5km
18	TV-CAL-12-TF1-81814	Brgy Cahil, Calaca	TF1	-2.0	-2 to >-1	~18km
18	TV-CAL-12-TF2-81814	Brgy Cahil, Calaca	TF2	0.50	-2 to >-1	~18km

Two significant factors that may explain the good correlation (0.9832) for the *TF1* deposits are the accuracy of the geological data and the selected initial conditions used as modelling input parameters including grain size range for median phi (*Md*ϕ) and standard deviation or sigma phi (σϕ) limits, that came from *TF1* outcrops, that combined provided good constraints for good inversion.

Further, the results of inversion showed that *Md*ϕ for *TF1* was near the low end of the range (-4 to -1.5ϕ) set as constraints (-1.5ϕ) while *σ*ϕ is at the top of the range (1 to 3ϕ). For *TF2*, *Md*ϕ value (-0.5ϕ) was in the middle section of the input range (-2.5 to 2ϕ) and the *σ*ϕ value (2.4ϕ) was near the low end of the input range (1 to 3ϕ). For the results of inversion modelling using one single data set, *Md*ϕ was 1.2, in the middle of the input range (-4 to 4ϕ) and *σ*ϕ was 2.2ϕ, likewise near the low end of the input range (0.5 to 3ϕ). The good fit of the *Md*ϕ and *σ*ϕ values indicate that the selected grain size ranges obtained from field investigations may be deemed sufficiently accurate even with the limited number of processed samples.

6.3.4. Predicted isopach for an AD1754 style eruption

The isopach maps were constructed using the forward solution of the best-fit parameters for *TF1* and *TF2* phases of the AD1754 event modelled over a 1 km resolution grid and interpolated using Generic Mapping Tools (GMT) software (Figure 6.8B and Figure 6.9B). Prior to undertaking forward solutions, an inclusive script was added to convert the mass values to thickness, using a bulk density of 700 $kg \cdot m^{-3}$, so that the isopach maps generated by forward modelling could be compared directly to isopach maps drawn solely from field-derived information (Figure 6.8A for *TF1* and Figure 6.9A for *TF2*).

Figure 6.8A shows the isopach map from measured thicknesses of *TF1* using 33 data points (Chapter 5, Section 5.1.4, Table 5.1), that was initially interpolated applying the Kriging Method with ArcGIS as the platform that autocorrelated sample points generating the contour lines. Contour lines were then smoothened.

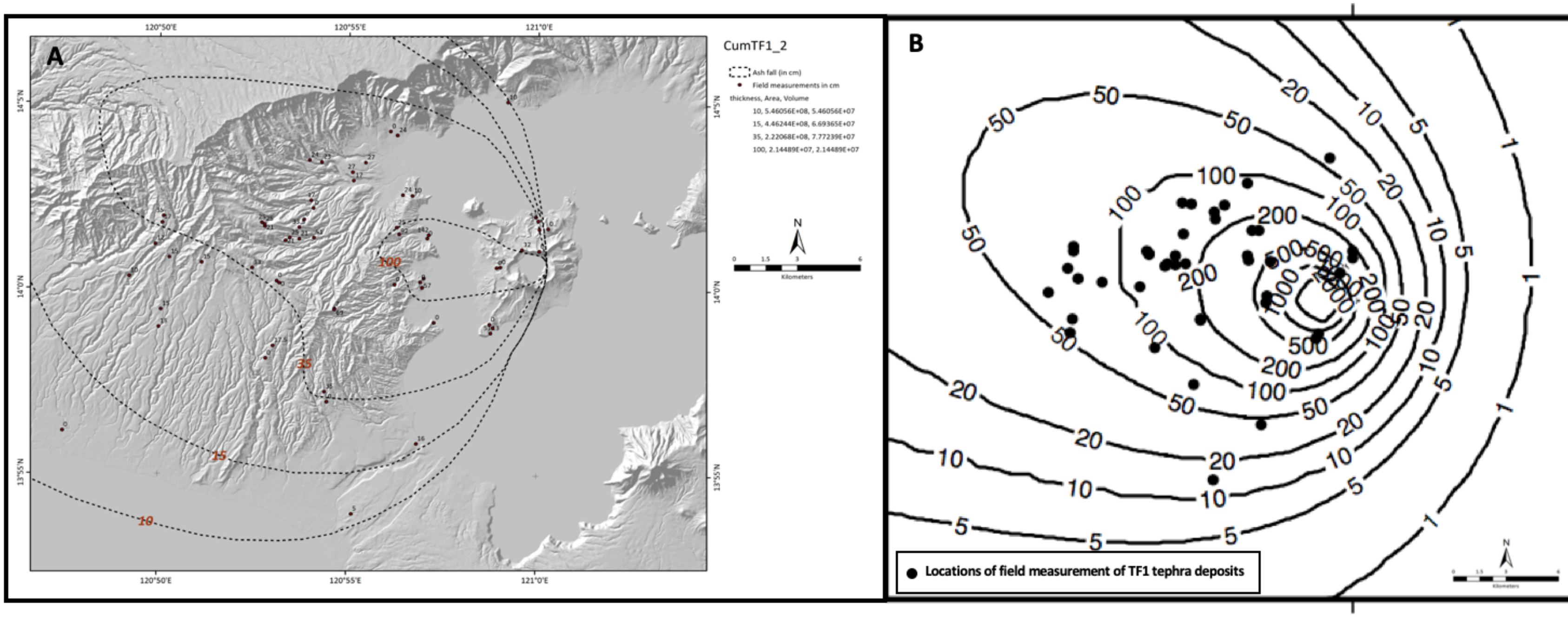


Figure 6.8. Comparison of dispersal footprint of the field derived and simulated isopach maps (in centimeters) for the *TF1* phase of the AD1754 tephra fallout deposit. A) isopach map displays contour lines of areas of generally equal thickness from measured total thicknesses of *TF1* in 33-point locations mapped in the field; B) isopach map generated from forward modelling of best-fit eruption source parameters. The dots plot the locations of the tephra outcrop with TF1 layer. Both isopach maps show a west-northwest (WNW) dispersal pattern.

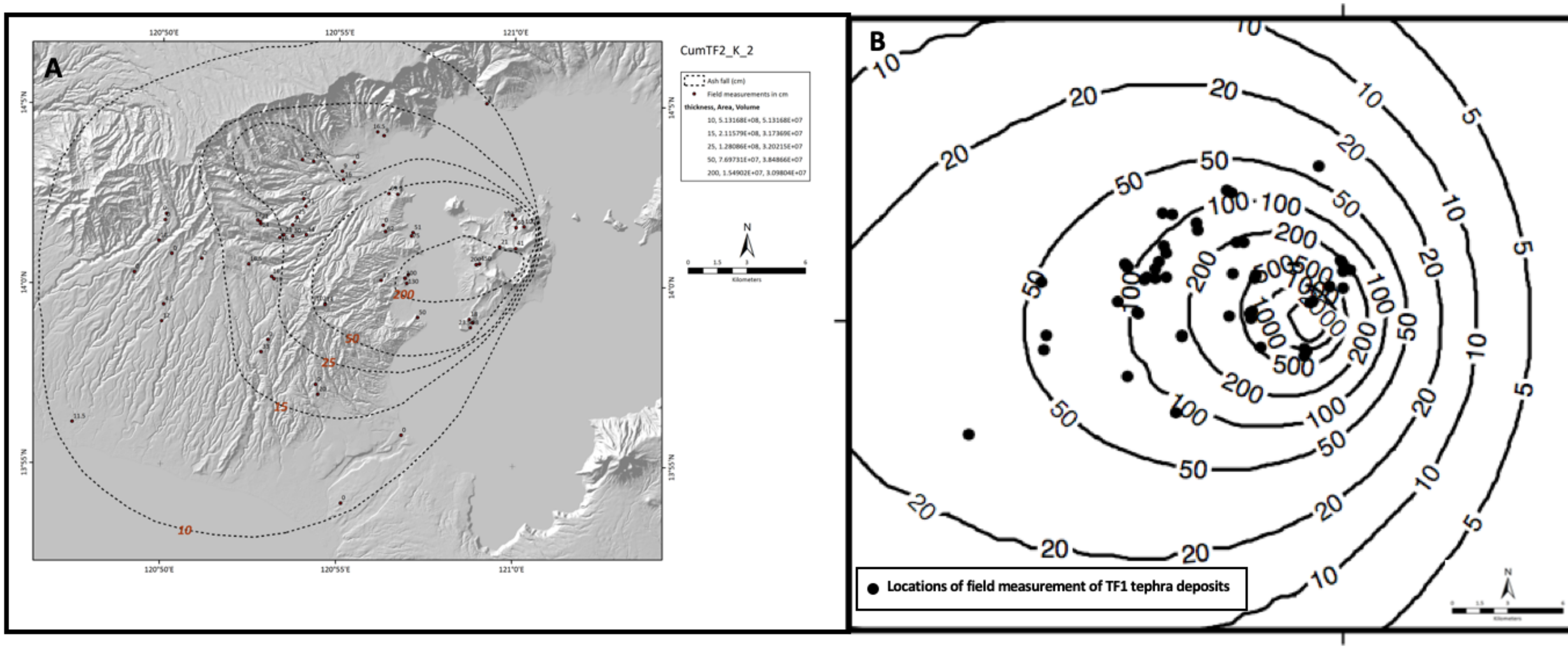


Figure 6.9. Comparison of dispersal footprint of the field derived and simulated isopach maps (in centimeters) for the *TF2* phase of the AD1754 tephra fallout deposit. A) isopach map displays contour lines of areas of generally equal thickness from measured total thicknesses of *TF1* in 33-point locations mapped in the field, then interpolated using GIS, then manually corrected and re-digitised; B) isopach map generated from forward modelling of best-fit eruption source parameters. The dots plot the locations of the tephra outcrop with *TF2* layer. Both the isopach and isomass maps show a westly dispersal pattern validated by the point locations of the *TF2* outcrops.

The northwest directed dispersal of *TF1* in the isopach map from simulated data (Figure 6.8B) correlates well with the northwest tephra dispersal in the isopach map derived from measured exposures (Figure 6.8A) and conforms with interpretations of narrative descriptions of volcanic ejecta being propelled to the northwest, destroying Bayuyungan and Laurel (Saderra Masó, 1911) (Appendix B). Similarly, the isopach map created with best fit simulated data (Figure 6.9B) conforms well with the field-derived isopach map generated from thicknesses of the 33 data points for *TF2* (Figure 6.9A and suggests the same westerly dispersal of tephra as described in narrative accounts during the 28 November to 2 December phase (Saderra Masó, 1911; Worcester, 1912).

6.3.5. Comparison of measured and simulated thicknesses of tephra

Measured and simulated thicknesses for *TF1* (33 sample locations obtained from surveys conducted for this research and 10 from the DOST-PHIVOLCS 2013 survey data gathered prior to my research commencement, identified as N), and *TF2* (33 sample locations obtained from surveys conducted for this research and 9 from 2013 surveys) are listed in Table 6.5 and Table 6.6, respectively. Locations of these outcrops are shown in Figure 5.1. I also provided the difference and difference percentage for each location to determine if simulated values underestimated or overestimated measured values. In Bonadonna et al. (2005), it was stated that simulated results generally overestimated observed data. Where the difference percentage is less than 20%, whether positive (simulated is less than measured or observed thickness) or negative (simulated is greater than measured thickness), there is a good fit between simulated and measured thicknesses. In the case of the inversion results for *TF1*, 17 of the 43 simulation results had difference percentage of less than 20%. In the case of *TF2*, 16 of 50 simulation

Table 6.5. Comparison of measured and simulated thicknesses for *TF1* tephra deposits from the 15 May to 2 June AD1754 eruption of Taal (in meters). The locations are listed and divided based on distance from the vent: A) proximal (0 – 4 km); B) medial (4 – 6 km); and C) distal (6 - 20 km). Thickness information related to 20 additional tephra outcrops mapped in 2013 by DOST-PHIVOLCS prior to my study were included in the modelling, identified as *N1* to *N20*. Difference of simulated to measured values that are in blue print are overestimated. Difference percentage of more than 20% are highlighted in yellow.

From vent	No.	Location	Quadrant	Measured Thickness (cm)	Simulated Thickness (cm)	Difference	Difference Percentage (%)
A	39	Alas-as, San Nicolas	SW	51	48.6	2.4	5
	40	Alas-as, San Nicolas	SW	49	44.3	4.7	11
	27	Daang Kastila, TVI	N	53	8.9	44.1	496
	28	Daang Kastila, TVI	NW	32	31.4	0.6	2
	29	Daang Kastila, TVI	N	7	10.3	-3.3	-32
B	6	Banyaga, Agoncillo	SW	190	185.7	4.3	2
	26	Bilibinwang, Agoncillo	W	178	157.1	20.9	13
	15	Busobuso-Gulod Boundary, Laurel	W	92	82.9	9.1	11
	N16	Busobuso, Laurel	W	142	141	1	1
	N13	200 m from Busobuso marker	W	25	71.4	-46.4	-65
C	30	Taal Volcano Observatory (TVO), Buco, Talisay	N	10	1.1	8.9	809
	25	Barigon, Agoncillo	W	69	47.1	21.9	46
	36	Barigon, Agoncillo	W	7	47.1	-40.1	-85
	22	Leviste, Laurel	NW	24	7.6	16.4	216
	N11	San Gabriel, Laurel	NW	17	20	-3	-15
	5	Pansipit, San Nicolas	SW	16	10	6	60
	24	As-is, Laurel	NW	10	35.7	-25.7	-72
	31	Bugaan East, Laurel	NW	24	32.9	-8.9	-27
	4	As-is, Laurel	NW	27	14.3	12.7	89
	23	As-is, Laurel	NW	27	17.1	9.9	58
	12	Matandang Gubat, Ticub, Laurel	W	51	31.4	19.6	62
	13	Culit, San Gregorio, Laurel	W	33.5	25.7	7.8	30

N9	San Gabriel, Laurel	W	17	21.4	-4.4	-21
11	Ticub, Laurel	W	21	25.7	-4.7	-18
33	San Jacinto, Agoncillo	SW	35	24.3	10.7	44
N6	Ticub, Laurel	W	25	27.1	-2.1	-8
N7	Ticub, Laurel	W	21	28.6	-7.6	-27
2	As-is, Laurel	NW	24	12.1	11.9	98
3	As-is, Laurel	NW	23	12.9	10.1	78
14	Culit, San Gregorio, Laurel	W	21	21.4	-0.4	-2
N3	Lubluban, San Gregorio, Laurel	W	25	20	5	25
N4	Lubluban, San Gregorio, Laurel	W	25	20	5	25
8	Masalisi, Lemery	W	17.5	27.1	-9.6	-35
1	Cawit, Taal	SW	5	5.4	-0.4	-7
10	Niogan, Lemery	W	33	24.3	8.7	36
16	Cahil, Calaca	W	35	12.3	22.7	185
17	Sitio Matala, Cahil, Calaca	W	17	12.7	4.3	34
18	Cahil, Calaca	W	12	13.7	-1.7	-12
N2	Bambang, Calaca	W	15	18.6	-3.6	-19
20	Madalunot, Calaca	W	15	17.1	-2.1	-12
21	Matipok, Calaca	W	15	17.1	-2.1	-12
N1	Matipok, Calaca	W	15	15.7	-0.7	-4
19	Calaca	W	10	13.6	-3.6	-26

Table 6.6. Comparison of measured and simulated thicknesses of *TF2* tephra deposits from the November AD1754 phase (in meters). The locations are listed and divided based on distance from the vent: A) proximal (0 - 4 km); B) medial (4 - 6 km); and C) distal (6 - 20 km). The key bed layer (*K)* consists of fine-grained tephra fallout deposits that forms a layer underlying some *TF2* deposits. Thickness information related to 20 additional tephra outcrops mapped in 2013 by DOST-PHIVOLCS were included in the modelling, identified as *N1* to *N20*. Difference of simulated to measured values that are in blue print are overestimated. Difference percentage of more than 20% are highlighted in yellow.

From vent	No.	Location	Quadrant	Measured Thickness (cm)	Simulated Thickness (cm)	Difference	Difference Percentage (%)
A	34	Daang Kastila, TVI	N	41	41.4	-0.4	-1
	28	Daang Kastila, TVI	NW	21	71.4	-50.4	-71
	37	Alas-as, San Nicolas	W	200	314	-114	-36
	38	Alas-as, San Nicolas	W	450	286	164	57
	29	Daang Kastila, TVI	N	33	25.7	7.3	28
	N20	Daang Kastila, TVI	N	100	20	80	400
	27	Daang Kastila, TVI	N	103	21.4	81.6	381
	N19	Daang Kastila, TVI	N	30	21.4	8.6	40
	N18	Saluyan, Pulang Bato, TVI	SW	18	131	-113	-86
	39	Alas-as, San Nicolas	SW	75+36	111	0	0
	40	Alas-as, San Nicolas	SW	64+34	90	4	4
B	6	Banyaga, Agoncillo	SW	124	106	18	17
	26	Bilibinwang, Agoncillo	W	130	103	27	26
	N14	Banyaga, Agoncillo	W	100	100	0	0
	N15	Banyaga, Agoncillo	W	75	75.7	-0.7	-1
	N16	Busobuso, Laurel	W	51	71.4	-20.4	-29
	N17	Bilibinwang, Agoncillo	SW	50	85.7	-35.7	-42
	15	Busobuso-Gulod Boundary, Laurel	W	62	52.9	9.1	17
	N12	Bilibinwang, Agoncillo	W	37	67.1	-30.1	-45
C	30	Taal Volcano Observatory (TVO), Buco, Talisay	N	3	34.3	-31.3	-91

25	Barigon, Agoncillo	W	102	30	72	240
36	Barigon, Agoncillo	W	7+7	30	-16	-53
22	Leviste, Laurel	NW	9	11.7	-2.7	-23
24	As-is, Laurel	NW	9	32.9	-23.9	-73
31	Bugaan East, Laurel	NW	69	31.4	37.6	120
35	Balaquilong, Laurel	N	65+10	11.1	63.9	576
23	As-is, Laurel	NW	9	18.6	-9.6	-52
N11	San Gabriel, Laurel	NW	16	20	-4	-20
12	Matandang Gubat, Ticub, Laurel	W	34	25.7	8.3	32
N9	San Gabriel, Laurel	W	32	20	12	60
N10	San Gabriel, Laurel	W	31	21.4	9.6	45
N7	Ticub, Laurel	W	30	22.9	7.1	31
N8	San Gabriel, Laurel	W	25	21.4	3.6	17
13	Culit, San Gregorio, Laurel	W	21	21.4	-0.4	-2
N6	Ticub, Laurel	W	21	21.4	-0.4	-2
32	San Jacinto, Agoncillo	SW	20	12	8	67
11	Ticub, Laurel	W	16	21.4	-5.4	-25
9	Payapa, Lemery	W	19	21.4	-2.4	-11
N5	Payapa Ilaya, Lemery	W	16	20	-4	-20
2	As-is, Laurel	NW	25	14.1	10.9	77
3	As-is, Laurel	NW	24	14.3	9.7	68
N4	Lubluban, San Gregorio, Laurel	W	21	17.1	3.9	23
N3	Lubluban, San Gregorio, Laurel	W	17	17.1	-0.1	-1
14	Culit, San Gregorio, Laurel	W	14	17.1	-3.1	-18
10	Niogan, Lemery	W	16.5	17.1	-0.6	-4
7	Masalisi, Lemery	SW	33	13.9	19.1	137
20	Madalunot, Calaca	W	12	9.71	2.29	24
21	Matipok, Calaca	W	4.5	10.3	-5.8	-56
18	Cahil, Calaca	W	10	10.4	-0.4	-4
41	San Rafael, Calaca	SW	11.5	4.43	7.07	160

results had difference percentage of less than 20%. Therefore, more point locations in *TF1* have difference percentage of less than 20% compared to *TF2* indicating a better fit between measured and simulated results.

The proximal outcrops of the AD1754 tephra fallout deposits were very limited, especially for *TF1,* and may be due in part to erosion and remobilisation resulting from subsequent major eruptive activities (e.g. *TF2* phase of AD1754 and the AD1911 eruption) centered at the Main Crater (Saderra Masó, 1911). As discussed in Section 6.2.2, remaining tephra outcrops might not reflect the true emplacement due to erosion, either during or in succeeding eruptions, or by precipitation. Spanu et al. (2016) acknowledged such difficulties in sampling tephra deposits in very proximal and very distal areas.

Table 6.7 provides the summary range of measured and simulated thicknesses for *TF1* and *TF2*. A general comparison of the range of measured and simulated thicknesses showed that for proximal distances, measured range of thicknesses was 7.0 to 53 cm while simulated results provide a range of 8.9 to 48.6 cm for *TF1*. On the other hand, for *TF2*, measured thicknesses of in proximal distances ranged from 18.0 to 450 cm while simulated thicknesses ranged from 41.4 to 314 cm. In medial distances, *TF1* results showed that measured thicknesses ranged from 25 to 190 cm while simulated thicknesses ranged from 71.4 to 185.7 cm. The *TF2* results showed thicknesses ranged from 50 to 130 cm while simulated thicknesses ranged from 71.4 to 106 cm. Comparison of tephra thicknesses in distal areas showed measured values ranged from 5 to 69 cm and 1.1 to 47.1 cm for simulated thicknesses for *TF1*. On the other hand, measured values ranged from 3 to 100 cm and 4.43 to 67.1 cm for simulated thicknesses for *TF2*. The does not seem to be a general or very strong indication that simulated thicknesses overestimated or underestimated measured thicknesses.

Table 6.7. Summary range of thicknesses from field measurements and numerical simulations. The locations are listed and divided based on distance from the vent: A) proximal (0 - 4 km); B) medial (4 - 6 km), and C) distal (6 - 20 km). A) measured thicknesses in proximal, medial and distal locations of tephra accumulation mapped in the field for *TF1* and *TF2*; and B) simulated thicknesses for proximal, medial and distal locations for *TF1* and *TF2*. Thicknesses in meters.

Radial distance from vent (km)		**Thickness** *TF1* **Results (cm)**	*TF2* **Results (cm)**
A. Measured Thickness			
Proximal	1-4	7.0 to 53.0	18.0 to 450+
Medial	4-6	25.0 to 190.0	50.0 to 130.0
Distal	6-16	5.0 to 69.0	3.0 to 100.0
B. Estimated Simulated Thickness			
Proximal	1-4	8.9 to 48.6	41.4 to 314.0
Medial	4-6	71.4 to 185.7	71.4 to 106.0
Distal	6-16	1.1 to 47.1	4.43 to 67.1

6.4 Modelling limitations

In the process of conducting the numerical modelling, I encountered some challenges that I needed to overcome to be able to generate good simulation results. At the outset, I had to understand the simplifying assumptions made including the assumption that eruption column height is considered the average condition for the whole duration of the eruption, which is not in reality the case given that the height of the column generally varies with time (Connor and Connor, 2005). To address this challenge, eruptions can be subdivided into phases to consider the variations in column heights, grain sizes, wind speed and direction. This same reasoning was applied here such that in my findings that results of simulations for the eruption sequence as a whole were poor compared to results for individual phases. Further, the Phreatomagmatic phases of the AD1754 event, known for fuel-coolant interaction of magma with external water, resulted in the generation of dense tephra columns with distinct tephra jets. The tephra jets and subsequent deposition of the tephra may have resulted in the absence of distinguishable layers from the other identified phases of the eruption.

Mass, on the other hand, is generally more well constrained by inversion modelling and results agreed closely with those obtained using the geometric method of Pyle. Further, *TEPHRA2* does not account for temporal variation in wind velocities and direction, even though in reality, wind velocities can and generally varies during the entire duration of the eruption. In inversion, this is accounted for my varying wind conditions with height in the eruption column.

In general, best-fit between measured and simulated accumulation was observed in *TF1* for medial and distal locations and this is supported by the regression plot. For proximal point locations, there were limited outcrops of the AD1754 tephra fallout deposits for *TF1* and may be due in part to erosion and remobilization resulting from subsequent major eruptive activities (e.g. *TF2* and the AD1911 eruption) centered at the Main Crater (Saderra Masó, 1911).

While there was good correlation between field-derived measured thicknesses and particle sizes and the simulated results, more geological observations of AD1754 exposures would provide additional thickness and grain size measurements that could improve my findings. Further, identification of lithologic units during stratigraphic mapping was a challenge, especially when distinguishing co-ignimbrite ashfall sourced from pyroclastic density currents from tephra fallout deposits. More detailed stratigraphic mapping of the tephra units in the future might result in identification of additional phases of the eruption, unless the suggestion that missing deposits were washed away by heavy precipitation is true.

While identifying the challenges in the inversion modelling, I am confident that the output of the numerical modelling provided significant information that will form part of a hazard and risk assessment for Taal.

6.5 Discussion

As an integral part of this interdisciplinary study, *TEPHRA2* inversion modelling was performed using information gathered from earlier chapters in this study. The comprehensive review of historical eruptions, with a focus on the AD1754 event, provided some key information on dispersal and relative thicknesses of tephra fallout, as well as estimates of the eruption style, processes and products, eruption column heights, impacts of the tephra fall and the locations of these impacts. Furthermore, field-derived data obtained from geological investigations and laboratory analysis provided critical input parameters for inversion modelling, including stratigraphic information for 41 identified and mapped tephra exposures (e.g. lithological unit identification, thickness measurements), grain size information (e.g. median phi and standard deviation), and bulk density. Wind constraints (minimum and maximum speeds, and likely directions), specifically mean wind speeds used in the numerical modelling, were obtained from NCEP/NCAR Reanalysis.

TEPHRA2 was chosen as the appropriate model to use for this study because it was found to be applicable to multi-phased eruptions such as the plinian/subplinian AD1754 eruption and because it has been used extensively in inversion modelling studies. Two specific objectives of the inversion modelling were: 1) to obtain best-fit eruption source parameters using inversion methods for the two identified phases of the AD1754 eruption; and 2) validate and compare the results of numerical modelling with empirical data from geological investigations.

Some key information for inversion modelling were considered in order to obtain good results. At least 61 tephra exposures (41 new outcrops during 2014 and 2016 field investigations and 20 from 2013 DOST-PHIVOLCS mapping prior to my research) were used as input data for modelling. Forty three of these exposures included tephra from the *TF1* phase (15 May to 2 June AD1754) and 49 exposures included tephra from the *TF2* phase (November AD1754). Multiple model runs were conducted for *TF1*, *TF2* and combined thicknesses as a single set. While I conducted analysis of inversion results from a single data set combining *TF1* and *TF2*, I believe that separating simulation by phases helped to address the problem of variation in eruption source parameters throughout the whole duration of the event.

From the inversion and subsequent forward modelling using best-fit parameters, I was able to obtain some significant results. The best-fit eruption source parameters determined for *TF1* and *TF2* included eruption column heights (above sea level) for *TF1* of 39,283 m and 37,423 m for *TF2*. The simulated heights conform well with the VEI 5 classification for the AD1754 eruption and narrative descriptions.

The total simulated mass obtained for the *TF1* phase was 1.52×10^{11} kg, equivalent to a volume of 217 million m^3 using a density of 700 $kg \cdot m^{-3}$. The total simulated mass obtained for *TF2* phase was 1.63×10^{11} kg, equivalent to a volume of more than 233 million m^3 using the same density. Combining the simulated masses provided a total of 3.15×10^{11} kg, equivalent to a total volume for *TF1* and *TF2* of more than 450 million m^3. The previous estimated total volume of all erupted materials during the AD1754 eruption was only 150 million m^3. The greater volume is reasonable considering historical accounts described a wide dispersal of tephra fallout and tephra reportedly falling in Metro Manila. The increase in the estimated volume of erupted materials implies more extensive hazard dispersal and accumulation, which will consequently generate more devastating impacts to communities around Taal and further afield.

*Md*ϕ obtained from grain size analysis of the tephra samples ranged from-3.0 to -1.5 for *TF1* and -2.5 to 0.5 for *TF2*. The best-fit inversion results for *Md*ϕ were -1.5 for *TF1* and -0.5 for *TF2*. The *Md*ϕ for various locations that were also obtained from the inversion showed that almost all of the simulated median sizes for *TF1* and *TF2* were in the -2.0ϕ to greater than -1.0ϕ range, with the simulated median particle size generally finer or equal in size to that measured. The simulated *Md*ϕ values were generally observed to underestimate the amount of coarser tephra in proximal and medial locations, while in distal reaches, measured *Md*ϕ values were equal or finer than simulated results. The coarser *Md*ϕ for field-derived grain size for both *TF1* and *TF2* is most likely due to the limited mapped point locations in distal areas that could have resulted in a bias towards coarser particles. The *Md*ϕ values from inversion of grain size were not affected by this bias because all sizes were simulated between 7 and -7 ϕ.

The $\sigma\phi$ obtained from empirical results for tephra samples (1.13ϕ to 2.84ϕ for *TF1* and 1.03ϕ to 1.81ϕ for *TF2*) also has good correlation with simulated results (1.84ϕ for TF1 and 1.5ϕ for TF2). Overall, the most significant observation when comparing the median and sigma ϕ values was that the tephra particles in *TF2* have finer sizes than those from *TF1*. This could imply that while both phases were classified as plinian/sub-plinian, the *TF2* eruptive phase was more explosive than the *TF1* phase.

Comparison of isopach maps from solely field derived thicknesses and from simulations allowed me to make some significant observations. The dispersal patterns showed that both maps had a west-north-west directed pattern for *TF1* and a westward directed dispersal for *TF2*. The northwesterly direction of dispersal for *TF1* conforms with the interpretation of narrative descriptions of volcanic ejecta being propelled to the northwest, destroying Bayuyungan. The westerly dispersal shown by the maps for the *TF2* eruptive phase also conforms narrative accounts during the 28 November to 2 December phase of the AD1754 event.

The regression of measured versus simulated accumulation (mass per unit area) for *TF1* had a correlation coefficient of 0.93832 and 0.7833 for *TF2*. The regression plot for *TF1* showed a better fit since the correlation coefficient was closer to 1. There is room for improvement for the results of *TF2*, particularly with the addition of outcrops from further geological investigations.

Measured and simulated thicknesses were also compared with distance. In general, best-fit between measured and simulated accumulation is observed in the *TF1* values for medial and distal point locations and this is supported by the regression plot for measured and simulated accumulation. Poor correlation was found in proximal locations for *TF2* point locations. With the overall positive correlation between measured and simulated thicknesses obtained in this research, the *TEPHRA2* model is confirmed to be a viable tool to use for probabilistic modelling of an AD1754 type Plinian eruption, the current maximum expected event at Taal. In the context of eruptions at Taal in general, tall eruption columns may be generated even with larger median grain sizes, as was the case for the AD1754 eruption.

Comparison of the column heights and total erupted volumes of the AD1754 event could not be compared to other mafic eruption listed in Mastin et al. (2009) since no listed basaltic eruptions had VEIs greater than 4. The assigned VEI for the AD1754 eruption is 5 and may be considered to be higher.

6.6 Conclusion

Based on simulated results, some of the municipalities that may be significantly affected by a *TF1* type scenario with west-northwest tephra dispersal and accumulation would be TVI itself (part of Talisay and San Nicolas), Laurel, Agoncillo, San Nicolas, Taal, Lemery and Calaca, with thickness varying from 5 cm (Calaca) to as much as 185 cm (TVI).

One particular study on resistance threshold to tephra loading conducted in the Vesuvius area showed that the resistance thresholds above which there is potential for roof collapse are as follows: 200 $kg{\cdot}m^{-2}$ for wood, 300 $kg{\cdot}m^{-2}$ for steel joist, and 400 $kg{\cdot}m^{-2}$ for reinforced concrete slab roofs (Spence et al., 2005). Another study on the effects of ash loading in New Zealand further provided an estimate of relative thickness to resistance values. A minimum tephra loading of ~15 cm can result in roof collapse and tephra thickness of ~70 cm for roof collapse for all buildings, given a deposit density of 1000 $kg{\cdot}m^{-3}$ was estimated by Bonadonna et al. (2005). The relative strengths of housing structures in the provinces, including Batangas may not always meet international building standards while buildings generally conform and apply the National Building Code of the Philippines. As such, housing structures near Taal may fail even under smaller thicknesses.

On the other hand, a *TF2* type scenario of tephra dispersal and accumulation (westerly wind drift) would significantly impact almost the same communities with estimated tephra thicknesses from 5 to 290 cm. Overall, considering an AD1754 type scenario occurring at the present time would result in catastrophic impacts, particularly considering the increased population and urbanisation in the areas that were greatly impacted by the AD1754 events.

Tephra hazard affects a wide area compared to other eruptive products (Scott, 1989; Thompson etal., 2017), and tephra from a Plinian type eruption at Taal may again reach Metro Manila. One critical and major impact of airfall tephra is the disruption it can cause to civil aviation operations (Alexander, 2013; Carslaw et al., 2012; Casadevall, 1994; Casadevall et al., 1996; Guffanti et al., 2005; Guffanti et al., 2009; Sulpizio et al., 2012; Tupper et al., 2006; Volentik & Houghton, 2015). An eruption at the present time, would be expected to disrupt aviation operations at Ninoy Aquino International Airport, and possibly also around the region. Further, the impacts of tephra accumulation on the lives and livelihood of the Taal communities must be seriously considered, especially for areas predicted to be significantly affected by tephra fall. The tephra fallout reportedly experienced in Metro Manila during the AD1911 event occurred during the same wind condition as the AD1754 Plinian type eruption scenario. Identified tephra fallout impacts based on recent eruptions worldwide include effects on agricultural crops via acid burning and burial, human and animal health issues through prolonged exposure to ash, destruction of critical buildings and infrastructure, damage to the environment, flora and fauna, water supply, transportation services, tourism, manufacturing and industry. These impacts were discussed in detail in Chapter 2, Section 2.5.1. Perhaps one critical issue pertaining to manufacturing and industry is the fact that for the *TF1* scenario, the predicted dispersal of tephra is estimated to reach the Municipality of Calaca, one of Batangas Province's major industrial parks. This industrial park in Calaca produces and distributes power, fuel, other petroleum products, industrial chemicals and salt; manufactures steel, dairy and beverage, bakery and confectionery, paints, textiles, food specialties and commodities; and provides warehousing, storage services, and construction supplies, all with a minimum declared approved investment of more than PhP14 billion (~AUD370 million). In the event of the occurrence of an explosive eruption, where tephra is dispersed to the southwest, contamination may result in disruption of manufacturing, resulting in interruption of supply and distribution that would have a domino effect on the industries where these supplies are distributed and utilised. As it now stands, most of these facilities have not largely considered impacts from volcanic eruptions, much less considered preventive production actions.

The inversion modelling implemented in this study addressed Research Question 1 and Research Question 2, and provides information for Research Question 3.

Critical modelling results include determination of best-fit eruption source parameters for the AD1754 eruption, likely distribution and thickness of tephra fall during future plinian type eruption with similar wind conditions as the AD1754 that may be considered in the development of DRR strategies related to tephra dispersion to potentially threatened communities and critical facilities. Further, with successful application of *TEPHRA2* in simulating the AD1754 eruption, the model is now confirmed as a viable tool for tephra fall hazard assessment. Using the derived eruption source parameters as a maximum expected event scenario for a plinian-type eruption at Taal, probabilistic modelling is the next step in tephra hazard assessment (Bonadonna et al., 2005; Magill et al., 2006; Hurst & Smith, 2010; Marzocchi & Bebbington, 2012; Yu et al, 2013).

In terms of hazards and risk management perspective, after understanding disaster risk by the identified potential dispersal and sedimentation based on modelling results, the next step reducing losses must now be considered that would require disaster risk reduction management offices to strengthen disaster risk governance in managing risk such as considering the potential loading threshold of infrastructures and health risk of tephra hazard, and developing and practicing resilience through disaster preparedness and drills in communities likely to be affected using the scenarios utilised for this research.

Future research on the utilisation of *TEPHRA2* and inversion methods should include: 1) further field-based research to search for additional tephra outcrops from the AD1754 event over a wider area, specifically, more proximal and distal locations to obtain additional thickness information for critical parts of the deposit, currently lacking information; 2) conduct additional dating methods to validate anecdotal recognition of the AD1754 deposits; 3) conduct more inversions for individual phases as more geological information (e.g. thickness measurements) becomes available; 4) conduct more inversions with improved grain size distribution data, especially for *TF2*; 5) conduct probabilistic modelling to determine tephra fall hazard and risk and assist management at Taal; 6) conduct inversion simulations for other explosive eruptions of Taal; 7) conduct comparative assessments of *TEPHRA2* results with other tephra dispersal models, such as *Fall3D* (Folch et al., 2009; Folch et al., 2012) in order to determine which provides more accurate results in terms of replicating past eruptions; and 8) apply tephra modelling approaches to other active volcanoes in the Philippines.

CHAPTER 7

The knowledge, education, awareness and preparedness of Barangay Captains: preliminary insights

7.0 Introduction

This chapter presents results and interpretations that address Research Questions 3: *How would a major/plinian eruption affect communities around Taal Volcano?* and Research Question 4: *Given that the barangay captains and their communities are located on or close to an active volcano like Taal, and as the key stakeholder in the community, how are the barangay captains responding to volcanic risk? What is the level of education, knowledge, experience, risk perception and preparedness of these specific stakeholders?*

With the potential for another explosive eruption at Taal, the Philippine government and its associated volcano disaster management agencies, are concerned about the likely socio-economic impacts of a catastrophic eruption to the region and its communities. A repeat of an AD1754 eruption would now directly impact more than 5,000 residents living on TVI and a further 1 million people living in the broader 20 km radius. Addressing the abovementioned questions permits me to gauge the ability of the Barangay Captains for supporting their communities during a volcanic emergency. Likewise, the outcome could identify the issues that may serve as hindrance to their capacity and capability to serve their mandated DRR responsibilities. The process to obtain the results discussed in this Chapter follows the process flow illustrated in Figure 7.1.

Eight out of ten Barangay Captains were selected because of the proximity of their communities to Taal. However, one respondent living on the east side of the volcano at an approximate distance of 15 km and one in a distal community to the south at a distance of 27 km (and barely effected by past eruptions) is included for comparative purposes. Table 7.1 lists the municipalities/cities, barangays and distance of each community to the main vent of the volcano and their locations are shown in Figure 7.2.

7.1 Demographic characteristics of the Barangay Captains

Bird et al. (2009) wrote that demographic data can position participants relative to others and may reveal information related to their knowledge, feelings and perceptions about hazards and risks. Some basic information on the demographic characteristics of the respondents surveyed include age, gender, marital status, highest level of education, current occupation and duration of residency at their current address (Table 7.2).

7.2 Presentation of results and discussion of their meanings

In the following sections, I will discuss the key elements (e.g. education, knowledge, experience, issue of taking volcanic risk seriously, and their preparedness) selected to gauge the preparedness of the Barangay Captains for supporting their communities during a volcanic emergency.

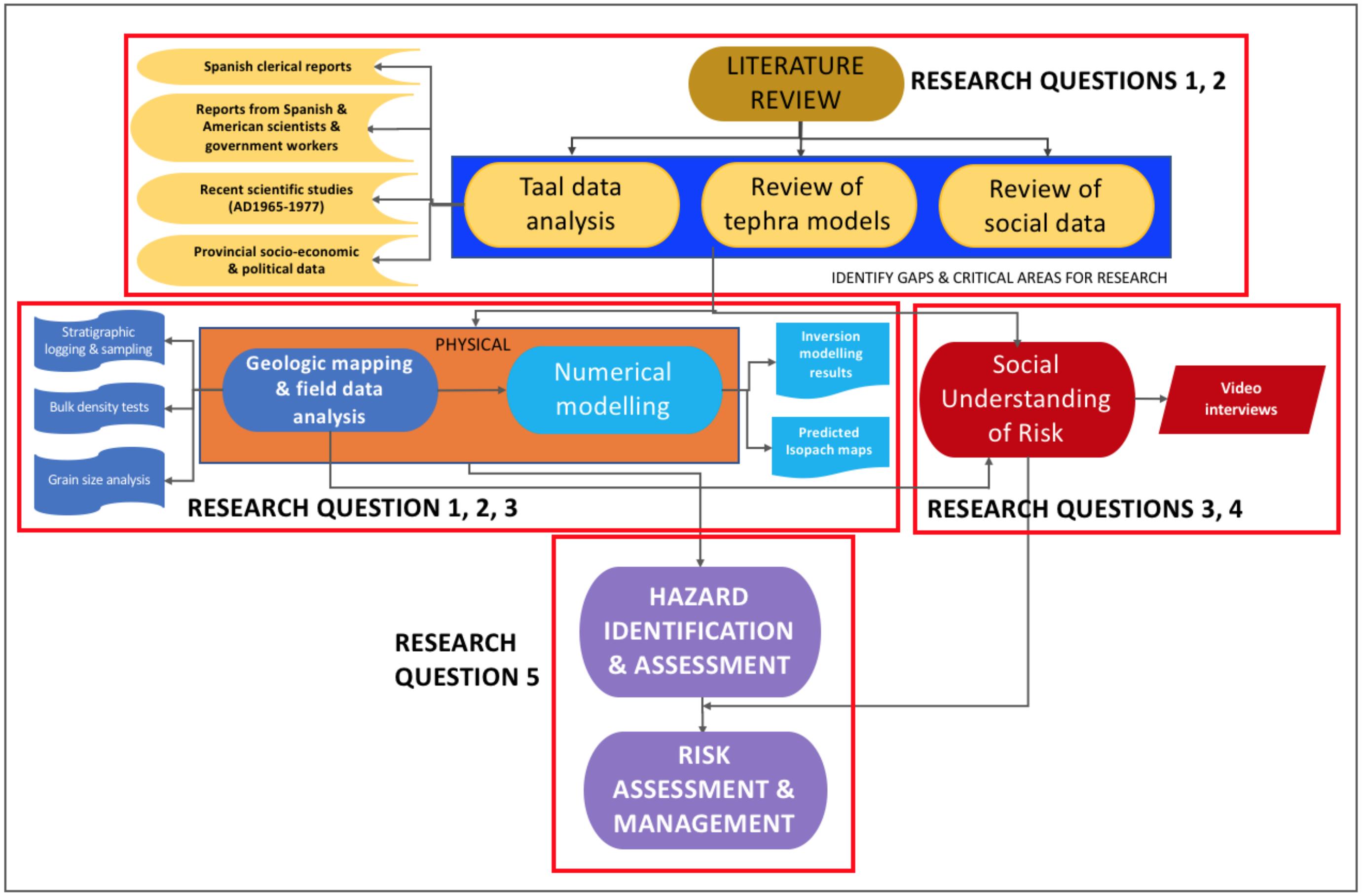


Figure 7.1. Research process flow for this interdisciplinary study at Taal.

Table 7.1. List of the Barangay Captains surveyed and interviewed for this study. Three Barangays Captains reside at TVI while the other seven live in communities on the mainland. Acronyms: N- North; NW- Northwest; W- West; SW- Southwest; S- South; SE- Southeast; NE- Northeast.

RESPON-DENT NO.	RESPON-DENT CODE	NORTHING	EASTING	DISTANCE (km)/ DIRECTION FROM THE VENT	MUNICIPALITY	BARANGAY	POSITION
1	GE001	1552834.42	285028.5	2.5/NE	Talisay	Pira-piraso- TVI	Officially considered as Sitio Leader but known as Barangay Captain
2	GE002	1558096.93	282465.38	~9/N	Talisay	Buco	Barangay Captain
3	GE003	1556589.81	277597.75	~9/NE	Laurel	Leviste	Barangay Captain
4	GE011	1541495.6	293519.49	~12.5/E	Lipa City	Duhatan	Barangay Captain
5	GE015	1555735.52	292125.38	~10.5/NE	Tanauan City	Wawa	Barangay Captain
6	GE019	1541117.71	278312.73	~10.5/SW	San Nicolas	Poblacion	Barangay Captain
7	GE028	1543091.02	277772.05	~9/SW	Agoncillo	Subic Ibaba	Barangay Captain
8	GE035	1552720.97	283397.21	~2/N	Talisay	San Isidro-TVI	Officially considered as Sitio Leader but known as Barangay Captain at TVI
9	GE044	1525714.93	284113.95	~30/S	Bauan	Poblacion2	Barangay Captain
10	GE050	1550229.09	280918.95	~2/SW	San Nicolas	Alas-as- TVI	Barangay 1st Councilor

Figure 7.2. Map showing locations of communities where Barangay Captains were interviewed. Numbers in blue represent the respondent numbers listed in Table 7.1.

Table 7.2. Summary of key personal characteristics asked of the ten respondents.

INTERVIEW QUESTIONS	RESPONSES/IMPLICATIONS
Participant's age	The Barangay Captains (BCs) were within the age ranges 40-55 (50%) and 56-65 (50%), considered older community members closer to retirement age.
Participant's gender	Nine out of ten BCs were male. Filipino society is generally patriarchal.
Marital status	Eight BCs were married with children, one was separated and one was single. All respondents have dependents living with them.
Highest level of education	Two BCs did not complete high school, six completed high school level and 2 finished undergraduate degrees, with one further holding a postgraduate degree. Average highest educational attainment of Filipinos was elementary to high school level (PSA, 2018).
Current occupation including part-time job	Seven of the respondents were officially elected barangay captains, two were Sitio Leaders acting as BCs for their communities (at TVI), and one was the elected 1st Councilor (Kagawad in Filipino) acting as head of the community when the BC is away.
Duration of residency	All BCs owned their current residence and had lived there since birth.

The summary of the key responses related to these elements and their meanings are provided in Appendix J. The responses are separated into "positive" or "negative" aspects that support or contradict the hypothesis.

7.2.1. On the education of the Barangay Captains

Education is listed as one criterion for designating authority in a community, along with the background, experience, local knowledge of a potential community leader (Donovan et al., 2012). The majority (80%) of the respondents were Elementary or High School graduates. Only two had completed an undergraduate degree, with one of the two respondents further completing a post graduate degree. That said, these levels of education mirror provincial and national levels of education (see Section 2.1.2 of Chapter 2, Table 2.2). As such, it is possible to say that the level of education attained by the Barangay Captains is typical of the highest attained level of education in relation to community norms and may be deemed acceptable to the community they serve.

However, in the study conducted by Barberi et al. (2008, p. 255), it stated that *"older residents and those with higher levels of education tended to be less confident in their own preparedness and that of the government officials, were less confident in the success of the evacuation plan, less satisfied with the amount of information they had about the threat, and less trusting with regard to scientists', government officials', or the media's ability to provide accurate information about a potential eruption".* Further, Wilkinson (2015) observed that as disaster risk governance in Montserrat evolved, it was realised that there is a need for a more comprehensive disaster management mentality with a clear governance structure and with inclusive training and education on DRRM at all levels.

Barangay Captains responses included:

> "*High School lang ho. Apat na buwan akong nag college. Bata akong nag-asawa.*" (High school only. Stayed in college for four months. Got married early.) (GE02/#2) (NEGATIVE)

> "*High School lang, third year high school."* (High school only, third year high school.) (GE04/#4) (NEGATIVE)

> "*High School. Nag college, di naman naka isang sem eh*." (High School. I went to college but did not even finish my first semester.) (GE06/#6) (NEGATIVE)

> "*High school graduate lang po.*" (High school graduate only.) (GE07/#7) (NEGATIVE)

> "*High School lang po.*" (High school only.) (GE10/#10) (NEGATIVE)

The mention of '*lang*' (only) is a common Filipino word used when the person talking feels the thing they are discussing is inadequate. Perhaps these Barangay Captains themselves were not confident that the level of education they have attained was adequate for the responsibility of their position. I therefore saw this low level of education as 'negative' in relation to their role as Barangay Captains.

I considered additional 'education' gained from attendance at seminars, training sessions and other specific volcano DRR-related events as a 'positive' aspect if the training received was translated to increased capacity and all ten barangay captains were recipients of one or more volcano-related educational campaigns. That said, whether the knowledge imparted was translated to knowledge that will equip the Barangay Captains in their roles must still be questioned. Evaluation of the application and effectiveness of the knowledge learned from volcano related seminars and trainings will be discussed in Sections 7.2.2 and 7.2.4.

7.2.2. What is the Barangay Captains' knowledge about volcanic hazards and risk?

Barangay Captains were asked if they think they will be directly affected by a future eruption and to identify the hazards that they perceive will affect their communities. Nine Barangay Captains believed they and their communities may be affected by one or more volcanic hazards (Table 7.3). The following sections provide the responses and discussion on their responses for each individual hazard identified. Specifically, I indicate if their responses are positive (blue font) or negative (red font).

7.2.2.1. Hazard threat from pyroclastic density currents (PDCs)

The assessment of threat from PDCs was based on the DOST-PHIVOLCS base surge hazard map (see Figure 2.10, Section 2.3.3. in Chapter 2). In general, the Barangay Captains are familiar with the maps since all participants have attended at least one information and education campaign on volcanic hazards in the past. However, during the interviews, the DOST-PHIVOLCS generated volcano hazard maps were presented to the participants. One Barangay Captain was sure his community was safe from PDCs and this perception is validated in Table 7.3. The majority of the Barangay Captains (six out of nine) were knowledgeable about PDCs' threat to their communities (Table 7.3). When asked about PDC/base surge hazard, some respondents stated for example:

> "*Opo, abot ng surge. Abot daw ho nung nag seminar kami noon eh*." (Yes, base surge can affect us. Base surge can reach this place based on the seminar I attended before.) (GE05/#5) (POSITIVE)

> "*Maaapektuhan po tayo dito. Aba'y syempre ho*!" (We will really be affected here) (Yes, we can be affected here. Of course!) (GE07/#7) (POSITIVE)

> "*Ay lahat po! Napakalaking apektado*!" (Yes, all hazard! We will greatly be affected!) (GE08/#8) (POSITIVE)

> "*Ah yung matitigas po sa San Nicolas? Ahh, yun! Opo. Tingin ko po*." (The ones that are hard in San Nicolas? Oh, that one! Yes, I think so.) (GE10/#10) (POSITIVE)

Table 7.3. Actual and perceived (known to the Barangay Captains as generally threatening or may impact their communities) exposure to particular volcanic hazards. The Table summarises the responses of the Barangay Captains or their representative to question #21 ("*Do you think you will directly be affected if an eruption occurs again?*"). A list was provided to them of the major volcanic hazards that can be generated at Taal (e.g., pyroclastic density currents (PDCs)/base surge (BS), lava/ballistic projectile (BP), lahars, and tsunami/seiche hazard) and they were asked which of these hazards they perceive to threaten their communities.

RESPON-DENT #	RESPON-DENT CODE	VOLCANIC HAZARD									
		PDC/BS		LAVA/BP		TSUNAMI/ SEICHE		TEPHRA FALL		LAHAR	
		ACTUAL	PERCEIVED	ACTUAL	PERCEIVED	ACTUAL	PERCEIVED	ACTUAL/ AFFECTED DURING AD1754	PERCEIVED	ACTUAL/ ADJACENT TO RIVER	PERCEIVED
1	GE01	✓	✓	✓	x	✓ Shoreline	x	✓	✓	x	x
2	GE02	✓	✓	x	x	✓ Shoreline	✓	✓	✓	✓	✓
3	GE03	✓	x	✓Small portion	x	✓ Shoreline	x	✓	✓	✓	x
4	GE04	Partial	x	x	x	✓ Shoreline	✓	Possible but no tephra deposits found during mapping	✓	✓	x
5	GE05	✓	✓	x	x	✓ Shoreline	x	Possible but no tephra deposits found during mapping	✓	✓	x
6	GE06	✓	x	x	x	✓	✓	✓	✓	✓	x
7	GE07	✓	✓	x	x	✓ Shoreline	x	✓	✓	✓	✓
8	GE08	✓	✓	✓	x	✓ Shoreline	x	✓	✓	✓	✓
9	GE09	x	x	x	x	x	x	Possible with sudden shift in wind pattern	✓	x	x
10	GE10	✓	✓	✓	✓	✓ Shoreline	✓	✓	✓	✓	x

Note: The pyroclastic density current (PDC)/base surge (BS), lava/ballistic projectile (BP), and volcanic tsunami/seiche hazard delineation is based on the DOST-PHIVOLCS Volcanic Hazard Maps (Figures 2.9, 2.10 & 2.11). The tephra fall hazard delineation is based on the isopach map generated for this study that reconstructed the AD1754 eruption of Taal. The lahar proneness is based on proximity to an existing river channel that could be potential avenues for erosion and remobilisation of old and new sediments during or after an eruption in the event of severe precipitation on the volcano slopes. Hazards with check (✓) are identified hazards from DOST-PHIVOLCS maps (Actual) and from respondents (Perceived). Cross mark means no hazard identified. Shaded areas denote that perceived hazard by respondents conforms with actual delineated hazard. "Small portion" indicates that area threatened is less than half of the total barangay area while "partial" means hazard area is more or less half of the total barangay area.

While Respondent #10 did not observe PDCs in their community, he remembered noting the deposits in one municipality where PDC deposits are still preserved.

On the other hand, three out of the nine respondents whose communities may be affected are either not sure or think they will only be affected by PDCs. Negative responses are cited here:

> "*Baka, hindi ko ho sigurado kung aabot dito eh*." (Maybe, I am not sure if it will reach our side. (GE03/#3) (NEGATIVE)

> "*Hindi pa naapektuhan. Walang potensyal na maaapektuhan kami. Ang buga alam ko. Eh kasi nagagamit din ipader yun*." (We have not been affected yet. (No potential to affect us. I know scoria fall deposit. It could be used for construction of walls.) (GE04/#4) (NEGATIVE)

> "*Dito pa lang ho sa amin ay abo. Abo laang ang nakarating dito*." (In our place, it is only ash. Only ash reaches our area.) (GE06/#6) (NEGATIVE)

7.2.2.2. Hazard threat from lava flows and ballistic projectiles (BP)

Based on Table 7.4, three communities are directly threatened by lava flows and ballistic projectiles. Two of the three respondents whose communities are at risk did not identify this hazard. Respondent #1 (GE01) responded:

> "*Walang lava*." (No lava threat.) (NEGATIVE)

Respondent #8 (GE08) originally responded that they will be affected by all volcanic hazards as he stated:

"*Ay lahat po! napakalaking apektado*!" (Yes, all hazard! We will greatly be affected!) (POSITIVE)

However, he did not identify lava flows and ballistic projectiles as a hazard that can affect his community. Consequently, I consider his response negatively in relation to his knowledge of volcanic hazards. Of great concern about the lack of knowledge of these two Barangay Captains is the fact that both represent and serve communities that actually live on TVI and are actually at greatest risk.

7.2.2.3. Hazard threat from volcano tsunami

Most of the communities of the interviewed Barangay Captains are located along the shorelines of Taal Lake directly facing TVI or are directly located on TVI. Five out of nine respondents whose communities are at risk to tsunami inundation did not identify this as a hazard that threatens their communities (Table 7.3).

Of the four who identified volcano tsunami as a hazard that might potentially affect their community (Table 7.3), one Barangay Captain (GE02/#2) provided an inherited memory about a volcano tsunami that most likely occurred in AD1911 that was told to them by their grandfather:

"*Parang yung mga lolo ko po noon ang nagsabi na mas malala noon yung mga putok na mga nauna* (likely the 1911 eruption) *dahil may kinukwento po dito na yung ang mga bahay po dito nakapatong sa bato ang haligi... ang sabi eh nagkapalit palit ang mga bahay-'Aba bakit ka lumapit? Bakit nandito na bahay mo*?'- *Nung pagdating na ang tubig, nailipat ang kanilang mga bahay. Nung una pa, hindi 1965."* (I remember our grandfather told us that the impact of the previous eruption of Taal was worst. He said that the houses built over there with wall leaning on the stone, they said the houses moved. And they said –'Why did you house become closer? Why is your house here?' -He said when the waves came in, the houses moved, during the earlier eruption, not the 1965) (POSITIVE)

Inherited memories, serving as indirect experience of an eruption, can influence the behaviour and reaction of the participant in a positive or a negative way (Shibata, 2012; Swanson, 2008). In this case, the knowledge of potential impact of a tsunami acquired through inherited memories from their elders who directly experienced a tsunami event has guided the Barangay Captain on what to do (in this case go to higher ground). Another respondent acknowledged the threat and said:

> "*Ang nakakatakot eh yung nasa tabi lang na yun* (pointing to the shoreline) *dahil syempre pag sumulong nga yung lake eh apektado sila*." (It's really frightening especially our nearby lakeshore areas because if the lake water moves towards the shores, they will be affected) (GE07/#7) (POSITIVE)

On the other hand, when questioned about volcano tsunami, another Barangay Captain falsely believed their community is not threatened by this hazard saying:

> "*Delikado yan. Sabagay, dito naman ay walang tsunami dahil napakaliit ng dagat natin eh*." (Yes, that is really dangerous. Anyway, here, there will be no tsunami since our lake is so small.) (GE08/#8) (NEGATIVE)

7.2.2.4. Hazard threat from tephra fallout

All ten respondents correctly identified the risk from tephra fallout in their communities demonstrating excellent knowledge about this hazard (Table 7.4). Positive comments by Barangay Captains included:

> "*Abo, ayy yun po sigurado*!" (Ash, we will be surely affected by it!) (GE03/#3) (POSITIVE)
>
> "*Depende ho sa magiging sitwasyon, dahil pagka medyo malakas, mag-saboy siya ng gabok, maaabot talaga dito kasi malapit lang sa bulkan*." (It will depend upon the situation, because if the eruption is explosive, it will reach our place here since we are close to the volcano) (GE04/#4) (POSITIVE)
>
> "*Abo, oo*." (Yes, ash.) (GE05/#5) (POSITIVE)
>
> "*Abo laang ang nakarating dito*." (Only ash reaches our area.) (GE06/#6) (POSITIVE)
>
> "*Meron nyan*." (Yes, there is) GE07/#7) (POSITIVE)
>
> "*Ay, di abo na lang, siguro ash na lang*." (I think we can be affected by ash only) (GE09/#9) (POSITIVE)

7.2.2.5. Hazard threat from lahars

The risk to lahars is based on proximity to an existing river channel that could act as a conduit for the remobilisation of old and new sediments during or after an eruption in the event of severe precipitation (Table 7.3). Of the eight communities identified as being at risk from lahars, three barangay captains acknowledge potential for lahar encroachment. One Barangay Captain stated:

> "*Lalo na po ang lahar. Pag umagos yang lahar sigurado*!" (Especially lahars. When lahar flows are initiated, we will be affected for sure!) (GE08/#8) (POSITIVE)

Five Barangay Captains did not know about the potential for lahar encroachment. Some stating:

> "*Lahar? Wala dito*." (Lahar, there is no threat here.) (GE04/#4) (NEGATIVE)

> "*Baka naman po hindi na kami apektado ng lahar*. " (Maybe we will not be affected by lahars.) (GE03/#3) (NEGATIVE)

> "*Wala namang lahar dito*." (There is no lahar threat (GE06/#6) (NEGATIVE)

While to date, no lahar hazard maps have been generated by DOST-PHIVOLCS, I personally identified the risk to lahars based on my extensive field experience of lahar mapping and assessment (Table 7.3). With five out of nine Barangay Captains not knowledgeable about the potential threat of lahar encroachment, this can be a significant hindrance from the perspective of volcano DRR.

In summary, while the absence of knowledge of some of the Barangay Captains to the threat posed by some of the volcanic hazards may be disadvantageous to their DRR roles, the more threatening hazard, the PDCs, is known to 70% of the respondents, and all have knowledge of the potential threat of tephra fallout to their communities. In the methodological framework for managing volcanic threat (MIA-VITA, 2012), knowledge is a key factor to crisis management. With the results provided in Table 7.3, the Barangays Captains are therefore assessed as having general knowledge of volcanic hazards related to Taal Volcano.

7.2.3. What is the Barangay Captains' level of experience of past eruptions of Taal?

Wachinger et al. (2013) identified experience of natural hazards as one of the factors that have considerable impact on risk perception. Experiences of past disasters of older adults were explored that became reference points for preparedness and having a sense of 'mastery' on knowing what to do during a natural hazard crisis (Tuohy & Stephens, 2016, 2012). Eight respondents have experienced an eruption at Taal, one remembers experiencing tephra fallout from the 1991 Pinatubo eruption, and one has never experienced an eruption. Six respondents could recall specific details related to a particular eruption they witnessed, mostly the occurrence of ashfall or the smell of sulfur. Three respondents who experienced the AD1965 eruption were too young at the time of the eruption and had only vague, or no recollections of the eruption saying:

> "*Dalawang taong gulang palang. Wala akong maalala.*" (I was only two years old. Can't remember anything) (GE01/#1) (NEGATIVE)
>
> "*Nakaranas na ho. Yung 1965. Maliit pa ko*." (I experienced the 1965 eruption. Was very young back then) (GE06/#6) (NEGATIVE)
>
> *"Wala po basta, palibhasa ano eh batang isip pa kami nasa bundok. Nung primero kami nun eh tuwang tuwa. Tingin mo maliwanag!*" (Not much, since

we were just kids staying in the mountains. At first, we were very happy. It was so bright!). (GE02/#2) (NEGATIVE)

However, GE02 went on to say they only experienced tephra fallout and from their farm in the highlands but that they evacuated to Tagaytay:

"*Ash lang. Lumikas pa din po kami. Palibhasa naman po nung panahon na yun eh kakaunti pa lang ang sasakyan. Kanya-kanya pa naman lakarin noong panahon na yun. Bale tatlong buwan po kami sa Tagaytay. Tumira sa mga kamag-anak.*" (Ash only. We still evacuated to Tagaytay. During those times, there were very few vehicles. People went their own way walking during that time. We stayed in Tagaytay for three months. We stayed with relatives.) (GE02/#2) (POSITIVE)

"*Kami ho nung 1965 di naman kami masyadong. Nagkaroon kami ng konting abo lamang. Hindi ho malaki. Natatandaan ko pa nga ho nun, noong naglalakad kami diyan paakyat ng bundok na yan nakatapat saming ganun yung maitim na usok. Naisip ko lang ngayon, kung kako yun ay bumagsak sa amin mga naglalakad, marami hong mamatay. Maitim talaga, ang kidlat nun talagang kitang kita ninyo. Parang walang hangin. Ang usok talagang nakatapat samin diyan, oh paakyat sa bundok sa Tagaytay na yan. Nagiging ilaw lang namin noon ay yung kidlat maya't maya eh kidlat sa taas.*" (Yes, we were not affected too much. Even during the 1965 eruption, we were only affected by small amount of ashfall. Not a significant amount of ash. I remembered back then when we were hiking towards the mountain, the black ash cloud was right above us. Thinking about it now, realised that if those ash fell on us while where walking, a lot of people would have been killed. It was really dark, and the lightning was really very bright. I think there was no wind. The ash cloud was directly on top of us when we were towards the mountain to Tagaytay. Our only source of light that time were the lightning flashes that frequently illuminated the sky.) (GE03/#3) (POSITIVE)

This account by Respondent #3 is interesting because it provided their experience of both ashfall and lightning flashes. Another Barangay Captain tells of his AD1965 experience when he was ten years old. The phenomena they heard sounded like a description of base surge:

> "*Yun e parang ugong, parang sirena, malakas ang ugong. Tapos ang nararamdaman mo laang ay lagabok tapos sumabay na yung mga gabok. Syempre yung mga matatanda naman noong araw takot na takot.*" (Yes, the rumbling sound is similar to a siren and it was very loud. Then we just heard noise and felt dry earth and can see that ash fall is depositing. Our elders were very scare then.) (GE06/#6) (POSITIVE)

While all the Barangay Captains were young during the major eruptions of Taal (e.g. AD1965), some key factors were raised that could be tapped for future DRR activities including the roles of inherited memories and 'shadow network'. Almijos et al. (2017, p. 218) identified the informal interactions that occur within communities as a 'shadow network', a term described as "*informal institutional arrangements and interactions that have developed alongside formal disaster risk management structures*". Further, while their lack of experience of an eruption at Taal may be less advantageous, most mentioned their experience of ashfall impact during the 1991 eruption of Pinatubo Volcano. These factors provide positive inputs for improvement of knowledge and awareness (through inherited memories) and more rapid accurate warning dissemination (through shadow networks).

7.2.4. To what extent do the Barangay Captains take the risk seriously and are prepared?

To gauge how seriously the Barangay Captains take the volcanic hazards and risk and determine their level of preparedness, I explored specific issues – namely: 1) understanding of the Volcano Alert Levels and the corresponding standard actions of the local government units (LGUs) to each alert level in relation to making decisions about evacuation and other preventive measures; 2) having a community-specific Disaster Risk Reduction and Management (DRRM) Plan; 3) the conduct of regular drills to test those plans; and 4) having a plan in the event that the volcano crisis requires communities to evacuate to safer areas. I deem these as crucial and in providing a road map to effective DRR strategies.

7.2.4.1. Volcano Alert Level Scheme and LGU response

Volcano Alert Levels were discussed in Chapter 2, Section 2.5.4., with the complete list of Alert Levels, monitoring observations and interpretations related to each Alert Level provided in Table 2.9. Local governments have corresponding actions related to each Alert Level that are independent from, and not dictated, by DOST-PHIVOLCS. Coordination and efficient communication of warning information is critical for enabling a prompt response by stakeholders at risk. DOST-PHIVOLCS issues eruption warnings and Volcano Alert Levels to the Provincial Government of Batangas, who in turn is responsible for dissemination of warning information to the

City and Municipal governments. The City and Municipal government units are responsible for relaying the warning information to their barangays. Barangay Captains were interviewed about the Volcano Alert Levels and associated actions of local governments units (LGUs). Some positively oriented statements include:

> "*Ehh sa ngayon ho talagang unang una nga basta yung nag alert level 3 eh talagang automatic na yun*." (As of now, if Alert level 3 is raised, we will automatically evacuate.) (GE02/#2) (POSITIVE).

> "*Pag Level 2 ay di mag-iikot na at magbibigay ka na ng babala… bawa't bahay, magbigay ng kaalaman sa kanila na maghanda na at pag tinaas na sa Level 3 eh likas na*." (Roam around and give warnings... every household will be provided with warning information and to be ready. Then when Level 3 is raised, evacuate.) (GE04/#4) (POSITIVE)

> "*Sa Alert 2, yan ho e nakikiramdam at kami ho ay naglalagay na ng damit sa bag, hindi na bale maiwan ang ibang kagamitan. Basta may damit, may pera, may kaunting bigas, lente, lahat ng kailangan sa paglikas ay naka-alisto na. Kung sakali pumutok man ang bulkan. Alert 3 eevacuate ho yan.*" (At Alert 2, we will be on alert and we will be preparing our bag with clothes, money, rice, lamp, etc., everthing that is needed for evacuation in case the volcano erupts. Alert 3 for evacuation.) (GE06/#6) (POSITIVE)

> "*Ang PHIVOLCS ay talagang alerto na nagbibigay po talaga pagdating po ng Level 2, ang mga yan nagbibigay ng babala na maghanda na* (PHIVOLCS is really very alert in giving warning information. When its Level 2, they give warning to prepare for evacuation) (GE08/#8) (POSITIVE)

"*E kasi po, sa ngayon po kaya po lumilikas na kaagad, nadala na daw po sila nung unang nangyari dahil yun daw naman po ay gabi kung pumutok e. Ang dami daw po nun namatay*." (Now, people immediately evacuate because they (the elderly) do not want to experience what happened during past eruptions that usually occur at night (possibly the AD1965 eruption). A lot of people died.) (GE10/#10) (POSITIVE)

However, some negatively oriented comments include:

"*Alam mo hindi ako masyadong pamilyar sa ganun. Ako mismo hindi masyadong maalam. Pag 1 ano yun*? " (You know I'm not very familiar with those. I personally, I'm not very knowledgeable about that. What does Alert 1 mean?) (GE05/#5) (NEGATIVE)

"*Sa kasanayan po namin kung kailan na rin talaga na nakikita na pumuputok na ang bulkan. Ang ibig ko ngang sabihin pag nakikita na ng mga tao*." (Based on our experience, we will evacuate when we see the volcano erupting. What I mean is, if the people can already see the eruption) (GE07/#7) (NEGATIVE)

Respondent #3 (GE03), initially responded as:

"*Mga 3 ganyan magsisimula na mag-handa."* (At Alert Level 3, we will start to prepare.) (NEGATIVE)

During the course of the interview however, he then stated:

"*Pag Alert 2, nagbibigay din po kami ng impormasyon para sila ay makapag-handa na kung ano ang kanilang dapat ihanda sapagkat talaga pong puputok* *na, Alert 3, meron din po kaming ginagawang bahagi para malaman nila na puputok na talaga ang bulkan. Automatic na po yun na sila ay aming eevacuate.*" (We also give information so they can prepare their things because of a possible eruption. We also have our own plans to disseminate the information that there is strong possibility that the volcano might erupt. We will make sure that the residents are automatically evacuated.) (GE03/#3) (POSITIVE)

The conflicting statements of Respondent #3 seem to indicate nonfamiliarity with the Alert Level Scheme. There is room of misinterpretation of LGU action when DOST-PHIVOLCS issues warning information through raising of Alert Levels should Taal show signs of unrest. The standard LGU action for Alert Level 2 is preparation for communities in general, but for the elderly, women and children, communities may opt to evacuate them to safety. Alert Level 3 is general evacuation for the threatened communities. As such, I deem his responses as negative in relation to his preparedness.

Overall, the majority of the respondents seemed to be familiar with the Volcano Alert Levels and associated LGU actions.

7.2.4.2. Barangay Disaster Risk Reduction and Management (BDRRM) Plans or Contingency Plans

Another critical way of determining preparedness is awareness of, and preparation and implementation of community-specific BDRRM Plans or Contingency Plans for all hazards that a community faces – including volcanic eruptions. In the Republic Act No. 10121, also known as the Philippine Disaster Risk Reduction and

Management Act of 2010, the LGUs are mandated to expedite and assist in barangay level risk assessment and contingency planning for all identified natural hazards including volcanic eruptions (Republic Act 10121, 2010). Of the ten Barangay Captains, four do not have volcano emergency measures. Three admitted they do not have BDRRM Plans including Respondent #1 (GE01) who said they do not have a BRDDM Plan of any kind and will rely on local government and wait for their instruction in the event of a volcano emergency. Further, two Barangay Captains admitted that they only have Contingency Plans for flooding and none for volcano emergencies:

> "*Ang contingency plan po namin dito ay sa flood lamang*." (Our contingency plan here is only for floods.) (GE05/#5) (NEGATIVE)

> "*Wala kami, parang baha lang dito eh. Dahil nakaranas na kami dito eh*." (We have none. It is always flooding that we frequently experience.) Respondent #9 (GE09) (NEGATIVE)

Furthermore, two Barangay Captains do not know if they have a BDRRM Plan or Contingency Plans for volcanic emergencies. The Barangay Captains responded:

> "*Parang wala yata*." (I do not think we have.) (GE10/#10) (NEGATIVE)

> "*Parang wala pa ho ako dahil bagong kapitan palang ho ako dito eh*." (It seems like I don't have one yet as I'm just a new captain here) (GE07/#7) (NEGATIVE)

Last, whilst Respondent #7 (GE07) was unaware whether a BDRRM exists, when I cross referenced with the documents received from the Municipal office, it was clear that such a plan (dated 2012) does indeed, exist thus indicating he is entirely unprepared.

During the interview about the BDRRM Plan, Respondent #5 (GE05) stated in relation to the inclusion of schools in the BDRRM structure:

> "*Pero pag school sakop namin yun? School yun eh. Di ga independent ang school*?" (But do we cover schools? Those are schools are they independent?) (NEGATIVE)

In Chapter 2, Section 2.1.5, I noted that the School Disaster Risk Reduction Coordinators (DRRCs) or the Principals, are the school representatives in the Barangay Disaster Risk Reduction and Management Councils (BDRRMCs) and in Table 2.3 showed that the Department of Education (DepEd) are members of the PDRRMC sub-committees of Batangas Province. Clearly in this barangay, the DepEd is not a member of the Disaster Prevention and Mitigation Committee nor is the Barangay Captain aware of these requirements – further suggesting a lack of preparedness.

7.2.4.3. Evacuation Plans

The DDRRM Plan requires that barangays identify safe evacuation areas 'within' their own barangay, or safe evacuation areas in other locations for each relevant volcanic hazard identified by DOST-PHIVOLCS. To be fair to the Barangay Captains, two important issues emerge here. First, some volcanic hazards identified in Chapters 2 and 4 have no associated hazard maps making it impossible for the Barangay Captains to undertake the required evacuation planning since they do not know where is safe or unsafe. Second, in the mainland, the locations of Barangay Calangay (southwest of TVI), Barangay Gulod (northwest of TVI) and Bancoro/Balete (southwest of TVI), are all located within the Base Surge (PDC) Hazard Map of DOST-PHIVOLCS and as such, are at risk from this hazard. Further, the designated evacuation sites for these communities actually lie within the hazard zone.

Despite these issues, several Barangay Captains confirmed that they have identified evacuation centers and pick-up points in their communities in the event of an eruption, and said they know where they are going. However, when asked about specific evacuation locations, I found only two positive comments by respondents:

> "*Tatawid at pupunta sa Talisay Elementary School*." (Will cross the lake and go to Talisay Elementary School.) (GE01/#1) (POSITIVE)

> "*Kami naman ay mayroong lokasyon ng evacuation. Dun po, tulad po sa Calangay, sa San Nicolas po. Pag daw po lilikas, pwede daw po dalhin dun ang mga residente. Pero kalimitan naman po yung taga-isla naman halimbawa ang iba po dito may bahay sa Gulod, may bahay sa Bancoro sa Balete yung iba doon nalang po pumupunta. Sa kanya-kanya pong ibang bahay*." (We have identified location in Calangay in San Nicolas. Residents can be brought there. But most of the residents in the island have other residences like in Gulod, or in Bancoro in Balete so they go to their other houses in the mainland) (GE10/#10) (POSITIVE)

Some of the negative responses include:

"*Sa ngayon ho ang nakukuha ko sa seminar, yun lang mayroon na hong evacuation center pero wala pa ho akong pagsasanay. Ang lagay ho, ang nasabi nga ng MDRRMC* (Municipal Disaster Risk Reduction and Management Council) *na hanggang sa nakipagcoordinate kami sa Tagaytay na talagang doon ang punta namin in case nga na pumutok. Basta yun lang sigurado lang yun evacuation center... di ko pa din alam saan doon*." (Right now, based on the seminars I have attended, I know we have existing evacuation centers but still do not have drills. MDRRMC told to go there, and that we should coordinate with Tagaytay for confirmation that we are going there. The only thing that is sure is the evacuation center in Tagaytay. I still do not know where.) (GE02/#2) (NEGATIVE)

"*Meron pong isang evacuation center dito yung amin pong gym. Meron po kami diyang basketbolan (covered court). Yun po yung aming pwedeng pagdalhan sa kanila. Mayroon pong plano kung kelangang lumayo dito. Yun po ay manggagaling na sa amin pong ano sa local*." (Our gymnasium also serves as one of our evacuation centers. It's a covered court here that can also serve as an evacuation. We can assemble our residents there. We have evacuation plans if we need to leave. It will come from our local government.) (GE03/#3) (NEGATIVE)

"*Alam po, nasa ano, nandoon sa CDRRMC. Nandoon sa kanila kung saan pupunta. Sila po ang nag designate kung talagang malala na pero yung evacuation areas dito, dito namin naplano ang aming evacuation area. ito yung school, simbahan, pero yung talagang ililikas na yung sa barangay nag designate sila per cluster kung saan dadalhin*." (We know, CDRRRMC knows where we are going. They are the ones who designate if it gets worse but if it's not that serious, we have our own plans on evacuation areas here. These include the school, church, but if the barangay needs to evacuate, they designated them per cluster where they will be brought.) (GE05/#5) (NEGATIVE)

"*Diyan po sa school, yung pag talaga hong matindi na, lilikas na talaga sa mataas na lugar. Maghihintay na lang po kami ng go signal ng kung pupunta kami ng Taal, kung pupunta kami ng Calaca. Ngayon e parang ang tinatarget nila eh ang Nasugbu.*" (There, in the school. But in the event that the eruption escalates, we will move them to higher place. We will just wait for a go signal to where we will go, if in Taal or in Calaca. Right now, they are targeting Nasugbu.) (GE06/#6) (NEGATIVE)

While Respondent #5 confirmed that an evacuation plan exists, he points to the City Disaster Risk Reduction and Management Council (CDRRMC) as having the list of designated evacuation centers for their community, something outside his control or knowledge. The attitude of Respondent #6 of leaving decisions about evacuation sites to the municipal government mirrors the attitude of Respondent #5. While several Barangay Captains correctly identified evacuation sites within their communities, they did not know anything about evacuation centres outside their barangay and had taken no responsibility for familiarising themselves with those sites nor in assessing they meet the needs of their communities in the event of a forced evacuation. As such, in general, most of the Barangay Captains are ill-prepared in terms of evacuation procedures.

One issue raised by several Barangay Captains is that when an eruption occurs, people instinctively evacuate themselves rather than waiting for coordinated instructions:

> "*Ang ganyan po ay kanya-kanyang likas na eh. Nabibigla din ng putok ang mga tao. Syempre yan magkakanya kanya na rin yan* (the authorities) *dahil may mga pamilya rin yan eh, na ililikas nila eh kaya ganoon*." (In those situations, people evacuate on their own because of course they were shocked by the eruption. Of course, they (the authorities) would also think about the safety of their families and will take them to safety.) (GE07/#7) (NEGATIVE)

7.2.4.4. Preparedness trainings and drills

The conduct of training for emergency management officials and drills for the community and management officials through simulations and scenario-based planning can help improve community preparedness as well as serve to highlight existing response weaknesses (Sword-Daniels et al., 2018). While the Hyogo Framework for Action 2005 – 2015 promoted the development of participatory and people-centred EWSs, studies showed that this has not been widely translated into actions and plans for DRR (Thomalla & Larsen, 2010). Volcano-related drills are needed in order to test communication protocols and timelines of dissemination of warning information from the scientists/volcanologists down to the communities, gauge coordination, response and action of participants, validate the performance of key stakeholders, check if there are adequate facilities and logistics for evacuation among others (Ciolli, 2012; Doyle et al., 2015). At Taal, in relation to training and drills, at the time of the interview, only one of the Barangay Captains has ever undertaken community-based drills. The Barangay Captains commented:

> "*Nagtraining na ho rin kami noon kasama mga tanod namin. Oo dahil kami naman minsan ho, e sinasanay din kami ng DENR, sinasanay din dahil nga diyan sa pagputok na yan. Isang beses pa lang*." (Yes, we already did it before together with my staff. Yes, sometimes the DENR also gives us trainings about volcanic eruption. Just once.) (GE06/#6) (POSITIVE)

Some of the negative comments included:

> "*Sa pagsasanay po di kami masyado pero yung paghahanda meron po kami niyan. Di pa po kami nagkakaroon ng drill patungkol sa bulkan*." (We are not doing any evacuation drills but when it comes to preparedness, we are ready We still have not done a volcano related drill.) (GE03/#3) (NEGATIVE)

> *"Mayroong seminar lang pero yung actual kung papaano kami kikilos hindi pa. Sa totoo lang, wala pa, hindi pa."* (We only have seminars but the actual thing on what we will do, not yet. In all honestly, we still haven't, not yet.) (GE04/#4) (NEGATIVE)

> "*Oo, alam ang gagawin. Kahit maam, kahit nagsanay ang tao lalo lalaki pag nangyari po eh lasing na lasing, tulog! Eh di mas maganda pa po na hindi nagsanay na nakahanda naman sa pangyayari. Mas maganda po yung alam nya ang gagawin*." (Yes, we know what we need to do. Actually, even if we have drills, especially the males, if they are drunk, they will fall asleep! Better

those who have not done drills but are prepared for any event. Better that they know what they need to do.) (GE08/#8) (NEGATIVE)

From the perspective of DRR, the absence of a volcano related communication and evacuation drill in eight of the ten communities where the Barangay Captains are situated indicate that the majority of the Barangay Captains are ill-prepared for a volcano emergency.

7.2.4.5. Eruption warnings and action

When interviewees were presented with the scenario that an eruption warning is issued by DOST-PHIVOLCS, they were asked what their reactions/responses would be. Only two Barangay Captains stated they would believe those warnings and immediately evacuate:

> "*Kung halimbawang level 3 na eh di ipupush na ho natin ang evacuation na yan. So maniwala agad, at agad na lilikas*." (If it is Alert level 3, we will implement evacuation. We will believe and evacuate immediately.) (GE02/#2) (POSITIVE)

> "*Aba'y lilikas na lang ako bago mamatay*!" (I will evacuate before I die!) (GE10/#10) (POSITIVE)

Conversely, eight Barangay Captains had varied responses - will wait and see, first seek consultation with their local government and/or family prior to making decisions on evacuation – rather than following the response actions dictated in the BDRRM Plan.

"*Opo, konsultasyon sa local pag Alert 3. Kasi di naman po pwedeng likas agad*." Yes, consult with local government at Alert 3 because we cannot just evacuate immediately.) (GE03/#3) (NEGATIVE)

"*Sa kasanayan po namin kung kailan na rin talaga na nakikita na pumuputok na ang bulkan*." (Based on our experience, we will evacuate when we see the volcano is erupting.) (GE07/#7) (NEGATIVE)

"*Karamihan po dito ay mag-aantay at mag-mamatyag. Basta po pag dumaan ang PHIVOLCS pag sinabing Level 2, maghanda handa na kayo, pag Level 3 di na po kami mag-aantay ng daan ng PHIVOLCS. Alam na, pakiramdam po natin yun pag malakas na, pag delikado na ay likas na*." (Most people here would wait and see. When PHIVOLCS goes around the island and they say its Level 2, that we will get ready. When its Level 3, we will not wait for PHIVOLCS to go around. We know, and our gut feelings tell us when it will be a big event, that it is dangerous and we need to leave.) (GE08/#8) (NEGATIVE)

"*Magmamatyag nalang*." (We will wait and see.) (GE09/#9) (NEGATIVE)

One Barangay Captain appeared to rely heavily on LGUs for evacuation plans. He stated:

"*Ang alam ko lang na paghahanda, syempre kami ay umaasa pa rin sa munisipyo para kung saan nga kami pwedeng pumunta*." (The only preparedness I know is consulting with municipal authorities on where we are going) (GE07/#7) (NEGATIVE)

I provided a scenario where their municipal office and their Mayor might forget their commitment to prioritise their needs during a volcanic crisis and he responded:

> "*Ay nako hindi po mangyayari yun*!" (No, that will not happen!) (GE07/#7) (NEGATIVE)

The varied alternate action of 'wait and see', further consultation with LGU at Alert 3 rather than immediate evacuation, reliance on gut feeling, and too much reliance on the local government prior to evacuation means further delay in evacuation that may have devastating consequences during an actual volcano crisis.

Whilst the majority of Barangay Captains indicate they would do something other than follow evacuation protocol, an interesting observation was made about following alternative sources of information that 'might' guide decision-making. Almijos et al. (2017, p. 218) identified the informal interactions that occur within communities as a 'shadow network', a term described as "*informal institutional arrangements and interactions that have developed alongside formal disaster risk management structures*". Some Barangay Captains told stories of how they received rapid warnings of past eruptions from sources 'prior' to official notices from DOST-PHIVOLCS or local government units presenting them with the opportunity for earlier evacuation in the absence of official notification by the relevant authorities:

> "*Ay sa amin, ang nagbigay ng babala ay yung aming tiyuhin tsaka yung aking kapatid dahil yung aking kapatid ay nasa dagat siya. Wala pong ibang nagsabi noon. Sila laang dahil si Manong Pablo lang nagsabi na-'aba'y bulkan na ika yan!'- Yun ang sabi ng aming tiyuhin*." (In our case, the people who gave us warning was our uncle and my brother because he stays near the

lake. Our uncle, Mang Pablo, observed there was something happening at Taal and said the volcano was erupting.) (GE06/#6) (POSITIVE)

"*E di may dumating sa amin na pinsang buo ko. Kaanak po. Talagang sila lang nagsabi sa amin- 'Aba! Bangon na kayo at pumuputok na ang bulkan!"* (My first cousin came. A relative. He told us, "*Get up! The volcano is erupting*!") (GE07/#7) (POSITIVE)

The use of 'shadow network' led to the to the quick relay of information about escalating unrest at Pinatubo in 1991 from nuns who were living within local communities on Pinatubo to DOST-PHIVOLCS. These nuns were the first to observe increased activity unseen by residents and authorities located further away. This was highly significant because at the time, there was no active seismic monitoring at Pinatubo but the action of this 'shadow network' resulted in the immediate deployment of seismologists and volcanologist to Pinatubo to initiate monitoring of the volcano.

7.2.5. Other issues raised by respondents

In the summary of responses in Appendix J, I provided other issues, themes and salient points. During the interviews, a number of other key issues emerged in the responses of the Barangay Captains that I thought had bearing to provision of the DRR initiatives that can be sustainable. Some of these issues are discussed in the following sections.

7.2.5.1. On the issue of attachment to place

'Attachment to place' in relation to respondents' desire to remain in their present locations despite the ongoing risk associated with living on and around Taal is clearly an important issue. Hidalgo & Hernandez (2001, p. 274) defined place attachment as *"an affective bond or link between people or individuals and specific places*". The bond residents have formed within their community may explain why they wish to stay in areas that are at continuing risk from volcanic eruptions. "*People are more likely to become psychologically invested in a place if they spend a lot of time there. For this reason, people's homes and local communities often become part of their identities, especially if they spend a lot of time in the community and know other people in the community*" (Anton & Lawrence, 2001, p. 146). Attachment to place recognises social and physical attachment as a key factor and this is developed through social ties and sense of belonging to a place that provides a sense of security to individuals (Scannel & Gifford, 2010; Riger & Lavrakas, 1981). Social influences to attachment to place, decision making and preparedness could also constitute collective efficacy, social networks and bonding social capital, leadership and responsibility for others, (Aldrich & Meyer, 2015; Becker et al., 2014; Paton, 2018).

When asked to describe their lives in their community, responses included:

> "*Masaya, kuntento kami.*" (We are happy and contented.) (GE01/#01)

> "*Nasisiyahan po dito. Di naman po ako titigil dito kung hindi nasisiyahan eh*! *Kahit may pupuntahan po, marami pong pupuntahan, pero napakaganda po talaga ng buhay dito.* (We are happy here. I will not be staying here if I am not

happy! We have other places we can go to, plenty, but our life here is really good!) (GE08/#8)

"*Okay naman samahan. Mayroon po kaming kooperasyon. Ay noon nga pong bumaha dito, talagang full-force*." (Our fellowship okay. There is cooperation. In fact, when we experienced flooding Before, everyone helped-full force!) (GE09/#9)

"*Okay lang po dito ang buhay. Masipag ka lamang di ka magugutom. Tsaka okay naman ang mga taga rito, maalwan pakisamahan*." (Life here is good. If you are hardworking, you will never go hungry. And the people are good and easy to get along with.) (GE10/#10)

The responses of happiness, contentment, feeling of fellowship etc as elements of attachment to place, can be both positive and negative in relation to DRR. It's positive in that if people are happy in their community, they are more likely to participate in social and community activities that bind people together in communities as part of 'a place' (Mesch & Manor, 1998).

Conversely, the same attachment to place (and community) may also be negative particularly when it influences decisions about whether to evacuate and resettle elsewhere (or not). Attachment to place may result in reluctance of individuals for "*place change because it can threaten continuity* (Anton & Lawrence, 2016, p. 147). When asked if respondents would return to their communities following severe eruption impacts, all but one respondent said they would return. While returning means continued exposure of the Barangay Captain to volcanic threat, I have provided positive and negative assessment based on the reasons for their return. Show of concern would imply they would do their best to protect their communities. Positive responses are stated here:

> "*Hindi maaaring hindi kami babalik dito, gaya namin punong barangay natural laang poprotektahan ko ang aking nasasakupang barangay*." (I need to return because as head of the community, it is natural for me to go back to my place and protect my barangay.) (GE06/#6) (POSITIVE)

> "*Aba'y natural po! Kinakailangan na ikaw ay bumalik palibhasa ikaw ang namumuno ng barangay.*" (Of course, naturally. I need to return especially since I'm the Barangay Captain.) (GE07/#7) (POSITIVE)

However, where Barangay Captains just provided a decision of returning because they are used to staying in their community, I identified them as negative comments:

> "*Parang di pa ho namin nadidiscuss yun ganyang sistema. Walang usapin sa resettlement.*" (We have not discussed anything yet on that issue. No discussion about resettlement.) (GE02/#2) (NEGATIVE)

> "Ah *babalik…kalimitan naman ganun*!" (Will return. That's usually the case.) (GE05/#5) (NEGATIVE)

> "*Kalimitan po basta po agad na bumabalik after ng putok*." (Most of the time, we return immediately after the eruption.) (GE10/#10) (NEGATIVE)

> "*Sariling bahay, doon po sa lolo ko po yung lupa. Pero may bahay din po ako sa Laurel sa Gulod. Dito po natutulog."* (Yes, we own the house and the lot is owned by my grandfather. But I also have a house in Barangay Gulod in Laurel. I sleep here- meaning TVI) (GE10/#10) (NEGATIVE)

7.2.5.2. Livelihoods in relation to potential resettlement

When questioned about the respondents' views towards the idea of resettlement, an issue that kept being raised related to the provision of or availability of livelihood options in the place where people live. Barangay Captains remarked:

> "*Kung may mas magandang magiging option po ang pamahalaan*" (If the government can provide us with better options). (GE03/#3) (POSITIVE)

> "*Baka siguro pag mayroong livelihood. Pero pagka ho ang binigay lang eh lupa at saka bahay, wala ka namang pagkaka-kitaan e di wala rin ho."* (Maybe if there is livelihood. But if they only provide house and lot but without sources of daily income then it's useless.) (GE07/#7) (POSITIVE)

Clearly for respondents in this study, if the government are able to provide alternative and sustainable livelihood options, then resettlement as a DRR strategy is much more palatable. Paying close attention to the issue of livelihood options and sustainability is critical since resettlement projects that cost billions of pesos, like those following the 1991 eruption of Pinatubo, were deemed to have failed because the livelihood options provided were not sustainable and relocated people lacked the skills necessary to undertake the alternative livelihoods provided (Gaillard, 2015). Subsequently, residents in the resettlement sites returned to the original location of the homes, re-exposing themselves to a set of ongoing volcanic hazards such as lahars and flooding (Gaillard, 2015).

7.2.5.3. On the potential value of 'inherited memories'

Shibata (2012, p. 1635) said that "*to mitigate the damages by natural disaster, the knowledge on the past natural disasters occurred in an area should be properly shared by the people in that area*" and that there is need to 'promote' major disasters continuously through educational materials so that children "*inherit the memories of natural disasters*" (Shibata, 2012:1645).

Very few of the interviewees had received information through 'inherited memories' about past eruptions of Taal. However, there were some significant and 'positive' inherited memories that seemed to make the Barangay Captain more alert. For example:

> "*Mabuti nga noon ganoon lang. Sabi ng matatanda, yung sistema ng pagputok nya, talagang dito nakaharap ang tapon ng mga bato. Talagang dito ang punta*." (We were lucky that time. Our elders told us that before the eruption was directed here. The ballistic projectiles were going this way.) (GE02/#2) (POSITIVE)

> *"Pero yung mga kinukwento sa amin sadya daw hong nakakatakot ang putok ng bulkan, yun daw pong di nakaka-experience pa ay baka sabihin gusto nila pero pag ka nakaranas na ay naku baka daw ho isumpa na lang yung pangyayari"* (The stories our elders told us was that the eruptions were frightening. Those who have not experienced an eruption would say they want to experience one, but if they have experienced what we experienced during the eruption having said that). (GE10/#10) (POSITIVE)

> "*Oho naman, oho. Nagkaroon ng abo. Ang ginawa po ng aming mga lola noon, mga ninuno namin noong araw, ang sabi ay mga nakaipon ang tubig so ang ginawa namin noon ay nag ipon ng tubig, mga inumin. Yung mga kulambo nung araw ay di naman gaya ngayon. Ang kulambo nung araw ay parang damit. Yun ay binasa siyang kinulambo sa amin para di makapasok ang gabok sa amin. Siyempre po naituro nila dahil sila'y naka-experience na noong una pang putok eh.*" (Yes, there was ash. Then our grandparents did what our ancestors taught us, store water for drinking. Our mosquito nets during those days are not like the ones bought now. They were fine like the texture of clothes. They (the mosquito nets) were soaked in water then covered around us so that ash would not be able to affect us. Of course, they taught us that because they have experienced it already since its first eruption. (GE06/#6) (POSITIVE)

In these instances, the Barangay Captains emphasised how traumatic the AD1965 events were for their elders to the point that they do not want that to happen to them. The inherited memories provided a positive aspect to their preparedness outlook that can be utilised for implementing more effective volcano related DRR activities and plans.

Conversely, some inherited memories may be detrimental and could generate complacency and a false sense of security. For example:

> "*Sabi nang matatanda, nandiyan kasi ang patron* (reason why they were safe from the effects of theAD1965 eruption) *kaya ganoon na lang ang debosyon ng mga taga-rito sa Poong Sta.Cruz.*" (The elders said it's because the Patron

Saint is there, that is why everyone in the community is devoted to the Patron Saint Sta. Cruz.) (GE09/#9) (NEGATIVE)

7.2.5.4. Other challenges that impede Barangay Captains' capacity to effect volcano DRR activity as part of their duties

Interviews with Barangay Captains revealed a number of other challenges to working effectively in the space of volcano DRR. These include: community attitudes and behaviours; issues related to disaster funding and the prioritisation of day to day duties in relation to high-frequency hazards.

One Barangay Captain said residents do not feel the need to participate in preparedness planning and training activities making it hard for [him] to do his duty noting:

> "*Ngayon nga po medyo lumalakas pa mga loob ng mga taga-rito eh. Nung una pong pumutok ang bulkan, walang banka e ngayon po e halos tigi-tigisa na kayang kaya na po ang mga tao. Kampante po sila.*" (At present, with most families having their own boats, they have become more daring/fearless and feel they can easily leave when the time comes, unlike before when there were not enough boats. They have become complacent.) (GE08/#8) (NEGATIVE)

Another Barangay Captain expressed frustration with some residents who were difficult to handle during past events:

> "*Syempre ho ang pinakamahirap po nating laging gagawin eh yung may matitigas na ulo sa barrio ho. Hindi ho nawawala yun. Yun ang lagi ho naming problema. Naging plano ho namin dyan sa mga matitigas ang ulong*

yan, pulis na lang ang kukuha sa kanila. Eh paano ho sasabihin 'hindi ako aalis, baka mawala ang aking ganito... ganon!' Hindi nila alam mam kaya nagsasakripisyo kami ganyan, kanilang buhay ang nakataya." (Of course, one of the most difficult problem in handling evacuation is when you have hard-headed residents in your community. There will always be one in the community. Our plan for the hard-headed residents, we will have the police pick them up. They often say 'We will not go because our properties may be stolen!'- They do not realise that we doing this because their lives are at stake.) (GE02/#2)

Another Barangay Captain described the difficulty of organising barangay assemblies because the community residents are not willing to attend. Consequently, sometimes they compel residents to participate by making attendance a requirement for accessing government financial support. Pantawid Pamilya Pilipino Program, popularly known as 4Ps, is a Philippine government program intended to eradicate extreme poverty by providing conditional cash transfers to selected Filipino families under the Department of Social Welfare and Development. The Barangay Captain stated:

> "*Sa 4000 na residente, mahigit isang daan. Yung tatakutin laang. Mga 4Ps pa. Sadya pong mahirap talaga. Ang mga 4Ps po yun at natatakot pa at di pipirmahan ang mga dokumento nila- 'pag di kayo umattend, di kayo pipirmahan'- eh di naka 100% naman na naattend*!" (Out of 4000 residents, only more than one hundred. They are the once you force to attend, those getting 4Ps benefits. It's really that difficult for us. The only ones who attend are those getting 4Ps benefits because they are afraid that their document

won't be signed because we say- '*If you don't attend, we won't sign your documents*', then we get 100% attendance!) (GE07/#7)

Another issue raised by a Barangay Captain is the utilisation of the Local Disaster Risk Reduction and Management (LDRRM) Fund known as the Calamity Fund. Specifically, the Captain noted that they do not possess early warning equipment such as megaphones or sirens and instead simply go house to house issuing warnings because:

> "*Wala pa ho kame. Medyo kasi ho ang mabigat ngayon sa ating gobyerno, yung kagaya naming maliit na barrio- kunwari may pondo kame sa calamity. Bakit yun ehh hindi magalaw. Sabi ko nga makaranas nga ng bagyong Glenda, ehh may calamity fund kami banda siguro mga PhP 65,000. Sabi ko ipamili natin to ng gamit. Halimbawa mega phone, itong gamot, yung pagkain, yun mga dilata para kung sakali nga hong pumutok yung bulkan para may makain ang tao. Eh ang problema bakit yung pondo hindi mailabas*? *Ang Calamity Fund ay sampung porsiyento based sa income ng barrio. Ang mangyayari ho sa 10% na yun, ang magagalaw pa rin ho doon eh yung 70%. Yung 30% ititira nyo pa yun. Hindi pepwedeng ubusin. Yun ay in case lang may kalamidad na dumating tsaka mo lang mawiwithdraw yun.*" (We still do not have any. The problem with the system of our government, we experienced Typhoon Glenda and we have calamity fund, around PhP65,000-AUD1950. I said we should buy some equipment like megaphones, food like canned goods. So that just in case Taal erupts people will have food to eat. The problem is why can't they release the funds? That is 10% of the barangay

income. Out of the 10%, you can only use 70%. The remaining 30% cannot be used. You can only get that if there is a calamity.). (GE02/#2) (NEGATIVE)

The LDRRM Funds are funds given to barangays and is about 10% of the estimated revenue of the barangays. Seventy percent of those allocated funds are intended for disaster risk reduction and management activities (e.g. pre-disaster preparedness training and seminars, purchase of DRR equipment, supplies and medicines, for post-disaster response activities, payment of premiums on calamity insurance, etc.) (NDRRMC, 2017). The remaining 30% serves as a "Quick Respond Fund", that remains as a standby fund for relief and recovery activities. Any unexpended Quick Respond Fund shall go into a special trust fund that the local government unit can use within the next five years exclusively for the purpose of DRR activities. So in fact, the barangays who do not experience a calamity within the next five year can utilise the fund for DRR activities. Perhaps this not explained or was not clear to some of the Barangay Captains. This gap should be addressed so that utilisation of the LDRRM Fund can be maximised.

The Republic Act No. 7160 that lists the multiple duties and responsibilities of a Barangay Captain, ranks DRR duties at 6th out of 15 specific responsibilities (DILG, 1991). When Barangay Captains were asked about their primary responsibilities, they indicated that they are compelled to address more urgent responsibilities as provided by the law (e.g. enforce laws and ordinances, maintain peace and order, etc.) compared to work associated with DRR in preparation for an eruption that they perceive as less important. For example, one Barangay Captain noted:

"*Peace and order. Yun po ang number one dito sa barrio. Isa pa, katulad po ngayon, isang buwan na kaming nagpapatanim ng galing DENR*." (Peace and order. That is the number one priority here in the barrio. Also, like now, we have been working for almost a month planting seedling of trees from DENR-Department of Environment and Natural Resources.) (GE02/#2)

In summary, the problems and issues identified by some of the Barangay Captains may have directly or indirectly resulted in the 'deprioritisation' of DRR activities in the communities where the Barangay Captains face those challenges.

7.3 Discussion

7.3.1. Summary results of the vignette study

Related to the vignette study aimed at gauging the ability of the Barangay Captains to lead their communities during a volcanic emergency using the five issues deemed most relevant, I note the following:

1. *Education.* Howard et al. (2017) identified higher levels of basic educational attainment as one factor that increases warning response, along with knowledge of hazard, community involvement, familiarity and trust in the institution where the information was acquired. The majority (80%) of the respondents were Elementary or High School graduates. Their responses seem to imply that they themselves are not confident with the level of education they have attained. I considered this as a negative aspect to the performance of DRR duties in their communities. While I deemed attendance at volcano related training events and seminars as additional education gained to prepare the Barangay Captains for their

DRR roles, translation of the knowledge to increased capacity was not reflected in their responses during the interviews. The general inadequate knowledge on volcanic hazards and risk and DRR related issues was prevalent amongst most of the Barangay Captains with both lower and higher levels of education. This implies that there is a need for better understanding of hazard communication experiences and expectations of recipients of hazards and risk information education campaigns in order to maximise learning, as well as attendance to these hazard communication sessions. Further, there is a need to extend this research to more respondents to be able to quantify if higher levels of basic education is indeed in order to improved DRR response.

2. *Knowledge*. The study showed that while nine respondents are aware that they can be affected by one or more volcanic hazards, the majority of the Barangay Captains have not been able to identify the hazards that may impact their communities, except for tephra fallout. More alarming is the fact that the Barangay Captains that actually live on TVI do not perceive lava flows/ballistic projectiles and volcano tsunami as threatening their communities. Further, from the results of the interviews on other DRR related questions, what was learned at volcano related training events were generally not translated to improved DRR actions. Some do not think volcano related drills are important, and some still do not have BDRRM Plans/Contingency Plans at the time of their interview.
3. *Experience*. While eight Barangay Captains experienced an eruption at Taal, three admitted they were too young to recall the major devastation wrought by the AD1965 event that they experienced. The rest only experienced minor impacts from past eruptions they witnessed. Those experiences could be a negative factor in decision making during a volcanic crisis because it might lead them to believe

that if they were not affected severely during the previous eruption, then they would be safe in a future eruption. However, one Barangay Captain expressed hope that the traumatic experiences of their elders from past explosive eruptions at Taal will not be repeated, and says that if an eruption warning is given, they will believe that warning and immediately evacuate. While the inherited memory of this one Barangay Captain is laudable, in general, the lack of eruption experience of the nine Barangay Captains interviewed is deemed as a negative aspect to their awareness and preparedness in the face of a major volcano crisis.

4. *Take the risk seriously and being prepared*. I identified some key factors to assess preparedness that included knowledge of Volcano Alert levels, preparation and implementation of BDRRM Plans in the communities of the Barangay Captains, execution of volcano related preparedness training and drills, design and execution of evacuation plans, and intended volcano emergency actions when given an eruption scenario. The majority were familiar with the Volcano Alert Levels and the corresponding actions expected from the LGUs including the Barangay Captains. Five of ten respondents admitted they do not have BDRRM Plans and two do not know if they do have one. In the course of one interview with one Barangay Captain, it was revealed that the Barangay Captain is not knowledgeable of the crucial participation of schools in the BDRRM activities. Of the ten respondents, only two have performed volcano related drills in their communities. The majority of the respondents have identified evacuation sites and pick-up points in their communities but a number of Barangay Captains do not even know where they are going if evacuation further from their barangay is necessary. At the time of the interview, they expressed reliance on their city and municipal governments on the issue of where they are going to be evacuated.

Only two respondents know where they are supposed to go. However, validation of the locations they have identified showed that those designated evacuation areas are also threatened by one or two volcanic hazards. With this critical issue identified, there is now a need for hazard reassessment of evacuation areas to ensure that Taal evacuees are indeed going to safer locations as intended. Further, too much reliance on their local government for evacuation could result in complacency and false sense of security that help will be there when they need it. Overall, the assessment of the key elements of preparedness I identified showed that in general, the ten respondents are ill-prepared if a major eruption occurs in the immediate future.

While reviewing and assessing the responses of the Barangay Captains, I tended to instinctively try to find a good or positive side to their responses. As a fellow government worker, I prefer to believe that they chose their profession because they are committed to their communities. Their responses showed they care and they work hard. While the results showed that they actually lack the basic education that can be detrimental to the performance of their DRR related responsibilities, I wanted to obtain results that would say that the additional learnings on volcano related hazard awareness and preparedness provided by DOST-PHIVOLCS and other experts has indeed been translated to knowledge and actions that can equip the Barangay Captains in ensuring the safety of their communities during volcano emergencies. I found it difficult to be critical of their actions and as a Filipino, it is not easy for me to be straightforward in expressing negative remarks about another person. Having said that, there now lies my responsibility, first as a PhD student, and second, as a government scientist working for DOST-PHIVOLCS who is mandated "*to help* *develop communities safe from and resilient to volcanic eruptions, earthquakes, tsunamis and other related hazards*" (DOST-PHIVOLCS, 2017) to provide an honest and impartial assessment of the responses of the Barangay Captains, as well as to provide recommendations to the gaps on key issues I identified.

However, in the process of categorising the responses of the Barangay Captains to the key elements of education, knowledge of hazards and risk, their experiences, and their preparedness actions/inactions, the abovementioned assessments regrettably and clearly showed that the ten Barangay Captain respondents were adequately knowledgeable and aware of volcanic hazards and risks, but most lack experience of an eruption. The problems and issues they encounter on the day-to-day basis directly or indirectly resulted in the deprioritisation of volcano-related DRR activities that consequently may affect their ability to effectively support their communities if a major explosive eruption occurs.

7.3.2. Re-evaluation of volcanic hazards assessment undertaken by the LGUs

In Chapter 2, Section 2.3.3, I provided a modified assessment of volcanic hazards sourced from the interpretation of the local government of Batangas. I re-evaluated their assessment, using the same DOST-PHIVOLCS Hazard Maps they used as reference and have subsequently provided a revised table (Table 7.4) showing an additional number of threatened barangays for each city and municipality compared to previous assessments. The greater number of barangays and populations at risk has implications for existing DRRM Plans and strategies of both provincial and

Table 7.4. Summary volcanic hazard assessment list modified from the information provided by the Provincial Disaster Risk Reduction and Management Office (PDRRMO) of the

Provincial Government of Batangas. Two cities and 12 municipalities of Batangas were identified as vulnerable to ballistic projectiles (BP), volcano tsunami/seiche (TSU/S), and /or pyroclastic density current/base surge (PDC/BS). They used the Taal hazard maps of DOST-PHIVOLCS (2011) as basis for their assessment. The assessment of the identified hazards interpreted by the local government are in RED print. Where reassessment and change were needed for the number of barangays threatened, the change is in BLUE print. Estimated population at risk derived from population data from Census 2015.

MUNICIPALITY / CITY	POPULATION AT RISK	DISTRICT	BARANGAYS W/ HAZARD(S)			IDENTIFIED HAZARDS EXPOSURE OF CITY/MUNICIPALITY
			BP	TSU/S	PDC/BS	
Agoncillo	38059	3rd	3/2	7/11	11/21	38059
Alitagtag	7899 (partial)	3rd		5	0/6	7899 (partial)
Balayan		1st				
Balete	20186 (partial)	3rd	1	10/9	0/12	20186 (partial)
Batangas City		5th				
Bauan		2nd				
Calaca		1st				
Calatagan		1st				
Cuenca	5784	3rd	1/0	2/3	0/6	5784
Ibaan		4th				
Laurel	39,444	3rd	12/0	3/11	3/19	39,444
Lemery	56990	1st		8	24/38	56990
Lian		1st				
Lipa City	11008 (partial)	6th		4/2	0/4	11008 (partial)
Lobo		2nd				
Mabini		2nd				
Malvar	7156 (partial)	3rd		0/2	4/6	7156 (partial)
Mataas Na Kahoy	7308 (partial)	3rd		4	0/9	7308 (partial)
Nasugbu		1st				
Padre Garcia		4th				
Rosario		4th				
San Jose		4th				
San Juan		4th				
San Luis		2nd				
San Nicolas (Mainland & TVI)	20599	3rd	2 (TVI)	10/12	6/18	20599
San Pascual		2nd				
Santa Teresita	8099 (Partial)	3rd		9/7	0/12	8099 (Partial)
Santo Tomas		3rd				
Taal	39919 (Majority)	1st		3/0	31/40	39919 (Majority)
Talisay (Mainland & TVI	39600	3rd	2 (TVI)	19/14	2/21	39600
City of Tanauan	173,366 (partial)	3rd	1/0	10/9	5/23	173,366 (partial)
Taysan		4th				
Tingloy		2nd				
Tuy		1st				

city/municipal governments that may have considered only the barangays previously identified by the local government. This issue needs to be addressed and verified.

7.3.3. Reflections on the risk perception paradigms

In Chapter 2, Section 2.5.2, I provided an overview of the three key risk perception paradigms dominant in natural hazard studies. While my vignette study only provides a preliminary insight into the knowledge, awareness and preparedness of a limited number of Barangay Captains, it does provide an overview of some of the key factors that influence their actions and decisions related to disaster risk reduction and management. In my mind, Barangay Captains behave the way they do and know what they know, not because they weigh their decisions and actions on 'acceptable risk' identified in the Psychometric approach or 'cultural biases' and social relations as defined by the Socio-cultural approach but rather on 'social experience of risk' (as detailed in the Social amplification of risk approach) whereby a risk event is received and amplified by experiences, direct or indirect communication with official (identified as professional information brokers) and social networks that to me, are similar to the 'shadow network' of Armijos et al. (2017). Professional brokers in the Taal community include DOST-PHIVOLCS, DRRMOs, provincial and regional offices of the Department of Agriculture (DA), the Department of Education (DepEd), the Department of Public Works and Highways (DPWH), the Philippine Coast Guard, the Armed Forces of the Philippines (AFP), the Philippine Red Cross (PRC), the Land Transportation Office, and the National Telecommunications Commission (NTC). The informal social networks include relatives, neighbours, etc. Both official and shadow networks serve as Department of Social Welfare and Development (DSWD), the Department of the Interior and Local Government (DILG), the Department of Environment and Natural Resources (DENR), the amplification stations. The information provided is subsequently filtered, decoded, and combined with intuitive thinking that is influenced by social and cultural values and issues. The resulting evaluation guides the behaviour, actions and decisions of community leaders. The decisions and actions to a particular risk event shall determine the consequences and impacts of the event to the community. The outcome of the application of the positive aspects identified for each DRR related issue (e.g. knowledge of hazards, eruption experiences, preparedness measures, etc.) is reduced risk for all stakeholders in the social process.

7.4 Conclusion

At the time of the interviews, only one Barangay Captain admitted that they are not prepared if an eruption where to occur in the near future. While nine of the ten respondents generally believe that they are prepared for an eruption, and while evacuation plans exist in some of the cities and municipalities of the Barangay Captains interviewed, analysis of the interview response actually shows that they are ill-prepared to handle an eruption at this time. Only two Barangay Captains said they have conducted drills. Two Barangay Captains mentioned that when an eruption occurs, residents would most likely act on their own -"*kanya-kanya na lang*" (to each his own) especially if they own a vehicle or a boat. Some respondents mentioned that some residents are more afraid of the police than listen to them. Some complain they are not able to address their DRR equipment requirements because of a lack of resources. Other respondents feel that more frequently occurring hazards need to be prioritised. Consequently, this study finds that despite best intensions, the Barangay Captains are sufficiently educated, knowledgeable and experienced with regards to volcano related DRR, and while some may take the risk seriously and are prepared to support their communities during a volcanic emergency, in general, they still lack the capacity to effectively perform their DRR duties when a major eruption occurs. Addressing the gaps identified in this vignette study needs the consolidated and extensive efforts by all stakeholders involved in volcano related disaster risk reduction. After my thesis, I intend to undertake some of the future studies I have recommended, specifically on conducting more comprehensive and wider set of stakeholder groups in order to continue the debate on preparedness of communities in the event of a volcano emergency. For future further research that is recommended by the examiners, the potential bias of only having one respondent to the east and one distal respondent to the south shall be addressed. I will also pursue the issues and gaps I have identified pertaining to DRR related activities of the Province of Batangas.

CHAPTER 8

Discussion and Integration

8.0 Introduction

This study was undertaken to pursue research on Taal, one of the most active volcanoes in the Philippines. Rather than approaching this as a traditionally trained geologist conducting solely field-based hazard mapping and assessment, I wanted to take on the challenge of incorporating modelling and social science components.

This interdisciplinary approach to hazard and risk assessment and management utilised a globally accepted risk framework allowing me to design a suitable research project. The major components of my research included: 1) comprehensive review of literature; 2) geologic mapping and field data analysis specifically focused on the AD1754 tephra deposits; 3) inversion modelling to reconstruct the AD1754 tephra fallout event; and 4) a vignette analysis of knowledge, education, awareness, preparedness and response of selected Barangay Captains.

The literature review identified the following knowledge gaps: 1) lack of comprehensive and complete collation of all known historical eruptions of Taal; 2) limited knowledge of the occurrence of all volcanic hazards during past eruptions of Taal; 3) an absence of numerical modelling of eruptions of Philippine volcanic eruptions, including Taal; and 4) limited socially-oriented studies of Barangay Captains in relation to volcano related emergencies. These knowledge gaps allowed me to generate the following key research questions:

1. What do we know, and not know, about the eruptions of Taal Volcano? What can a collation, synthesis and reinterpretation of information tell us about the record of past eruptions at Taal, their processes, products and hazards?

2. What is the predicted distribution of tephra deposits in the event of an explosive eruption such as the AD1754 Plinian/Sub-Plinian eruption of Taal?

3. How would a major/plinian eruption affect communities around Taal?

4. Given that the Barangay Captains and their communities are located on or close to Taal, and as they are key stakeholders in the community, how are the Barangay Captains responding to volcanic risk? What is the level of education, knowledge, experience, risk perception and preparedness of these specific stakeholders?

5. How can the key results obtained from this interdisciplinary study be utilised for developing or strengthening disaster risk management plans of the province?

Chapter 4, 5, 6 and 7 summarised key findings for each of these research questions. The results provide new geologic information explaining the eruptive behaviour, processes, and products of various eruptions of Taal. Reclassification of VEIs, re-interpretation of processes and products, eruption styles, and timing of eruptions including determination of various eruptive phases for some events were done that may serve as additional input for future volcanic hazard assessment for Taal. The geologic mapping and processing also provide important information on the spatial and temporal distribution of the tephra fallout deposits of the AD1754 event, with an additional 41 outcrops mapped and sampled for this research and for further studies. Bulk and particle densities of AD1754 scoria fall deposits were determined for the first time. Best-fit eruption source parameters for a mafic Plinian style eruption were estimated using the *TEPHRA2* model and can be utilised for probabilistic modelling of future maximum expected event (Barberi et al., 1990). As confirmed by the uncertainty analysis conducted by Volentik at al. (2010), the column heights predicted for the AD1754 eruptive phases, generated from the inversion integrating grain size data, seems reasonable. The isopach maps from forward solutions have identified predicted areas of tephra accumulation for an AD1754 style eruption. The Barangay Captains selected for the vignette study were located in areas were past and future threat exist. The Barangays Captains were assessed as having general knowledge and awareness of volcanic hazards related to Taal. However, problems and issues identified in Section 7.2.5 may have directly or indirectly resulted in the 'deprioritisation' of volcano related DRR activities. Consequently, these issues may affect their ability to effectively support their communities if a major explosive eruption occurs. These issues need to be urgently addressed before a DRR strategy designed for the Taal community can effective and sustainable.

8.1 Development/strengthening of DRRM plans

With the results I obtained from this interdisciplinary research, I ask myself, how can these results be utilised for the development or strengthening of DRRM plans in the province? The following summary I provide addresses Research Question 5.

I identified potential volcanic processes and products related to major eruptions at Taal, and also identified critical areas likely to be affected by products of an AD1754 type eruption. The result can now be used as initial input for volcano related DRRM Plans for Batangas Province. Through inversion modelling, I was able to obtain results that predicted the model source parameters for simulating an AD1754 type tephra fall. Thus, probabilistic modelling can be conducted in the future so that an accurate volcanic hazard and risk assessment can be generated for Taal using a maximum expected event scenario eruption. Consequently, DRRM Plans can be refined if better results are obtained. The results of my vignette study showed that at the time of the interviews, the Barangay Captains were ill-prepared to perform their roles in supporting their communities in the event of a major eruption at Taal. Consequently, there is a need for re-evaluation of the DRRM system such that more effective strategies are developed to improve the capacities of the Barangay Captains, the most important implementer of DRRM initiatives. In responding to Research Question # 5, I make the following 16 recommendations to improve volcano disaster risk management policies, planning and practice:

Recommendation #1: Re-evaluation of 'identified hazard and risk zones' by the local government units. While I commend the Provincial Disaster Risk Reduction and Management Office for their great efforts in utilising the volcano hazards maps of DOST-PHIVOLCS, and for identifying barangays likely to be affected, my own re-evaluation identified a much greater number of barangays within the delineated hazard areas than previously identified. The difference may be because the provincial identification used barangay boundaries that are different from those used by DOST-PHIVOLCS. Consequently, there is an urgent need to crosscheck both information sources so that a unified and more accurate listing of 'at risk' communities may be made, information disseminated, and appropriate volcano DRRM plans and actions implemented. Further, other volcanic hazards that have been observed at Taal and discussed in Chapter 2, have not been included in the volcanic hazard identification conducted by local government. With additional volcanic hazards (e.g. lahars, liquefaction effects, etc.) that have been identified and emphasised by DOST-PHIVOLCS, the assessment and inclusion of these hazards into land use and DRR planning must be seriously considered.

Recommendation #2: Improved education and training material. Government and non-government organisations conducting volcano-related DRRM information campaigns including seminars, trainings and workshops should design and implement education and outreach modules with innovative methods (e.g. gauge prior knowledge of participants through concept tests and concept maps, more interactive instructional methods that will show how much the participants have learned, connecting hazard topics to everyday lives of listeners, mixing lectures with actual videos of hazard topics, etc.) so that they become relevant and meet the needs and interests of various stakeholders. Particular attention should be given to the various volcanic hazards that have been known to impact communities during past eruptions of Taal. While DOST-PHIVOLCS is continually making great efforts to provide volcano hazard information to selected Taal communities including those located on TVI, of great concern arising from the study is the lack of knowledge of hazards and DRR measures of some Barangay Captains living on and around TVI. Education campaigns focusing on volcanic hazards awareness and preparedness must therefore be sustained to ensure that Barangay Captains are able to respond appropriately during future volcanic crises. Informal education through self-directed learning, socialization or incidental learning could also serve as an avenue for knowledge acquisition, hazard and risk awareness and other community based DRR (Feng et al., 2018).

Recommendation #3: Development of an effective information campaign module for DRR information dissemination campaigns. Information campaign modules can help the Barangay Captains in their efforts to encourage more participation of residents of their communities. These modules should consider the strong social-cultural-religious values of the residents and could be built around the social-cultural-religious activities and events which are well-attended through strong social and community relationships and bonds. Organising 'pot lucks' and designing learnings through video watching, games and reward system could make the learning process more fun and enjoyable to the residents.

Recommendation #4: Enhance incentives to effect volcano related DRR activities. I recommend the development of incentives to encourage Barangay Captains to design and draft their BDRRM Plans that are adapted to the conditions in their barangays. Effort should be made to avoid simply copying from other barangays in order to fulfil the requirements of DRRMOs and DILG, and to require the barangays to perform volcano related drills to practice warning communication and evacuation, with the municipal or city DRRMO ensuring they perform the drill and observing the activity. While there are existing awards to recognise individuals, government and non-government organisations and the private sector who have shown exemplary initiatives in uplifting the standard of disaster management in the country (e.g. Gawad Kalasag), small scale awards and financial rewards (e.g. increased DRR funding) specifically catering to Barangay DRRM initiatives can provide incentives for Barangay officials to be more proactive in disaster preparedness and response.

Recommendation #5: Utilisation of the DRRM Fund or Calamity Fund. Some of the Barangay Captains were unfamiliar with how to utilise the LDRRM Fund or

Calamity Fund. While OCD continuously provide Contingency Plan Formulation Workshops in various regions of the Philippines, there is a need to step up capacity enhancement that specifically address knowledge gap on maximising utilisation of these funds allocated for the DRRM activities in the barangay level.

Recommendation #6: Promotion of self-reliance in DRRM plans and actions. Communities should be supported to become more self-reliant in terms of preparedness rather than dependent on local government (e.g. provincial, city or municipal) units for evacuation and other emergency-related response and recovery actions. In order to do this, the DRRM Funds or Calamity Funds could be made more flexible and adjust to the needs of the barangay they were designed for. Specifically, funds should be made available first and foremost for preparedness and mitigation actions.

Recommendation #7: More active integration of schools and teachers into the DRRM system. Schools and teachers have a very important role educating students about natural hazards, including volcano related information. They are the best 'information officers' that should and could easily disseminate volcano hazard information to their students, who in turn could relay the information to their families, relatives, friends and neighbours. Time and again, we hear stories of communities being saved from a natural hazards because the children told elders of what they learned in school and what to do during a particular crisis. Thus, active participation of schools in the DRRM strategies of the barangays where the schools are located should be strongly encouraged.

Recommendation #8: Protocols to improve dissemination of volcano warning information. In relation to the role of DOST-PHIVOLCS in the DRRM system, there is a need ensure that protocols about warning information are clear to all '*amplification stations*' included in the DRRM structure previously discussed in Chapters 2 and 7 so that warning information is properly relayed and acted upon by all stakeholders. There is also a need to explore the potential role of "shadow networks" in future research that could augment prompt and accurate dissemination of volcano warning information. A seminar workshop and drill on eruption warnings could be organised by DOST-PHIVOLCS, much like what was intended prior to the AD1991 eruption of Pinatubo. Further, the reliance of communities on eruption warning information provided by DOST-PHIVOLCS means that DOST-PHIVOLCS must strive harder in its volcano monitoring efforts in order that it may provide more accurate and prompt eruption warnings to the Taal communities it serves and that the information provided is heeded and acted upon by the LGUs.

Recommendation #9: Proper design and implementation of Evacuation Plans. There is a critical need to assess existing and proposed evacuation plans and centers to ensure that they are well outside the delineated hazard zones as defined by the DOST-PHIVOLCS Volcano Hazard Maps. The evacuation information must be discussed between the various DRRMCs affected by the evacuation so that corresponding evacuation actions plans are designed and implemented effectively.

Recommendation #10: Livelihood development. While relocation does not seem to be an immediate option for the Taal communities, especially those living at TVI, resettlement may and could be considered and provided by the local government of Batangas in the future. Relevant government authorities need to consider the economic impact of relocation/resettlement (Usamah & Haynes, 2012), and must support and foster the development of alternative and sustainable livelihood options, if needed, where relocation is advised. This is critical if communities are to be convinced of the merits of relocation. Other factors like easy access to facilities like schools, hospitals, transportation and communication, business centers, etc. should also be integrated into the resettlement development.

Recommendation #11: Alternative housing for livestock. When communities are encouraged/forced to evacuate during an eruption, consideration must be given to providing safe evacuation for livestock that would otherwise be left behind. Providing livestock shelter close to human evacuation centres encourages residents not to re-enter hazard zones during an eruption, endangering their lives. This would address legitimate concerns raised by residents about the welfare of their animals.

Recommendation #12: Developing volcano related BDRRM Plans for critical, distal locations. Batangas Province is rapidly growing as an industrial province with a significant number of Industrial and Tourism Parks in various locations. The BDRRM Plans and Contingency Plans for volcano emergencies must be designed and implemented to take account of the risk posed to these high-value economic zones from volcanic hazards such as ash fall – even when they are located at some distance from Taal. Strict implementation of volcanic eruption contingency plans must be included as part of their security measures to ensure minimal disruption to services they provide.

Recommendation #13: Attachment to place as key issues to DRR efforts. This issue of 'sense of belonging' that the Barangay Captains feel about their communities could be explored in a positive way. Past studies have shown that attachment to place have both positive and negative influence to risk perception and risk coping (Anton & Lawrence, 2016; Bonaiuto et al., 2016; Fried, 1963). In terms of the DRR efforts, this attachment to place could be used to compel community residents to do more to ensure the safety of their communities, including active participations in Barangay assemblies that are required at least twice a year, echo trainings where Barangay officials teach their community residents what they learned from the DRR trainings they attended, and conducting volcano related drills.

Recommendation #14: Inherited memories as key issues to DRR efforts. So many narrative accounts of people's eruption experiences were written and compiled that now provided information of the natural calamities including processes and products and the magnitude of the eruption in the past (Becker et al., 2017; Hutchinson et al., 2016; Shibata, 2012). However, these '*memories*' are not known to all residents of the Taal communities. Most of the Barangay Captains were too young or were not born yet when the major and more recent destructive eruptions of Taal occurred. Some Barangay Captains were lucky enough that their elders provided them with stories about those traumatic experiences and their actions during those times that they are able add those '*inherited memories*' for their actions and decisions given a scenario that Taal erupts again. One Barangay Captain knows the impact of a tsunami and the need to go to higher places should the threat arise. One Barangay Captain told stories of how their elders prioritised saving water for drinking and having a wet mosquito net covering their bodies so they are not affected by ashfall. Another mentioned that their community went to specific places for evacuation because that was what their ancestors did during the past eruptions. In addition, the establishment of small museums or exhibitions in the affected Taal communities could be another way to preserve the inherited memories. We must find a way that these eruption memories are ingrained in the minds of the present residents of Taal so that they will not forget the potential catastrophic impacts of an explosive eruption at Taal Volcano. Documentation of volcanic eruption experiences, either in written or oral forms must be encouraged. Perhaps Barangay Captains and other residents with more prior experiences can be motivated to provide testimonials during volcano-related seminars and workshops in order to motivate fellow Barangay Captains to be more proactive in DRR related activities. In addition, the establishment of small museums or exhibitions in the affected Taal communities could be another way to preserve the inherited memories.

Recommendation #15: Trust as a key issue to DRR efforts. There is a need to develop trust and confidence in local governance in order for DRR programs and policies are implemented at the grass root level. In terms of eruption warning, DOST-PHIVOLCS continuously improves its monitoring and eruption prediction capability in order to provide prompt warning to LGUs, but there is a need to extend more effort in testing and strengthening the holistic warning communication system currently in place.

Recommendation #16: Establishment* of an effective and sustainable *community-based early warning system (CBEWS) and volunteer observers' program (VOP). While DOST-PHIVOLCS has the primary role of providing eruption warnings and associated information, the support of the communities around Taal is important. Residents, especially those living at TVI, are the potential first observers of unusual volcanic activity that are signs of unrest (e.g. occurrences of volcanic earthquakes felt as ground shaking, water geysering/bubbling in lake areas etc) that are sometimes not immediately observed in the Taal Volcano Observatory. The Volunteer Observers Program encourages local residents to participate actively in monitoring Taal and further increase their knowledge and awareness of the hazards and risk to their community (Delos Reyes, 1992). Strengthening the program especially at TVI could help ensure that prompt reporting of those unusual phenomena by the general public are given to the Taal Volcano Observatory personnel thus helping in early forecasting of volcanic unrest. Further, with the prompt delivery of observation of unrest, CBEWS can be activated and prompt warning to communities can be provided. Community participation will strengthen their resilience in the context of early warning and community preparedness (Thomalla & Larsen, 2010). However, the development of a VOP, CBEWS and other participatory approaches to mitigation must be initiated with the support of the government (e.g. DRRMOs, DOST-PHIVOLCS) (Cronin et al., 2004b). A similar CBEWS Program is currently being conducted in selected communities in the Philippines related to earthquakes and tsunami hazards. However, when developed, the success of the CBEWS primarily relies on the communities who participate in these endeavours.

8.2 Conclusion

Overall, as much as I acknowledge the difficulties of an interdisciplinary approach, I used this approach because I genuinely believe this may contribute useful new knowledge to enhance and expand existing hazard and risk assessment and management strategies at Taal. In this final section of the thesis, I outline the implications and contributions of the study and note its limitations as well as provide a roadmap for moving forward.

8.2.1. Implications and contribution of the study

Given the increasing urbanisation and population surrounding Taal, the societal and economic impacts of the recurrence of a Plinian type eruption such as the AD1754 event would be significantly greater than those associated with the past. The research presented here may be used to better understand the dynamics of the processes and products from a Plinian type eruption at Taal, and subsequently, to revise and enhance volcano disaster risk reduction policies, plans and practices. An explosive eruption at Taal would result in major socio-economic loss and disruption across the region. Impacts would be expected to include but not be limited to: death and injury of people; destruction of and damage to infrastructure and buildings, critical lifelines and power and communication distribution networks and systems; loss of a range of aqua- and agricultural infrastructure, products and output; industrial and tourism -related losses as well as on regional aviation activity. Having noted the range of impacts that might be expected with a future large eruption of Taal, of concern are the findings that the Barangay Captains - those elected to lead communities and in particular, prepare for, and respond when (volcanic) crisis occur - are entirely unprepared for the task at hand, despite their best intentions. Poor leadership, planning and preparedness will only lead to an amplification of losses after an event.

This interdisciplinary study has faced many challenges but the effort has been worthwhile and the approach and its findings may be used by relevant authorities in their volcano disaster risk reduction policy-making, planning and practice. If the recommendations proposed were adopted, I genuinely believe communities living on and around Taal, could prepare and respond better when faced with future eruptions.

8.2.2. Limitations of the study and the road map for going forward

The following outlines the limitations of this study and identifies a road map for moving forward.

The two primary limitations of this study were 'available time to do more' and 'resources' to support more detailed geological analysis of deposits – including geochemical fingerprinting of volcanic deposits and their absolute dating.

Eruptions at Taal deemed 'uncertain' in this research need further investigation and possible reclassification and the assigned VEIs for confirmed eruptions should be the subject of further analyses so that they truly reflect the magnitude and explosivity. For many individual eruptions, more work is needed to identify and separate out distinctive 'phases' within each eruption. Likewise, the approach taken in this thesis at Taal should be replicated at other volcanoes in the Philippines for which little if any work has been undertaken. However, I hope my research limitation of lack of funds to engage Spanish speaking expert to translate the Spanish documents will be considered and addressed for future research dealing with review of available records written in Spanish.

Future research should be undertaken to perform geochemical analysis and dating to confirm the deposits identified and mapped in association with the AD1754 event. Further, lake coring of Taal eruptive products preserved at Taal Lake, including those from the AD1754 eruptions, is a great method to document the stratigraphic sequence of the tephra fallout deposit in proximal sources. However, doing this could be a challenge. In the past, a collaborative study on tephrochronology already considered lake coring at Taal but this was discounted because aside from the great turbulence of lake waters, the presence of considerable number of fish ponds at Taal Lake would make it difficult for drilling and coring to be done.

Further mapping of the distal extent of PDCs, lahars and flooding could shed light on the magnitude of these hazards and the risk posed to Taal communities. Additional mapping of the distal extent of the tephra deposits from the AD1754 eruption should be continued. The additional geologic findings would then become key inputs for additional numerical modelling.

From the geologic investigations conducted for this research, most of the extensively distributed and thick Taal deposits are older Quaternary caldera-forming eruption deposits that are currently not dated. More research is critically needed on these caldera-forming events in order to build a better picture of the early evolution of Taal, as well as to provide an estimate of the recurrence rate and potential for large explosive eruptions from Taal Caldera and their associated processes.

Perhaps the biggest challenge in undertaking field investigations is the exposure and subsequent cover up of the AD1754 outcrops due to road cutting and local government engineering works (e.g. riprapping of the tephra surface) to prevent landslides and rockfalls. I recommend that a national or local legal policy should be drafted and implemented such that there will be a standard operating procedure in all provinces/municipalities/cities near a volcanic environment. This would mean that whenever a new highway road cutting activity is implemented that cuts through a volcanic deposit, a volcanologist should be allowed to conduct a rapid field assessment, measurement and sampling so as to create a record and establish a national database for these deposits prior to any engineering activity that might remove or hide those deposits.

Tephra fall dispersion had the most extensive impact of all volcanic hazards from Taal. While successful application of *TEPHRA2* was undertaken advancing understanding of the AD1754 eruption, calibration and validation could also be performed with the predicted eruption source parameters obtained in this research using inversion methods with other models such as ASHFALL, FALL3D and Python FALL3D. Further, the dispersal of tephra under different climactic conditions should be further assessed through probabilistic numerical modelling utilising the eruption source parameters generated from this research. This in turn would provide critical hazard information to stakeholders from the agricultural, engineering, tourism, aviation, and emergency management sectors in regards to future events. In addition, there are open source models for other volcanic hazards that can be used at Taal (e.g. Pyflow for dilute pyroclastic density currents, TITAN 2D for block and ashflows and lahars, and LAHARZ for lahars, etc.) which can be explored.

TEPHRA2 could also be applied to some of the more frequently erupting Philippine volcanoes like Mayon and Bulusan so that tephra fallout dispersal and accumulation from an explosive eruption may be predicted and hazard and risk assessed.

The results from the vignette analysis of the structured interviews I conducted with selected Barangay Captains provided preliminary insights to their knowledge, education, awareness, preparedness, and action/inaction when faced with a volcanic crisis. This socially-oriented research should be greatly expanded and encompass many more stakeholders and community members. Further, the methodology to be used could be more diverse (e.g. semi-structured, surveys, focus group discussions, participatory mapping, etc.) (Armijos et al., 2017; Bryman, 2006; Cashman & Cronin, 2008; Donovan et al., 2012b; Gregg et al. 2004; Johnson et al., 2007; Kelman et al.,

2012) that could provide more in-depth responses and deeper understanding of the issues and factors that influence the decisions and actions of residents around Taal Volcano. Another avenue to improving DRRM strategies at Taal would be to expand the study of Barangay Captains to those from Pinatubo and Mayon that have had more recent crisis with the specific question in mind: "*Is there a difference in the knowledge, perception, awareness, activity between Barangay Captains around Pinatubo and Mayon versus around Taal*?". A comparative study could provide 'lessons learned' that might identify successes and failures of community leaders during and after recent eruption crisis.

Finally, in my vignette study, my structured interviews limited my discussion to some extent and there is a need to explore the issues raised for my future research endeavours.

8.3 Final remarks

While I have identified some limitations on both the physical and social aspect of my research, I hope the enumerated recommendations for further studies may be conducted in the future to better understand Taal and mitigate its future impacts on communities surrounding the volcano. Further, I also hope that my recommendations for improvement of DRR strategies can be considered and adopted to gain a more positive response from the Taal communities. Likewise, having identified some of the positive (strengths) and negative (weaknesses) issues related to the volcano DRR knowledge, experiences, reactions and preparedness of some of the Barangay officials around Taal, reduction of the vulnerability by utilising the strengths and addressing the weaknesses may ensure the safety of the Taal communities from impacts of future eruptions and the related hazards. The same practical recommendations for strengthening DRR strategies in the Taal community emanating from my research could also provide important volcano related DRR inputs for considerations on the national and international level in as far as disaster risk reduction and management is concerned.

References

Acharya, H. K., & Aggarwal, Y. P. (1980). Seismicity and tectonics of the Philippine Islands. *Journal of Geophysical Research, 85*(B6), 3239-3250.

Adams, G. I. (1910). Geological reconnaissance of southwestern Luzon. *Philippine Journal of Science, Section A, 5*(2), 57-116.

Adams, J. (1995). *Risk*. London: U.C.L. Press.

AIDR. (2015). *Australian Disaster Resilience Handbook 10: National Emergency Risk Assessment Guidelines*. East Melbourne, Victoria 3002: Australian Institute for Disaster Resilience Retrieved from https://knowledge.aidr.org.au/media/2030/handbook-10-national-emergency-risk-assessment-guidelines.pdf.

Akerlind, G. S. (2015). Academic Growth and Development: How Do University Academics Experience It? *Higher Education, 50*(1), 1-32.

Alcaraz, A. (1966). Surveillance of Taal Volcano. *The Philippine Geologist, XX*(1), 1-13.

Alcaraz, A. & Datuin, R. (1974). Geothermal phenomena of the 1965 Phreatomagmatic eruption of Taal Volcano. *Journal of the Geological Society of the Philippines, XXVIII*(1), 31-40.

Alcaraz, A. P. & Datuin, R. (1977). Notes on Taal Volcano Prognostics. Journal of the Geological Society of the Philippines, 16(2), 18-20.

Alden, D.L., Friend, J.M., Lee, A.Y., de Vries, M., Osawa, R., & Chen, Q. (2015). Culture and medical decision making: Healthcare consumer perspectives in Japan and the United States. *Health Psychology*, 34 (12), p. 1133-1144.

Aldrich, D. P., & Meyer, M. A. (2015). Social Capital and Community Resilience. *American Behavioral Scientist, 59*(2), 254-269. doi:10.1177/0002764214550299

Alexander, D. (2013). Volcanic ash in the atmosphere and risks for civil aviation: A study in European crisis management. *International Journal of Disaster Risk Science, 4*(1), 9-19. doi:10.1007/s13753-013-0003-0.

Allen, C. R. (1962). Circum-Pacific Faulting in the Philippines-Taiwan Region. *Journal of Geophysical Research, 67*(12), 4795-4812. doi:10.1029/JZ067i012p04795.

Anton, C. E., & Lawrence, C. (2016). The relationship between place attachment, the theory of planned behaviour and residents' response to place change. *Journal of Environmental Psychology, 47*, 145-154. doi:http://dx.doi.org/10.1016/j.jenvp.2016.05.010.

Antos, J. A. (1984). *Responses of forest understory plants to burial by volcanic tephra from Mount ST. Helens, Washington.* (8415278 Ph.D.), Oregon State University, Ann Arbor. Retrieved from http://ezproxy.library.usyd.edu.au/login?url=http://search.proquest.com/docview/303302515?accountid=14757

http://DD8GH5YX7K.search.serialssolutions.com/?ctx_ver=Z39.88-2004&ctx_enc=info:ofi/enc:UTF-8&rfr_id=info:sid/ProQuest+Dissertations+%26+Theses+Global&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&rft.genre=dissertations+%26+theses&rft.jtitle=&rft.atitle=&rft.au=Antos%2C+Joseph+Avery&rft.aulast=Antos&rft.aufirst=Joseph&rft.date=1984-01-01&rft.volume=&rft.issue=&rft.spage=&rft.isbn=&rft.btitle=&rft.title=RESPONSES+OF+FOREST+UNDERSTORY+PLANTS+TO+BURIAL+BY+VOLCANIC+TEPHRA+FROM+MOUNT+ST.+HELENS%2C+WASHINGTON&rft.issn=&rft_id=info:doi/.

Armienti, P., Macedonio, G. & Pareschi, M. T. (1988a). Air traffic risk evaluation in volcanic ash clouds. *International Journal of Modelling and Simulation, 8*(1), 29-32.

Armienti, P., Macedonio, G., & Pareschi, M. T. (1988b). A numerical model for simulation of tephra transport and deposition: Applications to May 18, 1980, Mount St. Helens eruption. *Journal of Geophysical Research: Solid Earth, 93*(B6), 6463-6476. doi:10.1029/JB093iB06p06463.

Armijos, M. T., Phillips, J., Wilkinson, E., Barclay, J., Palacios, P., Monthes, P., & Stone, J. (2017). Adapting to changes in volcanic behaviour: Formal and informal interactions for enhanced risk management at Tungurahua Volcano, Ecuador. *Global Environmental Change, 45*, 217-226.

Arpa, M. C. B., Patino, L. C., & Vogel, T. A. (2008). The basaltic to trachydacitic upper Diliman Tuff in Manila: Petrogenesis and comparison with deposits from Taal and Laguna Calderas. *Journal of Volcanology and Geothermal Research, 177*(4), 1020-1034. doi:http://dx.doi.org/10.1016/j.jvolgeores.2008.07.024.

Arpa, M.C., Hernández, P.A., Padrón, E., Reniva, P., Padilla, G.D., Bariso, E., Melián, G.V., Barrancos, J., Nolasco, D., Carvo, D., Perez, N.M., & Solidum, R. U., Jr. (2013). Geochemical evidence of magma intrusion inferred from diffuse CO2 emissions and fumarole plume chemistry: the 2010–2011 volcanic unrest at Taal Volcano, Philippines. *Bulletin of Volcanology, 75*(10), 1-13. doi:10.1007/s00445-013-0747-9.

Aurelio, M. A. (2000). Shear partitioning in the Philippines: Constraints from Philippine Fault and global positioning system data. *Island Arc, 9*(4), 584-597. doi:10.1111/j.1440-1738.2000.00304.x.

Ayris, P. M., & Delmelle, P. (2012). The immediate environmental effects of tephra emission. *Bulletin of Volcanology, 74*(9), 1905-1936. doi:http://dx.doi.org/10.1007/s00445-012-0654-5.

Bacolcol, T. C., Solidum, R. U., Jr., Yu, S.-B., Luis, A., Jr., Jorgio, R., Pelicano, A., & Group, P. G. W. (2012). *Current motions of the Philippine Mobile Belt derived from Global Positioning Data*. Unpublished manuscript. Retrieved from Quezon City: DOST-PHIVOLCS.

Bankoff, G. (2004). In the Eye of the Storm: The Social Construction of the Forces of Nature and the Climatic and Seismic Construction of God in the Philippines. *Journal of Southeast Asian Studies, 35*(1), 91-111. doi:10.1017/S0022463404000050.

Bankoff, G., Hilhorst, T. and Frerks, G. (2004). *Mapping vulnerability: disasters, development, and people*. Sterling, VA; London: Earthscan Publications.

Banzon-Bautista, C. (1996). The Mount Pinatubo Disaster and the People of Central Luzon. In C. G. Newhall & R. S. Punongbayan (Eds.), *Fire and Mud: Eruptions and Lahars of Mt. Pinatubo, Philippines* (pp. 151-161). Seattle, USA; Quezon City, Philippines: Unversity of Washington Press.

Barberi, F., Martini, M., & Rosi, M. (1990). Nevado del Ruiz volcano (Colombia): pre-eruption observations and the November 13, 1985 catastrophic event. *Journal of Volcanology and Geothermal Research, 42*(1), 1-12. doi:http://dx.doi.org/10.1016/0377-0273(90)90066-O

Barberi, F., Davis, M. S., Isaia, R., Nave, R., & Ricci, T. (2008). Volcanic risk perception in the Vesuvius population. *Journal of Volcanology and Geothermal Research, 172*(3-4), 244-258. doi:10.1016/j.jvolgeores.2007.12.011.

Barnes, P. (2002). Approaches to Community Safety: Risk Perception and Social Meaning. *Australian Journal of Emergency Management, 17*(1), 15-23.

Barrier, E., Huchon, P., & Aurelio, M. (1991). Philippine fault: A key for Philippine kinematics. *Geology, 19*(1), 32-35. doi:10.1130/0091-7613(1991)019<0032:pfakfp>2.3.co;2.

Barsotti, S., Neri, A., & Scire, J. S. (2008). The VOL-CALPUFF model for atmospheric ash dispersal: 1. Approach and physical formulation. *Journal of Geophysical Research: Solid Earth, 113*(B3), n/a. doi:10.1029/2006JB004623

Barsotti, S., Andronico, D., Neri, A., Del Carlo, P., Baxter, P. J., Aspinall, W. P., & Hincks, T. (2010). Quantitative assessment of volcanic ash hazards for health and infrastructure at Mt. Etna (Italy) by numerical simulation. *Journal of Volcanology and Geothermal Research, 192*(1–2), 85-96. doi:http://dx.doi.org/10.1016/j.jvolgeores.2010.02.011.

Bartel, B. A., Hamburger, M. W., Meertens, C. M., Lowry, A. R., & Corpuz, E. (2003). Dynamics of active magmatic and hydrothermal systems at Taal Volcano, Philippines, from continuous GPS measurements. *Journal of Geophysical Research B: Solid Earth, 108*(10), ECV 4-1 - ECV 4-15. doi:10.1029/2002JB002194.

Baxter, P. J., Aspinall, W. P., Neri, A., Zuccaro, G., Spence, R. J. S., Cioni, R., & Woo, G. (2008). Emergency planning and mitigation at Vesuvius: A new evidence-based approach. *Journal of Volcanology and Geothermal Research, 178*(3), 454-473. doi:http://dx.doi.org/10.1016/j.jvolgeores.2008.08.015.

Becker, J., Smith, R. G., Johnston, D., & Munro, A. (2001). Effects of the 1995-1996 Ruapehu eruptions on communities in central North Island, New Zealand, and people's perceptions of volcanic hazards after the event. *The Australasian*

Journal of Disaster and Trauma Studies, 2001-1. Retrieved from http://www.massey.ac.nz/~trauma/issues/2001-1/becker.htm

Becker, J., Paton, D., Johnston, D., & Ronan, K. (2014). Societal Influences on Earthquake Information Meaning-Making and Household Preparedness. *International Journal of Mass Emergencies and Disasters, 32*(2), 317-352.

Becker, J. S., Paton, D., Johnston, D. M., Ronan, K. R., & McClure, J. (2017). The role of prior experience in informing and motivating earthquake preparedness. *International Journal of Disaster Risk Reduction, 22*, 179-193.

Behncke, B. (2009). Hazards from pyroclastic density currents at Mt. Etna (Italy). *Journal of Volcanology and Geothermal Research, 180*(2–4), 148-160. doi:http://dx.doi.org/10.1016/j.jvolgeores.2008.09.021.

Behnke, S. A., Thomas, R. J., McNutt, S. R., Schneider, D. J., Krehbiel, P. R., Rison, W. and Edens, H. E. (2013). Observations of volcanic lightning during the 2009 eruption of Redoubt Volcano. *Journal of Volcanology and Geothermal Research, 259*(0), 214-234. doi:http://dx.doi.org/10.1016/j.jvolgeores.2011.12.010.

Bell, F. G. (1999). Geological Hazards: Their assessment, avoidance and mitigation. New York: Routledge.

Belshaw, C. S. (1951). Social Consequences of the Mount Lamington Eruption. *Oceania, 21*(4), 241-252.

Berninghausen, W. H. (1969). Tsunamis and seismic seiches of southeast Asia. Bulletin of the Seismological Society of America, 59(1), 289-297.

Biass, S. & Bonadonna, C. (2011). A quantitative uncertainty assessment of eruptive parameters derived from tephra deposits: the example of two large eruptions of Cotopaxi volcano, Ecuador. Bulletin of Volcanology, 73(1), 73-90. doi:10.1007/s00445-010-0404-5.

Biass, S., Frischknecht, C., & Bonadonna, C. (2012). A fast GIS-based risk assessment for tephra fallout: the example of Cotopaxi volcano, Ecuador-Part II: vulnerability and risk assessment. *Natural Hazards, 64*(1), 615-639. doi:10.1007/s11069-012-0270-x.

Biass, S., Frischknecht, C., & Bonadonna, C. (2013). A fast GIS-based risk assessment for tephra fallout: the example of Cotopaxi volcano, Ecuador. *Natural Hazards, 65*(1), 497-521. doi:http://dx.doi.org/10.1007/s11069-012-0457-1.

Biass, S., Todde, A., Cioni, R., Pistolesi, M., Geshi, N., & Bonadonna, C. (2017). Potential impacts of tephra fallout from a large-scale explosive eruption at Sakurajima volcano, Japan. *Bulletin of Volcanology, 79*(10), 1-24. doi:10.1007/s00445-017-1153-5.

Bird, D. K. (2009). The use of questionnaires for acquiring information on public perception of natural hazards and risk mitigation - A review of current knowledge and practice. *Natural Hazards and Earth System Science, 9*(4), 1307-1325.

Bird, D. K. (2010). *Social dimensions of volcanic hazards, risk and emergency response procedures in southern Iceland.* (Doctor of Philosophy), Macquarie University and University of Iceland, Sydney, Australia. (Libraries Australia ID 46899627).

Bird, D. K., & Gisladottir, G. (2012). Residents' attitudes and behaviour before and after the 2010 Eyjafjallajokull eruptions-a case study from southern Iceland. *Bulletin of Volcanology, 74*(6), 1263-1279. doi:10.1007/s00445-012-0595-z.

Bird, D.K., Gisladottir, G., & Dominey-Howes, D. (2010). Volcanic risk and tourism in southern Iceland: Implications for hazard, risk and emergency response education and training. *Journal of Volcanology and Geothermal Research, 189*(1-2), 33-48. doi:10.1016/j.jvolgeores.2009.09.020.

Bird, D. K., Gisladottir, G., & Dominey-Howes, D. (2011). Different communities, different perspectives: Issues affecting residents' response to a volcanic eruption in southern Iceland. *Bulletin of Volcanology, 73*(9), 1209-1227. doi:10.1007/s00445-011-0464-1.

Blong, R. J. (1981). Some effects of tephra fall on buildings. In S. Self & R. S. J. Sparks (Eds.), *Tephra Studies*. Dordrecht, The Netherlands: D. Reidel Publishing Company.

Blong, R. J. (1984). *Volcanic Hazards: a sourcebook on the effects of eruptions*. Australia: Academic Press.

Blong, R. J. (2003). Building damage in Rabaul, Papua New Guinea, 1994. *Bulletin of Volcanology, 65*(1), 43-54. doi:10.1007/s00445-002-0238-x.

Blong, R., Grasso, P., Jenkins, S. F., Magill, C. R., Wilson, T. M., McMullan, K., & Kandlbauer. (2017). Estimating building vulnerability to volcanic ash fall for insurance and other purposes. *Journal of Applied Volcanology, 6*(2). doi:https://doi.org/10.1186/s13617-017-0054-9.

Boggs, S. (2006). Principles of sedimentology and stratigraphy. Upper Saddle River, N.J.: Pearson Prentice Hall.

Boholm, A. (1996). Risk perception and social anthropology: Critique of cultural theory. *Ethnos, 61*(1-2), 64-84. doi:10.1080/00141844.1996.9981528.

Bonadonna, C., Ernst, G.G.J. & Sparks, R.S.J. (1998). Thickness variations and volume estimates of tephra fall deposits: the importance of particle Reynolds number. *Journal of Volcanology and Geothermal Research, 81*(3–4), 173-187. doi:http://dx.doi.org/10.1016/S0377-0273(98)00007-9.

Bonadonna, C., Connor, C. B., Houghton, B. F., Connor, L., Byrne, M., Laing, A., & Hincks, T. K. (2005a). Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand. *Journal of Geophysical Research: Solid Earth, 110*(B3), B03203. doi:10.1029/2003JB002896.

Bonadonna, C. & Houghton, B. F. (2005b). Total grain-size distribution and volume of tephra-fall deposits. *Bulletin of Volcanology, 67*(5), 441-456. doi:10.1007/s00445-004-0386-2.

Bonadonna, C., Phillips, J. C., & Houghton, B.F. (2005c). Modeling tephra sedimentation from a Ruapehu weak plume eruption. *Journal of Geophysical Research: Solid Earth, 110*(B8). doi:10.1029/2004JB003515.

Bonadonna, C., Biass, S., & Costa, A. (2015). Physical characterization of explosive volcanic eruptions based on tephra deposits: Propagation of uncertainties and sensitivity analysis. Journal of Volcanology and Geothermal Research, 296, 80-100. doi:http://dx.doi.org/10.1016/j.jvolgeores.2015.03.009

Bonaiuto, M., Alves, S., De Dominicis, S., & Petruccelli, I. (2016). Place attachment and natural hazard risk: Research review and agenda. *Journal of Environmental Psychology, 48*, 33-53. doi:https://doi.org/10.1016/j.jenvp.2016.07.007.

Bonasia, R., Macedonio, G., Costa, A., Mele, D., & Sulpizio, R. (2010). Numerical inversion and analysis of tephra fallout deposits from the 472 AD sub-Plinian eruption at Vesuvius (Italy) through a new best-fit procedure. Journal of Volcanology and Geothermal Research, 189(3–4), 238-246. doi:http://dx.doi.org/10.1016/j.jvolgeores.2009.11.009

Bonasia, R., Capra, L., Costa, A., Macedonio, G., & Saucedo, R. (2011). Tephra fallout hazard assessment for a Plinian eruption scenario at Volcán de Colima (Mexico). *Journal of Volcanology and Geothermal Research, 203*(1–2), 12-22. doi:http://dx.doi.org/10.1016/j.jvolgeores.2011.03.006.

Bonasia, R., Costa, A., Folch, A., Macedonio, G., & Capra, L. (2012). Numerical simulation of tephra transport and deposition of the 1982 El Chichón eruption and implications for hazard assessment. Journal of Volcanology and Geothermal Research, 231–232, 39-49. doi:http://dx.doi.org/10.1016/j.jvolgeores.2012.04.006

Bonfils, L., Bosi, V., Constantini, L., Fontaine, M., Hidayati, S., Cozannet, G.L., Sumarti, S., Thierry, P., Vaccari, P. and Vagner, A. (2012). Living with a volcano: increasing preparedness. In C. Bignami, V. Bosi, L. Constantini, C. Cristiani, F. Lavigne, & P. Thierry (Eds.), *Handbook for Volcanic Risk Management: Prevention, Crisis Management, Resilience* (pp. 91-128). Orleans, France: MIAVITA.

Bornas, M. A. V. (2016). [The Geology and Hazards of Taal Volcano, Southern Luzon, Philippines]. Unpublished manuscript.

Bradbury, J. A. (1989). The Policy Implications of Differing Concepts of Risk. *Science, Technology, & Human Values, 14*(4), 380-399.

Brewer, J., & Hunter, A. (1989). Multimethod research: a synthesis of styles (J. Brewer & A. Hunter Eds.). Newbury Park, California: SAGE Publications.

Broom, S. J. (2010). Characterisation of 'synthetic ash' for quantitative testing of critical infrastructure components with a focus on roofing fragility *B.Sc. (Honours) dissertation, University of Canterbury*.

Brown, K., & Wherrett, A. (2017). Fact Sheets: Bulk Density Measurement. Retrieved from http://soilquality.org.au/factsheets/bulk-density-measurement

Braun, V., & Clarke, V. (2013). *Successful qualitative research; a practical guide for beginners* (Vol. 28). Portland: Ringgold Inc. https://us.sagepub.com/en-us/nam/successful-qualitative-research/book233059

Bryman, A. (2004). *Social research methods* (2nd ed. ed.). Oxford ;: Oxford University Press.

Bryman, A. (2006). Integrating quantitative and qualitative research: how is it done? *Qualitative Research, 6*(1), 97-113. doi:10.1177/1468794106058877

Buencuchillo, F. (1754). *Relacion de lo sucedido con el volcan de la laguna de "Bongbong" en la provincia de Taal y Balayan (English translation by Fr. P. Hernandez, Augustinian Convent, Manila).* Valladolid, Spain.

Bursik, M. I., Carey, S. N., & Sparks, R. S. J. (1992a). A gravity current model for the May 18, 1980 Mount St. Helens plume. *Geophysical Research Letters, 19*(16), 1663-1666. doi:10.1029/92GL01639.

Bursik, M. I., Sparks, R. S. J., Gilbert, J. S., & Carey, S. N. (1992b). Sedimentation of tephra by volcanic plumes: I. Theory and its comparison with a study of the Fogo A plinian deposit, Sao Miguel (Azores). *Bulletin of Volcanology, 54*(4), 329-344. doi:10.1007/BF00301486.

Burt, M. L., Wadge, G., & Curnow, R. N. (2001). An objective method for mapping hazardous flow deposits from the stratigraphic record of stratovolcanoes: a case example from Montagne Pelée. *Bulletin of Volcanology, 63*(2), 98. doi:10.1007/s004450100128.

Cardona, O. D. (1997). Management of the volcanic crises of Galeras volcano: Social, economic and institutional aspects. *Journal of Volcanology and Geothermal Research, 77*(1), 313-324. doi:http://dx.doi.org/10.1016/S0377-0273(96)00102-3.

Carey, S. N. (2005). Understanding the physical behavior of volcanoes. In J. Marti & G. Ernst (Eds.), *Volcanoes and the Environment*. Cambridge, United Kingdom: Cambridge University Press.

Carey, S., & Sparks, R. S. J. (1986). Quantitative models of the fallout and dispersal of tephra from volcanic eruption columns. *Bulletin of Volcanology, 48*(2-3), 109-125. doi:10.1007/BF01046546.

Carlino, S., Somma, R. and Mayberry, G.C. (2008). Volcanic risk perception of young people in the urban areas of Vesuvius: Comparisons with other volcanic areas and implications for emergency management. *Journal of Volcanology and Geothermal Research, 172*(3-4), 229-243. doi:10.1016/j.jvolgeores.2007.12.010.

Carroll, J. J., S.J., & Parco, S. A. (1966). *Social Organization in a Crisis Situation: the Taal disaster*. Philippine Sociological Society, Manila, Philippines.

Carslaw, D.C., Williams, M.L., & Barratt, B. (2012). A short-term intervention study — Impact of airport closure due to the eruption of Eyjafjallajökull on near-field air quality. *Atmospheric Environment, 54*(0), 328-336. doi:http://dx.doi.org/10.1016/j.atmosenv.2012.02.020.

Carver, R. E. (1971). Procedures in sedimentary petrology. New York: Wiley-Interscience.

Cas, R. A. F. & Giordano, G. (2014). Submarine Volcanism: a Review of the Constraints, Processes and Products, and Relevance to the Cabo de Gata Volcanic Succession. *Italian Journal of Geosciences, 133*(3). doi:10.3301/IJG.2014.46.

Cas, R. A. F. & Wright, J. V. (1987). *Volcanic successions : modern and ancient : a geological approach to processes, products and successions* London: Allen & Unwin Ltd.

Casadevall, T. J. (1994). The 1989–1990 eruption of Redoubt Volcano, Alaska: impacts on aircraft operations. *Journal of Volcanology and Geothermal Research, 62*(1–4), 301-316. doi:http://dx.doi.org/10.1016/0377-0273(94)90038-8.

Casadevall, T.J., Delos Reyes, P.J., & Schneider, D.J. (1996). The 1991 Pinatubo Eruptions and Their Effects on Aircraft Operations. In C. G. Newhall & R. S. Punongbayan (Eds.), *Fire and mud: Eruptions and Lahars of Mount Pinatubo, Philippines* (pp. 1071-1088): Quezon City: Philippine Institute of Volcanology and Seismology ; Seattle: University of Washington Press.

Cashman, K.V. & Cronin, S. J. (2008). Welcoming a monster to the world: Myths, oral tradition, and modern societal response to volcanic disasters. *Journal of Volcanology and Geothermal Research, 176*(3), 407-418. doi:https://doi.org/10.1016/j.jvolgeores.2008.01.040.

Cashman, K.V. & Giordano, G. (2008). Volcanoes and human history. *Journal of Volcanology and Geothermal Research, 176*(3), 325-329. doi:http://dx.doi.org/10.1016/j.jvolgeores.2008.01.036.

Cassidy, M., Watt, S. F. L., Palmer, M. R., Trofimovs, J., Symons, W., Maclachlan, S. E., & Stinton, A. J. (2014). Construction of volcanic records from marine sediment cores: A review and case study (Montserrat, West Indies). Earth-Science Reviews, 138, 137-155. doi:http://dx.doi.org/10.1016/j.earscirev.2014.08.008.

Castillo, P.R. & Newhall, C.G. (2004). Geochemical constraints on possible subduction components in lavas of Mayon and Taal Volcanoes, Southern Luzon, Philippines. *Journal of Petrology, 45*(6), 1089-1108. doi:10.1093/petrology/egh005.

Centeno, J. (1885). *Estudio geologico del volcan de Taal.* Madrid: Tello.

Chester, D.K. (2005). Theology and disaster studies: The need for dialogue. *Journal of Volcanology and Geothermal Research, 146*(4), 319-328. doi:10.1016/j.jvolgeores.2005.03.004.

Chester, D. K., Dibben, C. J. L., & Duncan, A. M. (2002). Volcanic hazard assessment in western Europe. *Journal of Volcanology and Geothermal Research, 115*(3–4), 411-435. doi:http://doi.org/10.1016/S0377-0273(02)00210-X.

Chester, D.K. & Duncan, A.M. (2010). Responding to disasters within the Christian tradition, with reference to volcanic eruptions and earthquakes. *Religion, 40*(2), 85-95. doi:10.1016/j.religion.2009.12.005.

Chester, D.K., Duncan, A.M., & Dibben, C.J.L. (2008). The importance of religion in shaping volcanic risk perception in Italy, with special reference to Vesuvius and Etna. *Journal of Volcanology and Geothermal Research, 172*(3–4), 216-228. doi:http://dx.doi.org/10.1016/j.jvolgeores.2007.12.009

Christiansen, E.H. (2015). *Dynamic Earth: an introduction to physical geology* (1st Edition ed.). USA: Jones & Bartlett Learning.

Ciolli, S. (2012). *Vuelco - Colima Exercise Debriefing Report*. https://www.researchgate.net/publication/316430703_Vuelco_-_Colima_Exercise_Debriefing_Report

Cobeñas, G., Thouret, J.-C., Bonadonna, C., & Boivin, P. (2012). The c.2030yr BP Plinian eruption of El Misti volcano, Peru: Eruption dynamics and hazard implications. *Journal of Volcanology and Geothermal Research, 241–242*(0), 105-120. doi:http://dx.doi.org/10.1016/j.jvolgeores.2012.06.006

Collins, B. D. & Dunne, T. (1986). Erosion of tephra from the 1980 eruption of Mount St. Helens. *GSA Bulletin, 97*. doi:10.1130/0016-7606(1986)97<896:EOTFTE>2.0.CO;2.

Congress of the Philippines, (2010). Republic Act 10121: Philippine Disaster Risk Reduction and Management Act of 2010. Retrieved from http://www.ndrrmc.gov.ph/attachments/article/45/Republic_Act_10121.pdf.

Connor, L.J., & Connor, C. B. (2005). Inversion is the key to dispersion: understanding eruption dynamics by inverting tephra fallout. In H. M. Mader, S. G. Cole, C. B. Connor, & L. J. Connor (Eds.), *Statistics in Volcanology* (Vol. Special Publications of IAVCEI, pp. 231-242). London: Geological Society.

Connor, L., Connor, C., & Courtland, L. (2011). Tephra2 User's Manual. Retrieved from https://vhub.org/resources/756/download/Tephra2_Users_Manual.pdf%E2%80%8E, downloaded 15 July 2013.

Connor, C., Hill, B., Winfrey, B., Franklin, N., & Femina, P. (2001). Estimation of Volcanic Hazards from Tephra Fallout. Natural Hazards Review, 2(1), 33-42. doi:doi:10.1061/(ASCE)1527-6988(2001)2:1(33)

Costantini, L., Bonadonna, C., Houghton, B. F., & Wehrmann, H. (2008). New physical characterization of the Fontana Lapilli basaltic Plinian eruption, Nicaragua. Bulletin of Volcanology, 71(3), 337. doi:10.1007/s00445-008-0227-9.

Constantini, L. & Thierry, P. (2012). Introduction to Volcanic Risk. In C. Bignami, V. Bosi, L. Constantini, C. Cristiani, & P. Thierry (Eds.), *Handbook for Volcanic Risk Management: Prevention, Crisis Management, Resilience* (pp. 13-23). Orleans, France: MIAVITA.

Cook, R. J., Barron, J. C., Papendick, R. I. and Williams, G. J. (1981). Impact of agriculture of the Mount St. Helens eruptions. Science, 211. doi:10.1126/science.211.4477.16.

Costa, A., Folch, A., Macedonio, G., Giaccio, B., Isaia, R., & Smith, V. C. (2012). Quantifying volcanic ash dispersal and impact of the Campanian Ignimbrite super-eruption. Geophysical Research Letters, 39(1). doi:http://dx.doi.org/10.1029/2012GL051605.

Costa, A., Macedonio, G. and Folch, A. (2006). A three-dimensional Eulerian model for transport and deposition of volcanic ashes. *Earth and Planetary Science Letters, 241*(3–4), 634-647. doi:http://dx.doi.org/10.1016/j.epsl.2005.11.019.

Costa, A., Pioli, L., & Bonadonna, C. (2016). Assessing tephra total grain-size distribution: Insights from field data analysis. *Earth and Planetary Science Letters, 443*, 90-107. doi:http://dx.doi.org/10.1016/j.epsl.2016.02.040.

Courtland, L.M., Kruse, S.E., Connor, C.B., Connor, L.J., Savov, I.P. and Martin, K. T. (2012). GPR investigation of tephra fallout, Cerro Negro volcano, Nicaragua: a method for constraining parameters used in tephra sedimentation models. *Bulletin of Volcanology, 74*(6), 1409-1424. doi:10.1007/s00445-012-0603-3.

Craig, H., Wilson, T., Stewart, C., Outes, V., Villarosa, G. and Baxter, P. (2016). Impacts to agriculture and critical infrastructure in Argentina after ashfall from the 2011 eruption of the Cordón Caulle volcanic complex: an assessment of published damage and function thresholds. *Journal of Applied Volcanology, 5*(1), 7. doi:10.1186/s13617-016-0046-1.

Creswell, J. W. (2007). *Qualitative inquiry and research design : choosing among five approaches* (2nd ed. ed.). Thousand Oaks: Sage Publications.

Cronin, S.J., Hedley, M.J., Neall, V.E., & Smith, R.G. (1998). Agronomic impact of tephra fallout from the 1995 and 1996 Ruapehu Volcano eruptions, New Zealand. *Environmental Geology, 34*(1), 21-30. doi:10.1007/s002540050253.

Cronin, S.J., Neall, V.E., Lecointre, J.A., Hedley, M J. and Loganathan, P. (2003). Environmental hazards of fluoride in volcanic ash: a case study from Ruapehu volcano, New Zealand. *Journal of Volcanology and Geothermal Research, 121*(3–4), 271-291. doi:http://dx.doi.org/10.1016/S0377-0273(02)00465-1.

Cronin, S.J., Gaylord, D. R., Charley, D., Alloway, B. V., Wallez, S., & Esau, J. W. (2004a). Participatory methods of incorporating scientific with traditional knowledge for volcanic hazard management on Ambae Island, Vanuatu. *Bulletin of Volcanology, 66*(7), 652-668. doi:10.1007/s00445-004-0347-9.

Cronin, S. J., Petterson, M. J., Taylor, M. W., & Biliki, R. (2004). Maximising multi-stakeholder participation in government and community volcanic hazard management programs: a case study from Savo, Solomon Islands. *Natural Hazards, 33*, 105-136.

Cronin, S.J., & Cashman, K.V. (2008). Volcanic oral traditions in hazard assessment and mitigation. In J. Grattan & R. Torrence (Eds.), *Living under the shadow: Cultural impacts of volcanic eruptions* (pp. 165-176). CA: Left Coast Press.

D'amours, R. (1998). Modeling the ETEX plume dispersion with the Canadian emergency response model. *Atmospheric Environment, 32*(24), 4335-4341. doi:https://doi.org/10.1016/S1352-2310(98)00182-4.

Dake, K. (1991). Orienting Dispositions in the Perception of Risk. *Journal of Cross-Cultural Psychology, 22*(1), 61-82. doi:10.1177/0022022191221006.

Dake, K. (1992). Myths of Nature: Culture and the Social Construction of Risk. *Journal of Social Issues, 48*(4), 21-37. doi:10.1111/j.1540-4560.1992.tb01943.x.

Damby, D.E., Horwell, C.J., Baxter, P. J., Delmelle, P., Donaldson, K., Dunster, C., Fubini, B., Murphy, F.A., Nattrass, C., Sweeney, S., Tetley, T.D. and Tomatis, M. (2013). The respiratory health hazard of tephra from the 2010 Centennial eruption of Merapi with implications for occupational mining of deposits. *Journal of Volcanology and Geothermal Research, 261*(0), 376-387. doi:http://dx.doi.org/10.1016/j.jvolgeores.2012.09.001.

Davies, L.J., Jensen, B. J. L., Froese, D. G., & Wallace, K. L. (2016). Late Pleistocene and Holocene tephrostratigraphy of interior Alaska and Yukon: Key beds and chronologies over the past 30,000 years. *Quaternary Science Reviews, 146*, 28-53. doi:https://doi.org/10.1016/j.quascirev.2016.05.026.

Davis, M. S. & Ricci, T. (2004). Perceptions of risk for volcanic hazards in Italy: a research note. *International Journal of Sociology and Social Policy, 24*(10/11), 159-165. doi:doi:10.1108/01443330410791091.

Davis, M.S. & Ricci, T. (2005). Perceptions of Risk for Volcanic Hazards at Vesuvio and Etna, Italy. *The Australasian Journal of Disaster and Trauma Studies, 2005-1*, 23p. http://trauma.massey.ac.nz/issues/2005-1/davis.htm.

De Boer, J.Z., Odom, L.A., Ragland, P.C., Snider, F.G., & Tilford, N.R. (1980). The Bataan orogene: Eastward subduction, tectonic rotations, and volcanism in the western Pacific (Philippines). *Tectonophysics, 67*(3–4), 251-282. doi:10.1016/0040-1951(80)90270-X.

Defant, M.J., De Boer, J.Z., & Dietmar, O. (1988). The western Central Luzon volcanic arc, the Philippines: two arcs divided by rifting? *Tectonophysics, 145*(3–4), 305-317. doi:http://dx.doi.org/10.1016/0040-1951(88)90202-8.

Defant, M. J., Jacques, D., Maury, R. C., De Boer, J., & Joron, J.-L. (1989). Geochemistry and tectonic setting of the Luzon arc, Philippines. *Geological Society of America Bulletin, 101*(5), 663-672. doi:10.1130/0016-7606(1989)101<0663:gatsot>2.3.co;2.

del Barrio Muñoz, J. A. (2015). Nuevas fuentes para el estudio de la erupcion del volcan de Taal en 1754. [New Sources to Study the Volcanic Eruption of Taal in 1754]. *Annuario de Estudios Americanos, 72*(1), 233-262. doi:10.3989/aeamer.2015.1.09.

Dellino, P., De Astis, G., La Volpe, L., Mele, D., & Sulpizio, R. (2011). Quantitative hazard assessment of phreatomagmatic eruptions at Vulcano (Aeolian Islands, Southern Italy) as obtained by combining stratigraphy, event statistics and physical modelling. Journal of Volcanology and Geothermal Research, 201(1–4), 364-384. doi:https://doi.org/10.1016/j.jvolgeores.2010.06.009.

del Monte-Sanico, L. R. (2018). *Communicating emergency preparedness and bahavioral repsonse among residents vulnerable to Taal volcanic hazards un Bgy. Gulod, Laurel, Batangas, Philippines.* (Master of Science in Development Communication (Minor in Environmental Science)), University of the Philippines.

Delos Reyes, P. J. (1992). Volunteer Observers Program: a tool for monitoring volcanic and seismic events in the Philippines. In G. J. H. McCall, D. J. C. Laming, & S. C. Scott (Eds.), *Geohazards: Natural and man-made* (pp. 13-24).

Delos Reyes, P. J., Bornas, M. A. V., Dominey-Howes, D., Pidlaoan, A. C., Magill, C. R., & Solidum, J. R. U. (2018). A synthesis and review of historical eruptions at Taal Volcano, Southern Luzon, Philippines. *Earth-Science Reviews, 177*, 565-588. doi:https://doi.org/10.1016/j.earscirev.2017.11.014.

De Loyola, F. A. (2011). *Provincial Ordinance No. 001*. Retrieved from Legislative Bldg., Capitol Site, Batangas City, Batangas Province, Philippines.

De Luna, E. U. (1988). *The geochemistry and petrography of the major eruptive units of Taal Volcano's 1965 to 1977 eruptions, Taal Volcano, Philippines.* University of the Philippines, Diliman, Quezon City, Philippines. Retrieved from http://www.elib.gov.ph/ Available from Science and Technology Information Institute.

de Vaus, D. A. (2002). Surveys in Social Research (5th ed. ed.). NSW, Australia: Allen & Unwin.

Dibben, C.J.L. (2008). Leaving the city for the suburbs-The dominance of 'ordinary' decision making over volcanic risk perception in the production of volcanic risk on Mt Etna, Sicily. *Journal of Volcanology and Geothermal Research, 172*(3-4), 288-299. doi:10.1016/j.jvolgeores.2007.12.014.

Dibben, C. & Chester, D. K. (1999). Human vulnerability in volcanic environments: the case of Furnas, São Miguel, Azores. *Journal of Volcanology and Geothermal Research, 92*(1–2), 133-150. doi:http://dx.doi.org/10.1016/S0377-0273(99)00072-4.

DILG. (1991). *Republic Act 7160: The Local Government Code of the Philippines*. Retrieved from http://www.officialgazette.gov.ph/downloads/1991/10oct/19911010-RA-7160-CCA.pdf.

Dixit, J., Dewaikar, D. M., & Jangid, R. S. (2012). Soil liquefaction studies at Mumbai city. Natural Hazards, 63(2), 375-390. doi:10.1007/s11069-012-0154-0.

Dominey-Howes, D. & Minos-Minopoulos, D. (2004). Perceptions of hazard and risk on Santorini. *Journal of Volcanology and Geothermal Research, 137*(4), 285-310. doi:10.1016/j.jvolgeores.2004.06.002.

Donovan, K. (2010). Doing social volcanology: exploring volcanic culture in Indonesia. *Area, 42*(1), 117-126.

Donovan, A. (2019). Critical volcanology? Thinking holistically about risk and uncertainty. *Bulletin of Volcanology, 81*(4), 1-20. doi:10.1007/s00445-019-1279-8.

Donovan, A., & Oppenheimer, C. (2015). At the Mercy of the Mountain? Field Stations and the Culture of Volcanology. *Environment and Planning A: Economy and Space, 47*(1), 156-171. doi:10.1068/a130161p.

Donovan, A., Oppenheimer, C., & Bravo, M. (2012a). Social studies of volcanology: knowledge generation and expert advice on active volcanoes. *Bulletin of Volcanology, 74*(3), 677-689. doi:10.1007/s00445-011-0547-z.

Donovan, K., Suryanto, A., & Utami, P. (2012b). Mapping cultural vulnerability in volcanic regions: The practical application of social volcanology at Mt Merapi, Indonesia. *Environmental hazards, 11*(4), 303-323. doi:10.1080/17477891.2012.689252.

Donn, W. L., & Balachandran, N. K. (1981). Mount St. Helens Eruption of 18 May 1980: Air Waves and Explosive Yield. Science, 213(4507), 539-541.

DOST-PHIVOLCS. (1991). *Taal Volcano Profile*. Compilation of eruptive history and geology of Taal Volcano. PHIVOLCS Library, Quezon City, Philippines.

DOST-PHIVOLCS. (1995). *Taal Decade Volcano International Workshop Interim Report.* Paper presented at the Taal Decade Volcano International Workshop Development Academy of the Philippines, Tagaytay City, Philippines.

DOST-PHIVOLCS. (2011). Taal Volcano: Volcanic Hazards. Retrieved from http://www.phivolcs.dost.gov.ph/html/update_VMEPD/Volcano/VolcanoList/taal.htm.

DOST-PHIVOLCS. (2016a). Classification of volcanoes. Retrieved from http://www.phivolcs.dost.gov.ph/index.php?option=com_content&view=article&id=50&Itemid=86

DOST-PHIVOLCS. (2016b). Historical eruptions of Taal Volcano. Retrieved from http://www.phivolcs.dost.gov.ph/html/update_VMEPD/vmepd/vmepd/TVHistEruptions.pdf.

DOST-PHIVOLCS. (2017). Mandates of PHIVOLCS. Retrieved from https://www.phivolcs.dost.gov.ph/index.php/about-us/about-phivolcs.

DOST-PHIVOLCS. (2018). PHIVOLCS Earthquake Intensity Scale (PEIS). Retrieved from http://www.phivolcs.dost.gov.ph/index.php?option=com_content&task=view&id=45&Itemid=100.

Douglas, M. (1985). *Risk acceptability according to the social sciences*. New York: Russel Sage Foundation.

Douglas, M. (1992). *Risk and blame: essays in cultural theory*. London; New York: Routledge.

Douglas, M. (1996). *Thought styles: critical essays on good taste*. London; Thousand Oaks, California: Sage Publications.

Douglas, M. & Wildavsky, A. (1982). *Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers*. Berkeley: University of California Press.

Dove, M.R. (2008). Perception of volcanic eruption as agent of change on Merapi volcano, Central Java. *Journal of Volcanology and Geothermal Research, 172*(3–4), 329-337. doi:http://dx.doi.org/10.1016/j.jvolgeores.2007.12.037.

Doyle, E.E.H., Johnston, D.M., McClure, J., & Paton, D. (2011). The communication of uncertain scientific advice during natural hazard events. *New Zealand Journal of Psychology, 40*.

Doyle, E.E.H., McClure, J., Johnston, D.M., & Paton, D. (2014a). Communicating likelihoods and probabilities in forecasts of volcanic eruptions. *Journal of Volcanology and Geothermal Research, 272*, 1-15. doi:10.1016/j.jvolgeores.2013.12.006.

Doyle, E.E.H., McClure, J., Paton, D., & Johnston, D.M. (2014b). Uncertainty and decision making: Volcanic crisis scenarios. *International Journal of Disaster Risk Reduction, 10*, 75-101. doi:http://dx.doi.org/10.1016/j.ijdrr.2014.07.006.

Doyle, E. E. H., Paton, D., & Johnston, D. (2015). Enhancing scientific response in a crisis: evidence-based approaches from emergency management in New Zealand. *Journal of Applied Volcanology, 4*(1).

Doyle, P., & Bennett, M.R. (1998). Introduction: Unlocking the Stratigraphical Record. In P. Doyle & M. R. Bennett (Eds.), Unlocking the Stratigraphical Record (pp. 1-7). West Sussex, England: John Wiley & Sons.

Doyle, P., Bennett, M.R., & Baxter, A.N. (2001). *The Key to Earth History: An introduction to stratigraphy* (2nd ed.). West Sussex, England: John Wiley & Sons, Ltd.

Draxler, R., Stunder, B., Rolph, G., & Taylor, A. (2005). HYSPLIT_4 User Guide. Retrieved from [http://www.arl.noaa.gov/HYSPLIT_info.php], downloaded 16 August 2013.

Druitt, T. H. (1998). Pyroclastic density currents. *Geological Society, London, Special Publications, 145*(1), 145-182. doi:10.1144/gsl.sp.1996.145.01.08.

Emergeo-Working-Group. (2013). Liquefaction phenomena associated with the Emilia earthquake sequence of May-June 2012 (Northern Italy). *Natural Hazards and Earth System Sciences, 13*(4), 935. doi:http://dx.doi.org/10.5194/nhess-13-935-2013.

Engwell, S. L., Sparks, R. S. J., & Aspinall, W. P. (2013). Quantifying uncertainties in the measurement of tephra fall thickness. *Journal of Applied Volcanology, 2*(1), 1-12. doi:10.1186/2191-5040-2-5.

Farrell, P. (2014). Soil Bulk Density. Retrieved from http://www.d.umn.edu/~pfarrell/BULK DENSITY LAB.htm.

Feldman, L. H. (1988). Report pertaining to volcano vollected from colonial archives in Spain, for the Philippine Islands. Smithsonian Institution Global Volcanism Program.

Feng, S., Hossain, L., & Paton, D. (2018). Harnessing informal education for community resilience. *Disaster Prevention and Management, 27*(1), 43-59. doi:10.1108/DPM-07-2017-0157

Fikos, I., Vargemezis, G., Zlotnicki, J., Puertollano, J.R., Alanis, P.B., Pigtain, R.C., Villacorte, E.U., Malilipot, G.A. and Sasai, Y. (2012). Electrical resistivity tomography study of Taal volcano hydrothermal system, Philippines. *Bulletin of Volcanology, 74*(8), 1821-1831. doi:10.1007/s00445-012-0638-5.

Fischhoff, B., Slovic, P., Lichtenstein, S., Read, S., & Combs, B. (1978). How Safe Is Safe Enough? A Psychometric Study of Attitudes Towards Technological Risks and Benefits. *Policy Sciences, 9*(2), 127-152.

Fitch, T.J. (1972). Plate convergence, transcurrent faults and internal deformation adjacent to Southeast Asia and western Pacific. *Journal of Geophysical Research, 77*(23), 4432-4460.

Folch, A. (2012). A review of tephra transport and dispersal models: Evolution, current status, and future perspectives. *Journal of Volcanology and Geothermal Research, 235–236*(0), 96-115. doi:http://dx.doi.org/10.1016/j.jvolgeores.2012.05.020.

Folch, A., Cavazzoni, C., Costa, A., & Macedonio, G. (2008). An automatic procedure to forecast tephra fallout. *Journal of Volcanology and Geothermal Research, 177*(4), 767-777. doi:http://dx.doi.org/10.1016/j.jvolgeores.2008.01.046.

Folch, A., Costa, A., & Macedonio, G. (2009). FALL3D: A computational model for transport and deposition of volcanic ash. *Computers & Geosciences, 35*(6), 1334-1342. doi:http://dx.doi.org/10.1016/j.cageo.2008.08.008.

Folch, A., Costa, A., & Basart, S. (2012). Validation of the FALL3D ash dispersion model using observations of the 2010 Eyjafjallajökull volcanic ash clouds. *Atmospheric Environment, 48*(0), 165-183. doi:http://dx.doi.org/10.1016/j.atmosenv.2011.06.072.

Folch, A., & Felpeto, A. (2005). A coupled model for dispersal of tephra during sustained explosive eruptions. *Journal of Volcanology and Geothermal Research, 145*(3–4), 337-349. doi:http://dx.doi.org/10.1016/j.jvolgeores.2005.01.010.

Fontaine, F.J., Rabinowicz, M., Boulègue, J., & Jouniaux, L. (2002). Constraints on hydrothermal processes on basaltic edifices: inferences on the conditions leading to hydrovolcanic eruptions at Piton de la Fournaise, Réunion Island, Indian Ocean. *Earth and Planetary Science Letters, 200*(1–2), 1-14. doi:http://dx.doi.org/10.1016/S0012-821X(02)00599-X

Fontijn, K., Ernst, G.J., Bonadonna, C., Elburg, M., Mbede, E. and Jacobs, P. (2011). The ~4-ka Rungwe Pumice (South-Western Tanzania): a wind-still Plinian eruption. *Bulletin of Volcanology, 73*(9), 1353-1368. doi:10.1007/s00445-011-0486-8.

Foreman, J. (1890). The Philippine Islands. A historical, geographical, ethnographical, social and commercial sketch of the Philippine Archipelago and its political dependencies, by London, S. Low, Marston, Searle & Rivington, ld.; [etc., etc.] 1890.

Förster, H., Oles, D., Knittel, U., Defant, M. J. and Torres, R. C. (1990). The Macolod Corridor: A rift crossing the Philippine island arc. *Tectonophysics, 183*(1–4), 265-271. doi:http://dx.doi.org/10.1016/0040-1951(90)90420-D.

Francis, P. (1993). Volcanoes: A Planetary Perspective. New York: Oxford University Press.

Fried, M. I. (1963). Grieving for a lost home. In D. L.J. (Ed.), *The urban condition* (pp. 151-171). New York: Basic Books.

Gaillard, J.-C. (2006). Traditional societies in the face of natural hazards: the 1991 Mt. Pinatubo eruption and the Aetas of the Philippines. *International Journal of Mass Emergencies and Disasters, 24*(1), 5-43.

Gaillard, J.-C. (2008). Alternative paradigms of volcanic risk perception: The case of Mt. Pinatubo in the Philippines. *Journal of Volcanology and Geothermal Research, 172*(3–4), 315-328. doi:http://dx.doi.org/10.1016/j.jvolgeores.2007.12.036.

Gaillard, J.-C. (2015). People's Response to Disasters in the Philippines: Disaster Studies (pp. 216). New York: Palgrave Macmillan. Retrieved from http://dx.doi.org/10.1057/9781137484291. doi:10.1057/9781137484291

Gaillard, J.-C., D'Ercole, R. and Leone, F. (2001). Cartography of population vulnerability to volcanic hazards and lahars of Mt. Pinatubo (Philippines): case of Pasig-Potrero river basin (province of Pampanga). *Geomorphologie: Relief, Processes, Environment, 3*, 209-222.

Gaillard, J.-C. & Dibben, C.J.L. (2008). Volcanic risk perception and beyond. *Journal of Volcanology and Geothermal Research, 172*(3–4), 163-169. doi:http://dx.doi.org/10.1016/j.jvolgeores.2007.12.015.

Gaillard, J.-C. & Le Masson, V. (2007). Traditional Societies' Response to Volcanic Hazards in the Philippines: Implications for Community-Based Disaster Recovery. *Mountain Research and Development, 27*(4), 313-317.

Gaillard, J.-C. & Texier, P. (2010). Religions, natural hazards, and disasters: An introduction. *Religion, 40*(2), 81-84. doi:http://dx.doi.org/10.1016/j.religion.2009.12.001.

Gaillet, L.L. (2012). (Per)Forming Archival Research Methodologies. *College Composition and Communication, 64*(1), 35-58.

Galgana, G., Hamburger, M., McCaffrey, R., Corpuz, E., & Chen, Q. (2007). Analysis of crustal deformation in Luzon, Philippines using geodetic observations and earthquake focal mechanisms. *Tectonophysics, 432*(1–4), 63-87. doi:http://dx.doi.org/10.1016/j.tecto.2006.12.001.

Galgana, G. A., Newman, A. V., Hamburger, M. W., & Solidum, R. U. (2014). Geodetic observations and modeling of time-varying deformation at Taal Volcano, Philippines. *Journal of Volcanology and Geothermal Research, 271*(0), 11-23. doi:http://dx.doi.org/10.1016/j.jvolgeores.2013.11.005.

Geronimo, S. G. (1988). *Characteristics, depositional facies and emplacement mechanisms of the Buco base surge sequence, Batangas Province.* (Master of Science in Geology), University of the Philippines, Diliman, Quezon City, Philippines.

Glaze, L. S., & Self, S. (1991). Ashfall dispersal for the 16 September 1986, eruption of Lascar, Chile, calculated by a turbulent diffusion model. *Geophysical Research Letters, 18*(7), 1237-1240. doi:10.1029/91GL01501.

Gokhale, V. (2008). *Role of Women in Disaster Management: An Analytical Study with Reference to Indian Society*. Paper presented at the The 14th World Conference on Earthquake Engineering, Beijing, China. https://www.iitk.ac.in/nicee/wcee/article/14_10-0049.PDF

Graettinger, A. H., Skilling, I., McGarvie, D., & Höskuldsson, Á. (2013). Subaqueous basaltic magmatic explosions trigger phreatomagmatism: A case study from Askja, Iceland. Journal of Volcanology and Geothermal Research, 264, 17-35. doi:https://doi.org/10.1016/j.jvolgeores.2013.08.001.

Greene, M., Perry, R., & Lindell, M. (1981). The March 1980 Eruptions of Mt. St. Helens: Citizen Perception of Volcano Threat. *Disasters, 5*(1), 49-66. doi:10.1111/j.1467-7717.1981.tb01129.x.

Gregg, C.E., Houghton, B.F., Johnston, D.M., Paton, D., & Swanson, D. A. (2004). The perception of volcanic risk in Kona communities from Mauna Loa and Hualalai volcanoes, Hawai'i. *Journal of Volcanology and Geothermal Research, 130*(3-4), 179-196. doi:10.1016/S0377-0273(03)00288-9.

Gregg, C.E., Houghton, B.F., Paton, D., Swanson, D.A., Lachman, R., & Bonk, W.J. (2008). Hawaiian cultural influences on support for lava flow hazard mitigation measures during the January 1960 eruption of Kīlauea volcano, Kapoho, Hawai‘i. *Journal of Volcanology and Geothermal Research, 172*(3–4), 300-307. doi:http://dx.doi.org/10.1016/j.jvolgeores.2007.12.025.

Grinnell, R. M. (1993). *Social work research and evaluation* (4th ed. ed.). Itasca, Illinois: F.E. Peacock Publishers.

Gubrium, J. F., & Holstein, J. A. (2001). *Institutional selves : troubled identities in a postmodern world*. New York: Oxford University Press.

Gubrium, J. F., & Holstein, J. A. (2002). *Handbook of interview research*. Thousand Oaks, [Calif.] SAGE.

Guffanti, M., Ewert, J. W., Gallina, G. M., Bluth, G. J. S., & Swanson, G. L. (2005). Volcanic-ash hazard to aviation during the 2003–2004 eruptive activity of Anatahan volcano, Commonwealth of the Northern Mariana Islands. *Journal of Volcanology and Geothermal Research, 146*(1–3), 241-255. doi:http://dx.doi.org/10.1016/j.jvolgeores.2004.12.011.

Guffanti, M., Mayberry, G. C., Casadevall, T. J., & Wunderman, R. (2009). Volcanic hazards to airports. *Natural Hazards, 51*(2), 287-302. doi:http://dx.doi.org/10.1007/s11069-008-9254-2.

Győri, E., Tóth, L., & Mónus, P. (2015). Secondary effects generated by earthquakes: liquefaction occurrences in and around Hungary. Acta Geodaetica et Geophysica, 50(1), 79-95. doi:10.1007/s40328-014-0079-z.

Haeckel, M., van Beusekom, J., Wiesner, M. G., & König, I. (2001). The impact of the 1991 Mount Pinatubo tephra fallout on the geochemical environment of the deep-sea sediments in the South China Sea. *Earth and Planetary Science Letters, 193*(1–2), 151-166. doi:http://dx.doi.org/10.1016/S0012-821X(01)00496-4.

Hamburger, M.W., Cardwell, R.K., & Isacks, B.L. (1983). *Seismotectonics of the northern Philippine island arc* (3 April 2013 ed. Vol. 27): American Geophysical Union.

Hargrove, T.R. (1991). The Mysteries of Taal- A Philippine volcano and lake, her sea life and lost towns. Manila: Bookmark Publishing. 204p.

Harris, A.J.L. (2015). Basaltic Lava Flow Hazard. In P. Papale (Ed.), *Volcanic Hazards, risks and Disasters* (pp. 17-46): Elsevier Science.

Hawkes, G. & Rowe, G. (2008). A characterisation of the methodology of qualitative research on the nature of perceived risk: trends and omissions. *Journal of Risk Research, 11*(5), 617-643. doi:10.1080/13669870701875776.

Hayes, D.E. & Lewis, S.D. (1985). Structure and tectonics of the Manila trench system, Western Luzon, Philippines. *Energy, 10*(3–4), 263-279. doi:http://dx.doi.org/10.1016/0360-5442(85)90046-5.

Haynes, K., Barclay, J., & Pidgeon, N.F. (2008). Whose reality counts? Factors affecting the perception of volcanic risk. *J. Volcanol. Geotherm. Res., 172*.

Heffter, J.L., & Stunder, B.J.B. (1993). Volcanic ash forecast transport and dispersion (VAFTAD) model. *Weather and Forecasting, 8*(4), 533-541. doi:https://doi.org/10.1175/1520-0434(1993)008%3C0533:VAFTAD%3E2.0.CO;2.

Hewitt, K. (1983). The idea of calamity in a technocratic age. In K. Hewitt (Ed.), *Interpretation of calamities* (pp. 3-32). Boston: Allen & Unwin Inc.

Hickling, J., Clements, M., Weinstein, P., & Woodward, A. (1999). Acute health effects of the Mount Ruapehu (New Zealand) volcanic eruption of June 1996. *International journal of environmental health research, 9*(2), 97-107. doi:10.1080/09603129973236.

Hicks, A., Barclay, J., Simmons, P., & Loughlin, S. (2014). An interdisciplinary approach to volcanic risk reduction under conditions of uncertainty: a case study of Tristan da Cunha. *Natural Hazards and Earth System Sciences, 14*(7), 1871. doi:http://dx.doi.org/10.5194/nhess-14-1871-2014.

Hidalgo, M.C., & Hernandez, B. (2001). Place Attachment: Conceptual and EmpiricalQuestions. *Journal of Environmental Psychology, 21*(3), 273-281. doi:http://dx.doi.org/10.1006/jevp.2001.0221.

Hodge, D., Sharp, V., & Marts, M. (1979). Contemporary responses to volcanism: Case studies from the Cascades and Hawaii. In P. D. Sheets & D. K. Grayson (Eds.), *Volcanic activity and human ecology* (pp. 221-248). New York: Academic Press.

Hollis, S. (2015). *The Role of Regional Organizations in Disaster Risk Management A Strategy for Global Resilience* doi:10.1057/9781137439307

Holloway, N. H. (1981). The North Palawan Block, Philippines: its .relation to the Asian mainland and its role in the evolution of the South China Sea. *Bulletin Geological Society of Malaysia, 14*, 19-58.

Horwell, C. & Baxter, P. (2006). The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. *Bulletin of Volcanology, 69*(1), 1-24. doi:10.1007/s00445-006-0052-y.

Horwell, C.J., Stannett, G.W., Andronico, D., Bertagnini, A., Fenoglio, I., Fubini, B., Le Blond, J.S. and Williamson, B. J. (2010). A physico-chemical assessment of the health hazard of Mt. Vesuvius volcanic ash. *Journal of Volcanology and Geothermal Research, 191*(3–4), 222-232. doi:http://dx.doi.org/10.1016/j.jvolgeores.2010.01.014.

Hsu, Y.-J., Yu, S.-B., Song, T.-R. A., & Bacolcol, T. (2012). Plate coupling along the Manila subduction zone between Taiwan and northern Luzon. *Journal of Asian Earth Sciences, 51*(0), 98-108. doi:http://dx.doi.org/10.1016/j.jseaes.2012.01.005

Hunn, E.S. & Norton, H.H. (1984). Impact of Mt. St. Helens Ashfall on Fruit Yield of Mountain Huckleberry, Vaccinium membranaceum, Important Native American Food. *Economic Botany, 38*(1), 121-127. doi:10.2307/4254580.

Hurst, T. & Smith, W. (2004). A Monte Carlo methodology for modelling ashfall hazards. *Journal of Volcanology and Geothermal Research, 138*(3–4), 393-403. doi:https://doi.org/10.1016/j.jvolgeores.2004.08.001.

Hurst, T., & Smith, W. (2010). Volcanic ashfall in New Zealand – probabilistic hazard modelling for multiple sources. *New Zealand Journal of Geology and Geophysics, 53*(1), 1-14. doi:10.1080/00288301003631129.

Hurst, A.W. & Turner, R. (1999). Performance of the program ASHFALL for forecasting ashfall during the 1995 and 1996 eruptions of Ruapehu volcano. *New Zealand Journal of Geology and Geophysics, 42*(4), 615-622. doi:10.1080/00288306.1999.9514865.

Hutchison, A. A., Cashman, K. V., Williams, C. A., & Rust, A. C. (2016). The 1717 eruption of Volcán de Fuego, Guatemala: Cascading hazards and societal response. *Quaternary International, 394*(C), 69-78. doi:10.1016/j.quaint.2014.09.050

Jackson, M., Harrison, P., Swinburn, B., & Lawrence, M. (2015). Using a Qualitative Vignette to Explore a Complex Public Health Issue. *Qualitative Health Research, 25*(10), 1395-1409. doi:10.1177/1049732315570119.

Janda, R. J., Daag, A. S., Delos Reyes, P. J., Newhall, C. G., Pierson, T. C., Punongbayan, R. S., Rodolfo, K.S., Solidum Jr., R.U., & Umbal, J. V. (1996). Assessment and response to lahar hazard around Mount Pinatubo, 1991 to 1993 In C. G. Newhall & R. S. Punongbayan (Eds.), *Fire and mud: Eruptions and Lahars of Mount Pinatubo, Philippines* (pp. 107-139): Quezon City: Philippine Institute of Volcanology and Seismology ; Seattle: University of Washington Press.

Janebo, M. H., Thordarson, T., Houghton, B. F., Bonadonna, C., Larsen, G., & Carey, R. J. (2016). Dispersal of key subplinian–Plinian tephras from Hekla volcano, Iceland: implications for eruption source parameters. *Bulletin of Volcanology, 78*(10), 66. doi:10.1007/s00445-016-1059-7.

Javellana, R. (1992). [The Mysteries of Taal: A Philippine Volcano and Lake, Her Sea life and Lost Towns, Thomas R. Hargrove]. *Philippine Studies, 40*(1), 130-131.

Jenkins, S., Komorowski, J.C., Baxter, P.J., Spence, R., Picquout, A., Lavigne, F., & Surono. (2013). The Merapi 2010 eruption: An interdisciplinary impact assessment methodology for studying pyroclastic density current dynamics. *Journal of Volcanology and Geothermal Research, 261*(0), 316-329. doi:http://dx.doi.org/10.1016/j.jvolgeores.2013.02.012.

Jenkins, S., Magill, C., McAneney, J., & Blong, R. (2012). Regional ash fall hazard I: a probabilistic assessment methodology. *Bulletin of Volcanology, 74*(7), 1699-1712. doi:10.1007/s00445-012-0627-8.

Johannesdottir, G. & Gisladottir, G. (2010). People living under threat of volcanic hazard in southern Iceland: Vulnerability and risk perception. *Natural Hazards and Earth System Science, 10*(2), 407-420.

Johnson, R. B., Onwuegbuzie, A. J., L. A. Turner, Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a Definition of Mixed Methods Research. *Journal of Mixed Methods Research, 1*(2), 112-133. doi:http://dx.doi.org/10.1177/1558689806298224.

Johnston, D.M., Bebbington, M.S., Lai, C.D., Houghton, B.F., & Paton, D. (1999). Volcanic hazard perceptions: comparative shifts in knowledge and risk. *Disaster Prevention and Management: An International Journal, 8*(2), 118-126. doi:doi:10.1108/09653569910266166.

Johnston, D. M., Houghton, B. F., Neall, V. E., Ronan, K. R., & Paton, D. (2000). Impacts of the 1945 and 1995–1996 Ruapehu eruptions, New Zealand: An example of increasing societal vulnerability. *Geol. Soc. Am. Bull., 112*. doi:2.0.co;2.

Johnston, E. N., Phillips, J. C., Bonadonna, C., & Watson, I. M. (2012). Reconstructing the tephra dispersal pattern from the Bronze Age eruption of Santorini using an advection–diffusion model. *Bulletin of Volcanology, 74*(6), 1485-1507. doi:10.1007/s00445-012-0609-x.

Kahan, D. M., & Braman, D. (2003). More Statistics, Less Persuasion: A Cultural Theory of Gun-Risk Perceptions. *University of Pennsylvania Law Review, 151*(4), 1291-1327. doi:10.2307/3312930.

Kahneman, D., Slovic, P., & Tversky, A. (1982). *Judgment under Uncertainty: Heuristics and Biases* (D. Kahneman, P. Slovic, & A. Tversky Eds.). Cambridge: Cambridge University Press.

Karig, D. E. (1983). Accreted terranes in the northern part of the Philippine Archipelago. *Tectonics, 2*(2), 211-236. doi:10.1029/TC002i002p00211.

Kasperson, R.E., Renn, O., Slovic, P., Brown, H.S., Emel, J., Goble, R., Kasperson, J. and Ratick, S. (1988). The Social Amplification of Risk: A Conceptual Framework. *Risk Analysis, 8*(2), 177-187.

Kates, R. W., & Kasperson, J. X. (1983). Comparative risk analysis of technological hazards (a review). *Proceedings of the National Academy of Sciences of the United States of America, 80*(22), 7027-7038.

Keating, G.N., Pelletier, J.D., Valentine, G.A. and Statham, W. (2008). Evaluating suitability of a tephra dispersal model as part of a risk assessment framework. *Journal of Volcanology and Geothermal Research, 177*(2), 397-404. doi:https://doi.org/10.1016/j.jvolgeores.2008.06.007.

Kelfoun, K., Legros, F. and Gourgaud, A. (2000). A statistical study of trees damaged by the 22 November 1994 eruption of Merapi volcano (Java, Indonesia): relationships between ash-cloud surges and block-and-ash flows. *Journal of Volcanology and Geothermal Research, 100*(1–4), 379-393. doi:http://dx.doi.org/10.1016/S0377-0273(00)00147-5.

Kelman, I., Mercer, J., & Gaillard, J. C. (2012). Indigenous knowledge and disaster risk reduction. *Geography, 97*(1), 12-21.

Khan, S., Crozier, M. J., & Kennedy, D. (2012). Influences of place characteristics on hazards, perception and response: A case study of the hazardscape of the Wellington Region, New Zealand. *Natural Hazards, 62*(2), 501-529. doi:10.1007/s11069-012-0091-y.

Kilgore, W. W., Roman, D. C., Biggs, J., & Hansen, R. (2011). Seismic and geodetic investigation of the 1996–1998 earthquake swarm at Strandline Lake, Alaska. Geophysical Journal International, 186(3), 1365-1379. doi:10.1111/j.1365-246X.2011.05115.x.

Klawonn, M., Wolfe, C. J., Frazer, L. N., & Houghton, B. F. (2012). Novel inversion approach to constrain plume sedimentation from tephra deposit data: Application to the 17 June 1996 eruption of Ruapehu volcano, New Zealand. *Journal of Geophysical Research: Solid Earth, 117*, n/a. doi:10.1029/2011JB008767.

Knittel, U., Defant, M.J., & Raczek, I. (1988). Recent enrichment in the source region of arc magmas from Luzon island, Philippines: Sr and Nd isotopic evidence. *Geology, 16*(1), 73-76. doi:10.1130/0091-7613(1988)016<0073:reitsr>2.3.co;2.

Komorowski, J. C., Legendre, Y., Caron, B., & Boudon, G. (2008). Reconstruction and analysis of sub-plinian tephra dispersal during the 1530 A.D. Soufrière (Guadeloupe) eruption: Implications for scenario definition and hazards assessment. Journal of Volcanology and Geothermal Research, 178(3), 491-515. doi:https://doi.org/10.1016/j.jvolgeores.2007.11.022.

Koyaguchi, T. & Ohno, M. (2001). Reconstruction of eruption column dynamics on the basis of grain size of tephra fall deposits: 1. Methods. *Journal of Geophysical Research: Solid Earth, 106*(B4), 6499-6512. doi:10.1029/2000JB900426.

Krumbein, W. E. (1996). Principles of sedimentology and stratigraphy: Sam Boggs Jr. Prentice Hall, Englewood Cliffs, N.J., 1995 (hardcover), XVII + 774 pp., ISBN 0-02311792-3. *Sedimentary Geology, 105*(1–2), 112-113. doi:http://dx.doi.org/10.1016/0037-0738(95)00151-4.

Kuhnt, W., Hess, S., Holbourn, A., Paulsen, H., & Salomon, B. (2005). The impact of the 1991 Mt. Pinatubo eruption on deep-sea foraminiferal communities: A model for the Cretaceous–Tertiary (K/T) boundary? *Palaeogeography,* *Palaeoclimatology, Palaeoecology, 224*(1–3), 83-107. doi:http://dx.doi.org/10.1016/j.palaeo.2005.03.042

Kumagai, H., Lacson, R., Maeda, Y., Figueroa, M. S., & Yamashina, T. (2014). Shallow S wave attenuation and actively degassing magma beneath Taal Volcano, Philippines. *Geophysical Research Letters, 41*(19), 6681-6688. doi:10.1002/2014GL061193.

Kumar, R. (2014). Research methodology: a step-by-step guide for beginners. Los Angeles: SAGE.

Kvale, S. (2009). *InterViews: learning the craft of qualitative research interviewing* (2nd ed. ed.). Los Angeles: Sage Publications.

Kvale, S. (2015). *InterViews: learning the craft of qualitative research interviewing* (Third edition. ed.). Los Angeles: Sage Publications.

Lachman, R. & Bonk, W. J. (1960). Behavior and Beliefs during the Recent Volcanic Eruption at Kapoho, Hawaii. *Science, 131*(3407), 1095-1096.

Lacroix, A. (1903). LES DERNIÈRES ÉRUPTIONS DE SAINT-VINCENT: MARS 1903. Annales de Géographie, 12(63).

Langer, P.C. (2016). The Research Vignette: Reflexive Writing as Interpretative Representation of Qualitative Inquiry—A Methodological Proposition. *Qualitative Inquiry, 22*(9), 735-744. doi:10.1177/1077800416658066.

Latter, J.H. (1981). Tsunamis of volcanic origin: Summary of causes, with particular reference to Krakatoa, 1883. *Bulletin Volcanologique, 44*(3), 467-490. doi:10.1007/BF02600578.

Lavigne, F., De Coster, B., Juvin, N., Flohic, F., Gaillard, J.-C., Texier, P., Morin, J., & Sartohadi, J. (2008). People's behaviour in the face of volcanic hazards: Perspectives from Javanese communities, Indonesia. *Journal of Volcanology and Geothermal Research, 172*(3–4), 273-287. doi:http://dx.doi.org/10.1016/j.jvolgeores.2007.12.013.

Lazrus, H. (2015). Risk Perception and Climate Adaptation in Tuvalu: A Combined Cultural Theory and Traditional Knowledge Approach. *Human Organization, 74*(1), 52-61.

Leathers, M.M. (2014). *Risk Perception and Beliefs about Volcanic Hazards: A comparative Study of Puna District Residents.* (M.S. Dissertations & Theses), University of South Florida, Ann Arbor, USA. Retrieved from http://ezproxy.library.usyd.edu.au/login?url=http://search.proquest.com/docview/1629017370?accountid=14757 Available from ProQuest Dissertations & Theses Global (1569539).

Lim, J.B.R. (1983). Correlating the orientation of tectonic stresses with the flank eruptions of Taal Volcano. *Philippine Journal of Volcanology, 1*(1), 41-68.

Lima, M.L. & Castro, P. (2005). Cultural theory meets the community: Worldviews and local issues. *Journal of Environmental Psychology, 25*(1), 23-35. doi:https://doi.org/10.1016/j.jenvp.2004.11.004.

Limon-Hernandez, C. & Macias, J. L. (2009). Volcanic hazards and risk perception at the "Zoque" community of Chapultenango: El Chichon volcano, Chiapas, Mexico. *Geofisica Internacional, 48*(1), 113-132.

Lindell, M. K., & Perry, R. W. (2000). Household Adjustment to Earthquake Hazard: A Review of Research. *Environment and Behavior, 32*(4), 461-501. doi:10.1177/00139160021972621

Listanco, E. (1994). *Space-time patterns in the geologic and magmatic evolution of calderas: a case study at Taal Volcano, Philippines.* (Doctor of Science PhD thesis), University of Tokyo, Tokyo, Japan.

Listanco, E. (1997). Taal Volcano *Field Guide Book for the International Conference on Materials Recycling Near Convergent Plate Boundaries, Puerto Azul, Philippines* (pp. 5-41): Carnegerie Institution of Washington-Institute for the study of the Earth's Interior- DOST-PHIVOLCS.

Liyanapathirana, D.S., & Poulos, H.G. (2004). Assessment of soil liquefaction incorporating earthquake characteristics. *Soil Dynamics and Earthquake Engineering, 24*(11), 867-875. doi:http://dx.doi.org/10.1016/j.soildyn.2003.11.010.

Lopez-Vazquez, E. (2009). Risk perception and coping strategies for risk from Popocatepetl Volcano, Mexico. *Geofisica Internacional, 48*(1), 133-147.

Lowry, A.R., Hamburger, M.W., Meertens, C.M. and Ramos, E.G. (2001). GPS monitoring of crustal deformation at Taal Volcano, Philippines. *Journal of Volcanology and Geothermal Research, 105*(1–2), 35-47. doi:http://dx.doi.org/10.1016/S0377-0273(00)00238-9.

Ludwig, W.J. (1970). The Manila Trench and west Luzon Trough, III; Seismic-refraction measurements. *Deep Sea Research, 17*, 553-571.

Macedonio, G., Costa, A., & Folch, A. (2008). Ash fallout scenarios at Vesuvius: Numerical simulations and implications for hazard assessment. *Journal of Volcanology and Geothermal Research, 178*(3), 366-377. doi:http://dx.doi.org/10.1016/j.jvolgeores.2008.08.014.

Macedonio, G., Costa, A., & Longo, A. (2005). A computer model for volcanic ash fallout and assessment of subsequent hazard. *Computers & Geosciences, 31*(7), 837-845. doi:http://dx.doi.org/10.1016/j.cageo.2005.01.013.

Macedonio, G., Pareschi, M. T., & Santacroce, R. (1988). A numerical simulation of the Plinian Fall Phase of 79 A.D. eruption of Vesuvius. *Journal of Geophysical Research: Solid Earth, 93*(B12), 14817-14827. doi:10.1029/JB093iB12p14817.

Maeda, Y., Kumagai, H., Lacson, R., Figueroa, M. S., & Yamashina, T. (2013). Source process of long-period seismic events at Taal volcano, Philippines: Vapor transportation and condensation in a shallow hydrothermal fissure. *Journal of Geophysical Research: Solid Earth, 118*(6), 2832-2846. doi:10.1002/jgrb.50205.

Magill, C. R., Hurst, A. W., Hunter, L. J., & Blong, R. J. (2006). Probabilistic tephra fall simulation for the Auckland Region, New Zealand. *Journal of*

Volcanology and Geothermal Research, 153(3–4), 370-386. doi:http://dx.doi.org/10.1016/j.jvolgeores.2005.12.002.

Magill, C., Mannen, K., Connor, L., Bonadonna, C., & Connor, C. (2015). Simulating a multi-phase tephra fall event: inversion modelling for the 1707 Hoei eruption of Mount Fuji, Japan. *Bulletin of Volcanology, 77*(9), 81. doi:10.1007/s00445-015-0967-2.

Magill, C. R., Wilson, T., & Okada, T. (2013). Observations of tephra fall impacts from the 2011 Shinmoedake eruption, Japan. *Earth Planets Space, 65*, 1-22. doi:10.5047/eps.2013.05.010.

Malin, M. C., & Sheridan, M. F. (1982). Computer-assisted mapping of pyroclastic surges. *Science, 217*(4560), 637-640. doi:10.1126/science.217.4560.637

Marris, C., Langford, I. H., & O'Riordan, T. (1998). A Quantitative Test of the Cultural Theory of Risk Perceptions: Comparison with the Psychometric Paradigm. *Risk Analysis, 18*(5), 635-647. doi:10.1111/j.1539-6924.1998.tb00376.x.

Martinez, M.M.L. (1997). *Stratigraphy and geochemistry of Taal Caldera Scoria Pyroclastic flow deposit, Philippines.* (Master of Science in Geology MS Thesis), Arizona State University.

Martinez, M.M.L. & Williams, S.N. (1999). Basaltic andesite to andesite scoria pyroclastic flow deposits from Taal Caldera, Philippines. *Journal of the Geological Society of the Philippines, 54*(1-2), 1-18.

Martinez-Villegas, M. M., Del Monte, L.R., Solidum, R.U. Jr., Lamela, R.C., Tanatan, B.P., Mondia, N.A., and Arellano, J.R. (2013). Hazards and risk perception of Kanlaon Volcano residents and communications strategy used towards strenthening the community resilience of Barangay Pula, Canlaon City, Negros Oriental, Philippines. Asian Journal of Environment and Disaster Management (AJEDM).

Marzocchi, W., & Bebbington, M. S. (2012). Probabilistic eruption forecasting at short and long time scales. *Bulletin of Volcanology, 74*, 1777-1805. doi: 10.1007/s00445-012-0633-x.

Masigla, L. M., & Ruelo, H. B. (1987). *Interpretation of the historical eruptive activity of Taal Volcano, Philippines*. Government report. Department of Science and Technology (DOST). DOST-PHIVOLCS. Quezon City, Philippines.

Mastin, L. G., Guffanti, M., Servranckx, R., Webley, P., Barsotti, S., Dean, K., Durant, A., Ewert, J. W., Neri, A., Rose, W. I., Schneider, D., Siebert, L., Stunder, B., Swanson, G., Tupper, A., Volentik, A. and Waythomas, C. F. (2009). A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions. *Journal of Volcanology and Geothermal Research, 186*(1–2), 10-21. doi:https://doi.org/10.1016/j.jvolgeores.2009.01.008

Mathers, N., Fox, N., & Hunn, A. (2007). *Surveys and Questionnaires* Retrieved from https://www.rds-yh.nihr.ac.uk/wp-content/uploads/2013/05/12_Surveys_and_Questionnaires_Revision_2009.pdf

Mather, T. A., & Harrison, R. G. (2006). Electrification of volcanic plumes. Surveys in Geophysics, 27(4), 387-432. doi:10.1007/s10712-006-9007-2.

Mauk, F. J. (1983). Utilization of seismically recorded infrasonic-acoustic signals to monitor volcanic explosions: The El Chichon Sequence 1982—A case study. Journal of Geophysical Research: Solid Earth, 88(B12), 10385-10401. doi:10.1029/JB088iB12p10385.

McGuirk, P. M., & O'Neill, P. (2005). Using Questionnaires in Qualitative Human Geography. In I. Hay (Ed.), *Qualitative Research Methods in Human Geography* (2nd ed. ed., pp. 147-162). Australia: Oxford University Press.

McNutt, S. R. & Davis, C. M. (2000). Lightning associated with the 1992 eruptions of Crater Peak, Mount Spurr Volcano, Alaska. *Journal of Volcanology and Geothermal Research, 102*(1–2), 45-65. doi:http://dx.doi.org/10.1016/S0377-0273(00)00181-5.

McNutt, S. R. & Williams, E. R. (2010). Volcanic lightning: global observations and constraints on source mechanisms. *Bulletin of Volcanology, 72*(10), 1153-1167. doi:10.1007/s00445-010-0393-4.

Mead, S., Magill, C., & Hilton, J. (2016). Rain-triggered lahar susceptibility using a shallow landslide and surface erosion model. *Geomorphology, 273*, 168-177. doi:http://dx.doi.org/10.1016/j.geomorph.2016.08.022.

Medici, E. F., Allen, J. S., & Waite, G. P. (2014). Modeling shock waves generated by explosive volcanic eruptions. Geophysical Research Letters, 41(2), 414-421. doi:10.1002/2013GL058340.

Mele, D., Sulpizio, R., Dellino, P., & La Volpe, L. (2011). Stratigraphy and eruptive dynamics of a pulsating Plinian eruption of Somma-Vesuvius: the Pomici di Mercato (8900 years B.P.). Bulletin of Volcanology, 73(3), 257-278. doi:10.1007/s00445-010-0407-2.

Mesch, G. S., & Manor, O. (1998). Social Ties, Environmental Perception, And Local Attachment. *Environment and Behavior, 30*(4), 504-519. doi:10.1177/001391659803000405.

MIAVITA. (2012). *Handbook for Volcanic Risk Management: Prevention, Crisis Management, Resilience* (C. Bignami, V. Bosi, L. Constantini, C. Cristiani, & P. Thierry Eds.). Orleans, France.

Miklius, A., Flower, M.F.J., Huijsmans, J.P.P., Mukasa, S.B., & Castillo, P. (1991). Geochemistry of lavas from Taal volcano, southwestern Luzon, Philippines: evidence for multiple magma supply systems and mantle source heterogeneity. *Journal of Petrology, 32*(3), 593-627.

Milazzo, M. F., Ancione, G., Basco, A., Lister, D. G., Salzano, E., & Maschio, G. (2013). Potential loading damage to industrial storage tanks due to volcanic ash fallout. *Natural Hazards, 66*(2), 939-953. doi:10.1007/s11069-012-0518-5

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis : an expanded sourcebook* (2nd ed. ed.). Thousand Oaks: Sage Publications.

Moore, J. G. (1967). Base surge in recent volcanic eruptions. *Bulletin Volcanologique, 30*(1), 337-363. doi:10.1007/BF02597678.

Moore, J.G. & Melson, W.G. (1969). Nuées Ardentes of the 1968 Eruption of Mayon Volcano, Philippines. *Bulletin Volcanologique, 33*(2), 600-620. doi:https://doi.org/10.1007/BF02596528.

Moore, J.G., Nakamura, K., & Alcaraz, A. (1966). The 1965 Eruption of Taal Volcano. *Science, 151*(3713), 955-960. doi:10.2307/1718667.

Morrissey, M.M. & Chouet, B.A. (1997). Burst Conditions of Explosive Volcanic Eruptions Recorded on Microbarographs. Science, 275(5304), 1290-1293.

Müller, E.H., Ford, R., Hort, M.C., Huggett, L., Riley, G., & Thomson, D. J. (2013). Parallelisation of the Lagrangian atmospheric dispersion model NAME. *Computer Physics Communications, 184*(12), 2734-2745. doi:https://doi.org/10.1016/j.cpc.2013.06.022.

Murton, B. J. & Shimabukuro, S. (1974). Human adjustments to volcanic hazard in Puna District, Hawaii. In G. F. White (Ed.), *Natural Hazards, local, national, global* (pp. 151-159). New York: Oxford University Press.

NCEP. (2019). National Center for Atmospheric Research Staff (Eds). Last modified 07 January 2019. "*The Climate Data Guide: NCEP Reanalysis (R2)*." Retrieved from http://climatedataguide.ucar.edu/climate-data/ncep-reanalysis-r2.

NDRRMC (2011). Republic Act 10121: Philippine Disaster Risk Reduction and Management Act of 2010, 10121. Retrieved from: http://www.ndrrmc.gov.ph/attachments/article/45/Republic_Act_10121.pdf.

NDRRMC. (2017). *Memorandum Circular No. 45, Series 2017: Guidelines on the administration of the National Disaster Risk Reduction and Management (NDRRM) Fund*. (Memorandum 47, Series 2017). NDRRMC Retrieved from http://www.ndrrmc.gov.ph/attachments/article/3103/Memo_No-45_s-2017.pdf.

Nelder, J. A. & Mead, R. (1965). A Simplex Method for Function Minimization. The Computer Journal, 7(4), 308-313. doi:10.1093/comjnl/7.4.308

Newhall, C.G. & Self, S. (1982). The volcanic explosivity index (VEI): an estimate of explosive magnitude for historical volcanism. *Journal of Geophysical Research, 87*(2), 123.

Nishigami, K., Shibutani, T., Ohkura, T., Hirata, M., Horikawa, H., Shimitzu, K., Maysuo, S., Nakao, S., Ando, M., Bautista, B., Bautista, M.L., Barcelona, E., Valero, R., Lanuza, A., Chu, A., Villegas, J.J., Rasdas, A., Mangao, E., Gabinete, E., Punongbayan, J., Narag, I., Marte, F., & Punongbayan, R. (1994). Shallow crustal structure beneath Taal Volcano, Philippines, revealed by the 1993 seismic explosion survey. *Bulletin of Disaster Prevention Research Institute, 44*(382), 123-138.

Njome, M. S., Suh, C. E., Chuyong, G., & de Wit, M. J. (2010). Volcanic risk perception in rural communities along the slopes of mount Cameroon, West-Central Africa. *Journal of African Earth Sciences, 58*(4), 608-622. doi:10.1016/j.jafrearsci.2010.08.007.

Nofrita, S. and Krol, B.G.C.M.B. (2014). The Livelihood Analysis in Merapi Prone Area After 2010 Eruption. *The Indonesian Journal of Geography, 46*(2), 195-207.

Ohkura, T., Nakano, T., Besana, G. M., Sicat, M. J., Hoso, Y., Mangao, E., Geraldo, I., Daligdig, J.A., Ando, M. and Punongbayan, R. S. (2001). GPS Measurements in the Macolod Corridor, Philippines. *Journal of the Geological Society of the Philippines, 56*(3 & 4), 97-104.

O'Keefe, P., Wisner, B., &Westgate, K. (1976). Taking the naturalness out of natural disasters. *Nature, 260*(5552), 566-567. doi:10.1038/260566a0.

Oles, D. (1991). *Geology of the Macolod Corridor intersecting the Bataan-Mindoro island arc, The Philippines*. *In*: Final Report for German Research Society Project No. Fo 53/ 16-1 to 2 and German Agency for Technical Cooperation Project No. 85- 2522.2.06.100.

Oltedal, S. & Rundmo, T. (2007). Using cluster analysis to test the cultural theory of risk perception. *Transportation Research Part F: Traffic Psychology and Behaviour, 10*(3), 254-262. doi:https://doi.org/10.1016/j.trf.2006.10.003.

Oppenheimer, C. (1991). People and volcanoes: Taal Island, Philippines. *Geology Today, 7*(1), 19-23.

Oswalt, J. S., Nichols, W., & O'Hara, J. F. (1996). Meteorological Observations of the 1991 Mount Pinatubo Eruption. In C. G. Newhall & R. S. Punongbayan (Eds.), Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Seattle and London: University of Washington Press.

Oze, C., Cole, J., Scott, A., Wilson, T., Wilson, G., Gaw, S., Hampton, S., Doyle, C., & Li, Z. (2014). Corrosion of metal roof materials related to volcanic ash interactions. *Natural Hazards, 71*(1), 785-802. doi:10.1007/s11069-013-0943-0.

PAGASA-DOST. (2014). *Climatological Normal Values for Batangas Province from 1981 to 2010*. Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), Department of Science and Technology (DOST).

PAGASA-DOST. (2017). Climate of the Philippines. Retrieved from http://www1.pagasa.dost.gov.ph/index.php/climate-of-the-philippines.

Paladio-Melosantos, M. L., Solidum, J., R.U., Scott, W. E., Quiambao, R. B., Umbal, J. V., Rodolfo, K. S., Tubianosa, B.S., Delos Reyes, P.J., Alonso, R.A. and Ruelo, H. B. (1996). Tephra Falls of the 1991 Eruptions of Mount Pinatubo. In C. G. Newhall & R. S. Punongbayan (Eds.), *Fire and mud: Eruptions and Lahars of Mount Pinatubo, Philippines*: Quezon City: Philippine Institute of Volcanology and Seismology; Seattle: University of Washington Press.

Paris, R., Switzer, A., Belousova, M., Belousova, A., Ontowirjo, B., Whelley, P., & Ulvrova, M.. (2014). Volcanic tsunami: a review of source mechanisms, past events and hazards in Southeast Asia (Indonesia, Philippines, Papua New Guinea). *Natural Hazards, 70*(1), 447-470. doi:10.1007/s11069-013-0822-8.

Paton, D., Smith, L., & Johnston, D.M. (2000). Volcanic hazards: Risk perception and preparedness. *New Zealand Journal of Psychology, 29*(2), 86.

Paton, D., Millar, M. & Johnston, D. (2001a). Community Resilience to Volcanic Hazard Consequences. *Natural Hazards, 24*(2), 157-169. doi:10.1023/a:1011882106373.

Paton, D., Johnston, D., Bebbington, M. S., Lai, C.-D., & Houghton, B. F. (2001b). Direct and Vicarious Experience of Volcanic Hazards: Implications for Risk Perception and Adjustment Adoption. *Australian Journal of Emergency Management, The, 15*(4), 58-63.

Paton, D., Smith, L., Daly, M., & Johnston, D. (2008). Risk perception and volcanic hazard mitigation: Individual and social perspectives. *Journal of Volcanology and Geothermal Research, 172*(3–4), 179-188. doi:http://dx.doi.org/10.1016/j.jvolgeores.2007.12.026.

Paton, D., & McClure, J. (2013). *Preparing for disaster; building household and community capacity* (Vol. 28): C.C. Thomas Publishing Inc.

Paton, D., Anderson, E., Becker, J., & Petersen, J. (2015). Developing a comprehensive model of hazard preparedness: Lessons from the Christchurch earthquake. *International Journal of Disaster Risk Reduction, 14*(1), 37-45. doi:10.1016/j.ijdrr.2014.11.011.

Paton, D. (2018). Disaster risk reduction: Psychological perspectives on preparedness. *Australian Journal of Psychology, 0*(0). doi:10.1111/ajpy.12237.

Patton, M.Q. (1990). *Qualitative evaluation and research methods* (M. Q. Patton Ed. 2nd ed. ed.). Newbury Park, California: Sage Publications.

Patton, M. Q. (2002). *Qualitative research and evaluation methods* (3rd ed. ed.). Thousand Oaks, Calif: Sage Publications.

Payne, G., & Payne, J. (2004). Secondary Analysis: Key Concepts in Social Research (pp. 214-218): SAGE Publications, Ltd. Retrieved from http://methods.sagepub.com/book/key-concepts-in-social-research. doi:http://dx.doi.org/10.4135/9781849209397.

PDRRMC. (2013). *Disaster Risk Reduction and Management and Climate Change Adaptation Plan 2013-2016*. Batangas Province, Philippines: Provincial Government of Batangas.

Perry, R.W. (1990.) Volcanic hazard perceptions at Mt. Shasta. *Environmental Professional*, *12*, 312–318.

Perry, R.W., Lindell, M.K., & Greene, M.R. (1982). Threat Perception and Public Response to Volcano Hazard. *Journal of Social Psychology, 116*(2), 199-204.

Perry, R.W. & Lindell, M.K. (1990). *Living with Mount St. Helens: human adjustment to volcano hazards*: Pullman, Wash.: Washington State University Press.

Perry, R.W. & Lindell, M.K. (2008). Volcanic risk perception and adjustment in a multi-hazard environment. *Journal of Volcanology and Geothermal Research, 172*(3–4), 170-178. doi:http://dx.doi.org/10.1016/j.jvolgeores.2007.12.006.

Pfeiffer, T., Costa, A., & Macedonio, G. (2005). A model for the numerical simulation of tephra fall deposits. *Journal of Volcanology and Geothermal*

Research, 140(4), 273-294. doi:http://dx.doi.org/10.1016/j.jvolgeores.2004.09.001.

Philippines. (1991). Republic Act 7160: Local Government Code of the Philippines. Quezon City, Philippines: Congress of the Philippines, Republic of the Philippines.

Poggie, J.J. (1980). Ritual Adaptation to Risk and Technological Development in Ocean Fisheries: Extrapolations from New England. *Anthropological Quarterly, 53*(2), 122-129. doi:10.2307/3317733.

PPDO. (2016). *Socio-Economic and Physical Profile of Batangas Province*. Batangas Province, Philippines: Batangas Provincial Government.

Pratt, W. E. (1911a). The Eruption of Taal Volcano. *Bulletin of the American Geographical Society, 43*(12), 903-916. doi:10.2307/200468.

Pratt, W. E. (1911b). The eruption of Taal volcano, January 30, 1911. *The Philippine Journal of Science, VI*(2), 63-86 plus plates.

Pratt, W. E. (1916). An Unusual Form of Volcanic Ejecta. *The Journal of Geology, 24*(5), 450-455.

PSA. (2010). Philippine Standard Geographic Code (PSGC) Income Classification. Retrieved from https://psa.gov.ph/classification/psgc/?q=psgc/provinces

PSA. (2015). Philippine Population 2015 Census of Population. Retrieved from http://www.psa.gov.ph/ website: https://psa.gov.ph/content/highlights-philippine-population-2015-census-population

PSA. (2015). Average household size in the Philippines. Retrieved from https://psa.gov.ph/content/highlights-household-population-number-households-and-average-household-size-philippines

PSA. (2018). *Batangas Quickstat.* Quezon City, Philippines: Philippine Statistics Office Retrieved from https://psa.gov.ph/content/batangas-quickstat-june-2018.

Pyle, D. (1989). The thickness, volume and grainsize of tephra fall deposits. Bulletin of Volcanology, 51(1), 1-15. doi:10.1007/BF01086757.

Ragland, P. C. a. D., M.J. (1983). Silica standardization: a discriminant technique applied to a volcanic arc system. *Earth and Planetary Science Letters, 64*(3), 387-395.

Ramos-Villarta, S. C., Corpuz, E. G., & Newhall, C. G. (1985). Eruptive history of Mayon Volcano, Philippines. *Philippine Journal of Volcanology, 2*, 1-35.

doi:10.1016/0012-821X(83)90098-5.

Ramos, E. G. (2001). Geomorphic features of Taal Volcano. *Journal of the Geological Society of the Philippines, 56*(3&4), 105-123.

Rangin, C., Le Pichon, X., Mazzotti, S., Pubellier, M., Chamot-Rooke, N., Aurelio, M., Walpersdorf, A. and Quebral, R. (1999). Plate convergence measured by GPS across the Sundaland/Philippine Sea Plate deformed boundary: the Philippines and eastern Indonesia. *Geophysical Journal International, 139*(2), 296-316. doi:10.1046/j.1365-246x.1999.00969.x

Ranke, U. (2016). Natural Disaster Risk Management: Geosciences and Social Responsibility. Switzerland: Springer International Publishing Switzerland.

Rayner, S. (1987). Risk and Relativism in Science for Policy. In B. B. Johnson & V. T. Covello (Eds.), *The Social and Cultural Construction of Risk*. Dordrecht; Boston: D. Reidel Publishing Company.

Rayner, S. (1988). The rules that keep us equal: Complexity and the costs of egalitarian organization. In J. F. Flanagan & S. Rayner (Eds.), *Rules, decisions, and inequality in egalitarian societies* (pp. 20-42). Aldershot, England: Avebury.

Rayner, S. (1992). Cultural Theory and Risk Analysis. In S. Krimsky & D. Golding (Eds.), *Social Theories of Risk.* Wesport, Connecticut: Praeger Publisher.

Rayner, S. & Cantor, R. (1987). How fair is safe enough. The cultural approach to societal technology choice. doi:10.1111/j.1539-6924.1987.tb00963.x.

Repetti, W.C. (1935). *Tectonic lines of the Philippine Islands*. Philippine Weather Bureau.

Republic Act 10121: Philippine Disaster Risk Reduction and Management Act of 2010, 10121 C.F.R. (2010).

Ricci, T., Barberi, F., Davis, M. S., Isaia, R. and Nave, R. (2013). Volcanic risk perception in the Campi Flegrei area. *Journal of Volcanology and Geothermal Research, 254*, 118-130. doi:10.1016/j.jvolgeores.2013.01.002.

Riger, S., & Lavrakas, P. J. (1981). Community ties: Patterns of attachment and social interaction in urban neighborhoods. *American Journal of Community Psychology, 9*(1), 55-66. doi:10.1007/bf00896360.

Rodríguez-VanGort, F. and Novelo-Casanova, D. A. (2015). Volcanic risk perception in northern Chiapas, Mexico. *Natural Hazards, 76*(2), 1281-1295. doi:10.1007/s11069-014-1549-x.

Rolandi, G., Barrella, A. M., & Borrelli, A. (1993). The 1631 eruption of Vesuvius. *Journal of Volcanology and Geothermal Research, 58*(1), 183-201. doi:https://doi.org/10.1016/0377-0273(93)90107-3.

Rose, W.I. and Durant, A J. (2009). Fine ash content of explosive eruptions. *Journal of Volcanology and Geothermal Research, 186*(1–2), 32-39. doi:http://dx.doi.org/10.1016/j.jvolgeores.2009.01.010.

Ruelo, H. B. (1983). Morphological and crater development of Mt. Tabaro Eruption Site, Taal Volcano, Philippines. *Philippine Journal of Volcanology, 1*(2), 19-68.

Saderra Masó, M. (1904). *Volcanoes and seismic centers of the Philippine Archipelago*. Retrieved from https://books.google.com.ph/books?id=m1cRAAAAIAAJ&printsec=frontcover&source=gbs_ge_summary_r&cad=0 - v=onepage&q&f=false

Saderra Masó, M. (1911). *The Eruption of Taal Volcano, January 30, 1911*. Manila, Philippines: Bureau of Printing.

Saquilon, C. S., & de Guzman, L. A. (2005). *Volcanic Risk Perception and Response Capability of Taal Volcano Island*. Department of Science and Technology (DOST). Philippine Institute of Volcanology and Seismology (PHIVOLCS).

Scannell, L., & Gifford, R. (2010). Defining place attachment: A tripartite organizing framework. *Journal of Environmental Psychology, 30*, 1-10. doi:10.1016/j.jenvp.2009.09.006.

Schauroth, J., Wadsworth, F.B., Kennedy, B., von Aulock, F.W., Lavallée, Y., Damby, D.E., Vasseur, J., Scheu, B., & Dingwell, D. B. (2016). Conduit margin heating and deformation during the AD 1886 basaltic Plinian eruption at Tarawera volcano, New Zealand. Bulletin of Volcanology, 78(2), 1-14. doi:10.1007/s00445-016-1006-7.

Schmidt, M. (2004). *Investigating risk perception: a short introduction. Chapter 3 in: Schmidt M. 2004. Loss of agro-biodiversity in Vavilov centers, with a special focus on the risks of genetically modified organisms (GMOs).* (PhD), Vienna, Austria.

Schwarz, M. & Thompson, M. (1990). *Divided we stand: redefining politics, technology, and social choice*. New York: Harvester Wheatsheaf.

Schweller, W.J. & Karig, D.E. (1982). Emplacement of the Zambales Ophiolite into the West Luzon margin. *Amer. Association Petrol. Geol. Mem.*

Schweller, W.J., Roth, P.H., Karig, D.E., & Bachman, S.B. (1984). Sedimentation history and biostratigraphy of ophiolite-related Tertiary sediments, Luzon, Philippines. *Geological Society of America Bulletin, 95*(11), 1333-1342. doi:10.1130/0016-7606(1984)95<1333:shaboo>2.0.co;2.

Scollo, S., Del Carlo, P., & Coltelli, M. (2007). Tephra fallout of 2001 Etna flank eruption: Analysis of the deposit and plume dispersion. *Journal of Volcanology and Geothermal Research, 160*(1–2), 147-164. doi:http://dx.doi.org/10.1016/j.jvolgeores.2006.09.007.

Scollo, S., Folch, A., & Costa, A. (2008). A parametric and comparative study of different tephra fallout models. *Journal of Volcanology and Geothermal Research, 176*(2), 199-211. doi:http://dx.doi.org/10.1016/j.jvolgeores.2008.04.002.

Scott, W. E. (1989). Volcanic and related hazards *Volcanic Hazards* (pp. 9-23): American Geophysical Union.

Scott, W. E., Hoblitt, R. P., Torres, R. C., Self, S., Ma. Mylene L. Martinez, M. M. L. a., & Nillos, J., T. (1996). Pyroclastic Flows of the June 15, 1991, Climactic Eruption of Mount Pinatubo. In C. G. Newhall & R. S. Punongbayan (Eds.), *Fire and mud: Eruptions and Lahars of Mount Pinatubo, Philippines*: Quezon City: Philippine Institute of Volcanology and Seismology; Seattle: University of Washington Press.

Searcy, C., Dean, K., & Stringer, W. (1998). PUFF: A high-resolution volcanic ash tracking model. *Journal of Volcanology and Geothermal Research, 80*(1), 1-16. doi:http://dx.doi.org/10.1016/S0377-0273(97)00037-1.

Self, S., Zhao, J.-X., Holasek, R. E., Torres, R. C., & King, A. J. (1996). The Atmospheric Impact of the 1991 Mount Pinatubo Eruption. In C. G. Newhall

& R. S. Punongbayan (Eds.), *Fire and mud : eruptions and lahars of Mount Pinatubo, Philippines*. Quezon City; Seattle: Philippine Institute of Volcanology and Seismology; University of Washington Press.

Seymour, V. A., Hinckley, T. M., Morikawa, Y. and Franklin, J. F. (1983). Foliage damage in coniferous trees following volcanic ashfall from Mt. St. Helens. *Oecologia, 59*, 339-343.

Shaw, D.M., Watkins, N.D. and Huang, T.C. (1974). Atmospherically transported volcanic glass in deep-sea sediments: Theoretical considerations. *Journal of Geophysical Research, 79*(21), 3087-3094. doi:10.1029/JC079i021p03087.

Sheridan, M. F., & Wohletz, K. H. (1983). Hydrovolcanism: Basic considerations and review. Journal of Volcanology and Geothermal Research, 17(1–4), 1-29. doi:http://dx.doi.org/10.1016/0377-0273(83)90060-4.

Shibata, A. (2012). *IMPORTANCE OF THE INHERITED MEMORIES OF GREAT TSUNAMI DISASTERS IN NATURAL DISASTER REDUCTION*. Paper presented at the International Symposium on Engineering Lessons Learned from the 2011 Great Japan Earthquake, Tokyo, Japan.

Shipley, S., & Sarna-Wojcicki, A. M. (1982). *Distribution, Thickness, and Mass of Late Pleistocene and Holocene Tephra from Major Volcanoes in the Northwestern United States: A Preliminary Assessment of Hazards from Volcanic Ejecta to Nuclear Reactors in the Pacific Northwest*. (1435). U.S.A.: Unites States Geological Survey (USGS) Retrieved from https://pubs.usgs.gov/mf/1983/1435/report.pdf.

Short, J. F. (1984). The Social Fabric at Risk: Toward the Social Transformation of Risk Analysis. *American Sociological Review, 49*(6), 711-725. doi:10.2307/2095526.

Simkin, T., & Fiske, R. S. (1983). Krakatau, 1883--the volcanic eruption and its effects (T. Simkin & R. S. Fiske Eds.). Washington, D.C.: Smithsonian Institution Press.

Sjöberg, L. (1995). Explaining Risk Perception: An Empirical and Quantitative Evaluation of Cultural Theory. *Risk Research Reports* (22).

Sjöberg, L. (1996). *Factors in Risk Perception*. Sweden: Center for Research, University of Stockholm.

Slaughter, M. and Hamil, M. (1970). Model for Deposition of Volcanic Ash and Resulting Bentonite. *Geological Society of America Bulletin, 81*(3), 961-968. doi:10.1130/0016-7606(1970)81[961:MFDOVA]2.0CO;2.

Slovic, P. (1987). Perception of Risk. *Science, 236*(4799), 280-285.

Slovic, P. (1999). Trust, Emotion, Sex, Politics, and Science: Surveying the Risk-Assessment Battlefield. *Risk Analysis, 19*(4), 689-701. doi:10.1111/j.1539-6924.1999.tb00439.x.

Slovic, P. (2000). *The perception of risk*. London: Earthscan Publishing.

Slovic, P., Fischhoff, B., & Lichtenstein, S. (1982). Why Study Risk Perception? *Risk Analysis, 2*(2), 83-93. doi:10.1111/j.1539-6924.1982.tb01369.x.

Smithsonian Global Volcanism Program, 2018. Taal Volcano (273070). In: Venzke, E. (Ed.), Volcanoes of the World, v. 4.5.1. Smithsonian Institution Downloaded 23 Apr 2018. http://volcano.si.edu/volcano.cfm?vn=273070. https://doi.org/10.5479/si. GVP.VOTW4.

Solberg, C., Rossetto, T., & Joffe, H. (2010). The social psychology of seismic hazard adjustment: re-evaluating the international literature. *Natural Hazards and Earth System Sciences, 10*(8), 1663. doi:10.5194/nhess-10-1663-2010

Spanu, A., Michieli Vitturi, M. d., & Barsotti, S. (2016). Reconstructing eruptive source parameters from tephra deposit: a numerical study of medium-sized explosive eruptions at Etna volcano. Bulletin of Volcanology, 78(9), 59. doi:10.1007/s00445-016-1051-2.

Sparks, R.S.J. (1986). The dimensions and dynamics of volcanic eruption columns. *Bulletin of Volcanology, 48*(1), 3-15. doi:10.1007/BF01073509.

Spence, R., Kelman, I., Baxter, P.J., Zuccaro, G., & Petrazzuoli, S. (2005). Residential building and occupant vulnerability to tephra fall. *Nat. Haz. Earth Sys., 5*. doi:10.5194/nhess-5-477-2005

Spence, R.J.S., Pomonis, A., Baxter, P.J., Coburn, A.W., White, M., Dayrit, M. and Team, F.E.T.P. (1996). Building Damage Caused by the Mount Pinatubo Eruption of June 15, 1991. In C. G. Newhall & R. S. Punongbayan (Eds.), *Fire and mud : eruptions and lahars of Mount Pinatubo, Philippines*: Quezon City : Philippine Institute of Volcanology and Seismology ; Seattle : University of Washington Press.

Starr, C. (1969). Social Benefit versus Technological Risk. *Science, 165*(3899), 1232-1238.

Stewart, C., Johnston, D.M., Leonard, G.S., Horwell, C.J., Thordarson, T. and Cronin, S.J. (2006). Contamination of water supplies by volcanic ashfall: A literature review and simple impact modelling. *Journal of Volcanology and Geothermal Research, 158*(3–4), 296-306. doi:http://dx.doi.org/10.1016/j.jvolgeores.2006.07.002.

Stewart, C., Pizzolon, L., Wilson, T., Leonard, G., Dewar, D., Johnston, D. and Cronin, S. (2009). Can volcanic ash poison water supplies? *Integrated Environmental Assessment and Management, 5*(4), 713-716.

Stoler, A. L. (2002). Colonial archives and the arts of governance. Archival Science, 2(1), 87-109. doi:10.1007/bf02435632.

Sudo, M., Listanco, E., Ishikawa, N., Tagami, T., Kamata, H., & Tatsumi, Y. (2000). K-Ar dating of the volcanic rocks from Macolod Corridor in Sothwestern Luzon, Philippines: towards understanding of the Quaternary volcanism and tectonics. *Journal of the Geological Society of the Philippines, 55*(1-2), 89-104.

Sulpizio, R., Folch, A., Costa, A., Scaini, C., & Dellino, P. (2012). Hazard assessment of far-range volcanic ash dispersal from a violent Strombolian eruption at Somma-Vesuvius volcano, Naples, Italy: implications on civil aviation. *Bulletin of Volcanology, 74*(9), 2205-2218. doi:http://dx.doi.org/10.1007/s00445-012-0656-3.

Sutton, L., & Restrepo, C. (2013). Natural Hazards, Diverse Economy and Livelihoods in the Sierra de las Minas, Guatemala. *Journal of Latin American Geography, 12*(3), 137-164.

Suzuki, T. (1983). *A theoretical model for dispersion of tephra*. Paper presented at the Arc Volcanism: Physics and Tectonics: proceedings of a 1981 IAVCEI Symposium, Arc Volcanism, Tokyo and Hakone , Japan.

Swanson, D. A. (2008). Hawaiian oral tradition describes 400 years of volcanic activity at Kīlauea. *Journal of Volcanology and Geothermal Research, 176*(3), 427-431. doi:http://dx.doi.org/10.1016/j.jvolgeores.2008.01.033.

Sword-Daniels, V., Eriksen, C., Hudson-Doyle, E. E., Alaniz, R., Adler, C., Schenk, T., & Vallance, S. (2018). Embodied uncertainty: living with complexity and natural hazards. *Journal of Risk Research, 21*(3), 290-307. doi:10.1080/13669877.2016.1200659

Tayag, J., Endencia, D., Daag, A., Aldon, V., Arante, R., Belo, M., Buen, R., Canlas, L., Domingo, M., Ducay, S., Espinosa, C., Gallardo, C., Garcia, D., Garcia, M.R., Kingking, M., Mendoza, D., Ramos. A., Ramos, E.G., Reyes, Y., Tan, E., Valdez, M., Wagan, L. and Punongbayan, R. S. (1988). *Preliminary Framework Plan for the Development of Taal Caldera*. Quezon City, Philippines: Philippine Institute of Volcanology and Seismology-Department of Science and Technology (PHIVOLCS)-University of the Philippines-School of Urban and Regional Planning (UP-SURP).

Tayag, J., Insauriga, S., Ringor, A., & Belo, M. (1996). People's Response to Eruption Warning: The Pinatubo Experience, 1991-92. In C. G. Newhall & R. S. Punongbayan (Eds.), *Fire and Mud: Eruptions and Lahars of Mt. Pinatubo, Philippines* (pp. 87-106). Seattle, USA; Quezon City, Philippines: Unversity of Washington Press.

Thomalla, F., & Larsen, R. K. (2010). Resilience in the context of tsunami early warning systems and community disaster preparedness in the Indian Ocean Region. *Environmental hazards, 9*(3), 249-265.

Thompson, M.A., Ellis, R. and Wildavsky, A. (1990). *Cultural theory*. Boulder, Colorado: Westview Press.

Thompson, M.A., Lindsay, J. M., Wilson, T. M., Biass, S., & Sandri, L. (2017). Quantifying risk to agriculture from volcanic ashfall: a case study from the Bay of Plenty, New Zealand. *Natural Hazards, 86*(1), 31-56. doi:10.1007/s11069-016-2672-7.

Tierz, P., Sandri, L., Costa, A., Sulpizio, R., Zaccarelli, L., Di Vito, M.A., Marzocchi, W. (2016). Uncertainty Assessment of Pyroclastic Density Currents at Mount Vesuvius (Italy) Simulated Through the Energy Cone Model *Natural Hazard Uncertainty Assessment, Geologic Hazards* (pp. 125-145). Hoboken, NJ, USA: John Wiley & Sons, Inc.

Tilling, R. I. (2005). Volcanic Hazards. In j. Marti & G. Ernst (Eds.), *Volcanoes and the Environment* (pp. 55-89). Cambridge, United Kingdom: Cambridge University Press.

Tobin, G. A., Whiteford, L. M., Jones, E. C., Murphy, A. D., Garren, S. J., & Padros, C. V. (2011). The role of individual well-being in risk perception and evacuation for chronic vs. acute natural hazards in Mexico. *Applied Geography, 31*(2), 700-711. doi:10.1016/j.apgeog.2010.12.008.

Tobin, G.A. & Montz, B.E. (1997). *Natural hazards: explanation and integration*. New York: Guilford Press.

Torres, R.C. (1989). *Tephra characteristics of the scoria deposits of Taal Volcano's 1754 eruption.* (Master of Science in Geology Masteral thesis), University of the Philippines, Diliman, Quezon City, Philippines.

Torres, R.C., Self, S., and Punongbayan, R.S. (1995). Attention focuses on Taal: decade volcano of the Philippines. *Eos, 76*(24), 241,246-247.

Tuohy, R., & Stephens, C. (2012). Older adults' narratives about a flood disaster: Resilience, coherence, and personal identity.(Clinical report). *Journal of Aging Studies, 26*(1), 26.

Tuohy, R., & Stephens, C. (2016). Older adults' meanings of preparedness: a New Zealand perspective. *Ageing and Society, 36*(3), 613-630. doi:10.1017/S0144686X14001408

Tough, A. G. (2012). Oral culture, written records and understanding the twentieth-century colonial archive. The significance of understanding from within. Archival Science, 12(3), 245-265. doi:10.1007/s10502-011-9162-1.

Tupper, A., Davey, J., Stewart, P., Stunder, B., Servranckx, R., & Prata, F. (2006). Aircraft encounters with volcanic clouds over Micronesia, Oceania, 2002-03. *Australian Meteorological Magazine, 55*(4), 289-299.

UNISDR. (2015). Sendai Framework for Disaster Risk Reduction 2015-2030, 36p. Retrieved from https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf

UNISDR. (2009). 2009 UNISDR Terminology on Disaster Risk Reduction. Retrieved from http://www.unisdr.org/ website: http://www.unisdr.org/files/7817_UNISDRTerminologyEnglish.pdf

Usamah, M. & Haynes, K. (2012). An examination of the resettlement program at Mayon Volcano: What can we learn for sustainable volcanic risk reduction? *Bulletin of Volcanology, 74*(4), 839-859. doi:10.1007/s00445-011-0567-8.

USGS. (2015). Volcanic ash impact and mitigation. Retrieved from https://volcanoes.usgs.gov/volcanic_ash/density_hardness.html.

Vogel, T.A., Flood, T.P., Patino, L.C., Wilmot, M.S., Maximo, R.P.R., Arpa, C.B., Arcilla, C.A., & Stimac, J. A. (2006). Geochemistry of silicic magmas in the Macolod Corridor, SW Luzon, Philippines: evidence of distinct, mantle-derived, crustal sources for silicic magmas. *Contributions to Mineralogy and Petrology, 151*(3), 267-281. doi:10.1007/s00410-005-0050-7.

Volentik, A. C.M., Bonadonna, C., Connor, C.B., Connor, L.J., & Rosi, M. (2010). Modeling tephra dispersal in absence of wind: Insights from the climactic phase of the 2450 BP Plinian eruption of Pululagua volcano (Ecuador).

Journal of Volcanology and Geothermal Research, 193(1–2), 117-136. doi:http://dx.doi.org/10.1016/j.jvolgeores.2010.03.011.

Volentik, A.M. & Houghton, B. (2015). Tephra fallout hazards at Quito International Airport (Ecuador). *Bulletin of Volcanology, 77*(6), 1-14. doi:10.1007/s00445-015-0923-1.

Wahyunto, K., Nuroho, K., & Sarwani, M. (2012). Agricultural recovery action for area affected by 2010 Merapi Volcano eruption, Indonesia. *International Journal of Geoinformatics, 8*(4), 41-48.

Walker, G. P. L., Self, S., & Wilson, L. (1984). Tarawera 1886, New Zealand - A basaltic plinian fissure eruption. J Volcanol Geotherm Res, 21. doi:10.1016/0377-0273(84)90016-7.

Wardman, J.B., Wilson, T.M., Bodger, P.S., Cole, J.W., & Johnston, D. M. (2012a). Investigating the electrical conductivity of volcanic ash and its effect on HV power systems. *Physics and Chemistry of the Earth, Parts A/B/C, 45–46*(0), 128-145. doi:http://dx.doi.org/10.1016/j.pce.2011.09.003.

Wardman, J. B., Wilson, T. M., Bodger, P. S., Cole, J. W., & Stewart, C. (2012b). Potential impacts from tephra fall to electric power systems: a review and mitigation strategies. *Bulletin of Volcanology, 74*(10), 2221-2241. doi:10.1007/s00445-012-0664-3.

Waters, A. C., & Fisher, R. V. (1971). Base surges and their Deposits: Capelinhos and Taal Volcanoes. *Journal of Geophysical Research, 76*(23), 5596-5614. doi:10.1029/JB076i023p05596.

White, J.T., Connor, C.B., Connor, L. and Hasenaka, T. (2017). Efficient inversion and uncertainty quantification of a tephra fallout model. *Journal of Geophysical Research: Solid Earth*, n/a-n/a. doi:10.1002/2016JB013682.

Wildavsky, A. & Dake, K. (1990). Theories of Risk Perception: Who Fears What and Why? *Daedalus, 119*(4), 41-60.

Williams, H., & McBirney, A. R. (1979). *Volcanology*. San Francisco, CA: Freeman, Cooper, c1979.

Williams, S. N. (1983). Plinian airfall deposits of basaltic composition. Geology (Boulder) (0091-7613), 11(4), 211. doi: 10.1130/0091-7613(1983)11<211:PADOBC>2.0.CO;2.

Willis, B. (1937). *Geologic observations in the Philippine archipelago*.

Wilkinson, E. (2015). Beyond the volcanic crisis: co-governance of risk in Montserrat. *Journal of Applied Volcanology, 4*(1), 3. doi:10.1186/s13617-014-0021-7.

Wilks, T. (2004). The Use of Vignettes in Qualitative Research into Social Work Values. *Qualitative Social Work, 3*(1), 78-87. doi:10.1177/1473325004041133.

Wilson, T. M. & Cole, J. W. (2007). Potential impacts of ash eruptions on dairy farms from a study of the effects on a farm in eastern Bay of Plenty, New Zealand; implications for hazard analysis. *Nat. Haz., 43*. doi:10.1007/s11069-007-9111-8.

Wilson, T., Cole, J., Cronin, S., Johnston, D., & Stewart, C. (2011). Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: Lessons for recovery. *Nat. Haz., 57*. doi:10.1007/s11069-010-9604-8.

Wilson, T.M., Stewart, C., Sword-Daniels, V., Leonard, G.S., Johnston, D.M., Cole, J.W., Wardman, J., Wilson, G. and Barnard, S.T. (2012). Volcanic ash impacts on critical infrastructure. *Physics and Chemistry of the Earth, Parts A/B/C, 45–46*(0), 5-23. doi:http://dx.doi.org/10.1016/j.pce.2011.06.006.

Wisner, B., Blaikie, P., Cannon, T. and Davis, I. (2004). *At Risk: Natural Hazards, People's Vulnerability and Disasters* (2nd ed.). London; New York: Routledge.

Wolfe, J. A. (1986). Breccias related to explosive volcanism (Philippines). *Journal of Southeast Asian Earth Sciences, 1*(2), 63-79. doi:10.1016/0743-9547(86)90022-X.

Wolfe, J. A. (1988). Arc magmatism and mineralization in North Luzon and its relationship to subduction at the East Luzon and North Manila Trenches. *Journal of Southeast Asian Earth Sciences, 2*(2), 79-93. doi:http://dx.doi.org/10.1016/0743-9547(88)90011-6.

Wolfe, E. W. & Hoblitt, R. P. (1996). Overview of the eruptions. In C. G. Newhall & R. S. Punongbayan (Eds.), *Fire and mud : eruptions and lahars of Mount Pinatubo, Philippines*. Quezon City; Seattle Philippine Institute of Volcanology and Seismology; University of Washington Press.

Wolfe, J. A. & Self, S. (1983). Structural lineaments and Neogene volcanism in Southwestern Luzon. In D. E. Hayes (Ed.), *The Tectonic and geologic evolution of Southeast Asia seas and island, Part 2* (Vol. 27, pp. 157-172).

Worcester, D. C. (1912). Taal Volcano and its recent destructive eruption. *The National Geographic Magazine, 23,* 314-267.

Wright, J. V., Smith, A. L., Roobol, M. J., & Mattioli, G. S. (2016). Distal ash hurricane (pyroclastic density current) deposits from a ca. 2000 yr B.P. Plinian-style eruption of Mount Pelée, Martinique: Distribution, grain-size characteristics, and implications for future hazard. *GSA Bulletin, 128*(5-6), 777-791. doi:10.1130/B31282.1.

Yu, H., Xu, J., Luan, P., Zhao, B. and Pan, B. (2013a). Probabilistic assessment of tephra fallout hazard at Changbaishan volcano, Northeast China. *Natural Hazards, 69*(3), 1369-1388. doi:10.1007/s11069-013-0683-1.

Yu, S.-B., Hsu, Y.-J., Bacolcol, T., Yang, C.-C., Tsai, Y.-C., & Solidum, R. (2013b). Present-day crustal deformation along the Philippine Fault in Luzon, Philippines. *Journal of Asian Earth Sciences, 65*(0), 64-74. doi:http://dx.doi.org/10.1016/j.jseaes.2010.12.007.

Zimanowski, B., & Büttner, R. (2013). Phreatomagmatic Explosions in Subaqueous Volcanism Explosive Subaqueous Volcanism (pp. 51-60): American Geophysical Union.

Zobel, D.B. and Antos, J.A. (1997). A Decade of Recovery of Understory Vegetation Buried by Volcanic Tephra From Mount St. Helens. *Ecological Monographs, 67*(3), 317-344. doi:10.2307/2963458.

APPENDICES

APPENDIX A

Appendix A is the manuscript that summarises the results of the critical and comprehensive review of historical eruptions of Taal published in *Earth-Science Reviews.* The complete manuscript was written by me. My co-authors, Ma. Antonia Bornas, my research supervisors Professor Dale Dominey-Howes and Dr. Christina Magill, and the Department of Science and Technology (DOST) Undersecretary and DOST-PHIVOLCS Officer-In-Charge Renato Solidum, Jr. provided detailed and critical peer-reviews of the completed manuscript. I designed and generated the manuscript figures with the help of DOST-PHIVOLCS colleagues Abigail Pidlaoan, while the Summary Tables were solely compiled and generated by me.

Earth-Science Reviews 177 (2018) 565–588

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

A synthesis and review of historical eruptions at Taal Volcano, Southern Luzon, Philippines

Perla J. Delos Reyes[a,b,*,1], Ma. Antonia V. Bornas[b,c], Dale Dominey-Howes[a], Abigail C. Pidlaoan[b], Christina R. Magill[d], Renato U. Solidum, Jr.[b]

[a] Asia – Pacific Natural Hazards and Disaster Risk Research Group, School of Geosciences, The University of Sydney, Sydney, New South Wales 2006, Australia
[b] Philippine Institute of Volcanology and Seismology (PHIVOLCS), Department of Science and Technology (DOST), C.P. Garcia Ave., UP Diliman, Quezon City 1101, Philippines
[c] Département Géosciences, Environnement et Société, Université Libre de Bruxelles, Belgium
[d] Department of Environmental Sciences, Faculty of Science and Engineering, Macquarie University, New South Wales 2109, Australia

ARTICLE INFO

Keywords:
Taal Volcano
Eruption history
Tephra fall
Pyroclastic density current
Volcanic tsunami

ABSTRACT

The Philippines is an area of persistent volcanism, being located in one of the most tectonically active regions in the world. Taal Volcano in Southern Luzon is the second most frequently erupting volcano of the 24 active volcanoes in the Philippines. A comprehensive and critical review of published and unpublished references describing the 33 known historical eruptions of Taal may provide answers to knowledge gaps on past eruptive behavior, processes, and products that could be utilized for hazard and risk assessment of future eruptions.

Data on the prehistoric eruptions and evolution of Taal Caldera and subsequent deposits are limited. Only four caldera-forming events were identified based on four mapped ignimbrite deposits. From oldest to youngest, these are the silicic Alitagtag (ALI) and Caloocan (CAL) Pumice Flow deposits, the dacitic Sambong Ignimbrite (SAM), and the basaltic-andesitic Taal Scoria Flow, renamed Scoria Pyroclastic Flow (SFL). Except for SFL with ^{14}C dating yielding 5380 ± 70 to 6830 ± 80 ky, there are no age constraints or estimates of extent for the three older deposits.

A comprehensive review of the historical eruptions of Taal Volcano is the central element of this paper and includes all eruptions from AD1572 (the first known historic event) to AD1977. Eruption styles and the interplay between processes and products for each eruption are reinterpreted based on the narrative descriptions from all available accounts. A change of classification of eruption styles and eruptive products is undertaken for some events. At least nine reported eruptions were deemed uncertain including the AD1605-AD1611 event (more likely seismic swarms), the AD1634, AD1635, and AD1645 (may simply be solfataric or hydrothermal activity) events, and the AD1790, AD1825, AD1842, AD1873 and AD1903 events that were listed in recent published and unpublished documents but do not provide any details to describe and confirm the eruptions except for listing a default VEI of 2.

Pyroclastic density currents brought devastating impacts to the communities around Taal during the AD1749, AD1754, AD1911 and AD1965 eruptions and remain the biggest threat in the case of renewed volcanic activity. Significant implications for aviation are implied by the narrative of tephra fall dispersal towards Manila, the central gateway of international aviation operation in the Philippines, during the AD1754 eruptions. The dispersal of tephra in the event of an explosive eruption at Taal towards Metro Manila would have catastrophic effects to transport, utilities and business activity, potentially generating enormous economic losses. Hazards from earthquake events associated with future volcanic activity may also have localized impacts. Occurrences of liquefaction phenomena as a consequence of severe ground shaking are interpreted during the AD1749, AD1754, and AD1911 eruptions.

More work needs to be done to develop a comprehensive understanding of the hazards and risks associated with an explosive eruption at Taal Volcano, especially related to the older Quaternary caldera-forming eruptions that produced large-volume pyroclastic deposits that are extensively distributed and exposed. We acknowledge that there may be additional prehistoric eruptions where the eruptive products have not been preserved, recognized or reported. Events that cannot be verified or do not have sufficient details to confirm the eruption,

* Corresponding author at: Room 444, Madsen Bldg. (F09), School of Geoscience, The University of Sydney, New South Wales 2006, Australia.
E-mail address: perla.delosreyes@sydney.edu.au (P.J. Delos Reyes).
[1] Permanent/Main address: Philippine Institute of Volcanology and Seismology (PHIVOLCS), Department of Science and Technology (DOST), C.P. Garcia Ave., UP Diliman, Quezon City 1101, Philippines.

https://doi.org/10.1016/j.earscirev.2017.11.014
Received 10 November 2016; Received in revised form 6 November 2017; Accepted 14 November 2017
Available online 02 December 2017
0012-8252/

have been downgraded to "uncertain". Eruptions that are confirmed with identified dispersal and emplacement of tephra fall and other eruptive deposits, as interpreted from narrated records, could provide crucial information that may be utilized in hazard assessment.

1. Introduction and aims

The geologic setting of the Philippines in one of the most tectonically active regions in the world makes it an area of persistent volcanism. It is located at the interface of the Philippine Sea Plate and the Eurasian Plate (Fig. 1A). The Philippines is home to 24 of some 400 global volcanoes currently classified as active (Fig. 1B). According to the national agency, the Philippine Institute of Volcanology and Seismology (PHIVOLCS-DOST, 2016a), an active volcano is defined as "one that has erupted within historical times (within the last 600 years), accounts of which were documented by man, or has erupted within the last 10,000 years based on analyses of datable materials". While the Smithsonian Global Volcano Program (GVP) (2016) lists 342 volcanoes, PHIVOLCS-DOST (2016a) identified 407 volcanoes in the Philippines. Table 1 lists the volcanoes in the Philippines classified as active and Fig. 1B provides the location of the distribution of volcanoes in the Philippines. Taal Volcano ranks as the second most frequently erupting volcano with 33 identified historical eruptions (Table 2). A future large magnitude eruption of Taal threatens the lives and livelihoods of about two million people in Batangas Province alone that are within a 35-km radius, including those living within the Taal Caldera and Taal Volcano island. The farthest Taal eruption outcrop mapped was found 35 km north of Taal (Martinez and Williams, 1999). Tephra dispersal from a potential explosive eruption of Taal Volcano represents a major risk to Metro Manila, the National Capital Region of the Philippines, depending on prevailing wind direction at the time of an eruption.

Given the significant local and regional risk to communities, and in order to develop adequate volcano hazard and risk management strategies for at risk communities, it is vital to have a comprehensive understanding of the evolution of the volcano including eruptive history, processes, accompanying hazards and impacts associated with past eruptions.

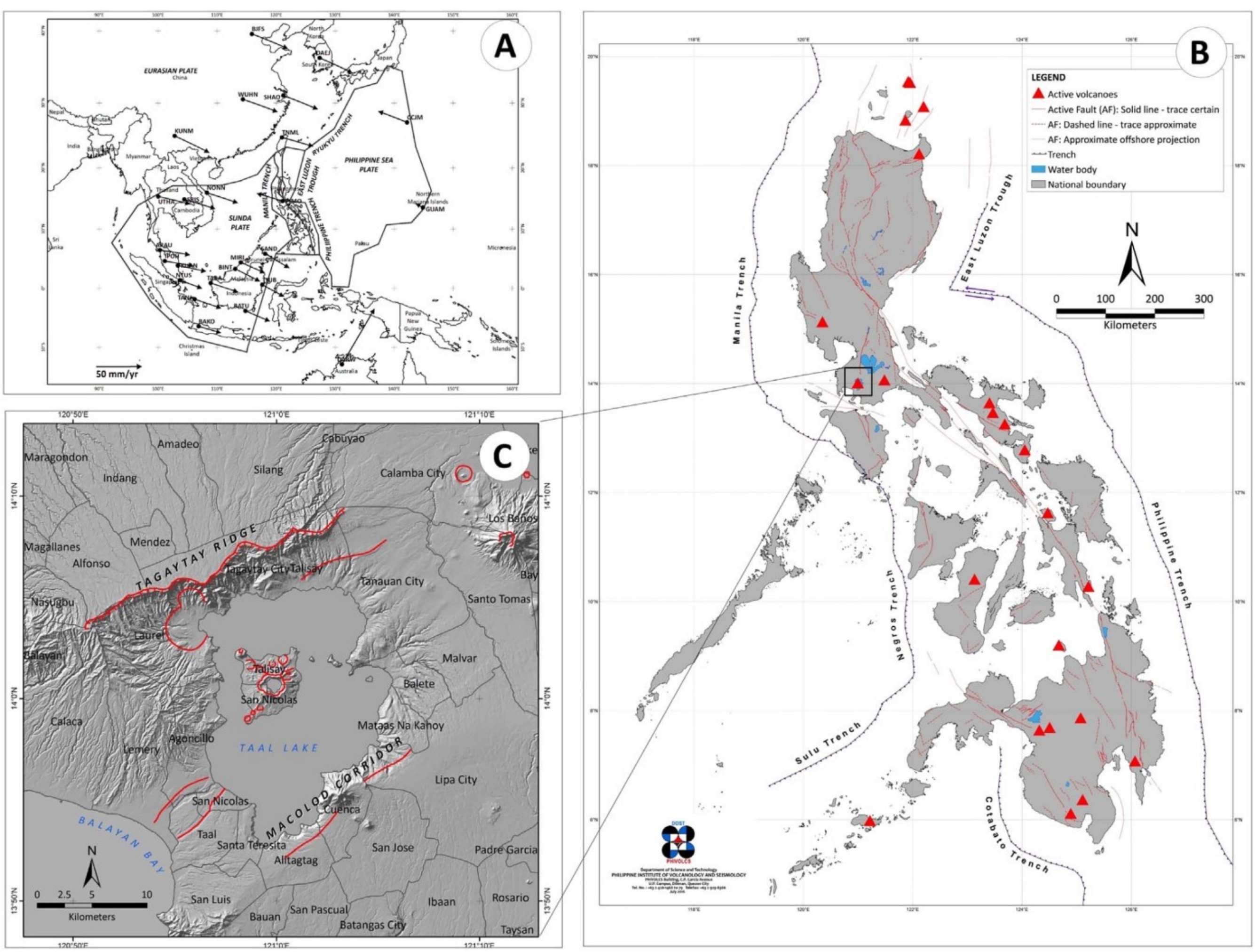


Fig. 1. (A) Regional tectonic setting of the Philippines. Black dots indicate the International Global Navigational Satellite Systems Service (IGS) sites and the continuous GPS (cGPS) sites in Hsu et al. (2016), and the vectors show GPS velocities indicating rate of movement of the major tectonic plates. Map source: Modified from Hsu et al., 2016, overlain on data from Global Self-consistent, Hierarchical, High-resolution Geography (GSGGG) Database version 2.3.6 from NGDC (NOAA) (Wessel and Smith, 1996). (B) Distribution of active fault, trenches and volcanoes in the Philippines, with the location of Taal Volcano bounded by black square (Source: PHIVOLCS-DOST, 2016a). (C) Local tectonic setting in the vicinity of Taal Volcano, Southern Luzon, Philippines, overlain on NAMRIA 2013 Interferometric Synthetic Aperture Radar - Digital Terrain Model (IfSAR-DTM). Red solid lines are interpreted structures and craters.

Table 1
List of active volcanoes in the Philippines. The locations of the active volcanoes are in World Geodetic System (WGS) 84. Source: PHIVOLCS-DOST (2016a).

Name of volcano	Latitude	Longitude	Location/province
Babuyan Claro	19.52408	121.95005	Babuyan Island Group, Cagayan in Luzon
Banahaw	14.06038	121.48803	Boundaries of Laguna and Quezon in Luzon
Biliran (Anas)	11.63268	124.47162	Leyte in
Visayas Bud Dajo	6.01295	121.05772	Sulu
Bulusan	12.76853	124.05445	Sorsogon, Bicol Region in
Luzon Cabalian	10.27986	125.21598	Southern Leyte in Visayas
Cagua	18.22116	122.1163	Cagayan in Luzon
Camiguin de Babuyanes	18.83037	121.86280	Babuyan Island Group, Cagayan in Luzon
Didicas	19.07533	122.20147	Babuyan Island Group, Cagayan in Luzon
Hibok-Hibok	9.20427	124.67115	Camiguin in Mindanao
Iraya	20.46669	122.01078	Batan Island, Batanes in Luzon
Iriga	13.45606	123.45479	Camarines Sur in Luzon
Isarog	13.65685	123.38087	Camarines Sur in Luzon
Kanlaon	10.41129	123.13243	Boundaries of Negros Oriental and Negros Occidental in Visayas
Leonard Kniaseff	7.39359	126.06418	Davao del Norte in Mindanao
Makaturing	7.64371	124.31718	Lanao del Sur in Mindanao
Matutum	6.36111	125.07603	Cotobato in Mindanao
Mayon	13.25519	123.68615	Albay, Bicol Region in Luzon
Musuan (Calayo)	7.87680	125.06985	Bukidnon in Mindanao
Parker	6.10274	124.88879	South Cotobato/General Santos/ North Cotabato/Saranga ni Provinces in Mindanao
Pinatubo	15.14162	120.35084	Boundaries of Pampanga, Tarlac and Zambales in Luzon Ragang
	7.69066	124.50639	Lanao del Sur and Cotobato in Mindanao
Smith	19.53915	121.91367	Babuyan Island Group, Cagayan in Luzon
Taal	14.01024	120.99812	Batangas in Luzon

Since AD1572, there had been 33 known historical eruptions of Taal Volcano (Saderra Maso, 1911; Worcester, 1912; Moore et al., 1966; Ruelo, 1983; PHIVOLCS-DOST, 1991, 1995; Listanco, 1994; Smithsonian GVP, 2016) (Table 2). The most recent eruption occurred in AD1977. At least four of these eruptions, occurring in AD1749, AD1754, AD1911 and AD1965, are categorized as violent with Volcanic Explosivity Index (VEI) values of 3 to 5. These four eruptions resulted in > 1500 casualties and considerable loss of livelihood and properties. Additional casualties may have gone unrecorded resulting from burial by pyroclastic density currents or swept away by volcanic tsunami. Written accounts of historical eruptions of Taal during the Spanish era provide basic but useful information through descriptions of eruption style and intensity, and approximation of deposit dispersal and thick- nesses (Buencuchillo, 1754; Centeno y Garcia, 1885; Pratt, 1911a, 1911b; Saderra Maso, 1911). Numerous authors have previously sum- marized Spanish colonial documents to help better understand various eruption dynamics (Martin, 1911; Pratt, 1911a, 1911b, 1916; Worcester, 1912; Alcaraz, 1966; Moore et al., 1966; Moore, 1967; Ruelo, 1983; Feldman, 1988; PHIVOLCS-DOST, 1991). More detailed descriptions of the processes and products associated with the AD1754, AD1911 and AD1965 eruptions have been undertaken (Pratt, 1911a, 1911b, 1916; Alcaraz, 1966; Moore et al., 1966; Moore, 1967; Waters and Fisher, 1971; Ruelo, 1983; Punongbayan and Tilling, 1989; Torres, 1989). Reports, some unpublished, and regional manuscripts also syn- thesize historical and recent eruptions of Taal (Masigla and Ruelo, 1987; Newhall and Dzurisin, 1988; Hargrove, 1991; PHIVOLCS-DOST, 1991, 1995; Torres et al., 1995). Information on the geology (Worcester, 1912; Moore, 1967; Waters and Fisher, 1971; Wolfe, 1986; Geronimo, 1988; Torres, 1989; Listanco, 1994; Martinez, 1997; Martinez and Williams, 1999), stratigraphy and geochemistry (Ragland and Defant, 1983; De Luna, 1988; Geronimo, 1988; Miklius et al., 1991; Martinez, 1997; Martinez and Williams, 1999; Sudo et al., 2000; Castillo and Newhall, 2004; Arpa et al., 2008; Vogel et al., 2006; Arpa et al., 2013), geomorphology (Saderra Maso, 1904; Ruelo, 1983; Ramos, 2001), and tectonics and geophysics (Alcaraz and Datuin, 1974; Acharya and Aggarwal, 1980; Hamburger et al., 1983; Lim, 1983; Wolfe and Self, 1983; Wolfe, 1988; PHIVOLCS-DOST, 1991; Nishigami et al., 1994; Listanco, 1997; Lowry et al., 2001; Ohkura et al., 2001; Bartel et al., 2003; Fikos et al., 2012; Hsu et al., 2012; Maeda et al., 2013; Yu et al., 2013; Galgana et al., 2014; Kumagai et al., 2014) offer more comprehensive detail on various aspects related to Taal Volcano.

However, notwithstanding these numerous accounts of past erup- tions, there has not been a single, comprehensive synthesis of all known information on the historical eruption record of Taal Volcano in the peer-reviewed scientific literature. This stands as a barrier to volca- nologists wanting to better understand the geology and behavior of the volcano and to disaster hazards and risk managers wanting to prepare and plan for future eruptions.

The aim of this paper is to examine and summarize existing eruption accounts in order to provide a comprehensive chronological eruption profile for Taal Volcano based on existing historical accounts, narrative descriptions and mapping. Information analyzed will include eruption types and magnitudes, erupted deposits, estimated distribution and thicknesses of deposits and the impacts of these eruptions on people and properties. It is hoped that the information provided will be useful for understanding potential eruptive activities of Taal, with future studies filling in knowledge gaps as more volcano information becomes avail- able, and for ensuring that impacts and economic and social con- sequences of future eruptions can be managed or mitigated.

To achieve the aim, the paper is structured as follows. First, Section 2 summarizes the tectonic and geologic setting of the Philippines, with specific focus on Taal Volcano sourced from various authors to provide an overview of the origin of the formation of the volcano and adjacent landforms. Section 3.1 is a brief review of the pre-historic (Quaternary) eruption history of the volcano. This is followed by a critical review of all known historic eruptions at Taal between AD1572 and AD1977 (Section 3.2). Section 3.3 reviews and interprets eruptive processes and products identified from the descriptive accounts. A synthesis is provided in Section 4, followed by a series of recommendations in Section 5 for future research at Taal Volcano, and lastly, brief concluding re- marks are provided in Section 6.

2. Tectonic and geographic setting and regional geology

In order to understand the geological processes underpinning the behavior of Taal Volcano, it is necessary to have a grasp of the regional tectonic, geological and geographical setting of the Philippines and the area in which Taal is located.

The Philippine Archipelago, located at the interface between the Eurasian Plate and the Philippine Sea Plate, was formed by the oblique convergence of the westward-subducting Philippine Sea Plate along the East Luzon Trench and the Philippine Trench, and the eastward-sub- ducting Sunda/Eurasian Plate along the Manila Trench and the mar- ginal basins of the Sulu and Celebes Seas along the Negros and Cotabato Trenches, giving rise to a complex accumulation of sedimentary and island arc terranes and ophiolitic assemblage (Acharya and Aggarwal, 1980; Hamburger et al., 1983; Hayes and Lewis, 1985; Knittel et al., 1988; Galgana et al., 2007; Yu et al., 2013) (Fig. 1A). Westward sub- duction of the Philippine Sea Plate is thought to have begun in the Late Mesozoic to Early Cenozoic. Subduction along the Manila Trench is thought to have commenced in the Mid-Oligocene (Ludwig, 1970; De Boer et al., 1980; Schweller et al., 1983; Hamburger et al., 1983; Karig, 1983; Schweller et al., 1984; Wolfe, 1988).

Another dominant tectonic feature of the Philippines is the Philippine Fault Zone (PFZ) (Repetti, 1935; Willis, 1937; Allen, 1962; Aurelio, 2000), a 1200 km-long system of left-lateral strike-slip faults transecting the archipelago from Ilocos in the north, to Eastern

Table 2
Recorded historical eruptions of Taal Volcano from AD1572 to 2015. Sources: Pratt, 1911a, 1911b; Saderra Maso, 1911; Worcester, 1912; Moore et al., 1966; Ruelo, 1983; PHIVOLCS-DOST, 1991, 1995, 2016a, 2016b; Smithsonian GVP, 2016. Volcanic Explosivity Index (VEI) marked in RED are recommended to be changed based on the new interpretations.

Eruption No.	Date(s) of eruption	Series/ eruption site (1)	VEI (2)	Significant description of activity	Interpretation of eruptive activity (3)	Eruptive processes/ deposits (4)	Eruptive impacts (5)	Confirmed/ uncertain
1	1572	Series A/MC	3	"volcano of fire" that "spit forth many and large rocks" (Saderra Maso, 1911, p.6)	More likely ST than PM, as previously interpreted	TF, LVFO with BP	Damage to agricultural crops	Confirmed
2	1591	Series A/MC	3	"belch forth extraordinary masses of smoke" (Saderra Maso, 1911, p.6)	Minor PH, SA	TF	ND	Confirmed
3	1605–1611	Series A/MC	2/3	"frequent rumblings" (Saderra Maso, 1911, p.7)	SA	RS, VE	ND	Uncertain
4	1634	Series A/MC	3		SA or minor PH	ND	ND	Uncertain
5	1635	Series A/MC Crater	3		SA or minor PH	ND	ND	Uncertain
6	1641	Series A/MC	3	"two craters opened up" (PHIVOLCS, 1991, p.31)	PH	TF	Activity confined to TVI	Confirmed
7	1645	Series A/MC	3		SA	ND	ND	Uncertain
8	1707	Series B/ BMA	2	"tremendous display of thunder and lightning" (Saderra Maso, 1911, p.7)	PH, presumably with tephra column	TF, EA, SW	Activity confined to TVI; ND	Confirmed
9	1709	Series B/ BMU	2	"vomited forth a deafening noise" (PHIVOLCS, 1991, p.32); "loud detonation" (PHIVOLCS, 1995, p.49)	Sound presumably from an explosion; PM	VE, RS	No reported damage	Confirmed
10	1715	Series B/ BMA	2	"loud explosions and threw out incandescent materials, giving an impression of a river of fire" (PHIVOLCS, 1995, p49)	More likely ST	LVFO with BP, LVF	No reported damage	Confirmed
11	1716 24–27 Sep	Series B/ CAL	2/4	"great number of detonations heard in the air"; "great commotion in the earth which stirred up the water in the lake, forming immense waves which lashed the shores as though a violent typhoon were raging"; tephra columns described as "looking like towers" (Saderra Maso, 1911, p7; Worcester, 1912, p314)	Violent sublacustrine PM with tephra columns from series of eruptions estimated at heights of 100 to150 m	VE, TF, PDC, VT, AR, G	Fish kill; VT causing inundation limit of 17 m (S, SW); undetermined casualties	Confirmed
12	1729	Series B/ BMU	2	"a new outburst of the volcano" (Saderra Maso, 1911, p.7)	PH or solfataric or hydrothermal activity	ND	ND	Confirmed
13	1731	Series B/PP	2	"frightful and all-devouring conflagration that the whole region was panic-stricken" (Saderra Maso, 1911, p8); "accompanied by subterranean rumblings which caused the entire region to tremble" (Saderra Maso, 1911, p.8)	Violent sublacustrine PM with large tephra column accompanied by volcanic earthquakes	TF, BP, VE, PDC, VT	Numerous explosion; formed an island named Bubuin; fish kill but no destructive impact to adjacent communities	Confirmed
14	1749 11 Aug	Series C/MC	3/4	"ascended in the shape of pyramids to marvelous heights then fell back into the lake like illuminated fountains. Some of the pyramids surged towards north, others towards east, the sight lasting until 9 o'clock of the morning" (Saderra Maso, 1911, p.8); "entire territory of Sala and part of Tanauan have been rendered practically uninhabitable – the water courses have been altered, former springs have ceased to flow and new ones made their appearance, the whole country is traversed by fissures, and extensive subsidences have occurred in many places" (Saderra Maso, 1911, p8; Worcester, 1912, p317).	Eruption series more likely PL or a very violent PM, with column-collapse pyroclastic density current	TF, BP, VE, PDC, VT, AR, SU, F, EA, LIQ, G, SW	Volume of ejecta estimated at 50–100 million m^3; TVI and lakeshore towns of Taal, Sala and Tanauan; PDC towards N & E; LIQ effects; fatalities unknown	Confirmed

(continued on next page)

Table 2 (*continued*)

Eruption No.	Date(s) of eruption	Series/ eruption site (1)	VEI (2)	Significant description of activity	Interpretation of eruptive activity (3)	Eruptive processes/ deposits (4)	Eruptive impacts (5)	Confirmed/ uncertain
15	1) 1754 15 May–02 Jun	Series C/MC	5	"the volcano quite unexpectedly commenced to roar and emit, sky-high, formidable flames intermixed with glowing rocks which, falling back upon the island and rolling down the slopes of the mountain, created the impression of a large river of fire"	PL with column collapse leading to generation of pyroclastic flows/base surges	TF, BP, VE, PDC	> 100 explosions; ~150 million m^3 of ejecta; eruption column ~40 km; TF drifted W, SW & S resulting in collapse of houses with ~1.1 m TF deposits; TF deposits covered an area of 400 km^2 and reached Manila but thickness undetermined; PDC affected entire TVI, crossing the lake and affected shoreline communities but majority towards W & SW; complete devastation of Old Taal, Old Lipa, Sala and Old Tanauan; damming of Pansipit River causing flooding in Old Lipa and Old Tanauan; livestock perished; 12 known fatalities reported	Confirmed
	2) 1754 02 June–26 Sep			"volcano never ceased to eject fire and mud"; "within the black column of smoke issuing from the volcano ever since June 2, there frequently formed thunderstorms"	PM	TF, PDC, EA, VE		
	3) 1754 1–15 Nov			"resumed its former fury, ejecting fire, rocks, sand, and mud"				
	4) 1754 28 Nov–02 Dec			"columns of fire and smoke ascended higher than ever before"; "accompanied by terrific lightning and thunder above, and violent shocks of earthquake underneath"; "waves of the angry lake began already to flood the houses nearest to the beach" (Saderra Maso, 1911, p.9); "in other parts of the lakeshore have likewise opened many cracks" (Saderra Maso, 1911, p.10-11)	PL or PM PL and PM	TF, PDC, VE TF, PDC, VE, EA, SW, VT, FL, AR, F, G, LIQ		
16	1790	Series C/MC	2		SA	ND	ND	Uncertain
17	1808	Series C/MC	2	"Formerly the depth seemed immense and unfathomable, and at the bottom was seen a liquid mass in continual ebullition. After the eruption the whole aspect was changed; the crater had widened, the pond within it had been reduced to one-third and the rest of the crater floor is dry enough to walk over it" (Saderra Maso, 1911, p11)	Moderate PM	TF, GE	Main activity confined to TVI; 84 cm TF deposits at TVI but thicker in distal areas; change in depth and configuration of MC, with former two lakes merged as one	Confirmed
18	1825	Series C/MC	2		SA	ND	ND	Uncertain
19	1842	Series C/MC	2		SA	ND	ND	Uncertain
20	1873	Series C/MC	2		SA	ND	ND	Uncertain
21	1874 19 Jul	Series C/MC	2	"took place an eruption of gases and ashes which killed all the livestock which were being raised on Volcano Island and withered or burned the entire vegetation on the western slopes of the crater" (Saderra Maso, 1911, p11; Worcester, 1912, p328)	Moderate PM	TF, G	Confined to TVI; complete destruction of flora & fauna	Confirmed
22	1878 12–15 Nov	Series C/MC	2	"noises were frequently heard proceeding from the volcano which finally, from November 12 to 15, ejected a quantity of ashes sufficient to cover the entire island" (Saderra Maso, 1911, p11)	Moderate PH	TF	Affected entire TVI	Confirmed
23	1903	Series C/MC	2		SA	ND	ND	Uncertain
24	1904 Apr to 5 Jul	Series C/MC	1/2	"showered with mud, which burned viciously, not because it was hot, but because of the strong acid which it contained" describing the 5th July event (Worcester, 1912, p334)	Minor PH	TF, BP, G	Column about 150 m high; absence of wind confining dispersal and deposition within the Main Crater and/or S and SE slopes	Confirmed

Table 2 (*continued*)

Eruption No.	Date(s) of eruption	Series/ eruption site (1)	VEI (2)	Significant description of activity	Interpretation of eruptive activity (3)	Eruptive processes/ deposits (4)	Eruptive impacts (5)	Confirmed/ uncertain
25	1) 1911 27 Jan.	Series C/MC	3/4	"the volcano had been ejecting mud, ashes, and some rocks" (Saderra Maso, 1911, p.12); 26 volcanic earthquakes recorded, some felt in Metro Manila commencing at 11:06 pm	PM and/or PL	VE, TF, BP	Volume of ejecta ~80 million m^3; PDC affected 15 km of land including entire TVI, Talisay and other lakeshore barrios W of TVI; TF ~25–80 cm thick that affected entire TVI and	Confirmed
	2) 1911 28 Jan.			"huge column of black smoke" (Saderra Maso, 1911, p12); 197 volcanic earthquakes recorded by Manila Observatory	PM	VE, TF	towns N–NW–W–SW of the island (Talisay, Laurel, Tagaytay, Agoncillo) & can be seen 400 km away from Taal; accretionary lapilli	
	3) 1911 29 Jan.			"visited the volcano and found its top covered by recent mud and ashes" (Saderra Maso, 1911, p12); increased intensity of volcanic earthquakes with 113 recorded by Manila Observatory	PM	VE, TF, EA, F, SU, RS, SW	was observed; fissures at Lemery & Taal; explosions heard in Manila (60 km away); 1335 fatalities; damage to flora & fauna	
	4) 1911 30 Jan.			"explosions began to assume a terrific violence at 1o'clock in the morning"; "immense, threatening, black cloud, crossed by brilliant flashes of lightning" (Saderra Maso, 1911, p13); "electric discharges which took place upward within the column" (Saderra Maso, 1911, p13).	PM and/or PL	VE, TF, EA, SU, AR, PDC, SW, G, VT, LIQ		
26	1) 1965 28 Sep	Series D/MT	4	"incandescent material shooting high in the air from the general vicinity of the newly formed cinder cone"; "enormous Roman candle"; "directed towards the lake" observed at 2 am on 28 September (Moore et al., 1966, p.955)	Strombolian	LVFO, LVF, VE, TF	PDC affected S of TVI from Balantoc (W) to Calauit (E), lakeshore barrios W of the island (from Gulod to Bilibinwang); TF deposited 20–50 cm as far as 60 km, affected entire TVI and towns S-SW of Taal; accretionary lapilli	
	2) 1965 from 02:40–03:30 AM 28 Sep			-"continuous display of lightning in the eruption cloud accompanied by thunder" observed (Moore et al., 1966, p.955) -"at the base of the main cloud column a flat turbulent cloud spread out, radially transporting ejected material with hurricane velocity" (Moore et al., 1966, p958)	PM	RS, TF, BP, EA, PDC, SW, VT, G	observed; 40 million m^3 of ejecta covering 60 square km; 200 fatalities	Confirmed
	3) 1965 From 9:20 am 28 Sep. to 6 am 30 Sep			Eruptions were less intense and the columns not as high	Minor PM	TF		
27	1966 5 Jul to 4 Aug the	Series D/MT	3	Center of activity was located on the southwest sector of 1965 cinder cone; "122-meter high ellipsoidal tuff cone measuring 500 × 400 meters at its base" (PHIVOLCS, 1991, p.53) resulting from series of minor eruptions	Moderate PM	TF, BP, VE	TVI, formed a tuff cone; impact to houses & vegetation due to TF deposition	Confirmed
28	1967 16–18 Aug	Series D/MT	1	Eruption created "a small doughnut-shaped cinder cone" (PHIVOLCS, 1995, p.51)	Minor PM	TF, BP, VE	Explosion centered at 1966 tuff cone; tephra column as high as 400 m	Confirmed
29	1968 31 Jan-1 Feb	Series D/MT	2	Centered within the 1966 eruption cone lake and a few meters from the 1967 conelet	Minor PM	TF, VE	LV temperature about 1175 °C; breached rim of 1966 cone; LV reached shoreline	Confirmed

	2 Feb–28 Mar				Moderate ST	LVF, LVFO		
	29 Mar-2 Apr				Minor PM	TF		
30	1969 29 Oct	Series D/MT	1/2	Ejecta consisted of ash, steam and incandescent materials	PM	TF, VE	LV exceeded extent of 1968 LV; LVF moved at	Confirmed
	30 Oct to 10 Dec				Moderate ST	LV	20 m/h	
31	1970 9–13 Nov	Series D/MT	1/2	"incandescent volcanic ejecta, ash and steam"	PH or PM	TF, VE	5-m explosion pit within 1969 cone	Confirmed
32	1976 3 Sep–22 Oct	Series D/MT	2	Activity centered at the southern foot of the 1966 cone; rhythmic explosions resulted in a 400 m by 200 m explosion crater	Minor PH	TF, VE	1.5 km column drifted to SW	Confirmed
33	1977 3–4 Oct	Series D/MT	1/2	Ejection ash producing tephra column with height of 500 m	Minor PH	TF, VE	Centered at NE sector of 1976 crater	Confirmed

Legend:

(1) Eruption site: MC - Main Crater; BMA - Binintiang Malaki; BMU - Binintiang Munti; CAL - Calauit; PP - Pira-piraso; MT - Mt. Tabaro.

(2) Volcano Explosivity Index – VEI, previously assigned in the reviewed papers

(3) Nature of eruptive activity: SA - solfataric activity; PH - phreatic; PM - phreatomagmatic; ST - strombolian; PP - phreatoplinian; SP - sub-plinian; PL - plinian; ND - not determined/no description.

(4) Eruptive processes/deposits: VE - volcanic earthquakes; RS - rumbling sounds; F - fissuring; SU - subsidence; EA - electrical activity (e.g. vent discharges, near-vent lightning, plume lightning); SW - shock waves; PDC - pyroclastic density current (e.g. pyroclastic flows, base surge); PF - pyroclastic flow; VT – volcanic tsunami/seiche; TF - tephra fall; LVF - lava flow; LVFO - lava fountaining; AR - acid rain; LIQ - liquefaction effects; FL - flooding; GE - geysering; G - toxic gases; ND - no description.

(5) Eruptive impacts: TVI - Taal Volcano island, N - north; S - south; E - east, W - west; SE - southeast; SW - southwest; ND - no description; UF - undetermined fatalities.

Mindanao in the south (Fig. 1B). Essentially, an arc-parallel component of the oblique convergent motion of the Philippine Sea Plate is taken up by shear within the Philippine Mobile Belt with the PFZ as the feature formed by this shear partitioning (Aurelio, 2000; Fitch, 1972). The significant role of the PFZ in the west- and east-facing subduction movement is supported by various authors (Holloway, 1981; Förster et al., 1990; Barrier et al., 1991; Rangin et al., 1999; Aurelio, 2000; Yu et al., 2013).

Volcanic arcs trending north-south were developed as a consequence of subduction-related magnetism. About 300 volcanoes were formed in the Philippines during the Cenozoic. The Luzon region, in particular, is dominated by products of arc-related volcanism associated with subduction along the Manila Trench (Wolfe and Self, 1983; Torres, 1989; Torres et al., 1995). Taal Volcano, located in eastern Luzon Island, is part of the Luzon-Bataan-Mindoro Arc (LBMA). Taal belongs to the group of volcanoes that formed within the Macolod Corridor as a result of the subduction along the Manila Trench that began in Early Miocene (Defant et al., 1988, 1989) (Fig. 1C). The Macolod Corridor, a 50–60 km wide northeast-southwest-trending rift zone, also includes the other volcanoes, Mt. Makiling, the Banahao Volcanic Complex and the Seven Lakes of San Pablo, as well as other smaller cones, maars, and edifices (Defant et al., 1988, 1989; Förster et al., 1990). Volcanic activity within the Macolod Corridor commenced some 1 Ma to 0.6 Ma B.P. based on K-Ar dating of Makiling lava (Torres, 1989; Förster et al., 1990), although Oles (1991) obtained 2.3 Ma B.P. by KeAr dating for even older Macolod rocks. Furthermore, a NNW-SSE trending extensional deformation is confirmed to be occurring in southern Luzon incorporating activity of the Macolod Corridor through to that of the present time (Bacolcol et al., 2012), and this may have significant influence on volcanic activity at Taal and in the Laguna maar field.

3. Eruption history and products

This section provides a brief overview of Taal's prehistoric eruption history followed by a comprehensive summary of the historical and recent eruptions of Taal between AD1572 and AD1977, as well as new interpretations of processes and products by the present authors. The historic eruptions are divided into four series covering the recorded history of the Philippines that stretches back approximately 600 years. Reports of friars and others during and since the Spanish and American occupation, and in scientific studies from AD1965 up to AD1977 cited 33 of Taal's eruptions. Some of the identified historical eruptions have very limited or no descriptions in the records and can either be presumed to be minor events that provided little information for observers and historians, or may have only been solfataric or hydrothermal activities that were noted by historians but may not necessarily have culminated in full scale eruptions. Only 24 of the 33 identified eruption events are confirmed. The nine uncertain events should be considered for reassessment and reclassification that may further reduce the number of eruptions of Taal Volcano. There are more detailed de- scriptions of some of the eruptions, such as the AD1749, AD1754, AD1911 and AD1965 events, indicating that these eruptions may have been significantly larger and more devastating.

1) *Evolution and prehistoric eruptive history of Taal*

Taal Caldera is a 25 km × 30 km-wide caldera flanked by extensive and thick successions of dacite-basaltic andesite ignimbrite and base surge deposits. The caldera is estimated to have formed from a series of eruptions and edifice collapses; however, no dating has confirmed the age of the Caldera (Wolfe and Self, 1983; PHIVOLCS-DOST, 1991). Listanco (1994) postulated that Taal Caldera is made up of two calderas influenced by an extensional setting combined with fault activity. The evolutionary history of Taal Caldera was established by the seminal work of Listanco (1994), which identified four caldera-forming events based on four major ignimbrite deposits. From oldest to youngest, these are the silicic Alitagtag (ALI) and Caloocan (CAL) Pumice Flow Deposits, the dacitic Sambong Ignimbrite (SAM) and the basaltic-andesitic Taal Scoria Flow (SFL) (Listanco, 1994), renamed Scoria Pyroclastic Flow (SPF) (Martinez and Williams, 1999). There are no age constraints or estimates of extent for the three older deposits. The uppermost and best-studied deposit is the SPF (Martinez, 1997; Martinez and Williams, 1999), with ^{14}C dating yielding an age of 5380 ± 70 to 6830 ± 80 ky (Martinez and Williams, 1999). These deposits can be found in the now highly urbanized and densely populated areas of Batangas, Cavite and Laguna, and Martinez and Williams estimate the bulk volume to be about 50 km^3. The termination of Taal's calderagenic activity is re- presented by the eruption that emplaced the Buco Base Surge deposits with no established eruptive age but with an estimated volume of about 5 km^3 (Geronimo, 1988).

Taal Volcano Island (TVI) is a post-caldera edifice within the lake-filled moat of the large Taal Caldera (Fig. 1C). It is a 25 km^2 scoria-tuff cone-maar complex with its own central caldera that is the present center of volcanism. TVI was formed initially as a subaerial post-caldera constructional edifice, that later emerged above the surface of the lake. The highest peak is approximately 300 m above sea level (asl) (Listanco, 1997). The existence of northeast-southwest and northwest- southeast structures transecting TVI controlled the location of eruption sites (Torres et al., 1995; Listanco, 1997). Many historical accounts of Taal eruptions allude to fissure eruptions. Listanco (1997) interpreted the "Roman candle" phenomenon described by Moore et al. (1966) and Kokelaar (1986) for the initial stage of the AD1965 eruption as a fis- sure-fed Strombolian-type eruption.

Today, TVI consists of > 40 volcanic vents, the largest being the Main Crater, formed during various eruption events with pyroclastic density current, tephra fall and lava flow deposits emplaced on various parts of the edifice (PHIVOLCS-DOST, 1991; Listanco, 1994) (Fig. 2). The major historical eruption centers are Binintiang Malaki (north- west), Pirapiraso (northeast), Calauit (southeast), Binintiang Munti (southwest), Mt. Tabaro (southwest), and the Main Crater or the central caldera. Taal Volcano Island's Main Crater is occupied by a 1.9 kilo- meter-diameter and 80-meter deep acid lake (PHIVOLCS, 1991).

2) *Chronology of the historical eruptions at Taal*

Of the 33 known eruptions of Taal, at least four were categorized as violent, with Volcanic Explosivity Index (VEI) values between 3 and 5 (Newhall and Self, 1982; PHIVOLCS-DOST, 1991) (Table 2). The Volcanic Explosivity Index (VEI) is a composite estimation of the explosivity of an eruption (Newhall and Self, 1982). The most destructive historical eruptions originated from the Main Crater in AD1749, AD1754 and AD1911. Historical accounts of these three eruptions allow them to be characterized as plinian or subplinian, phreatomagmatic or phreatoplininan. However, ongoing studies of the AD1754 eruption could indicate a higher VEI for this eruption considering the wider extent of pyroclastic density current deposits as mapped in recent field surveys.

Eruptions at Taal were categorized by Masigla and Ruelo (1987) into four series based on the locations of eruption centers and ensuing repose periods. *Series A* included all eruptions from AD1572 to AD1645 that were centered in the Main Crater (Fig. 2, Table 2). *Series B* covered eruptions from AD1707 to AD1731 that occurred alternately between the flank craters located around the volcano. *Series C*, from AD1749 to AD1911, was centered again at the Main Crater. *Series D*, from AD1965 to AD1977, occurred on the southwestern flank at Mt. Tabaro. The repose period between Eruption Series A and B was 62 years, 18 years between Series B and C, and 54 years between Series C and D. Since the most recent eruption in AD1977, the current repose period is nearly 40 years.

3.2.1. *Eruption series a: main crater*

Most of the descriptive accounts for the eruptions between AD1572

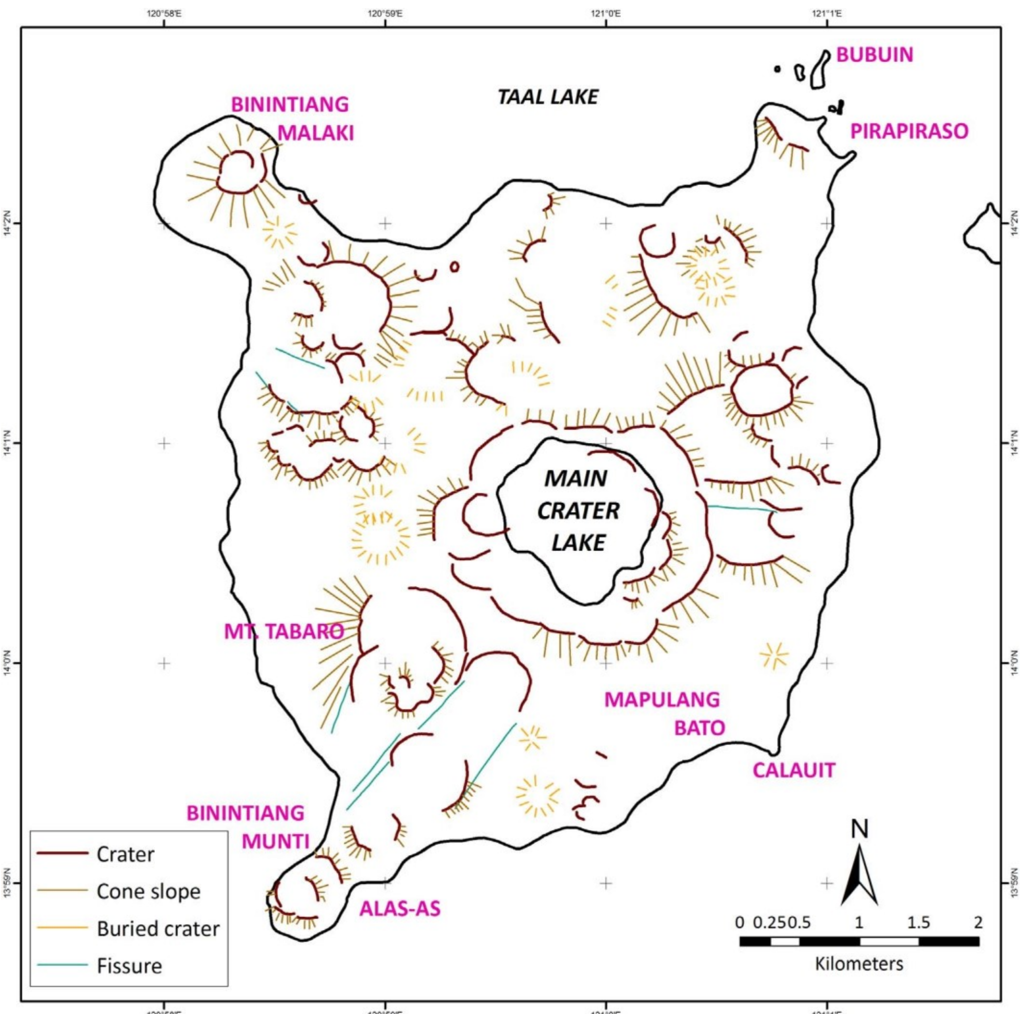


Fig. 2. Location map of Taal Volcano Island with major eruption centers: Binintiang Malaki (northwest), Pira-piraso (northeast), Calauit (southeast), Binintiang Munti (southwest), Mt. Tabaro (southwest), and the Main Crater or the central caldera. Brown lines and hachured lines delineate existing craters. Source: Modified from Ruelo (1983).

and AD1645 were sourced from chronicles and reports written by Augustinian friars in parochial establishment located at the original town of Taal, Batangas (Buencuchillo, 1754; Centeno y Garcia, 1885). These accounts were subsequently collated, reviewed, and interpreted by Saderra Maso (1911), Worcester (1912), Masigla and Ruelo (1987), and PHIVOLCS-DOST (1991, 1995, 2016b).

3.2.1.1. AD1572. Although constrained by limited eruption accounts, eruptive activity of the AD1572 was assigned a VEI of 3 (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016). The description of activity relayed by Father Gaspar de San Agustin (1699, In Saderra Maso, 1911, p6; In Worcester, 1912, p313) was written as follows: “there is a volcano of fire which is wont to spit forth many and very large rocks, which are glowing and destroy the crops of the native”. The eruption was previously interpreted as phreatomagmatic (PHIVOLCS-DOST, 1991). We suggest an alternative interpretation of the phenomena as possibly Strombolian activity with lava fountaining and/or lava flow. Further, Father Gaspar de San Agustin made reference to damages to agricultural crops but did not describe dispersal or the extent of this damage. Saderra Maso and Worcester affirms the activity in AD1572 by the action of the first rector of the new town, Father Alburquerque, who performed mass at TVI in order to calm the fears of residents. Further affirmation of the eruption was made by Father Rada (identified as Father Nada by Worcester) when he recorded that Taal was in eruption in AD1572. The performance of a mass was the first show of the influence of religion in relation to an occurrence of a natural phenomenon at Taal Volcano and in the Philippines. Table 2 summarizes important details of the eruption.

3.2.1.2. AD1591. Limited information on this eruption is provided by the description that “Fr. B. de Alcantara, O.S.A., repeated the ceremony performed by Fr. Alburquerque for the reason that the volcano had begun to belch forth extraordinary masses of smoke” (Saderra Maso, 1911, p6, Worcester, 1912, p313, PHIVOLCS-DOST, 1995, p49). This is considered a minor phreatic eruption with ejection of ash, or solfataric activity. A default VEI of 3 was assigned to this event (Newhall and Self, 1982; PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016) (Table 2). A default VEI of 3 is assigned for any explosion with no additional description, whether magmatic or phreatic, which occurred before more complete records (taken to be AD1700 in the Philippines) (Newhall and Self, 1982). Considering that we confirm the eruption to be minor phreatic, a change of assigned VEI from 3 to 2 is more appropriate.

3.2.1.3. Between AD1605 and AD1611. Saderra Maso (1911, p7) mentioned that print media reported “frequent rumbling which terrified the inhabitants of the neighboring villages”. The description provided maybe correlated to seismic swarms that in present day monitoring commonly occur but do not necessarily culminate in an eruption. The seismic swarm is further substantiated by Worcester (1912, p313) when he wrote that in this year Father Tomas de Abreu not only performed mass but also built a wooden cross on the rim of the

Main Crater "for the reason that from this crater there had come frequent subterranean rumblings which greatly terrified the inhabitants of neighboring villages". Although a default VEI of 3 is assigned by PHIVOLCS-DOST (1991), the occurrence of eruptions during these years is uncertain (Table 2). On the other hand, the Smithasonian GVP (2016) listed the eruption as AD1608 ± 3 years, and using information sourced from historical observations, listed a default VEI of 2. A default VEI is assigned for any explosion that has been identified with no additional description available (Newhall and Self, 1982). We assess the event as uncertain and it is more likely that the event comprised solfataric activity only.

3.2.1.4. AD1634 and AD1635. Saderra Maso (1911, p.7) and Worcester (1912, p.313) quoted naturalist Semper as he stated that "in several chronicles are found vague statements concerning two eruptions of the volcano which took place during these years". Saderra Maso identified the two eruptions as being in AD1634 and AD1645. However, more authors reported these two ambiguous accounts as having occurred in AD1634 and AD1635. A default VEI of 3 is assigned for both eruptions (PHIVOLCS-DOST, 1991; Smithasonian GVP, 2016) (Table 2). The vague reports implying eruptions during these years seem uncertain and the VEI needs to be downgraded. It is more likely that the events comprised solfataric activities or minor phreatic eruptions.

3.2.1.5. AD1641. San Agustin (1699, In PHIVOLCS-DOST, 1991, p31) wrote that during the eruption in this year, "two craters opened-up, one with sulfur in it while the other with green water in it which was constantly boiling". These two craters were identified as the Yellow and Green lakes and believed to be formed by the AD1641 eruption (PHIVOLCS-DOST, 1995). The crater lakes were described by Faustino (1933, In PHIVOLCS-DOST, 1991) as existing even after the explosive eruptions in AD1754. Although neither Saderra Maso (1911) nor Worcester (1912) made mention of this eruption in their accounts, Fr. San Agustin's account clearly implies that an eruption occurred and that it formed the new craters. The eruption is currently classified as phreatic (PHIVOLCS-DOST, 2016b) with a default VEI of 3 (PHIVOLCS- DOST, 1991; Smithasonian GVP, 2016). While we affirm the eruption style to be a small to moderate phreatic eruption, we recommend that the default VEI of 3 be downgraded to 2 following the criteria set for estimating VEI's by Newhall and Self (1982).

3.2.1.6. AD1645. No accounts are available for this eruption but PHIVOLCS-DOST (1991) and Smithasonian GVP (2016) assigned a default VEI of 3. No mention of this eruption was made in Adams (1910), Worcester (1912) or PHIVOLCS-DOST (1995), but Saderra Maso (1911) and PHIVOLCS-DOST (1991) included the 1645 eruption. The limited description of the event could imply that it did not culminate into an eruption, and we therefore classify the eruption as uncertain. A major tectonic earthquake that occurred in AD1645, likely emanating from a source in Central Luzon, resulted in damages in Manila. In the Catalogue of Philippine Earthquakes (Garcia et al., 1985, p. 16), the earthquake was described as follows: "Its mesoseismic or epicentral diameter was not less than 490 kms. From north to south; that is, from the southern coast of Batangas and Tayabas to the northern part of Cagayan." Ground shaking felt by residents in the Taal region might have been misconstrued as being related to Taal Volcano.

In summary, the eruptions in Series A were centered at the Main Crater area (Fig. 2). The eruptions of AD1572, AD1591 and AD1641 are confirmed and supported by historical observations or reports. The accounts for the eruptions between AD1605 and AD1611, and for AD1634, AD1935, and AD1645 are considered uncertain and may only have been solfataric or hydrothermal activity that did not culminate into a full-blown eruption. Neumann van Padang (1953) identified the events between AD1605 and 1611, AD1634 and AD1635 as question- able explosions. These events were assigned a default VEI of 2 that was later upgraded to VEI 3 because of the age in the first Smithsonian catalogue.

Eruption series B: flank eruptions

The eruptions between AD1707 and AD1731 occurred from flank craters of Taal Volcano including from Binintiang Malaki during the AD1707 and AD1715 eruptions, Binintiang Munti during the AD1709 and AD1729 eruptions, near Calauit in AD1716, and at Pira-piraso during the AD1731 eruption (Fig. 2).

3.2.2.1. AD1707. During this eruption, Arce wrote that "the cone called Binintiang Malaqui burst forth with tremendous display of thunder and lightning; but aside from fear and trembling, no damage was done in the towns situated on the shores of Lake Bombon" (Saderra Maso, 1911, p7; Worcester, 1912, p313). The eruption site is currently known as Binintiang Malaki and Lake Bombon is now called Taal Lake (Fig. 2). The abovementioned phenomenon clearly describes electrical activity in the form of volcanic lightning. Volcanic lightning frequently accompanies large eruption columns (Behnke et al., 2013) but some cases of lightning have been observed during eruptions of VEI 1 or 2 (McNutt and Williams, 2010). Although tephra fall was not mentioned, it is presumed to have occurred. There were no reports of structural or agricultural damage in adjacent Taal communities, suggesting that tephra fall deposition was not thick enough to cause damage. The eruption was classified as VEI 2 (PHIVOLCS-DOST, 1991; Smithasonian GVP, 2016) (Table 2) and the eruption style as phreatic (PHIVOLCS-DOST, 1991).

3.2.2.2. AD1709. Foreman (1890, In PHIVOLCS, 1991, p32) wrote that in AD1709, the volcano "vomited forth a deafening noise". Most likely, this referred to an explosion that produced a tephra column. The center of eruptive activity was at Binintiang Munti (Fig. 2). The eruption was classified as phreatomagmatic based on the above narration, and assigned a VEI of 2 (PHIVOLCS-DOST, 1991, 1995; Global Volcanism Program, 2016). The limited narrative description of the eruption and products precludes contrary interpretation of eruption style and assigned VEI. Although the eruption was not cited in the eruption summaries of Saderra Maso (1911) or Worcester (1912), explosions heard by observers confirms the occurrence of an eruption. Moreover, the AD1709 event was listed in the Saderra Maso (1904, p. 63) paper where he referred to the eruption as an "eruptions without loss of life and property".

3.2.2.3. AD1715. The AD1715 event has a very limited descriptive account so it was classified with a default VEI of 2 (PHIVOLCS-DOST, 1995; Smithsonian GVP, 2016). The eruptive activity was centered at Binintiang Malaki (Fig. 2). The eruption was briefly described as "loud explosions and threw out incandescent materials, giving an impression of a river of fire" (PHIVOLCS-DOST, 1995, p49). The eruptive style was previously not identified and we ascribe the abovementioned description as being strombolian activity with lava fountaining and lava flows. Although this eruption was also not mentioned in Saderra Maso (1911) or Worcester (1912), the above description validates the occurrence of the AD1715 eruption.

3.2.2.4. AD1716. Sublacustrine phreatomagmatic flank eruptions occurred on the 24th September 1716 lasting four days in the Taal Lake area near Calauit, southeast of TVI (Fig. 2). This is the first eruptive event for which more detailed documentation of the activity and impacted areas is available. The eruptive activity began at 6 pm with a "great number of detonations heard in the air" (Saderra Maso, 1911, p7; Worcester, 1912, p314) describing the series of explosions that occurred. Tephra columns described as "looking like towers" rose from the southeastern sector of the lake. Based on typical heights of church towers constructed during the Spanish era, the height of the tephra columns could be within the range of 100 to 150 m. Lake water was described by Foreman (1890, In PHIVOLCS-DOST, 1991, p32) to be as “black as ink”, possibly resulting from tephra column collapse and subsequent base surges and volcanic tsunami, that subsequently hit and inundated communities on the southern and southwestern shorelines (e.g. at Convento of Taal originally located in the present town of San Nicolas), with a horizontal inundation of 17 m (Berninghausen, 1969; PHIVOLCS-DOST, 1991; Saderra Maso, 1911; Worcester, 1912) (Fig. 3). The heated lake and hot volcanic ejecta resulted in fish kill with Worcester (1912, p314) writing “Father Manuel de Arce described as follows –fishes cooked by the boiling lake”. Sulfur stench was pervasive, especially in communities near the shoreline (Saderra Maso, 1911; Worcester, 1912; PHIVOLCS-DOST, 1991). On the fifth day, eruptive activity at Taal abated, followed by intense rainfall. A default VEI of 2 was assigned to this eruption (Newhall and Self, 1982; PHIVOLCS-DOST, 1991) although Smithasonian GVP (2016) assigned a VEI of 4. Considering that this is a sublacustrine eruption, and the depth of Taal Lake is estimated to be > 50 m, most of the eruptive materials produced presumably collapsed without making it outside the lake, and typically only tephra jets were seen above water. However, with the eruption lasting almost a week and ground deformation generating volcanic tsunami towards the southwestern shorelines, we consider a VEI of 3 more likely.

3.2.2.5. AD1729. There is a notable absence of descriptions for the AD1729 eruption centered at Binintiang Munti (Worcester, 1912) (Fig. 2). Saderra Maso (1911) provided confirmation of the eruption by stating that “a new outburst of the volcano” occurred, which is documented in the church archive of Old Tanauan in Batangas in 1849, the location now known as Talisay (Fig. 3). The VEI assigned for this eruption is a default 2 (PHIVOLCS-DOST, 1991; Smithasonian GVP, 2016). No ascribed eruptive style was provided by written accounts but activity may be considered minor in magnitude and likely phreatic. We propose downgrading the VEI from 2 to 1.

3.2.2.6. AD1731. The AD1731 eruption was another sublacustrine phreatomagmatic eruption classified as VEI of 2 (PHIVOLCS-DOST, 1991; Smithasonian GVP, 2016). Although the exact day of the eruption is unknown, the onset of the eruption was described as having occurred at night. Saderra Maso (1911, p.7) cited Father Torrubia's observation, who at the time of the eruption was in Los Banos, Laguna, about 25 km northeast of Taal Volcano, as follows: “during one of the nights a continuous fire of heavy artillery”. Saderra Maso further added that “vast and towering obelisks of earth and sand rose out of the water” and “formed a new islet”, presumed to be the island of Bubuin measuring 1.8 km in diameter, located 1.9 km southeast of Mt. Pira-piraso (Fig. 2). Another documentation of the AD1731 eruption is provided by Adams (1910, p. 94-95) when he cited Centeno (1885), and described the event as “an eruption in Taal Lake east of the island, forming a new island the larger part of which subsided, leaving remnants which are known as Bubuing and Napayong Islands”, although the known geology and K-Ar dating by Oles (1991) point to a pre-caldera age of both islands

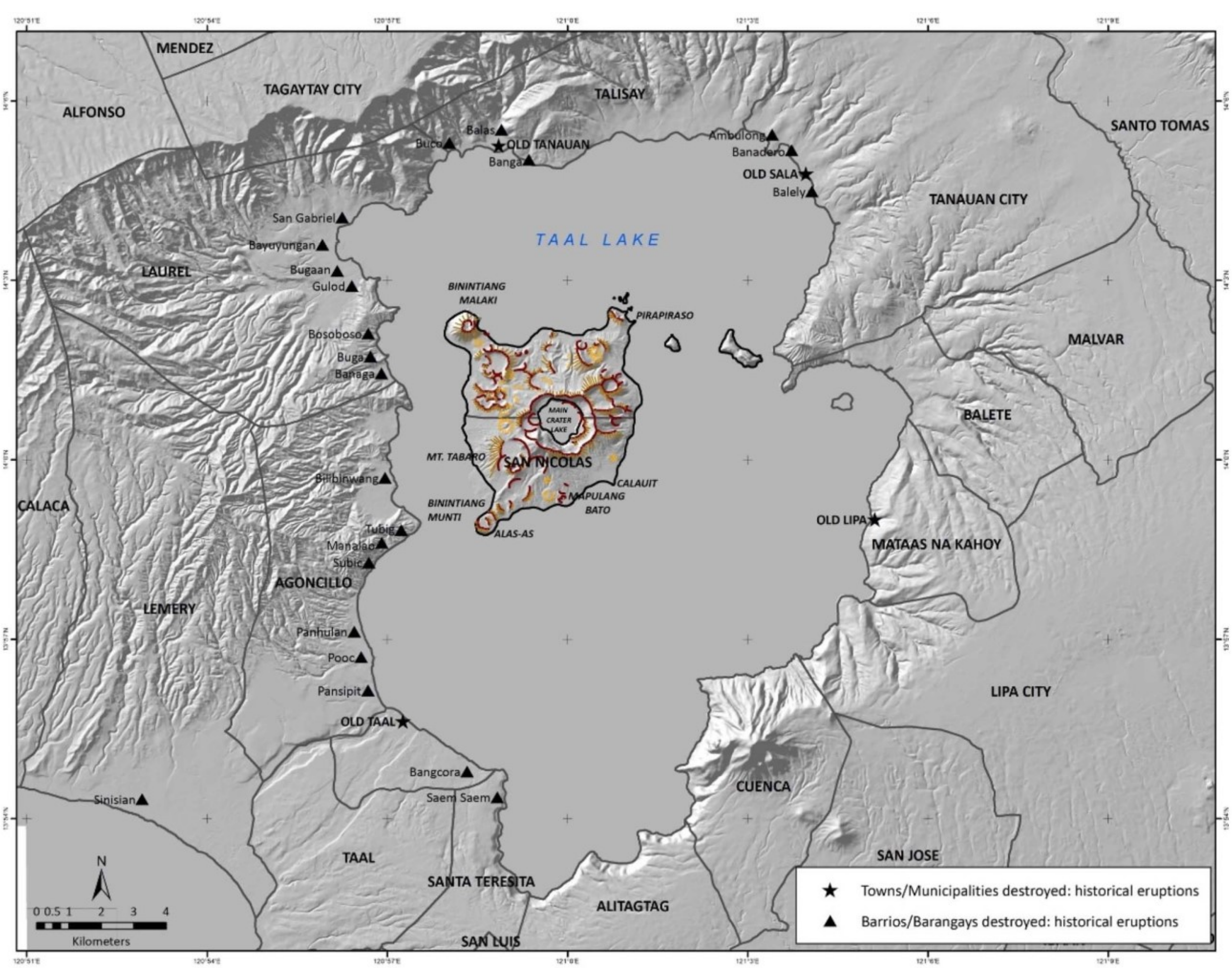


Fig. 3. Location map of Taal Volcano adjacent towns/municipalities and barrios/barangays devastated by eruptions and identified eruption centers at Taal Volcano Island. Sources: Modified from Saderra Maso (1911) and PHIVOLCS-DOST (1991); map overlain on NAMRIA 2013 Interferometric Synthetic Aperture Radar - Digital Terrain Model (IfSAR-DTM).

Bubuing presumably refers to the island of Bubuin and Napayong is now known as Napayun. Father Torrubia further recounted "the terrible phenomenon which lasted during many days" and described volcanic earthquake occurrences as "subterranean rumblings which caused the entire region to tremble" (Saderra Maso, 1911, p.8). Father Torrubia also possibly described a massive tephra column hovering over the Taal community as a "frightful and all-devouring conflagration that the whole region was panic-stricken" (Saderra Maso, 1911, p8). Subaerial incandescent lava extrusions and sulfur gases were also observed. Though this eruption was considered violent, there were no significant reports of damage to communities adjacent to Taal Volcano (Worcester, 1912).

In summary, all the eruptions in Series B are confirmed and supported by limited (i.e. AD1709, AD1715 and AD1729) or more detailed historical observations and documentations (i.e. AD1716 and AD1731). The AD1709, AD1716 and AD1731 eruptions were classified as phreatomagmatic, while the AD1707 eruption was more likely phreatic. The AD1715 eruption is newly interpreted as possibly being Strombolian. The eruptive style of the AD1729 eruption remains unclassified due to limited narrative description. The eruptions in Series B are summarized in Table 2.

3.2.3. Eruption series C: main crater

Series C includes twelve eruptions from AD1749 to AD1911 that were once again centered at the Main Crater. The AD1874 and AD1878 eruptions have limited reported observations, while the AD1790, AD1825, AD1842, AD1873, and AD1903 eruptions have no historical documentation but are listed as part of the 33 eruptions of Taal Volcano (PHIVOLCS-DOST, 1991). There is extensive documentation for the AD1749, AD1754, AD1808, AD1904 and AD1911 eruptions because of the magnitude of damage and impacts to communities.

3.2.3.1. AD1749. The AD1749 event commenced on 11 August and lasted approximately three months. The event is interpreted as violent phreatomagmatic. The VEI for the eruption was estimated at 3 by PHIVOLCS-DOST (1991) but more recently, the Smithasonian GVP (2016) assigned a VEI of 4 based upon a review of historical observations (sources not provided).

Father Buencuchillo, then the Parish Priest of Sala, now a part of Talisay, Batangas (Fig. 3), described an "extensive glare over the top of the island" at 11 pm on 11 August 1749 with the eruptive center at the Main Crater (Saderra Maso, 1911, p8; Worcester, 1912, p317) (Fig. 2). Father Buencuchillo further narrated that by 3 am on 12 August, he heard a series of explosions matching the sounds of "heavy artillery fire" and counted more than a hundred of these events (Saderra Maso, 1911; Worcester, 1912; PHIVOLCS-DOST, 1995). By dawn, he observed a tall tephra column that he described as an "immense column of smoke which rose from the summit of the island, while several smaller whiffs issued from the other openings" implying there were other minor active eruptive vents on the island (Saderra Maso, 1911, p8; Worcester, 1912, p317). A sublacustrine eruption was also observed and described by Father Buencuchillo as follows: "from the water there arose enormous columns of sand and ashes, which ascended in the shape of pyramids to marvelous heights and then fell back into the lake like illuminated fountains" (Saderra Maso, 1911, p.8; Worcester, 1912, p317). These phreatomagmatic eruptions with tephra columns and tephra jets generated deposits directed mostly towards the western and southwestern shoreline, but also to the north and eastern sectors (PHIVOLCS-DOST, 1991). A similar phenomenon was described by Moore et al. (1966) during the 1965 eruption of Taal Volcano.

Large-magnitude volcanic earthquakes frequently accompanied the pyramid-shaped sand and ash clouds. One earthquake event was succeeded by subsidence/submergence of a small piece of land known as the "tierra destruida" located in the northeast quadrant, as well as the lakeshores at Sala and Old Tanauan, northeast of Taal Volcano (Fig. 3). Likewise, during the occurrences of earthquakes, "fissures opened in the ground amid horrifying roars, said fissures extending from the northern and northeastern beach of the lake as far as the neighborhood of the town of Calamba" (Saderra Maso, 1911, p8; Worcester, 1912, p317; PHIVOLCS-DOST, 1991, p34). The fissuring event occurred as a consequence of a large magmatic (dike) intrusion that was accompanied by ground deformation. The fissures were aligned along a north-northeast trend following the lakeshore as far as Calamba (PHIVOLCS-DOST, 1995; Torres et al., 1995). As a consequence of the violent ground shaking produced by the fissuring and ground deformation, liquefaction effects could also be implied from the following descriptions: "the entire territory of Sala and part of Tanauan have been rendered practically uninhabitable – the water courses have been altered, former springs have ceased to flow and new ones made their appearance, the whole country is traversed by fissures, and extensive subsidences have occurred in many places" (Saderra Maso, 1911, p8; Worcester, 1912, p317). Liquefaction is defined as "a process by which water-saturated sediments temporarily loses strength and acts as a fluid" (USGS, 2016). Although there is no written documentation to substantiate liquefaction occurrence, based on personal communications with residents from the floodplains near Pinatubo volcano, liquefaction phenomena like sand boils were observed after the occurrences of large-magnitude volcanic earthquakes related to the June 1991 eruption. The appearance and disappearance of springs and lateral spreading along the lakeshore areas are now being interpreted as likely liquefaction. This is the first time that the abovementioned phenomena are being interpreted as li- quefaction effects.

Impacts from tephra fall were also observed and documented.

Buencuchillo narrated: "During my flight I saw great many tall trees, such as coconut and betel-nut palms, either miserably fallen, or so deeply buried that their tops were within reach of my hands" (Saderra Maso, 1911, p8; Worcester, 1912, p317). Combined pyroclastic flow/surge and tephra deposits were observed by Father Buencuchillo during their evacuation where he made the observation: "I likewise saw several houses which formerly, in accordance with Philippine custom, had their floors raised several yards above ground, but had sunk to such a degree that the same ladder which once served to ascend into them, was now used to descend to them." (Saderra Maso, 1911, p8; Worcester, 1912, p317). This description implied that the deposition could be as much, if not more than, one to two meters if traditional ladders made during that time were about one-meter long.

Another significant observation came from Father Murillo who wrote in Geografia Historica that the Santuary of Antipolo, > 50 km from Taal Volcano, experienced three to four large-magnitude earthquakes, as well as over a hundred smaller tremors (Saderra Maso, 1911).

The total bulk volume of ejecta produced by this explosion is estimated at 50–100 million m^3 (PHIVOLCS-DOST, 1991). Although this eruption was considered violent, Saderra Maso (1911) determined from Father Buencuchillo's narrative account that there were no victims during the event. Sala and portions of Old Tanauan were so severely damaged that several residents abandoned the towns and, within the same year, the two towns were merged. Given the bulk volume and the impacts of the AD1749 eruption, a VEI of 4 (rather than 3) is more reasonable.

3.2.3.2. CE 1754. The other major eruption in Series C was the AD1754 event that commenced on 15 May at around 9 pm, and lasted for several months (PHIVOLCS-DOST, 1991). There are four notable eruptive phases with eruption activity alternating from plinian/sub-plinian to phreatomagmatic. The first phase occurred from 15 May to 2 June with Father Buencuchillo's narration as follows: "the volcano quite unexpectedly commenced to roar and emit, sky-high, formidable flames intermixed with glowing rocks which, falling back upon the island and rolling down the slopes of the mountain, created the impression of a large river of fire" (Saderra Maso, 1911, p9; Worcester, 1912, p319). The plinian/subplinian eruptive phase

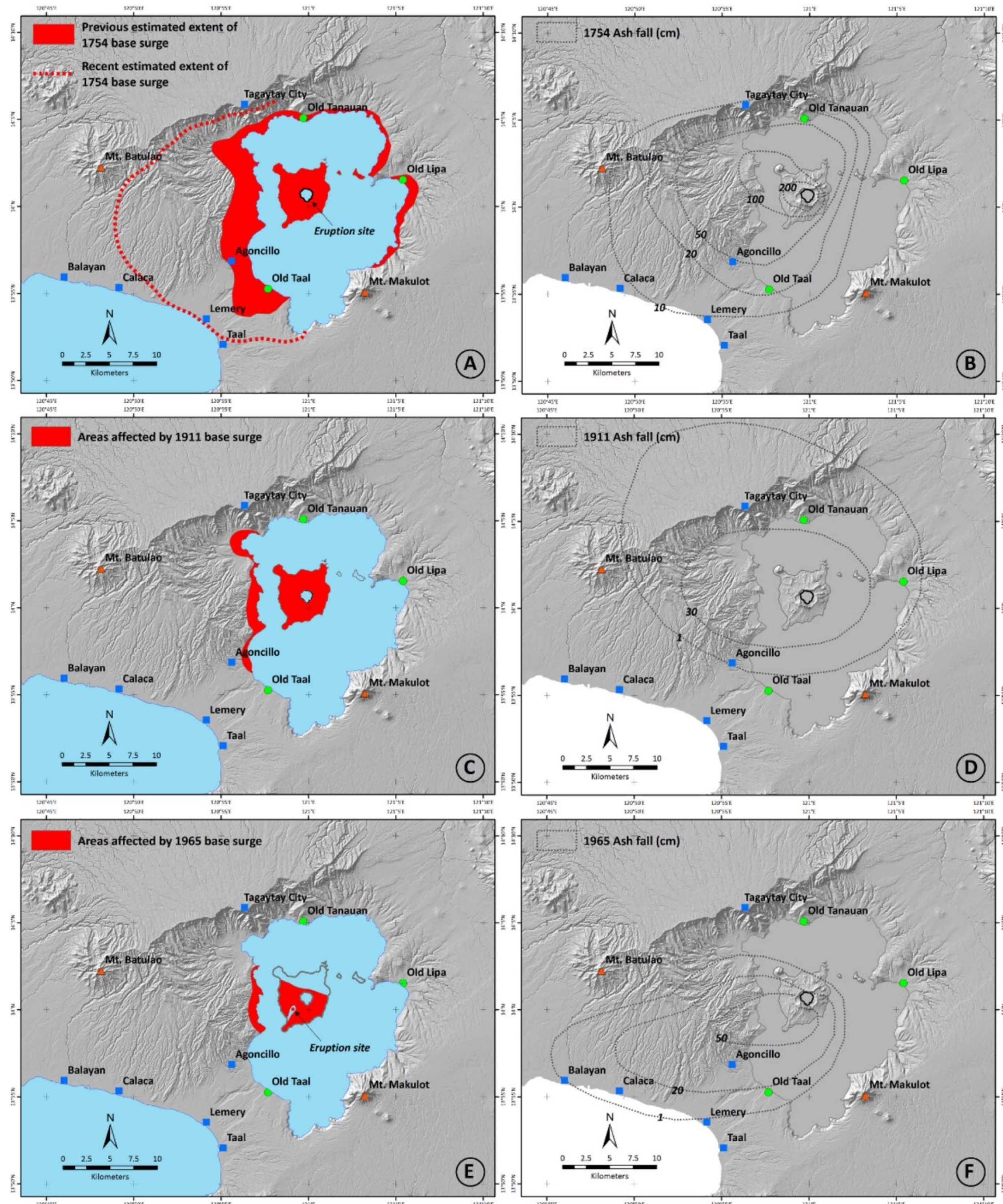


Fig. 4. Deposit maps of major eruptions from Taal Volcano, Philippines. (A) Extent of base surge deposits during the AD1754 plinian/sub-plinian eruptions centered at the Main Crater. Previously delineated extent of the 1754 base surge shown as red shaded area adapted from PHIVOLCS-DOST (1991), while the dashed line approximate extent from ongoing mapping by Bornas et al. (2016) with distal run-out of > 16 km. (B) Estimated tephra fall dispersal during the AD1754 eruptions based on PHIVOLCS-DOST (1991) and Saderra Maso (1911). (C) Extent of base surge deposits during the AD1911 phreatomagmatic eruption centered at the Main Crater. (D) Tephra fall dispersal during the AD1911 eruption. (E) Extent of base surge deposits during the AD1965 eruption centered near Mt. Tabaro. (F) Tephra fall dispersal during the AD1965 eruptions. Isopach units in centimeters. Sources: Modified from Saderra Maso (1911) and PHIVOLCS-DOST (1991); map overlain on NAMRIA 2013 Interferometric Synthetic Aperture Radar - Digital Terrain Model (IfSAR-DTM).

generated tall eruption columns with some estimated to be about 40 km high. Column-collapse ensued generating pyroclastic flows or base surges. The eruption deposits reached and completely destroyed the community of Bayuyungan (Fig. 3), approximately 8 km northwest of the volcano (Saderra Maso, 1911; Worcester, 1912).

The phreatomagmatic eruptive phase occurred from 02 June to 26 September with Fr. Buencuchillo describing the continuous eruptive episodes of Taal as the "volcano never ceased to eject fire and mud". Coincident with the formation of the tephra columns, thunder and lightning flashes were also observed with Father Buencuchillo making this observation: "the strangest thing was, that within the black column of smoke issuing from the volcano ever since June 2, there frequently formed thunderstorms" (Saderra Maso, 1911, p9; Worcester, 1912, p319). The phenomenon is interpreted as describing an explosive phase and volcanic lightning storm (Behnke et al., 2013).

A lull in eruptive activity ensued from 26 September until activity resumed on 1 November. The third eruptive phase lasted from 1 to 15 November and was described as follows: "Taal resumed its former fury, ejecting fire, rocks, sand, and mud". On 15 November, Fr. Buencuchillo narrated that Taal "vomited enormous bowlders which rolling down the slopes of the island, fell into the lake and caused huge waves" (Saderra Maso, 1911, p9; Worcester, 1912, p319), interpreted as volcanic tsunami generated by eruptive deposits invading the lake (PHIVOLCS-DOST, 1991).

The last eruptive phase commenced on 28 November and ceased on 2 December. The 28 November event included tall eruption columns with electrical activity, likely a volcanic lightning storm, observed within the column as described by Father Buencuchillo: "columns of fire and smoke ascended higher than ever before" and these were "accompanied by terrific lightning and thunder above, and violent shocks of earthquake underneath" (Saderra Maso, 1911, p9; Worcester, 1912, p319). The tephra column dispersed and drifted to the west and south. It is not clear from the narration if the electrical activity occurred above the vent (vent discharges), was near-vent lightning, or was plume lightning, typically described as larger lightning flashes within the tephra column (Behnke et al., 2013). Considering the magnitude of the eruption, it is more likely that a combination of the three processes occurred. Volcanic tsunami were also observed during this phase as confirmed by Fr. Buencuchillo's narration that "waves of the angry lake began already to flood the houses nearest to the beach" (Saderra Maso, 1911, p9; Worcester, 1912, p319). A short lull in eruptive ac- tivity occurred until dawn of 29 November when another eruption occurred at 8 AM and described as follows: "I noticed smoke was rising from the point of the island which looks towards east" (Worcester, 1912, p320), possibly indicating an eruption center other than the Main Crater, or potentially a secondary explosion and steaming if pyroclastic flow deposits entered Taal Lake. At around 3 or 4 pm of the same day, Father Buencuchillo again describes electrical activity when he narrated "the whole sky was shrouded in such darkness that we could not have seen the hand placed before the face, had it not been for the sinister glare of the incessant lightnings" (Saderra Maso, 1911, p10; Worcester, 1912, p320), a description closer to that of plume lightning. Tephra fell accompanied by rainfall resulted in collapse of several houses from the weight of tephra, described as "stones, mud and ashes" on the roofs.

The maximum run-out distance of the base surge deposit formed during the AD1754 eruption centered at the Main Crater is currently thought to be more than the original estimate of 16 km. The base surge deposit map shown in Fig. 4A provides a major modification of the approximate extent of the 1754 base surge based on ongoing mapping being conducted by Bornas et al. compared to the extent delineated by PHIVOLCS-DOST (1991) that was modified from Saderra Maso (1911). The estimated extent of tephra fall with corresponding average thicknesses during the same eruptive period, based on previous mapping and interpretation of narrative accounts by Saderra Maso (1911), is shown in Fig. 4B. Revision of the isopach map may be expected after more detailed information is gathered during ongoing investigations of the 1754 eruptive products.

After the eruption and the resulting devastation, the old towns of Taal, Lipa, Tanauan and Sala were completely deserted and were then relocated (Fig. 3) (Saderra Maso, 1911; Worcester, 1912; Alcaraz, 1966). By 1 December 1754, tephra fall deposits were estimated at 1.1 m thick approximately 6 km southwest and northwest of Taal Volcano Island as observed and reported by Father Buencuchillo while he was still in the church located in Old Taal (Saderra Maso, 1911; Worcester, 1912). The average thickness of tephra over an area in excess of 400 km^2 was 10 cm (PHIVOLCS, 1991). The estimated total bulk volume of ejecta was 150 million m^3 (PHIVOLCS, 1991). However, with the more extensive run-out of the 1754 base surge deposits now suggested, the total volume may be larger. Considerable structural failures occurred due to the weight of saturated tephra on the roofs of houses. A potentially more important feature of the tephra fall is that dispersal reached Metro Manila, a distance of 60 km from Taal Volcano. Furthermore, with tephra deposits clogging river channels, including Pansipit River that drains water from Taal Lake, there was a significant increase in the lake level and subsequent inundation of Old Lipa (Fig. 3). With tephra fall cover on adjacent slopes, rainfall that occurred between 29 November and 4 December due to the passage of a typhoon resulted in numerous local landslides. Other phenomena such as lateral spreading and mudslides provided evidence of liquefaction along the lake shorelines including Father Buencuchillo's description: "In other parts of the lake shore have likewise opened many cracks and occurred very extensive slides" (Saderra Maso, 1911, pp10-11; Worcester, 1912, p327). While there were fissures and subsidence aligned NE-SW that were more likely from deeply seated extension, some of these occurrences along the lakeshore may be due to liquefaction effects. Similar extensional fissures were observed in Lemery and Taal during the AD1911 eruption (Pratt, 1911a, 1911b). Sulfur stench was prevalent as much as six months after the eruptive activity ceased. Vegetation was reported to have been annihilated. The official number of deaths associated with the event was twelve and the causes of death were associated with building collapse due to the weight of tephra on roofs and by the occurrence of volcanic tsunami that swept away communities on the western shorelines of Taal Lake. Smithsonian GVP assigned a VEI 4, while PHIVOLCS-DOST (1991) gave a VEI of 5. With the current detailed research on the 1754 eruption being conducted by Bornas et al. showing possible greater volume of pyroclastic density current and tephra deposits, we affirm that the assigned VEI of 5 (PHIVOLCS-DOST, 1991) is appropriate but the potential for the VEI to be > 5 cannot be discounted at the present time.

3.2.3.3. AD1790. No descriptive records are available for this identified eruption (PHIVOLCS-DOST, 1991). A default VEI 2 was assigned for this eruption (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016). The lack of further descriptions other than the default VEI makes this listed event a questionable eruption.

3.2.3.4. AD1808. Based on the accounts of Saderra Maso (1911), an eruption commenced in the middle of March of this year, which he described as not comparable to the AD1754 event, either in intensity and duration, but resulted in considerable impact to adjacent communities due to "ashes and pumice stone" and a major change in the configuration of the Main Crater (Fig. 2). Saderra Maso (1911, p11) cited an unidentified author (1849) describing the change as follows: "Formerly the depth seemed immense and unfathomable, and at the bottom was seen a liquid mass in continual ebullition. After the eruption the whole aspect was changed; the crater had widened, the pond within it had been reduced to one-third and the rest of the crater floor is dry enough to walk over it". The Main Crater Lake presumably became shallow and modified due to the eruption. The "continual ebullition" presumably describes geysering that to this current date can still be observed. The widening of the Main Crater resulted from the amalgamation of the Yellow and Green lakes into one, reducing to a third of the former lake coverage and depth. Worcester (1912, p328) affirmed the Main Crater change when he said “This eruption is said to have modified profoundly the form of the principal crater”. There also appeared to be a cone from which minor explosions occurred accompanied by hissing sound. The crater walls, covered with newly erupted materials, experienced erosion by rainfall (Saderra Maso, 1911).

Further, Saderra Maso (1911, p. 11) narrated: “In more immediate vicinity of the volcano there were places where the ground was covered with ashes to a depth exceeding 84 centimeters (33 inches), and in more distant localities the fall was proportionately heavy.” This is interpreted to mean that the thickness of the tephra deposits in proximal areas (assumed to include TVI) was observed to be > 84 cm, while those in distal areas are still considerably thick. This eruption was categorized as phreatomagmatic with VEI of 2 (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016). The eruption was explosive considering the significant amount of deposited tephra and the damage to neighboring towns. Furthermore, the Main Crater was notably modified by the eruption and the eruption lasted several days. We recommend revising the VEI for this event from 2 to 3.

3.2.3.5. AD1825, AD1842 and AD1873. There are no available details of these eruptions but recent documents record that there were eruptive activities in these years, and assigned a default VEI of 2 for these events (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016). Eruptions in these years were not mentioned in Saderra Maso (1911) or by Worcester (1912). We therefore consider these eruptions to be uncertain and more likely solfataric activities only. A VEI of 0 is recommended for these listed events.

3.2.3.6. AD1874. The 19 July AD1874 eruption is classified as phreatomagmatic (PHIVOLCS-DOST, 2016a, 2016b) and we maintain the assigned a VEI of 2 (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016). Saderra Maso (1911, p11) and Worcester (1912, p328), cited that: “took place an eruption of gases and ashes which killed all the livestock which were being raised on Volcano Island and withered or burned the entire vegetation on the western slopes of the crater”, interpreted as ejection of tephra and toxic gases. The most significant impact of this eruption was the annihilation of most livestock on TVI due to damage caused to plants by the tephra and subsequent starvation, or from digestion of toxic materials or both (PHIVOLCS- DOST, 1995).

3.2.3.7. AD1878. This eruption occurred from 12 to 15 November AD1878 and was described as a moderate phreatic event with a VEI of 2 (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016). Saderra Maso (1911, p11) wrote that “noises were frequently heard proceeding from the volcano which finally, from November 12 to 15, ejected a quantity of ashes sufficient to cover the entire island”. Worcester (1912) also described tephra fall deposits covering the entire volcano island. There were no details of impacts to adjacent lakeshore communities. The abovementioned limited, but significant, descriptions confirm that an eruption occurred.

3.2.3.8. AD1903. No details of this eruption could be obtained but it is currently listed as one of the 33 eruptions of Taal with a default VEI of 2 (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016). While the event was listed in Saderra Masó’s, 1904 paper as occurring in April, the eruption was not mentioned in the Saderra Maso (1911) or Worcester (1912) accounts. We are inclined to believe that the reported April 1903 event (Saderra Maso, 1904) is the April 1904 eruption described in Saderra Maso (1911). We therefore consider this eruption as uncertain and assess it to be more likely a solfataric activity.

3.2.3.9. AD1904. Eruptive activity began in April AD1904 with the formation of a funnel-shaped crater located in the southeastern section of the Main Crater that then became the center of eruptive activity (Saderra Maso, 1911; Worcester, 1912). Eruptive episodes lasted for several months, culminating on 4 and 5 July with electrical activity observed and earthquakes coincident with explosions (Worcester, 1912). Ash and boulders were ejected but fell back into the crater or onto the southern and southeastern slopes of the Main Crater (Saderra Maso, 1911; Worcester, 1912). The 5 July tephra fall was saturated and was described by Worcester (1912, p334) as being “showered with mud, which burned viciously, not because it was hot, but because of the strong acid which it contained”. The eruption style is affirmed to be minor phreatic with sporadic occurrences of voluminous emissions of steam and tephra (“mud and rocks”) with the column reaching up to 150 m (Saderra Maso, 1911, p11). The VEI assigned to this eruption is 2 by PHIVOLCS-DOST (1991) but more recently, Smithsonian GVP (2016) assigned a VEI of 1 on the basis of a review of historical observations (original sources not provided). The formation of a funnel- shaped crater in the southeast sector of the Mani Crater implies that the event was explosive. Therefore, a VEI of 2 is more appropriate (Newhall and Self, 1982).

3.2.3.10. AD1911. The last large-scale eruptive event in Series C was the 27 to 30 January AD1911 eruption that was preceded by volcanic earthquakes commencing on 27January at 11 pm, felt as far as Metro Manila and recorded by the Manila Observatory seismographs (Saderra Maso, 1911). Volcanic earthquakes continued for several days with increasing frequency and intensity, often coinciding with reported eruptions. The eruption description of Saderra Maso (1911) stated: “during the night of Friday the volcano had been ejecting mud, ashes, and some rocks” (Saderra Maso, 1911, p12), substantiated the fact that an eruption commenced on the evening of 27 January and not early morning of 28 January. The 28 January event was observed as an enormous eruption column described as a “huge column of black smoke” (Saderra Maso, 1911, p12), accompanied by rumbling sounds. More plume lightning was likely observed within the column described by residents as “electric discharges which took place upward within the column” (Saderra Maso, 1911, p13). At least 197 earthquake events were recorded on 28 January by the seismograph at the Manila Observatory, ten of which were felt (Saderra Maso, 1911; Worcester, 1912). Eyewitness account from Private William Couch of the 2nd Battalion, Engineers, U.S.A. made mention of “severe reports caused by the explosion of gases above the crater and electrical display lighted up the heavens. Large volumes of smoke were pouring out of the crater and were carried off southward by the wind” (Worcester, 1912, p.358), implying very explosive eruptions and the formation of a tall eruption column. Electrical activity was more likely plume lightnings from the description that lightning was sky-high and not near the vent. The camp was located in Bayuyungan, now part of the town of Laurel, 6.4 km northwest of Taal Main Crater and about 400 m from the shoreline (Fig. 3). Tephra fall was experienced at the camp for almost the whole day.

On 29 January, the Manila Observatory seismograph recorded 113 volcanic earthquakes with greater intensities than those felt on 28 January. At 8 pm, an eyewitness accounts from Mr. Charles Martin, a government photographer, narrated that “there rolled an enormous column of vapour, which towered skyward until caught by the morning breeze, and was then swept, black and threatening, westward over the neighboring province of Cavite” (Worcester, 1912, p339). An isopach map delineating dispersal and cumulative thickness of tephra fall deposits during the AD1911 eruption is shown on Fig. 4D.

By 3:30 pm, “large cracks opened in the earth near the towns of Lemery and Taal” (Pratt, 1911a, 1911b, p.65), located on the north-eastern shores of Balayan Bay (Fig. 3). Similar but smaller fissures reported in Talisay were assumed by Pratt (1911a, 1911b) to have occurred at the same time and were accompanied by earthquakes. The day culminated in another eruption at 11 pm accompanied by a large magnitude earthquake, and enormous tephra column with accompanying lightning flashes that were either near-vent or plume lightning described as follows: "cloud above the volcano was frequently crossed and streaked with lightning, and often showed flashes or sheets of light" (Pratt, 1911a, 1911b, p.65).

At 1 am on 30 January, a large-magnitude earthquake occurred followed by another explosion with an enormous tephra column streaked with lightning flashes (Saderra Maso, 1911; Pratt, 1911a, 1911b; Worcester, 1912). Accompanying detonations were heard in Manila, > 60 km away (Saderra Maso, 1911; PHIVOLCS-DOST, 1995). The tephra column presumably drifted to the north-northeast because after twelve minutes, tephra fall was experienced by residents at the new location of Tanauan, 17 km northeast of the Main Crater, described as a "rain of mud" (Worcester, 1912, p339) (Fig. 3). By 2:20 am that same day, two successive eruptions occurred generating a huge tephra column described as follows: "a great black cloud shot up higher than before and finally spread out at the top like an umbrella, or a giant cauliflower", this resulted in total darkness (Pratt, 1911a, 1911b, p65). Saderra Maso (1911, p.13) further described that "this tempestuous cloud must have risen to an enormous height, since it was observed from distances of some 400 km, where it was mistaken for a distant thunderstorm". The 12 June AD1991 Pinatubo eruption cloud exceeded the height range of the Cubi Point radar located in Subic Bay in Zam- bales, and was estimated to be about 19 km high as seen from 100 km or more (Hoblitt et al., 1996). The umbrella cloud of the 15 June AD1991 event, with an estimated height of about 34 km, was seen from within a radius of 250 km. This would imply that the tephra column from the AD1911 Taal eruption could be > 35 km considering that it was seen from a radial distance of 400 km and this strongly suggests that the climactic event was a plinian eruption. Electrical activity, possibly plume lightning, was again noted but more intense than pre- viously observed. Based on eyewitness accounts, lumps of molten ju- venile material were ejected from the crater looking like balls of fire and described as being "hurled high up into the air and scattered in all directions glowing rocks, earth, mud, ashes, and gases" (Saderra Maso, 1911; p14). This mention of mud is the first possible disclosure of ac- cretionary lapilli as products of an eruption at Taal Volcano. Accre- tionary lapilli consist of concentric accumulation of fine ash around a wet nucleus of, usually, much coarser tephra, and are formed due to electrostatic attraction and condensed moisture in the tephra cloud (Moore et al., 1966).

Another interesting phenomenon was the observation of shock waves/atmospheric pressure in Talisay (north of the volcano) and San Nicolas (southwest of the volcano and formerly known as the town of Taal) that was described by Pratt (1911a, b, p65) as s"tarong wind that came from the volcano" (Fig. 3). Shock waves are generated by ex- plosive eruptions (Medici et al., 2014). A similar process was recorded during the paroxysmal eruption of Pinatubo in 1991, with barograph signals produced by laterally directed eruption processes like surges or pyroclastic flows (Oswalt et al., 1996). Presumably, the changes in at- mospheric pressure experienced came from occurrence of base surges that were described as follows: "as if shot from the mouth of a gigantic cannon. This death-dealing mixture mowed down and destroyed whatever it encountered in its path on the entire island and on neigh- boring western shores of Lake Bombon", now known as Taal Lake (Saderra Maso, 1911, p14). Additional confirmation of shock waves/ acoustic gravity waves being generated by an explosive eruption is provided by Donn and Balachandran (1981) when the same phenomena were produced by explosions during the 1980 eruption of Mount St. Helens. Furthermore, during the 2011 eruption of Shinmoedake vol- cano in Kirishimayama, Kyushu, Japan, there were significant shock waves produced from explosive activity (Magill et al., 2013).

Saderra Maso (1911) compared the pyroclastic flows at Taal to the "fiery cloud" described by Lacroix (1903, In Saderra Maso, 1911, p20) occurring at Mt. Pelee during the 1903–1904 eruption. Lacroix narrated that the surges "issue obliquely from the crater and have a creeping, downward movement. Seen at night, they appeared invariably in- candescent when issuing from the crater" (Lacroix, 1903, In Saderra Maso, 1911, p20). Saderra Maso further added that Lacroix estimated the temperature of the pyroclastic density currents at Mt. Pelee as ex- ceeding 125 °C. The abovementioned description aptly applies to the observations and impacts experienced by communities on the volcano island and the western side of Taal Volcano during the AD1911 erup- tion. Likewise, base surges impacted at least 15 km to the west and 5 to 6 km to the east of the Main Crater (Fig. 4C) (PHIVOLCS-DOST, 1995). On the western portion of TVI, trees were shredded and broken 0.3 to 0.5 m from the ground. A wave front generated by the advancing base surges detached roofing approximately ten kilometers from the vol- cano. The pyroclastic density current (PDC) formed from the collapse of the tephra column described to "act equally in all directions, downward as well as upward" (Pratt, 1911a, 1911b, p67). Further, he added that "the cloud spread downward over the base of the volcano" (Pratt, 1911a, 1911b, p67). Evidence of base surge include cogon grasses flattened directed away from the volcano, and trees destroyed, either uprooted or broken off but not buried, with further evidence of abra- sive effect (Pratt, 1911a, 1911b).

The presence of toxic gases was also observed during the AD1911 eruption. Acid burns were reported to have affected people and vege- tation (PHIVOLCS, 1995). In one community, known previously as Guillot, located on the northwest shores and now a part of the town of Laurel (Fig. 3), residents died in the absence of any scorching or burning and this is attributed to toxic gases (Saderra Maso, 1911). Additional confirmation of the presence of these gases was provided by this narrated account: "In a house of a village belonging to the muni- cipality of Talisay, at a distance of over 10 kilometers (6 miles) north of the volcano, the inhabitants covered themselves with mats to escape the mud; but when the worst of the eruption was already over, there oc- curred an explosion in the kitchen which hurled the sheets of iron roofing to a distance of more than 18 meters (20 yards)" (Saderra Maso, 1911, p. 15). The reports of explosions presumably indicate that gases were released during the eruption. Moreover, there were reports of casualties "from the effects of gases and heat" in Bugaan, Laurel, lo- cated on the western shore, similarly affected to Guillot (Saderra Maso, 1911, p15) (Fig. 3). Although tephra deposition on plants can be harmful when significantly thick, the ash that covered the plants and trees during the AD1911 eruption affected them in a different way. Saderra Maso (1911, p14) described it as follows: "The plants - even up to distances of 10 kilometers from the volcano - showed parts whose color and consistency indicated real carbonization. In general, it may be said that the destruction of vegetation is likewise evidently due not so much to the scalding effects of the mud as to chemically active sub- stances in its composition".

Volcanic tsunamis were also reported during the AD1911 eruption. The villages of Bosoboso, Banaga, Bilibinang (now Bilibinwang), and Manalao, located on the western shore of Taal Lake, and now part of the Municipality of Agoncillo (Fig. 3), were completely destroyed with houses, livestock and residents washed away by waves at least three meters high (Saderra Maso, 1911). Pratt (1911a, b, p. 69) reported the occurrence of a tsunami when he narrated "this wave (or series of waves close together) washed up on the lake shore through a vertical distance of 2.5 or 3 meters carrying away houses and causing loss of life in some of the barrios". Berninghausen (1969) affirmed the tsunami occurrence citing Saderra Maso (1911), Pratt (1911a, 1911b), and Worcester (1912) as sources.

Fissures and landslides were observed both on the volcano island and along the shoreline. The northeast-southwest fissure zones were reactivated extending from Lemery to Calamba (PHIVOLCS, 1995). Near the shoreline at Sinisian, about 20 solfataric cracks opened that could also be interpreted as lateral spreading (Fig. 3). Reported mud cones and explosion pits, presumably sand boils, were also observed around lakeshore areas, noted to have a maximum diameter of two meters and height of about thirty centimeters. These structures may have been liquefaction effects generated by severe ground shaking due to the large-magnitude volcanic earthquake. Győri et al. (2015) con- cluded in their paper that a Peak Ground Acceleration (PGA) ranging from 0.2 to 0.3 g were found in areas where liquefaction occurred. This is roughly equivalent to MMI Intensity VII to VIII (M.L.P. Bautista, personal communication, 18 September 2016) or Rossi-Forel Intensity VIII to IX, the intensities reported at Taal Volcano during the peak of the AD1911 eruption (Pratt, 1911a, 1911b, p.23). Taal Volcano Island subsided by at least three meters and the level of water at Taal Lake was lowered by about one meter. The eruption also brought significant changes in crater floor morphology, with the three small lakes pre- viously existing inside the Main Crater fused into one (PHIVOLCS- DOST, 1995).

The total bulk volume of ejecta from the AD1911 eruption is estimated at about 80 million m^3. The base surge deposit map is shown in Fig. 4C, with estimated run-out distance approximately 9 km. The thickness of tephra fall deposits was estimated at around 25 cm, cov- ering and damaging an area of around 230 km^2, and > 80 cm within 8 km west of the Main Crater (PHIVOLCS-DOST, 1991) (Fig. 4D). The entire volcano island was devastated. As with earlier eruptions, the AD1911 eruption also resulted in considerable damage to properties, flora and fauna. Observed eruptive processes can be interpreted as phreatomagmatic or phreatoplinian eruptions categorized with a VEI of 4 (PHIVOLCS-DOST, 1991) but Smithsonian GVP (2016) assigned a VEI

3. The number of casualties, officially registered at 1335, came from the damage assessment report carried out by Col. William C. Rivers of the Philippine Constabulary. Fatalities came mostly from TVI as well as the western shorelines, with the causes of death mostly from the base surges or the tsunami that ensued (Saderra Maso, 1911; Moore et al., 1966). Survivors who sustained injuries were estimated at 199 (Saderra Maso, 1911; PHIVOLCS-DOST, 1991). The number of casualties maybe greater as there were a considerable number of unregistered migrant residents on the island as well as in the adjacent communities around Taal Volcano and some bodies were presumably also (Saderra Maso, 1911).

Of the twelve eruptions in Series C between AD1749 and AD1911, with activities centered at the Main Crater, the AD1749, AD1754, and AD1911 are considered the most destructive, resulting in severe de- vastation to Taal Volcano island and adjacent communities. The AD1790, AD1825, AD1842, AD1873 and AD1903 eruptions are con- sidered uncertain due to the absence of any detailed historical doc- umentation and could simply have been solfataric activities that did not necessarily culminate into eruptions.

3.2.4. *Eruption series D: Mt. Tabaro*

The AD1965 to AD1977 eruptions in Series D were centered at Mt. Tabaro (Figs. 4E, F, 5 and 6, Table 2). Based on observed processes, the eruptions alternated between strombolian, phreatomagmatic, and phreatic. A more detailed description was available for the AD1965 eruption due to its larger magnitude, observed deposits and impacts to adjacent communities. With a 54-year repose period since AD1911, people had forgotten the devastating effects and again returned to Taal Volcano island, notwithstanding the fact that PHIVOLCS-DOST (then the Commission on Volcanology or COMVOL), recommended no per- manent settlement on Taal Volcano island after the establishment of a volcano station on the island in December 1952.

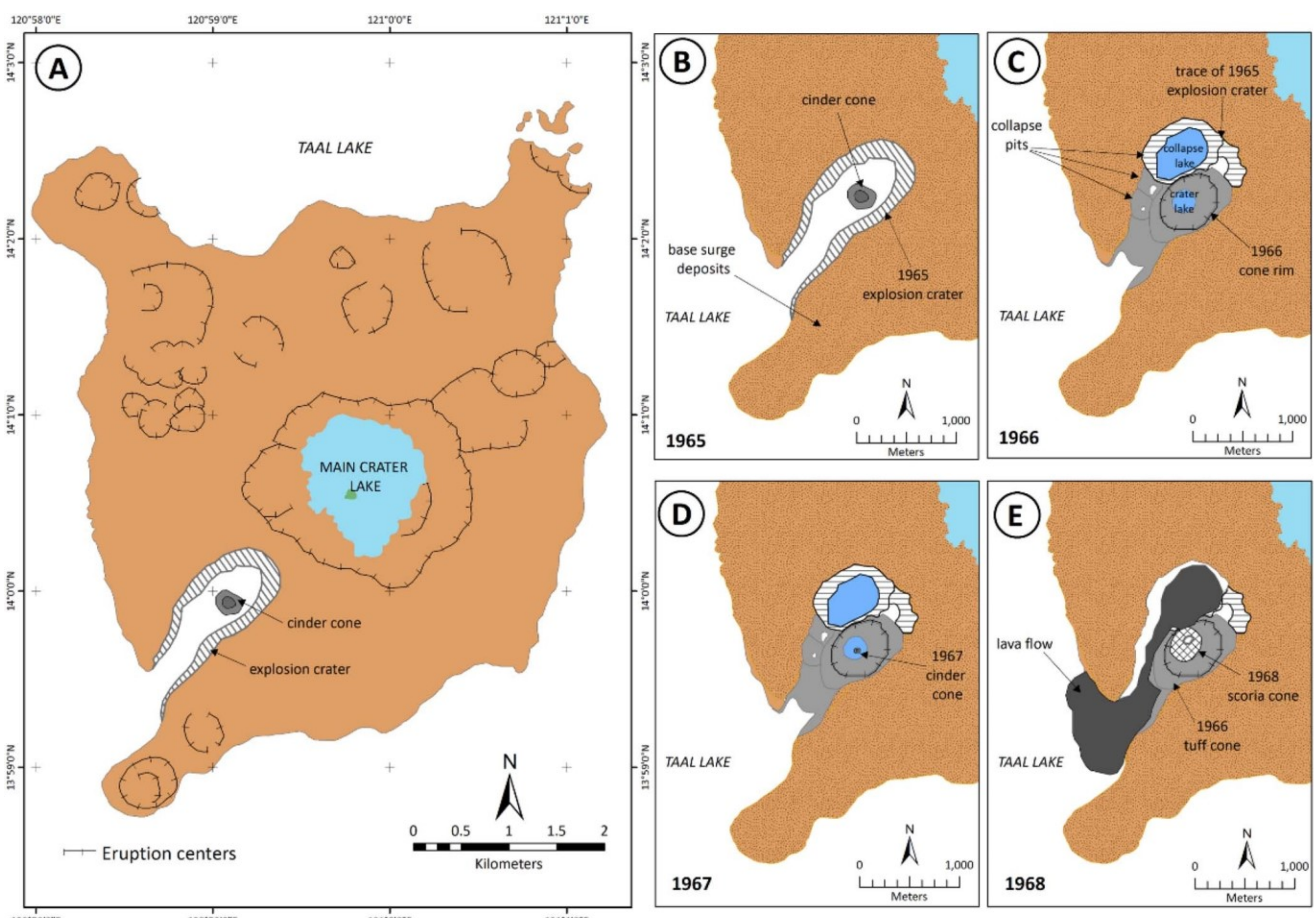


Fig. 5. (A) Physiographic map showing features following the AD1965 eruptions of Taal Volcano, Southern Luzon, Philippines. (B) Close-up view of the post-AD1965 eruption morphological features of Mt. Tabaro eruption crater. Morphological features of Mt. Tabaro eruption crater following: (C) the AD1966 eruption; (D) the 1967 eruption; (E) the AD1968 eruption. Sources: Modified from Ruelo (1983) and PHIVOLCS-DOST (1991).

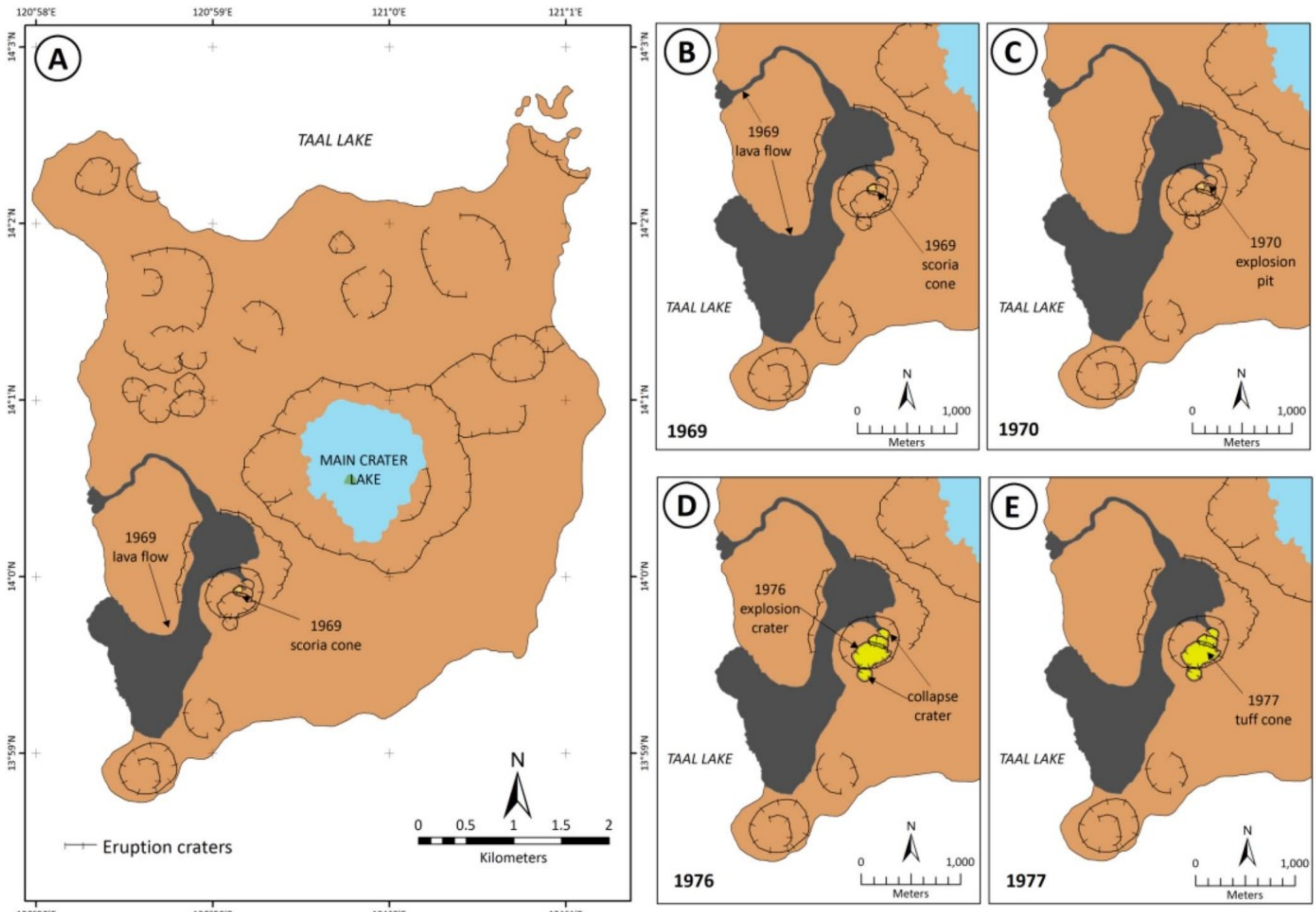


Fig. 6. (A) Physiographic map following the AD1969 eruptions of Taal Volcano, Southern Luzon, Philippines. (B) Close-up view of the post-AD1969 eruption. Morphological features of Mt. Tabaro eruption crater following: (C) the AD1970 eruption; (D) the AD1976 eruption; and (E) the AD1977 eruption. All eruptive activities centered at the Mt. Tabaro area. Sources: Modified from Ruelo (1983) and PHIVOLCS-DOST (1991).

3.2.4.1. AD1965. The AD1965 eruption lasted three days and activity varied from an initial strombolian phase to phreatomagmatic phase (Alcaraz and Datuin, 1977), and was classified VEI 4 (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016) (Table 2). Based on written descriptions of the eruption columns ranging from 15 to 20 km and estimated volume of erupted materials (90 M m^3), we confirm that the assigned VEI of 4 should be retained.

COMVOL established a manned volcano station on the west-central part of the island with 24/7 seismic monitoring and visual observations, as well as taking measurements of lake temperatures and other geochemical and geotechnical studies. An increase in lake temperature at the Main Crater Lake was noted from the AD1964 average readings of 30 to 33 degrees centigrade (°C) to 45 °C on 21 July AD1965 (Moore et al., 1966; Andal, 1984). There was also a short seismic precursor to the eruption.

The initial strombolian phase occurred after 2 am on 28 September and consisted of lava fountaining and lava flows. The lava fountaining was described as "incandescent material shooting high in the air from the general vicinity of the newly formed cinder cone" that looked like an "enormous Roman candle" (Moore et al., 1966, p.955). The occurrence of a lava flow was implied by the description as fountaining "directed towards the lake". The eruption was accompanied by large-magnitude volcanic earthquakes, recorded and felt at the COMVOL station. By the time the COMVOL observer evacuated the island at 02:13 AM together with 19 residents, sand-sized tephra fall was already being experienced.

Between the hours of 2:40 am and 3:30 am of 28 September, a resident from the northwest sector of the island described a "continuous display of lightning in the eruption cloud accompanied by thunder" (Moore et al., 1966, p.955). This can be interpreted as a volcanic lightning storm that can only be generated within a large eruption column during an explosive event (Behnke et al., 2013). This may have been the onset of the phreatomagmatic phase of eruptive activity. The activity peaked between 3:25 am and 9:20 am, with eruption cloud height estimated at 15–20 km, which was visible in the Manila area. Column collapse generated pyroclastic density currents that were described by Moore et al. (1966; p958) as follows: "at the base of the main cloud column a flat turbulent cloud spread out, radially transporting ejected material with hurricane velocity". Trees were sandblasted and coated with fine eruption deposits. The extent of base surge deposition is shown in Fig. 4E, with an estimated run-out distance of 4.5 km, causing devastation to the southern part of Taal Volcano island from Balantoc (W) to Calauit (E), and the lakeshore barrios west of the island, from Brgy. Gulod, Laurel to Brgy. Bilibinwang, Agoncillo. The blast effect reached 2–6 km from the crater with as much as 15 cm of tree trunk thickness removed by abrasion on the side directly facing the crater (Moore et al., 1966). At least three, but maybe up to five, blast sequences were recognized in the volcano island base surge deposits indicating multiple base surge events. There was an absence of charring or burning of flora or fauna, and the temperature of the surge was es-mud marks and sandblasting effects provide an estimated height of about five meters above the ground surface. Volcanic bombs were seen up to a distance of one kilometer from the vent with average diameters of 50 cm, but with a maximum size of about three meters (Moore et al., 1966).

Tephra from the eruption column was dispersed southwest by prevailing winds to a distance of > 80 km west from the vent (Moore et al., 1966). Tephra fall deposits ranged from 20 to 50 cm within a 60 km^2 area (PHIVOLCS-DOST, 1991) (Fig. 4F). Residents from the western shoreline experienced severe tephra accumulations by 5 am and were simultaneously affected by tsunami (Moore et al., 1966). This paroxysmal phase subsequently created a new explosion crater measuring 1.5 by 0.3 km with an average depth of about 25 m.

Between 9:20 am on 28 September and 6 am on 30 September, explosions were less intense and the columns generated were not as high as earlier, still being concentrated within the explosion crater (Fig. 5A). Further decline of eruptive activity was observed from 6 am until the last explosion at 3:50 pm on 30 September. Steaming was observed at the newly formed cinder cone, which was about 170 m in diameter and 19 m high (Fig. 5B). Several post-eruption landslides and erosion re- sulted in breaching of the AD1965 explosion crater, forming a horse- shoe-shaped cone that became open to Taal Lake on its southwestern sector (Moore et al., 1966; Ruelo, 1983).

Other observed phenomena reported were shock waves/atmo- spheric waves similar to those experienced during the AD1911 eruption (Moore et al., 1966). Moore et al. related the volcanic tsunami occur- rence during this eruption to shock waves. The tsunami resulted in deaths of evacuating islanders as well as devastating communities on the western shoreline with wave run-up of 4.7 m above the lake level and inundating areas up to about 80 m from the shore (Moore et al., 1966; Berninghausen, 1969).

The AD1965 eruption claimed at least 200 lives. At the time of the eruption, the population at TVI was about approximately 4000. The total volume of ejecta from the AD1965 eruption was estimated at 90 million m^3 spread over TVI, Taal Lake, and the western shoreline (Moore et al., 1966). Tephra fall deposit thickness was recorded as 25 cm within an area of 60 km^2. Damage to vegetation resulting from tephra deposition was observed as follows: "where the ash blanket was thicker than about 10 centimeters the fronds of palm trees are broken down, and banana trees are damaged where the ash thickness is more than 5 centimeters" (Moore et al. 1966, p.960). Only a dusting of tephra fall was experienced by residents in the north, northeast and east lakeshore areas.

3.2.4.2. AD1966. The AD1966 event commenced on 5 July and continued to 5 August and was described as a moderate phreatomagmatic eruption (Alcaraz and Datuin, 1977; Ruelo, 1983; PHIVOLCS-DOST, 1991) with a VEI of 3 (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016). The center of activity was located on the southwest sector of the AD1965 cinder cone. A series of minor eruptions resulted in the accumulation of volcanic ejecta that filled the AD1965 explosion crater (PHIVOLCS-DOST, 1995) and created a "122-meter high ellipsoidal tuff cone measuring 500x400 meters at its base" (PHIVOLCS, 1991, p53) (Fig. 5C). The volcanic ejecta was a mix of juvenile and lithic fragments exploded from the crater walls (Alcaraz and Datuin, 1977). During the waning stages of the eruptive activity, a new large collapse crater about 500 m in diameter, and two adjacent 100-meter pits, were formed, which were subsequently filled with water after activity ceased (PHIVOLCS-DOST, 1991). Damage to houses and vegetation was reported as a result of tephra fall.

3.2.4.3. AD1967. The onset of the AD1967 eruption occurred on 16 August and activity lasted for three days. The minor phreatomagmatic event was centered at the AD1966 cone lake, and classified as VEI 1 (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016). The eruptive activity and products of the eruption created "a small doughnut-shaped cinder cone" (PHIVOLCS-DOST, 1995, p51) (Fig. 5D). The cone had an outer diameter of 40 m and was 22 m in its inner diameter. Steam laden clouds with dark fine basaltic ash were ejected from the cone as high as 400 m (Ruelo, 1983; PHIVOLCS-DOST, 1991).

3.2.4.4. AD1968. More than five months after the AD1967 eruption, a minor phreatomagmatic eruption occurred on 31 January AD1968 lasting 2 days and centered within the AD1966 eruption cone lake, a few meters from the AD1967 conelet (Ruelo, 1983; PHIVOLCS-DOST, 1991) (Fig. 5E). This was followed by a strombolian phase from 2 February to 28 March, with lava fountaining and lava flows towards the western base of a cinder cone formed during the eruption. Lava was ejected from the cone with a regular 5-min interval until 12 February and then subsequently breached the lowest rim. Lava flows filled up and reoccupied most of the original pre-AD1965 eruption southwestern shoreline in Alas-as at 3:45 am on 12 March (Fig. 5E). The maximum temperature of the lava flow was measured at 1175 °C (Ruelo, 1983; PHIVOLCS-DOST, 1991). After 28 March and until 2 April, eruptive activity reverted back to a minor phreatomagmatic eruptive phase, with ejection of "ballistic ashes" creating an elongated scoria cone with two vents oriented northeast-southwest located in the southwestern sector of Taal Volcano island (PHIVOLCS-DOST, 1991). The AD1968 eruptive activity was classified as VEI 2 (PHIVOLCS-DOST, 1991; Smithsonian GVP, 2016).

3.2.4.5. CE 1969. Phreatomagmatic eruptive activity recommenced on 29 October AD1969 (Ruelo, 1983; PHIVOLCS-DOST, 1991). The eruptive center was situated on the southeastern upper slope of the AD1968 scoria cone and the new explosion formed a pit about five meters wide (Ruelo, 1983); the volcanic ejecta consisted of ash, steam and incandescent material. The activity transitioned into strombolian at 7:30 pm on 30 October with lava flows towards the eastern base of the 1968 cone moving at a rate of 20 m per hour (Ruelo, 1983; PHIVOLCS- DOST, 1991). The AD1969 lava flow deposits overtopped and exceeded the extent of those from AD1968 (PHIVOLCS-DOST, 1995) (Fig. 6A and B). Simultaneously, lava fountaining was observed forming a new scoria cone (Fig. 6B). The strombolian phase continued for a few days, with a new lava crater found at the base of the AD1968 cone (Ruelo, 1983). At 3:30 pm on 20 November, lava began to flow towards the northwest sector and into a creek until it reached the river mouth towards Taal Lake. Eruptive activity again shifted from the southwest sector of the volcano during the strombolian phase, to the northeast sector during another minor phreatomagmatic phase, with the ejection of volcanic materials centered at the AD1969 scoria cone (Fig. 6B) lasting until 10 December AD1969 (PHIVOLCS, 1991). Oppenheimer (1991) assigned a VEI of 1 while PHIVOLCS-DOST (1991) and Smithsonian GVP (2016) provided a VEI of 2 for this event. The explosive nature of the eruption, transitioning from phreatomagmatic to strombolian to phreatomagmatic style, seems to indicate that a VEI of 2 is more appropriate.

3.2.4.6. AD1970. This eruption took place on 9 November AD1970 and lasted for four days (PHIVOLCS-DOST, 1991). The eruption was presumed a phreatic event but could also have been a phreatomagmatic event based on description of "incandescent volcanic ejecta, ash and steam" (PHIVOLCS-DOST, 1991, p60; PHIVOLCS-DOST, 1995, p51). Initial activity was centered at the eastern section of the AD1969 cone (Ruelo, 1983) (Fig. 6C). A five- meter diameter explosion pit within the AD1969 cone was formed during this eruption (Ruelo, 1983). The assigned VEI of Oppenheimer (1991) was 2, while PHIVOLCS-DOST (1991) and Smithsonian GVP (2016) assigned a VEI of 1. Alcaraz & Datuin (1974, p. 37) described the 1967 and 1970 events as "weak and short-lived eruptions". Therefore, even with the limited eruptive narrative, we are more inclined to think that VEI should be 1.

3.2.4.7. AD1976. The 3 September to 22 October AD1976 eruptive activity was categorized as a mild phreatic eruption (PHIVOLCS-DOST, 1991). In PHIVOLCS-DOST (1995, p. 51), the eruption was described as “an explosive activity featured as regular outbursts of ash, forming a 1.5 km-high eruption column.” The tephra column was observed to drift to the southwest. A northeast-southwest elongated explosion crater was formed during the AD1976 eruption with two collapse craters found in the north and southeast section of the AD1968–1969 eruption cones (Ruelo, 1983; PHIVOLCS, 1995) (Fig. 6D). Further, Andal and Aguila (1976, p. 1) provided a description of the event: “The eruption was characterized by forceful and continuous emission of voluminous ash-laden clouds, first from a vent it made open between the ridge of Mt. Tabaro and the New Eruption Site, and then from the 1966-1969 eruption cone and remained in a state of fury during the next two months.” The assigned VEI was 2 (Masigla and Ruelo, 1987; PHIVOLCS- DOST, 1991; Smithsonian GVP, 2016). We affirm the VEI 2 classification considering the explosivity and the height of the tephra column produced by the eruption (Newhall and Self, 1982).

3.2.4.8. AD1977. The most recent recorded eruption of Taal Volcano occurred from 3 to 4 October AD1977. The activity was considered as a minor phreatic event. The assigned VEI of PHIVOLCS-DOST (1991) was 1, and Smithsonian GVP (2016), 2. Steam and ash ejection took place on 3 October, centered in the northeast sector of the 1976 elongated explosion crater and with a tephra column reaching a height of 500 m (Ruelo, 1983) (Fig. 6E). On 4 October, a new conelet was formed that is about five meters above the base and ten meters in diameter (Ruelo, 1983; Masigla and Ruelo, 1987; PHIVOLCS-DOST, 1991).

In summary, the eight eruptions in Series D from AD1965 to AD1977 were centered at the Mt. Tabaro eruption site (Figs. 4 and 5). The AD1965 event was one of the last explosive and damaging eruption of Taal Volcano. Strombolian activity was interpreted from the AD1965, AD1968 and AD1969 eruption descriptions. The AD1966 and AD1967 events were considered phreatomagmatic. The eruptions of AD1970, AD1976 and AD1977 were considered to be characterized by minor phreatic activity that had very little impact on the Taal com- munities except for minor ashfall deposition drifted by prevailing winds. Since AD1977, Taal Volcano has not erupted but has sporadically manifested unrest. More than 20 significant episodes of seismic swarms were recorded that did not culminate in eruptions: 30 October to 04 November 1987, August 1988, June to October 1989, March to July 1991, 14 to 28 February 1994, 9 April 1993, 23 February 1994, 11 March to 31 May 1994, 27 July 1999, 19 July to 31 October 2000, 23 September to November 2004, January to February 2005, 21 November 2005, January & November 2006, June 2007, August and September 2008, 8 June 2010, March and April 2011, November 2012, January to early March 2015, and 5 May 2015 (PHIVOLCS-DOST/Volcano Mon- itoring and Eruption Prediction Division (VMEPD), 7 October 2017. Personal communication).

3.3. Eruptive processes and products

Having summarized the eruption history of Taal Volcano in Section 3.2, the processes and products of these eruptions are determined from a review of the historical records. Present day landforms around Taal may not always provide evidence of the processes and products gen- erated during these historical eruptions. Being in a tropical country, preservation of the eruptive deposits from Taal is very poor, especially tephra fall deposits that are easily eroded and washed away during high precipitation.

A significant number of the historical eruptions from Taal Volcano were hydrovolcanic. In these instances, interaction of magma, or heat from magma, with external sources of water frequently generated ex- plosive ejection of water, steam and volcanic fragments (Fontaine et al., 2002). The AD1605-1611, AD1634, AD1635 and AD1645 eruptions

were identified as solfataric and may not have been full-blown eruptions. The AD1591, AD1641, AD1707, AD1878, AD1904 and AD1977 eruptions were classified as phreatic. *Phreatic eruptions* are caused by contact of water with hot country rocks resulting in the ejection of steam with or without fragmented lithic material, and with no magmatic material erupted (Cas, 1987). The AD1709, AD1716, AD1731, AD1808, AD1874, AD1966, and AD1967 eruptions were all *phreatomagmatic*. These eruptions were produced by the interaction of external water and magma that resulted in an explosive ejection of steam with lithic and juvenile fragmented material (Cas, 1987). This explosive ejection creates dense and short tephra columns. The AD1572, AD1715, AD1968, and AD1969 eruptions were *strombolian*. These are mild to violent eruptions of gas-charged, low viscosity ba- saltic magma (Carey, 2005). The AD1749 eruption was previously in- terpreted as a phreatomagmatic with a description of the occurrence of a column-collapse pyroclastic density current. Alternatively, with the suggested magnitude of the eruption, the event could also have been plinian. *Plinian eruptions* are very explosive, generated by high viscosity and large volumes of magma, generally of andesitic to rhyolitic com- position (Cas, 1987). Fragmented magma is propelled with great force high in the air forming tall mushroom-shaped columns frequently pe- netrating the stratosphere. The AD1754 event transitioned from plinian to phreatomagmatic as implied from the narrated behavior during the eruptive activity and the subsequent deposits. While the AD1911 event was previously classified as phreatomagmatic, the eruptive processes and products suggest that the eruptive phases transitioned from phreatomagmatic and plinian. A *phreatoplinian eruption* is a plinian event consisting of fine-grained and poorly sorted material due to magma interacting with water as it passes through the vent (Chester, 1993). The AD1965 eruptive phase transitioned from strombolian to phreatomagmatic. The eruptions in AD1790, AD1825, AD1842, AD1873, and AD1903 are uncertain and not classified with any erup- tive style. Table 2 summarizes the year and duration of eruptive ac- tivity, location of eruption sites, style and nature of eruption, assigned VEI, eruptive processes, deposits, and impacts of the historical erup- tions of Taal Volcano (PHIVOLCS-DOST, 1991).

Between the last eruption in *Series A* (AD1645) and the first eruption in *Series C* (AD1749), both centered at the Main Crater, was a period of 104 years. As described in Section 3.2.3, the AD1749 eruption was very explosive. A significant period of time has elapsed since the last erup- tion. The question of future explosivity is therefore of great concern. Close monitoring of seismic activity may provide some indication as to where the next center of eruptive activity will be located.

3.3.1. Volcanic hazards from Taal

The following subsections provide a discussion of various phe- nomena and associated deposits produced by the historical eruptions of Taal Volcano.

3.3.1.1. Pyroclastic density currents: pyroclastic flows and base surges. Pyroclastic density currents (PDCs) are ground-hugging, gravity-driven flows moving at very high speeds consisting of volcanic ejecta and gases (Druitt, 1998; Scott, 1989). The typical mechanism for PDCs are from “gravitational collapse of lava domes, by the fallback or continuous fountaining of vertical eruption columns or by lateral blasts” (Druitt, 1998, p.45). Two types of PDC are identified based on textural characteristics of the deposits: massive and poorly-sorted pyroclastic flows that are frequently density- stratified, and pyroclastic/base surges that travel at great speed (tens of meters per second) and drape the landscape (Fisher and Schmincke, 1984; Cas, 1987; Scott, 1989; Druitt, 1998). Base surge deposits generally consist of blocks, lapilli, and ash that are observed to be plastered on objects in their path, providing evidence that the blasted materials were mixed with water (Moore, 1967; Cas, 1987). The PDCs at Taal generated lateral forces due to dynamic pressures that created sand blast effects on objects in their paths, as observed during the AD1911 eruption.

Pyroclastic density currents are considered as one of the primary hazards at Taal Volcano, with numerous authors providing accounts of these phenomena during most destructive historical eruptions (Saderra Maso, 1911; Worcester, 1912; PHIVOLCS-DOST, 1991). One me-chanism for the generation of PDCs at Taal Volcano is from eruption column-collapse. Other eruptions have also produce laterally directed high energy PDCs/base surge (Jenkins et al., 2013) that have blasted trees and plants as during the AD1749, AD1754 and AD1911 events. Eruptions of Taal Volcano that generated PDCs included the AD1716, AD1731, AD1749, AD1754, AD1911, and AD1965 events (Table 2).

During the AD1754 eruption, the base surges completely engulfed the entire volcano island, as well as the lakeshore communities on the mainland (Saderra Maso, 1911; PHIVOLCS-DOST, 1991). The AD1911 base surges devastated the whole of Taal Volcano island but only af-fected the western lakeshore communities on the mainland. The AD1965 eruption generated seven major PDC events that impacted two thirds of TVI, as well as the western lakeshore communities to a dis- tance of about 6 km from the vent (PHIVOLCS-DOST, 1991). During that eruption, Moore (1967, p385) described the base surge event as follows: “At the base of the main cloud column, flat turbulent clouds spread out, radially transporting ejected material with hurricane velocity”.

3.3.1.2. Tephra fall deposits and ballistic projectiles. Tephra fall is gravitational settling of air-borne fragments of volcanic material ejected into the atmosphere during explosive eruptions (Scott, 1989; Tilling, 2005). Tephra dispersal depends on prevalent wind strengths and directions, as well as the height of the eruption column (Scott, 1989). Tephra fall generally thins down-wind as it is dispersed farther away from the eruption center. It has one of the widest and farthest impacts of all volcanic hazards. Tephra emplacement may cause widespread damage and disruption to infrastructure, agriculture, health, flora and fauna, lifelines, aviation, and the environment (Casadevall et al., 1996; Kuhnt et al., 2005; Horwell and Baxter, 2006; Ayris and Delmelle, 2012; Carslaw et al., 2012; Wahyunto et al., 2012; Wardman et al., 2012; Wilson et al., 2012, 2014; Magill et al., 2013).
Most of the 33 recognized historical eruptions of Taal Volcano generated significant tephra fall deposition (Table 2) (PHIVOLCS-DOST, 1991). Details of dispersal and thickness of tephra fall deposits were discussed in Section 3.2. Eruption accounts of the AD1754 erup-tion mentioned that tephra fall reached Manila, a distance of $>$ 60 km from Taal Volcano.

Another airborne hazard is ballistic projectiles that have also been observed during the eruptions at Taal Volcano. These are rock frag-ments (blocks or bombs) that are explosively thrown outward into the air from the vent of an erupting volcano (Tilling, 2005). The rocks may be hurled as far as 5 km depending on the explosivity of the eruption (Blong, 1984; Tilling, 2005; Banks et al., 1989). In previous Taal eruptions, ballistic projectiles generally coincided with the ejection of tephra, including in AD1572, AD1715, AD1731, AD1731, AD1749, AD1754, AD1904, AD1911, AD1965, AD1966 and AD1967 (Table 2). Ballistic projectiles from these eruptions damaged houses and agri-cultural crops at Taal Volcano island (PHIVOLCS-DOST, 1991).

3.3.1.3. Lava deposits. Lava flows are incandescent rivers of hot molten materials from effusive eruptive phases (Tilling, 2005). The main impacts of lava are burial, burning, and crushing of structures (Scott, 1989). The eruptions of AD1572, AD1715, AD1965, AD1968, and AD1969 produced lava deposits from lava fountaining and/or lava flows. The AD1968 and AD1969 strombolian eruptions exhibited lava flows that encroached past the shoreline at Mt. Tabaro (Fig. 2) into the lake waters (Figs. 5E and 6B) (Ruelo, 1983; PHIVOLCS-DOST, 1991).

3.3.1.4. Volcanic tsunami and Seiche. Volcanic tsunami are generated by the sudden displacement of water due to the occurrence of large-magnitude earthquakes, subsidence of a volcano edifice, landslides and/or other types of entry of volcanic materials into bodies of water, or by shock waves occurring close to bodies of water (Latter, 1981; Scott, 1989; Tilling, 2005; Paris et al., 2014). Seiches are oscillations of a landlocked body of water (such as a lake) that vary in duration from a few minutes to several hours and may be generated by disturbance due to a volcanic activity (e.g. underwater volcanic eruption) or emplacement of volcanic deposits. Based on our review, most of the wave movements related to Taal eruptions were volcanic tsunami generated by PDCs entering the lake. Eruptions that generated volcanic tsunami include those in AD1716, AD1731, AD1749, AD1754, AD1911, and AD1965 (Table 2); thus, they are quite common. Volcanic tsunami during eruptions at Taal resulted in waves invading lakeshore areas and causing damage and deaths due to inundation and drowning. Although narrative accounts during most of the abovementioned eruptions reported undetermined casualties, they cannot be discounted. Some of the 12 reported casualties during the AD1754 eruption were associated with drowning due to volcanic tsunami.

3.3.1.5. Toxic volcanic gases. Volcanic gases are released into the atmosphere during eruptions and even during times when magma is at near the surface of the volcano (Scott, 1989). Water vapor is the most prevalent volcanic gas, while carbon dioxide (CO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), sulfur dioxide (SO_2), fluorine and chlorine are also common toxic gases near the vents of erupting volcanoes (Williams and McBirney, 1979; Scott, 1989). During large-magnitude eruptions, toxic gases can have global impacts from the injection of SO_2 into the stratosphere, or reverse greenhouse effects similar to that experienced during the AD1991 eruption of Pinatubo Volcano, Philippines (Self et al., 1996). Health effects of some toxic gases include asphyxiation, respiratory tract and airway constriction, and eye irritation. Taal eruptions with recorded toxic gases released were those in AD1716, AD1749, AD1754, AD1874, AD1911, and AD1965 events (Table 2). The underwater flank eruption of AD1716 released “pestilential sulfur stench molesting the inhabitants along the lakeshore towns in old Taal” (Foreman, In Ruelo, 1983). The 19 July AD1874 phreatomagmatic eruption centered at the Main Crater also released gases that along with ash deposition killed all livestock on TVI and damaged agricultural crops on the western slopes of the crater (Saderra Maso, 1911; PHIVOLCS-DOST, 1991). Acid rains are commonly formed when combined with sulfur dioxide substances released in the atmosphere (Christiansen, 2015). These phenomena are known to cause burns, with acid rains recorded during the AD1716, AD1749, AD1754, AD1911 and AD1965 eruptions (PHIVOLCS-DOST, 1991) (Table 2).

3.3.1.6. Volcanic earthquakes. Volcanic earthquakes may be generated by movement of magma to the surface or volcanic explosions, or they can be generated by related mass movement or induced by tectonic activity in the vicinity of the volcanic area (Blong, 1984; Scott, 1989). Swarms of moderate to large-magnitude volcanic earthquakes were felt before and during most eruptions at Taal Volcano (Table 2). With the establishment of seismic monitoring during the American occupation, the seismic activity during the AD1911 eruption of Taal Volcano was recorded, with some earthquakes felt as far as Manila. Although eruption documentation for the AD1965 to AD1977 events does not specifically describe occurrences of earthquakes, they were recorded by seismographs already installed at Taal Volcano island and Talisay Volcano stations of PHIVOLCS-DOST in AD1965.

3.3.1.7. Ground fissuring and subsidence. Ground fissuring occurs due to movement of magma beneath the surface or adjustments along faults in the volcano's vicinity. More often than not, this phenomenon is accompanied by the occurrence of earthquakes. Fissures and subsidence were observed after the AD1749, AD1754 and AD1911

Taal eruptions, immediately after intense earthquake shaking (Table 2). As a consequence of subsidence, lakeshore areas were inundated by lake water (PHIVOLCS-DOST, 1991). The phenomena also resulted in damage to infrastructure. Ground fissures and subsidence occurred in Lemery, Batangas Province, during or after the 1911 eruption of Taal Volcano (Pratt, 1911a, 1911b; PHIVOLCS-DOST, 1991).

3.3.1.8. Lahars and flooding. Although past lahar occurrences at Taal Volcano are not as frequent or as devastating as those which occurred at Mayon Volcano in the Bicol area, or Pinatubo Volcano in central Luzon, there was notable reference to ash being washed to the ground presumably with landslides and lahars occurring after heavy downpour on 29 November AD1754 (PHIVOLCS-DOST, 1991). On the other hand, the damming of Pansipit River by volcanic materials resulted in flooding on the southeastern and eastern lakeshores including Old Lipa and Old Tanauan (Fig. 3). Saderra Maso (1911, p.11) made the following description pertaining to the occurrence of flooding during the AD1754 eruption: "the mouth of the river Pansipit having been blocked, the lake is rising and invading the towns of Lipa and Tanauan, both being on the lowest level, and inundating their building". The location of Old Lipa mentioned by Saderra Maso was previously near the shoreline but was relocated following the devastation of the AD1754 eruption (Fig. 3).

3.3.1.9. Liquefaction effects. Liquefaction is a phenomenon that occurs in saturated alluvial environments when loosely consolidated materials are subjected to intense ground shaking during large-magnitude earthquakes (Liyanapathirana and Poulos, 2004; Emergeo Working Group, 2013). Build-up of pore water pressures results in loss of soil strength and liquefaction effects are then manifested. Narrative records detailing the AD1749, AD1754 and AD1911 eruptions (Section 3.2.3) described some subsidence (settlement), fissuring near the shoreline (some interpretable as lateral spreading), sand boils, and changes in water courses that were mostly observed near the shoreline adjacent to Taal Lake subsequent to occurrence of large-magnitude volcanic earthquakes (Saderra Maso, 1911). These phenomena are now interpreted by us to be liquefaction effects (Table 2).

3.3.1.10. Electrical activity. Electrical activity is inherent phenomena during volcanic eruptions that generate tall eruption columns (McNutt and Williams, 2010; Behnke et al., 2013). Electrical discharges are more likely to be observed when fine tephra particles are present in large quantities within the plume and where friction occurs with the interaction of tephra particles, steam and other gases (Blong, 1984). Identified types of lightning include: *vent discharges* that are generally small and close to or directly above the vent, *near-vent lightning* that extends from the volcano towards the plume about 1 to 7 km in length, and *plume lightning* that is observed within the plume far from the vent (Behnke et al., 2013). Lightning may move upwards or downwards, as observed during the AD1911 eruption (Pratt, 1911a, 1911b). Electrical activity accompanying large eruption columns was described during the AD1707 (VEI 2), AD1749 (VEI 4), AD1754 (VEI 5), AD1911 (VEI 3) and AD1965 (VEI 3) eruptions of Taal Volcano (Table 2). One important feature of lightning during an eruption is that it can verify the presence of an eruption plume. McNutt and Davis (2000, p. 45) wrote "volcanic lightning is important because it can help confirm that explosive eruptions are in progress". This information could be important for aviation operation, especially during a new eruption and at night time when observation of eruption column may not always be possible. Electrical activity could also be useful in estimating the size of an eruption by distinguishing the type of electrical activity (Behnke et al., 2013).

3.3.1.11. Atmospheric shock waves. Atmospheric shock waves are formed when volcanic materials are ejected at supersonic velocity during an explosive eruption. Shock waves dissipate as they move farther from the source (Scott, 1989). During the AD1717 eruption of Vesuvio, observers described the sound as "a sort of murmeuring, sighing, throbbing, churning, dashing of waves, and between whiles a noise like that of thunder or cannon, which was constantly attended with a clattering like that of tiles falling from the tops of houses on the streets" (Anon., 1717, In Blong, 1984, p.58). The primary impact of shock waves is structural damage and glass breakage. Shock waves were reported during the AD1707, AD1749, AD1754, AD1911 and AD1965 eruptions (Table 2).

3. Discussion

We first provided an overview of the regional and local tectonic and geologic setting of Taal Volcano, collated and summarized from published references. There is very limited descriptive geological data available on the prehistoric eruptions and the evolution of Taal during older Quaternary eruptions. However, one important work on the evolution of Taal Caldera was published by Listanco (1994) where he identified four caldera-forming events based on four ignimbrite deposits. Others are works on the c. 5700 y old Scoria Pyroclastic Flow (Martinez and Williams, 1999) and on the Buco Base Surge (Geronimo, 1988).

The central part of this paper provides a detailed review of the historical eruptions from Taal Volcano based upon a synthesis of all available published and unpublished literature. The critical review provides a summary of significant narrated observations, as well as some new insights and interpretations on the processes and products from eruptions between AD1572 and AD1977, summarized in Section 3.2 and listed in Table 2. Of the 33 identified eruptions of Taal Volcano, in this time, the AD1749, AD1754, AD1911, and AD1965 events were described in greater detail than others largely because of more information being available due to the magnitude and intensity of these eruptions, as well as the catastrophic impacts resulting that resulted.

The most significant updated interpretations provided in this paper are that:

1. The eruption style of the AD1572 eruption is more likely strombolian than phreatomagmatic as previously classified, with the occurrence of lava fountaining identified. Likewise, the eruptive style of the AD1715 event was newly classified as strombolian with lava fountaining and lava flows.
2. At least 9 previously identified eruptions were deemed as uncertain. The AD1605-AD1611 events more likely corresponds to seismic swarms that did not result in eruptions. The AD1634, AD1635, and AD1645 events were described simply as solfataric activity but occurrence of an eruption is uncertain. The AD1790, AD1825, AD1842, AD1873 and AD1903 eruptions were listed in recent published and unpublished documents but do not ascribe any reference to support or confirm their occurrence and we therefore interpret these as solfataric activities that did not culminate in eruptions.
3. The AD1731 and AD1878 events are newly classified as phreatomagmatic.
4. The eruptions in AD1749, AD1754, AD1911 and AD1965 could not be classified as one single eruptive style throughout their duration. The AD1754 eruption was initially plinian/subplinian, then transitioned to a phreatomagmatic. The AD1968 and AD1969 eruptions transitioned from phreatomagmatic then became strombolian, while the AD1965 eruption transitioned from strombolian to phreatomagmatic.
5. A significant implication to aviation hazard is implied by the nar- rative of tephra fall reaching Manila during the AD1754 eruption. Should a major eruption occur similar in magnitude to the AD1754 event, an aviation crisis could be expected, similar to the ones ex- perienced during the AD1991 eruption of Pinatubo volcano and the AD2010 eruption of Eyjafjallajokull volcano, Iceland. Additional

literature review and geological investigation is still needed in order to obtain details on dispersal and thickness of tephra during past major eruptions of Taal.

6. Electrical activities accompanied most of the large-magnitude eruptions of Taal including during the AD1707, AD1749, AD1754, AD1911 and AD1965 events. The AD1707 eruption, with an assigned VEI of 2 implies that even with less than a 5 km high plume, lightning can be generated.
7. Liquefaction effects are interpreted to have occurred during the AD1749, AD1754, and AD1911 eruptions. The accompanying large-magnitude volcanic earthquakes resulted in severe ground shaking that most likely generated sand boils, lateral spreading, and settlement in lakeshore areas. This is the first time that the above-mentioned phenomena are interpreted as liquefaction.
8. Pyroclastic surges in AD1754 travelled significantly farther than previously known, and well into areas that are today densely populated.

5. Recommendations for future work

1. More research is critically needed on the older Quaternary caldera-forming eruptions that produced large-volume pyroclastic deposits. These are extensively distributed and exposed and will build a better picture of the early evolution of Taal Volcano, as well as provide an estimate of recurrence rate of large eruptions from Taal Caldera.
2. One especially important question is whether and how small eruptions can grow into large explosive eruptions like that of c. 5700 BP. Knowledge of any precursory eruptions (or absence thereof) is important for anticipating a future caldera-forming event.
3. Nine previously listed eruptions have descriptions that only indicate solfataric activity. These eruptions are deemed uncertain and need further investigation for possible reclassification.
4. Tephra fall dispersion had the most extensive impact of all volcanic hazards from Taal Volcano. The potential dispersal of tephra fall in various climactic conditions can be assessed through numerical modeling. This in turn can provide critical hazard information to stakeholders from the agricultural, engineering, tourism, aviation, and emergency management sectors in regards to future events.
5. The PDCs at Taal created sand blast effects on objects in their paths, not only at Taal Volcano island but also in communities on the mainland. Additional mapping of the distal extent of the PDCs could shed light on the potential hazard these deposits pose to Taal communities.
6. Although there were only limited accounts of lahar occurrence, the threat still exists, especially if tephra fall is subsequently followed by heavy precipitation. Further investigation of lahar hazards and risks should be undertaken, especially with increasing numbers living around Taal Volcano.
7. Lastly, although we have provided a summary overview of all known historical eruptions of Taal Volcano, more work needs to be done to understand the changes in eruptive styles interpreted from available records. Assigned VEIs may still be further reviewed so that they truly reflect the magnitude and explosivity of the eruptions from Taal Volcano.

6. Conclusion

With increasing population and urbanization of communities in and around Taal Volcano island, and the growing societal impact of a recurrence of a worst-case scenario at Taal Volcano similar to eruptions in AD1749, AD1754, AD1911 and AD1965, better understanding of the mechanism and dynamics of potential processes and products could provide important information for hazard and risk assessment, and emergency management.

This critical review of eruption reports provides new insights and interpretations of the processes and products of historical eruptions of Taal Volcano going back to AD1572 and through to the last eruption in AD1977. Using the knowledge from these past eruptions, and combined with development and application of technologies for monitoring, mapping, and hazard modeling, it is hoped that we can move closer to the goal of finding a more relevant and effective solution to disaster risk reduction in the event of another explosive eruption from Taal Volcano.

Acknowledgements

The authors wish to acknowledge the efforts done by previous authors to provide monumental descriptions of the eruptive history of Taal Volcano. This paper tried to summarize these very significant ef- forts, as well as provide additional interpretations of eruptive phe- nomena where required.

We would like to express our sincere gratitude to the Philippine Institute of Volcanology and Seismology of the Department of Science and Technology issued PHIVOLCS Office Order No. 33, Series of 2016 which provides travelling expenses during field surveys conducted at Taal Volcano; no financial grant was given by The University of Sydney except use of Library and school facilities during the main author's stay in the university as a PhD student; the main author was an Australia Awards PhD scholar from 2013 to 2017 (Only Application ID IRIS 22207806801 and File No. H124013 available). We thank the editor and referee for invaluable comments and suggestions that greatly im- proved this review.

References

Acharya, H.K., Aggarwal, Y.P., 1980. Seismicity and tectonics of the Philippine Islands. J. Geophys. Res. 85 (B6), 3239–3250.
Adams, G.I., 1910. Geological reconnaissance of southwestern Luzon. Philipp. J. Sci. Sect. A 5 (2), 57–116.
Alcaraz, A., 1966. Surveillance of Taal Volcano. Philipp. Geol. 20 (1), 1–13.
Alcaraz, A., Datuin, R., 1974. Geothermal phenomena of the 1965 phreatomagmatic eruption of Taal Volcano. J. Geol. Soc. Philipp. 28 (1), 31–40.
Alcaraz, A.P., Datuin, R., 1977. Notes on Taal Volcano Prognostics. J. Geol. Soc. Philipp. 16 (2), 18–20.
Allen, C.R., 1962. Circum-Pacific faulting in the Philippines-Taiwan region. J. Geophys. Res. 67 (12), 4795–4812. http://dx.doi.org/10.1029/JZ067i012p04795.
Andal, G.A., Aguila, L.G., 1976. Prognostic Criteria of the 1976 eruption of Taal Volcano. (PIV055). Commission on Volcanology (COMVOL), Quezon City, Philippines Unpublished report.
Andal, C., 1984. Summary of observed precursory signs: Taal Volcano. In: Volcano monitoring. National Science Development Board (NSDB). Commission on Volcanology. COMVOL, Quezon City.
Arpa, M.C.B., Patino, L.C., Vogel, T.A., 2008. The basaltic to trachydacitic upper Diliman Tuff in Manila: petrogenesis and comparison with deposits from Taal and Laguna calderas. J. Volcanol. Geotherm. Res. 177 (4), 1020–1034. http://dx.doi.org/10.1016/j.jvolgeores.2008.07.024.
Arpa, M.C., Hernández, P.A., Padrón, E., Reniva, P., Padilla, G.D., Bariso, E., Melian, G.V., Barrancos, J., Nolasco, D., Calvo, D., Perez, N.M., Solidum Jr., R.U., 2013. Geochemical evidence of magma intrusion inferred from diffuse CO_2 emissions and fumarole plume chemistry: the 2010–2011 volcanic unrest at Taal Volcano, Philippines. Bull. Volcanol. 75 (10), 1–13. http://dx.doi.org/10.1007/s00445-013-0747-9.
Aurelio, M.A., 2000. Shear partitioning in the Philippines: constraints from Philippine Fault and global positioning system data. Island Arc 9 (4), 584–597. http://dx.doi.org/10.1111/j.1440-1738.2000.00304.x.
Ayris, P.M., Delmelle, P., 2012. The immediate environmental effects of tephra emission. Bull. Volcanol. 74 (9), 1905–1936.
Bacolcol, T.C., Solidum Jr., R.U., Yu, S.-B., Luis Jr., A., Jorgio, R., Pelicano, A., the PHIVOLCS GPS Working Group, 2012. Current Motions of the Philippine Mobile Belt Derived From Global Positioning Data. Unpublished manuscript.
Banks, N.G., Tilling, R.I., Harlow, D.H., Ewert, J.W., 1989. Volcano monitoring and short-term forecasts. In: Tilling (Ed.), Volcanic Hazards. American Geophysical Union, pp. 25–49. Retrieved from. https://doi.org/10.1029/SC001p0051.
Barrier, E., Huchon, P., Aurelio, M., 1991. Philippine fault: a key for Philippine kinematics. Geology 19 (1), 32–35. http://dx.doi.org/10.1130/0091-7613(1991)019<0032:pfakfp>2.3.co;2.
Bartel, B.A., Hamburger, M.W., Meertens, C.M., Lowry, A.R., Corpuz, E., 2003. Dynamics of active magmatic and hydrothermal systems at Taal Volcano, Philippines, from continuous GPS measurements. J. Geophys. Res. B: Solid Earth 108 (10). http://dx.doi.org/10.1029/2002JB002194. (ECV 4-1–ECV 4-15).
Behnke, S.A., Thomas, R.J., McNutt, S.R., Schneider, D.J., Krehbiel, P.R., Rison, W., Edens, H.E., 2013. Observations of volcanic lightning during the 2009 eruption of Redoubt Volcano. J. Volcanol. Geotherm. Res. 259, 214–234. http://dx.doi.org/10.1016/j.jvolgeores.2011.12.010.

Berninghausen, W.H., 1969. Tsunamis and seismic seiches of southeast Asia. Bull. Seismol. Soc. Am. 59 (1), 289–297.
Blong, R.J., 1984. Volcanic Hazards: A Sourcebook on the Effects of Eruptions. Academic Press, Australia.
Bornas, M.A.V., Delos Reyes, P.J., Lim, R.B., Rivera, D.V., Pidlaoan, A.C., 2016. Preliminary Map of Base Surge Deposits Related to the AD1754 Eruption of Taal Volcano, Philippines.
Buencuchillo, F., 1754. Relacion de lo sucedido Con el Volcan de la Laguna de "Bongbong" en la Provincia de Taal y Balayan (English Translation by Fr. P. Hernandez, Augustinian Convent, Manila). Valladolid, Spain.
Carey, S.N., 2005. Understanding the physical behavior of volcanoes. In: Marti, J., Ernst, G. (Eds.), Volcanoes and the Environment. Cambridge University Press, Cambridge, United Kingdom.
Carslaw, D.C., Williams, M.L., Barratt, B., 2012. A short-term intervention study — impact of airport closure due to the eruption of Eyjafjallajökull on near-field air quality. Atmos. Environ. 54, 328–336. http://dx.doi.org/10.1016/j.atmosenv.2012.02.020.
Cas, R.A.F., 1987. Volcanic Successions: Modern and Ancient: A Geological Approach to Processes, Products and Successions. Allen & Unwin Ltd., London.
Casadevall, T.J., Delos Reyes, P.J., Schneider, D.J., 1996. The 1991 Pinatubo Eruptions and their effects on aircraft operations. In: Newhall, C.G., Punongbayan, R.S. (Eds.), Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology; (Seattle: University of Washington Press), Quezon City, pp. 1071–1088.
Castillo, P.R., Newhall, C.G., 2004. Geochemical constraints on possible subduction components in lavas of Mayon and Taal Volcanoes, Southern Luzon, Philippines. J. Petrol. 45 (6), 1089–1108. http://dx.doi.org/10.1093/petrology/egh005.
Centeno y Garcia, J., 1885. Estudio Geologico del Volcan de Taal. Tello, Madrid.
Chester, D., 1993. Volcanoes and Society. Routledge, Chapman and Hall, Inc., Great Britain.
Christiansen, E.H., 2015. Dynamic Earth: An Introduction to Physical Geology. Jones & Bartlett Learning, USA.
De Boer, J.Z., Odom, L.A., Ragland, P.C., Snider, F.G., Tilford, N.R., 1980. The Bataan orogene: eastward subduction, tectonic rotations, and volcanism in the western Pacific (Philippines). Tectonophysics 67 (3–4), 251–282. http://dx.doi.org/10.1016/0040-1951(80)90270-X.
De Luna, E.U., 1988. The Geochemistry and Petrography of the Major Eruptive Units of Taal Volcano's 1965 to 1977 Eruptions, Taal Volcano, Philippines. University of the Philippines, Diliman, Quezon City, Philippines(Retrieved from http://www.elib.gov.ph/ Available from Science and Technology Information Institute).
Defant, M.J., De Boer, J.Z., Dietmar, O., 1988. The western Central Luzon volcanic arc, the Philippines: two arcs divided by rifting? Tectonophysics 145 (3–4), 305–317. http://dx.doi.org/10.1016/0040-1951(88)90202-8.
Defant, M.J., Jacques, D., Maury, R.C., De Boer, J., Joron, J.-L., 1989. Geochemistry and tectonic setting of the Luzon arc, Philippines. Geol. Soc. Am. Bull. 101 (5), 663–672. http://dx.doi.org/10.1130/0016-7606(1989)101<0663:gatsot>2.3.co;2.
Donn, W.L., Balachandran, N.K., 1981. Mount St. Helens eruption of 18 May 1980: air waves and explosive yield. Science 213 (4507), 539–541.
Druitt, T.H., 1998. Pyroclastic density currents. Geol. Soc. Lond., Spec. Publ. 145 (1), 145–182. http://dx.doi.org/10.1144/gsl.sp.1996.145.01.08.
Emergeo Working Group, 2013. Liquefaction phenomena associated with the Emilia earthquake sequence of May–June 2012 (Northern Italy). Nat. Hazards Earth Syst. Sci. 13 (4), 935. http://dx.doi.org/10.5194/nhess-13-935-2013.
Feldman, L.H., 1988. Report Pertaining to Volcano Collected From Colonial Archives in Spain, for the Philippine Islands. Unpublished report for Smithsonian Institution Global Volcanism Program. pp. 36.
Fikos, I., Vargemezis, G., Zlotnicki, J., Puertollano, J.R., Alanis, P.B., Pigtain, R.C., Villacorte, E.U., Malipot, G.A., Sasai, Y., 2012. Electrical resistivity tomography study of Taal Volcano hydrothermal system, Philippines. Bull. Volcanol. 74 (8), 1821–1831. http://dx.doi.org/10.1007/s00445-012-0638-5.
Fisher, R.V., Schmincke, H.-U., 1984. Pyroclastic Rocks. Springer-Verlag, Berlin; New York.
Fitch, T.J., 1972. Plate convergence, transcurrent faults and internal deformation adjacent to Southeast Asia and western Pacific. J. Geophys. Res. 77 (23), 4432–4460.
Fontaine, F.J., Rabinowicz, M., Boulègue, J., Jouniaux, L., 2002. Constraints on hydrothermal processes on basaltic edifices: inferences on the conditions leading to hydrovolcanic eruptions at Piton de la Fournaise, Réunion Island, Indian Ocean. Earth Planet. Sci. Lett. 200 (1–2), 1–14. http://dx.doi.org/10.1016/S0012-821X(02)00599-X.
Förster, H., Oles, D., Knittel, U., Defant, M.J., Torres, R.C., 1990. The Macolod Corridor: a rift crossing the Philippine island arc. Tectonophysics 183 (1–4), 265–271. http://dx.doi.org/10.1016/0040-1951(90)90420-D.
Galgana, G., Hamburger, M., McCaffrey, R., Corpuz, E., Chen, Q., 2007. Analysis of crustal deformation in Luzon, Philippines using geodetic observations and earthquake focal mechanisms. Tectonophysics 432 (1–4), 63–87. http://dx.doi.org/10.1016/j.tecto.2006.12.001.
Galgana, G.A., Newman, A.V., Hamburger, M.W., Solidum, R.U., 2014. Geodetic observations and modeling of time-varying deformation at Taal Volcano, Philippines. J. Volcanol. Geotherm. Res. 271, 11–23. http://dx.doi.org/10.1016/j.jvolgeores.2013.11.005.
Garcia, L.C., Valenzuela, R.G., Arnold, E.P., Macalingcag, T.G., Ambubuyog, G.F., Lance, N.T., Cordeta, J.D., Doniego, A.G., Dabi, A.C., Balce, G.R., Su, S.S., 1985. In: Arnold, E.P. (Ed.), Catalogue of Philippine Earthquakes (1589–1983). vol. 4 U.S. Geological Survey and Office of Foreign Disaster Assistance, Agency for International Development, United States Department of State, Quezon City, Philippines.
Geronimo, S.G., 1988. Characteristics, Depositional Facies and Emplacement Mechanisms of the Buco Base Surge Sequence, Batangas Province. (Master of Science in Geology), University of the Philippines, Diliman, Quezon City, Philippines.
Győri, E., Tóth, L., Mónus, P., 2015. Secondary effects generated by earthquakes: liquefaction occurrences in and around Hungary. Acta Geodaetica Geophys. 50 (1), 79–95. http://dx.doi.org/10.1007/s40328-014-0079-z.
Hamburger, M.W., Cardwell, R.K., Isacks, B.L., 1983. Seismotectonics of the Northern Philippine Island Arc. American Geophysical Union.
Hargrove, T.R., 1991. The Mysteries of Taal - A Philippine Volcano and Lake, Her Sea Life and Lost Towns. Book,ark Publishing, Manila, pp. 204.
Hayes, D.E., Lewis, S.D., 1985. Structure and tectonics of the Manila trench system, Western Luzon, Philippines. Energy 10 (3–4), 263–279. http://dx.doi.org/10.1016/0360-5442(85)90046-5.
Hoblitt, R.P., Wolfe, E.W., Scott, W.E., Couchman, M.R., Pallister, J.S., Javier, D., 1996. The preclimactic eruptions of Mount Pinatubo, June 1991. In: Newhall, C.G., Punongbayan, R.S. (Eds.), Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology, Quezon City, pp. 457–511 (Seattle: University of Washington Press).
Holloway, N.H., 1981. The North Palawan block, Philippines: its relation to the Asian mainland and its role in the evolution of the South China Sea. Bull. Geol. Soc. Malaysia 14, 19–58.
Horwell, C., Baxter, P., 2006. The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. Bull. Volcanol. 69 (1), 1–24. http://dx.doi.org/10.1007/s00445-006-0052-y.
Hsu, Y.-J., Yu, S.-B., Song, T.-R.A., Bacolcol, T., 2012. Plate coupling along the Manila subduction zone between Taiwan and northern Luzon. J. Asian Earth Sci. 51, 98–108. http://dx.doi.org/10.1016/j.jseaes.2012.01.005.
Hsu, Y.-J., Yu, S.-B., Loveless, J.P., Bacolcol, T., Solidum, R., Luis, A., Pelicano, A., Woessner, J., 2016. Interseismic deformation and moment deficit along the Manila subduction zone and the Philippine Fault system. J. Geophys. Res. Solid Earth 121 (10), 7639–7665. http://dx.doi.org/10.1002/2016JB013082.
Jenkins, S., Komorowski, J.C., Baxter, P.J., Spence, R., Picquout, A., Lavigne, F., Surono, 2013. The Merapi 2010 eruption: an interdisciplinary impact assessment methodology for studying pyroclastic density current dynamics. J. Volcanol. Geotherm. Res. 261, 316–329. http://dx.doi.org/10.1016/j.jvolgeores.2013.02.012.
Karig, D.E., 1983. Accreted terranes in the northern part of the Philippine Archipelago. Tectonics 2 (2), 211–236. http://dx.doi.org/10.1029/TC002i002p00211.
Knittel, U., Defant, M.J., Raczek, I., 1988. Recent enrichment in the source region of arc magmas from Luzon island, Philippines: Sr and Nd isotopic evidence. Geology 16 (1), 73–76. http://dx.doi.org/10.1130/0091-7613(1988)016<0073:reitsr>2.3.co;2.
Kokelaar, P., 1986. Magma-water interactions in subaqueous and emergent basaltic. Bull. Volcanol. 48 (5), 275–289. http://dx.doi.org/10.1007/BF01081756.
Kuhnt, W., et al., 2005. The impact of the 1991 Mt. Pinatubo eruption on deep-sea foraminiferal communities: a model for the Cretaceous–Tertiary (K/T) boundary? Palaeogeogr. Palaeoclimatol. Palaeoecol. 224 (1–3), 83–107. http://dx.doi.org/10.1016/j.palaeo.2005.03.042.
Kumagai, H., Lacson, R., Maeda, Y., Figueroa, M.S., Yamashina, T., 2014. Shallow S wave attenuation and actively degassing magma beneath Taal Volcano, Philippines. Geophys. Res. Lett. 41 (19), 6681–6688. http://dx.doi.org/10.1002/2014GL061193.
Latter, J.H., 1981. Tsunamis of volcanic origin: summary of causes, with particular reference to Krakatoa, 1883. Bull. Volcanol. 44 (3), 467–490. http://dx.doi.org/10.1007/BF02600578.
Lim, J.B.R., 1983. Correlating the orientation of tectonic stresses with the flank eruptions of Taal Volcano. Philipp. J. Volcanol. 1 (1), 41–68.
Listanco, E., 1994. Space-Time Patterns in the Geologic and Magmatic Evolution of Calderas: A Case Study at Taal Volcano, Philippines (Doctor of Science PhD thesis). University of Tokyo, Tokyo, Japan.
Listanco, E., 1997. Taal Volcano Field Guide Book for the International Conference on Materials Recycling Near Convergent Plate Boundaries, Puerto Azul, Philippines. Carnegerie Institution of Washington/Institute for the study of the Earth's Interior/PHIVOLCS-DOST, pp. 5–41.
Liyanapathirana, D.S., Poulos, H.G., 2004. Assessment of soil liquefaction incorporating earthquake characteristics. Soil Dyn. Earthq. Eng. 24 (11), 867–875. http://dx.doi.org/10.1016/j.soildyn.2003.11.010.
Lowry, A.R., Hamburger, M.W., Meertens, C.M., Ramos, E.G., 2001. GPS monitoring of crustal deformation at Taal Volcano, Philippines. J. Volcanol. Geotherm. Res. 105 (1–2), 35–47. http://dx.doi.org/10.1016/S0377-0273(00)00238-9.
Ludwig, W.J., 1970. The Manila Trench and west Luzon Trough, III; seismic-refraction measurements. Deep-Sea Res. 17, 553–571.
Maeda, Y., Kumagai, H., Lacson, R., Figueroa, M.S., Yamashina, T., 2013. Source process of long-period seismic events at Taal volcano, Philippines: vapor transportation and condensation in a shallow hydrothermal fissure. J. Geophys. Res. Solid Earth 118 (6), 2832–2846. http://dx.doi.org/10.1002/jgrb.50205.
Magill, C.R., Thomas, W., Okada, T., 2013. Observations of tephra fall impacts from the 2011 Shinmoedake eruption, Japan. Earth Planets Space 65, 1–22 (doi:10.5047).
Martin, C., 1911. Observations on the recent eruption of Taal Volcano. Philipp. J. Sci. 6A (2), 87–91.
Martinez, M.L., 1997. Stratigraphy and Geochemistry of Taal Caldera Scoria Pyroclastic Flow Deposit, Philippines (Master of Science in Geology Masteral Thesis). Arizona State University, Tempe, Arizon, USA.
Martinez, M.M.L., Williams, S.N., 1999. Basaltic andesite to andesite scoria pyroclastic flow deposits from Taal caldera, Philippines. J. Geol. Soc. Philipp. 54 (1–2), 1–18.
Masigla, L.M., Ruelo, H.B., 1987. Interpretation of the Historical Eruptive Activity of Taal Volcano, Philippines. Retrieved from Quezon City, Philippines.
McNutt, S.R., Davis, C.M., 2000. Lightning associated with the 1992 eruptions of Crater Peak, Mount Spurr Volcano, Alaska. J. Volcanol. Geotherm. Res. 102 (1–2), 45–65. http://dx.doi.org/10.1016/S0377-0273(00)00181-5.
McNutt, S.R., Williams, E.R., 2010. Volcanic lightning: global observations and

constraints on source mechanisms. Bull. Volcanol. 72 (10), 1153–1167. http://dx.doi.org/10.1007/s00445-010-0393-4.
Medici, E.F., Allen, J.S., Waite, G.P., 2014. Modeling shock waves generated by explosive volcanic eruptions. Geophys. Res. Lett. 41 (2), 414–421. http://dx.doi.org/10.1002/2013GL058340.
Miklius, A., Flower, M.F.J., Huijsmans, J.P.P., Mukasa, S.B., Castillo, P., 1991. Geochemistry of lavas from Taal volcano, southwestern Luzon, Philippines: evidence for multiple magma supply systems and mantle source heterogeneity. J. Petrol. 32 (3), 593–627.
Moore, J.G., 1967. Base surge in recent volcanic eruptions. Bull. Volcanol. 30 (1), 337–363. http://dx.doi.org/10.1007/BF02597678.
Moore, J.G., Nakamura, K., Alcaraz, A., 1966. The 1965 eruption of Taal Volcano. Science 151 (3713), 955–960. http://dx.doi.org/10.2307/1718667.
Neumann van Padang, M., 1953. Catalogue of Active Volcanoes of the World Including Solfatara Fields, Philippine Island and Cochin, China. Int. Volcanol. Assoc., United States.
Newhall, C.G., Dzurisin, D., 1988. Historical Unrest at Large Calderas of the World. U. S. Geological Survey, Reston, VA, United States.
Newhall, C.G., Self, S., 1982. The volcanic explosivity index (VEI): an estimate of explosive magnitude for historical volcanism. J. Geophys. Res. 87 (2), 1231–1238.
Nishigami, K., Shibutani, T., Ohkura, T., Hirata, M., Horikawa, H., Shimitzu, K., Matsuo, S., Nakao, S., Ando, M., Bautista, B.C., Baustista, M.L.P., Barcelona, E.S., Valerio, R., Lanuza, A.G., Chu, A.V., Villegas, J.J., Rasdas, A.R., Mangao, E.A., Gabinete, E., Punongbayan, B.J.T., Narag, I.C., Marte, F., Punongbayan, R., 1994. Shallow crustal structure beneath Taal volcano, Philippines, revealed by the 1993 seismic explosion survey. Bull. Disaster Prev. Res. Inst. 44 (382), 123–138.
Ohkura, T., Nakano, T., Besana, G.M., Sicat, M.J., Hoso, Y., Mangao, E., Geraldo, I., Daligdig, J.A., Ando, M., Punongbayan, R.S., 2001. GPS measurements in the Macolod Corridor, Philippines. J. Geol. Soc. Philipp. 56 (3&4), 97–104.
Oles, D., 1991. Geology of the Macolod Corridor intersecting the Bataan-Mindoro island arc, The Philippines. In: Final Report for German Research Society Project No. Fo 53/16-1 to 2 and German Agency for Technical Cooperation Project No. 85-2522.2.06.100.
Oppenheimer, C., 1991. People and volcanoes: Taal Island, Philippines. Geol. Today 7 (1), 19–23.
Oswalt, J.S., Nichols, W., O'Hara, J.F., 1996. Meteorological observations of the 1991 Mount Pinatubo Eruption in the 1991 Pinatubo eruptions and their effects on aircraft operations. In: Newhall, C.G., Punongbayan, R.S. (Eds.), Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology; Seattle: University of Washington Press, Quezon City, pp. 625–636.
Paris, R., Switzer, A.D., Belousova, M., Belousov, A., Ontowirjo, B., Whelley, P.L., Ulvrova, M., 2014. Volcanic tsunami: a review of source mechanisms, past events and hazards in Southeast Asia (Indonesia, Philippines, Papua New Guinea). Nat. Hazards 70 (1), 447–470. http://dx.doi.org/10.1007/s11069-013-0822-8.
PHIVOLCS-DOST, 1991. Taal Volcano profile. In: Compilation of Eruptive History and Geology of Taal Volcano. PHIVOLCS Library, Quezon City, Philippines.
PHIVOLCS-DOST, 1995. Taal decade volcano international workshop interim report. In: Paper Presented at the Taal Decade Volcano International Workshop: Development Academy of the Philippines, Tagaytay City, Philippines, (23–27 October).
PHIVOLCS-DOST, 2016a. Classification of Volcanoes. Retrieved from. http://www.phivolcs.dost.gov.ph/index.php?option=com_content&view=article&id=50&Itemid=86.
PHIVOLCS-DOST, 2016b. Historical Eruptions of Taal Volcano. Retrieved from. http://202.90.128.67/html/update_VMEPD/vmepd/vmepd/TV%20HistEruptions.pdf.
Pratt, W.E., 1911a. The eruption of Taal Volcano, January 30, 1911. Philipp. J. Sci. 6, 2 (63-86 plus plates).
Pratt, W.E., 1911b. The eruption of Taal Volcano. Bull. Am. Geogr. Soc. 43 (12), 903–916. http://dx.doi.org/10.2307/200468.
Pratt, W.E., 1916. An unusual form of volcanic ejecta. J. Geol. 24 (5), 450–455.
Punongbayan, R.S., Tilling, R.I., 1989. Some Recent Case Histories In Volcanic Related Hazards, American Geophysical Union Short Course. pp. 81–101.
Ragland, P.C., Defant, M.J., 1983. Silica standardization: a discriminant technique applied to a volcanic arc system. Earth Planet. Sci. Lett. 64 (3), 387–395. http://dx.doi.org/10.1016/0012-821X(83)90098-5.
Ramos, E.G., 2001. Geomorphic features of Taal Volcano. J. Geol. Soc. Philipp. 56 (3&4), 105–123.
Rangin, C., Le Pichon, X., Mazzotti, S., Pubellier, M., Chamot-Rooke, N., Aurelio, M., Walpersdorf, A., Quebral, R., 1999. Plate convergence measured by GPS across the Sundaland/Philippine Sea Plate deformed boundary: the Philippines and eastern Indonesia. Geophys. J. Int. 139 (2), 296–316. http://dx.doi.org/10.1046/j.1365-246x.1999.00969.x.
Repetti, W.C., 1935. Tectonic Lines of the Philippine Islands. Philippine Weather Bureau.
Ruelo, H.B., 1983. Morphological and crater development of Mt. Tabaro eruption site, Taal Volcano, Philippines. Philipp. J. Volcanol. 1 (2), 19–68.
Saderra Maso, M., 1904. Volcanoes and seismic centers of the Philippine Archipelago, bulletin 3, census of the Philippine Islands. 80p. Retrieved from: https://books.google.com.ph/books?id=m1cRAAAAIAAJ&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false.
Saderra Maso, M., 1911. The Eruption of Taal Volcano, January 30, 1911. Bureau of Printing, Manila, Philippines.
Schweller, W.J., Karig, D.E., Bachman, S.B., 1983. Original setting and emplacement history of the Zambales ophiolite, Luzon, Philippines from stratigraphic evidence. In: Hayes, D.E. (Ed.), The tectonic and Geologic Evolution of Southest Asian Seas and Islands: Part 2. Geophysical Monograph Service, vol. 27. American Geological Union, Washington, D.C., pp. 124–138.
Schweller, W.J., Roth, P.H., Karig, D.E., Bachman, S.B., 1984. Sedimentation history and biostratigraphy of ophiolite-related tertiary sediments, Luzon, Philippines. Geol. Soc. Am. Bull. 95 (11), 1333–1342. http://dx.doi.org/10.1130/0016-7606(1984) 95<1333:shaboo>2.0.co;2.
Scott, W.E., 1989. Volcanic and Related Hazards Volcanic Hazards. American Geophysical Union, pp. 9–23.
Self, S., Zhao, J.-X., Holasek, R.E., Torres, R.C., King, A.J., 1996. The atmospheric impact of the 1991 Mount Pinatubo eruption. In: Newhall, C.G., Punongbayan, R.S. (Eds.), Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology; University of Washington Press, Quezon City; Seattle (2013).
Smithsonian Global Volcanism Program, 2016. Taal Volcano (273070). In: Venzke, E. (Ed.), Volcanoes of the World, v. 4.5.1. Smithsonian Institution Downloaded 26 Sep 2016. http://volcano.si.edu/volcano.cfm?vn=273070. https://doi.org/10.5479/si.GVP.VOTW4.
Sudo, M., Listanco, E., Ishikawa, N., Tagami, T., Kamata, H., Tatsumi, Y., 2000. K-Ar dating of the volcanic rocks from Macolod Corridor in Sothwestern Luzon, Philippines: towards understanding of the Quaternary volcanism and tectonics. J. Geol. Soc. Philipp. 55 (1–2), 89–104.
Tilling, R.I., 2005. Volcanic hazards. In: Marti, J., Ernst, G. (Eds.), Volcanoes and the Environment. Cambridge University Press, Cambridge, United Kingdom, pp. 55–89.
Torres, R.C., 1989. Tephra Characteristics of the Scoria Deposits of Taal Volcano's 1754 Eruption (Master of Science in Geology Masteral thesis). University of the Philippines, Diliman, Quezon City, Philippines.
Torres, R.C., Self, S., Punongbayan, R.S., 1995. Attention focuses on Taal: decade volcano of the Philippines. Eos 76 (24), 241,246–247.
USGS, 2016. Earthquake Hazards Program, Earthquake Glossary-Liquefaction. Retrieved from. http://earthquake.usgs.gov/learn/glossary/?term=liquefaction.
Vogel, T.A., Flood, T.P., Patino, L.C., Wilmot, M.S., Maximo, R.P.R., Arpa, C.B., Arcilla, C.A., Stimac, J.A., 2006. Geochemistry of silicic magmas in the Macolod Corridor, SW Luzon, Philippines: evidence of distinct, mantle-derived, crustal sources for silicic magmas. Contrib. Mineral. Petrol. 151 (3), 267–281. http://dx.doi.org/10.1007/ s00410-005-0050-7.
Wahyunto, K., et al., 2012. Agricultural recovery action for area affected by 2010 Merapi Volcano eruption, Indonesia. Int. J. Geoinf. 8 (4), 41–48.
Wardman, J.B., Wilson, T.M., Bodger, P.S., Cole, J.W., Stewart, C., 2012. Potential impacts from tephra fall to electric power systems: a review and mitigation strategies. Bull. Volcanol. 74 (10), 2221–2241. http://dx.doi.org/10.1007/s00445-012-0664-3.
Waters, A.C., Fisher, R.V., 1971. Base surges and their deposits: Capelinhos and Taal Volcanoes. J. Geophys. Res. 76 (23), 5596–5614. http://dx.doi.org/10.1029/JB076i023p05596.
Wessel, P., Smith, W.H.F., 1996. A global, self-consistent, hierarchical, high-resolution shoreline database. J. Geophys. Res. 101 (B4), 8741–8743. http://dx.doi.org/10.1029/96JB00104.
Williams, H., McBirney, A.R., 1979. Volcanology. Freeman, Cooper, San Francisco, CA (c1979).
Willis, B., 1937. Geologic observations in the Philippine archipelago. Natl. Res. Counc. Philipp. Bull. 13.
Wilson, T.M., Stewart, C., Sword-Daniels, V., Leonard, G., Johnston, D.M., Cole, J.W., Wardman, J., Wilson, G., Barnard, S., 2012. Volcanic ash impacts on critical infrastructure. Phys. Chem. Earth A/B/C 45–46, 5–23. http://dx.doi.org/10.1016/j.pce.2011.06.006.
Wilson, G., Wilson, T.M., Deligne, N.I., Cole, J.W., 2014. Volcanic hazard impacts to critical infrastructure: a review. J. Volcanol. Geotherm. Res. 286, 148–182. http://dx.doi.org/10.1016/j.jvolgeores.2014.08.030.
Wolfe, J.A., 1986. Breccias related to explosive volcanism. J. SE Asian Earth Sci. 1 (2), 63–79. http://dx.doi.org/10.1016/0743-9547(86)90022-X.
Wolfe, J.A., 1988. Arc magmatism and mineralization in North Luzon and its relationship to subduction at the East Luzon and North Manila Trenches. J. SE Asian Earth Sci. 2 (2), 79–93. http://dx.doi.org/10.1016/0743-9547(88)90011-6.
Wolfe, J.A., Self, S., 1983. Structural lineaments and neogene volcanism in Southwestern Luzon. In: Hayes, D.E. (Ed.), The Tectonic and Geologic Evolution of Southeast Asia Seas and Island, Part 2. vol. 27. pp. 157–172.
Worcester, D.C., 1912. Taal Volcano and its recent destructive eruption. In: The National Geographic Magazine, XXIII, (267–313).
Yu, S.-B., Hsu, Y.-J., Bacolcol, T., Yang, C.-C., Tsai, Y.-C., Solidum, R., 2013. Present-day crustal deformation along the Philippine Fault in Luzon, Philippines. J. Asian Earth Sci. 65, 64–74. http://dx.doi.org/10.1016/j.jseaes.2010.12.007.

APPENDIX B

Appendix B summarises the recorded historical eruptions of Taal from AD1572 to 2015. Sources of information include Saderra Masó (1904, 1911); Pratt (1911); Worcester (1912); Moore et al. (1966); Ruelo (1983); Masigla and Ruelo (1987); Oppenheimer (1991); DOST-PHIVOLCS (1991, 1995, 2016); Smithsonian (2016); Delos Reyes et al. (2018).

Recorded historical eruptions of Taal Volcano from AD1572 to 2015. Dash lines represent divisions of the eruptions into four series based on the locations of the eruption centers and eruption repose periods. Sources: Masó, 1911; Pratt, 1911; Worchester, 1912; Moore et al., 1966; Ruelo, 1983; Oppenheimer, 1991; DOST-PHIVOLCS, 1991, 1995, 2016; Smithsonian, 2016, Delos Reyes et al., 2018)

ERUP-TION NO.	DATE(S) OF ERUPTION	SERIES/ ERUPTION SITE (1)	VEI (2)	SIGNIFICANT DESCRIPTION OF ACTIVITY	INTERPRETATION OF ERUPTIVE ACTIVITY (3)	ERUPTIVE PROCESSES/ DEPOSITS (4)	ERUPTIVE IMPACTS (5)	CONFIRMED/ UNCERTAIN
1	1572	Series A/ MC	3	"volcano of fire" that "spit forth many and large rocks" (Saderra Masó, 1911, p.6)	More likely ST than PM, as previously interpreted	LVFO and/or LVF with BP, TF	Damage to agricultural crops	Confirmed
2	1591	Series A/ MC	3	"belch forth extraordinary masses of smoke" (Saderra Masó, 1911, p.6)	Minor PH, SA	TF	ND	Confirmed
3	1605 - 1611	Series A/ MC	2/3	"frequent rumblings" (Saderra Masó, 1911, p.7)	SA	RS, VE	ND	Uncertain
4	1634	Series A/ MC	3		SA or minor PH	ND	ND	Uncertain
5	1635	Series A/ MC	3		SA or minor PH	ND	ND	Uncertain
6	1641	Series A/ MC	3	"two craters opened up" (DOST-PHIVOLCS, 1991, p.31)	PH	TF	Activity confined to TVI	Confirmed
7	1645	Series A/ MC	3		SA	ND	ND	Uncertain
8	1707	Series B/ BMA	2	"tremendous display of thunder and lightning" (Saderra Masó, 1911, p.7)	PH, presumably with tephra column	VE, TF, EA, SW	Activity confined to TVI; ND	Confirmed
9	1709	Series B/ BMU	2	"vomited forth a deafening noise" (DOST-PHIVOLCS, 1991, p.32); "loud detonation" (DOST-PHIVOLCS, 1995, p.49)	Sound presumably from an explosion; PM	VE, RS	No reported damage	Confirmed
10	1715	Series B/ BMA	2	"loud explosions and threw out incandescent materials, giving an impression of a river of fire" (DOST-PHIVOLCS, 1995, p49)	More likely ST	LVFO with BP, LVF	No reported damage	Confirmed

11	1716 24-27 Sep	Series B/ CAL	2/4	"great number of detonations heard in the air"; "great commotion in the earth which stirred up the water in the lake, forming immense waves which lashed the shores as though a violent typhoon were raging"; tephra columns described as "looking like towers" (Saderra Masó, 1911, p7; Worcester, 1912, p314)	Violent subaqueous PM with tephra columns from series of eruptions estimated at heights of 100 to 150m	VE, TF, PDC, VT, AR, G	Fish kill; VT causing inundation limit of 17m (S, SW); undetermined casualties	Confirmed
12	1729	Series B/ BMU	2	"a new outburst of the volcano" (Saderra Maso, 1911, p.7)	PH or solfataric or hydrothermal activity	ND	TF	Confirmed
13	1731	Series B/PP	2	"frightful and all-devouring conflagration that the whole region was panic-stricken" (Saderra Maso, 1911, p8); "accompanied by subterranean rumblings which caused the entire region to tremble" (Saderra Maso, 1911, p.8)	Violent sublacustrine PM with large tephra column accompanied by volcanic earthquakes	TF, BP, VE, PDC, VT	Numerous explosion; formed an island named Bubuin; fish kill but no destructive impact to adjacent communities	Confirmed

14	1749 11 Aug	Series C/ MC	3/4	"ascended in the shape of pyramids to marvelous heights then fell back into the lake like illuminated fountains. Some of the pyramids surged toward north, others toward east, the sight lasting until 9 o'clock of the morning" (Saderra Maso, 1911, p.8); "entire territory of Sala and part of Tanauan have been rendered practically uninhabitable – the water courses have been altered, former springs have ceased to flow and new ones made their appearance, the whole country is traversed by fissures, and extensive subsidence have occurred in many places" (Saderra Maso, 1911, p8; Worchester, 1912, p317).	Eruption series more likely PL or a very violent PM, with column-collapse pyroclastic density current	TF, BP, VE, PDC, VT, AR, SU, F, EA, LIQ, G, SW	Volume of ejecta estimated at 50-100 million m^3; TVI and lakeshore towns of Taal, Sala and Tanauan; PDC towards N & E; LIQ effects; fatalities unknown	Confirmed

15	1754 1) 15 May-02 June phase	Series C/ MC	3/4/5	-"the volcano quite unexpectedly commenced to roar and emit, sky-high, formidable flames intermixed with glowing rocks which, falling back upon the island and rolling down the slopes of the mountain, created the impression of a large river of fire";	- PL/SP with column collapse leading to generation of pyroclastic flows/base surges	TF, BP, VE, PDC	More than 100 explosions; ~150 million m^3 of ejecta; eruption column ~40km; TF drifted W, SW & S resulting in collapse of houses with ~1.1 meters TF deposits; TF deposits covered an area of 400 square km and reached Manila but thickness undetermined; PDC affected entire TVI, crossing the lake and affected shoreline communities but majority towards W & SW; complete devastation of Old Taal, Old Lipa, Sala and Old Tanauan; damming of Pansipit River causing flooding in Old Lipa and Old Tanauan; livestock	Confirmed
	2) 02 June-31 Oct phase			-"volcano never ceased to eject fire and mud"; "within the black column of smoke issuing from the volcano ever since June 2, there frequently formed thunderstorms"	-PM	TF, PDC, EA, VE		
	3) 1-15 Nov			-"resumed its former fury, ejecting fire, rocks, sand, and mud";	-PL/SP or PM	TF, PDC, VE		
	4) 28 Nov-02 Dec			-"columns of fire and smoke ascended higher than ever before"; "accompanied by terrific lightning and thunder above, and violent shocks of earthquake underneath"; "waves of the angry lake began already to flood the houses nearest to the beach" (Saderra Maso, 1911, p.9); "in other parts of the lakeshore have likewise opened many cracks" (Saderra Maso, 1911, p.10-11)	-PL/SP and PM	TF, PDC, VE, EA, SW, VT, FL, AR, F, G, LIQ		
16	1790	Series C/ MC	2		ND	ND	ND	Uncertain
17	1808 Mar	Series C/ MC	2	"Formerly the depth seemed immense and unfathomable, and at the bottom was seen a liquid mass in continual ebullition. After the eruption the whole aspect was changed; the crater had widened, the pond within it had been reduced to one-third and the rest of the crater floor is dry enough to walk over it" (Saderra Maso, 1911, p11)	Moderate PM	TF, GE	Main activity confined to TVI; 84 cm TF deposits at TVI but thicker in distal areas; change in depth and configuration of MC, with former two lakes merged as one	Confirmed
18	1825	Series C/ MC	2		ND	ND	ND	Uncertain

19	1842	Series C/ MC	2		ND	ND	ND	Uncertain
20	1873	Series C/ MC	2		ND	ND	ND	Uncertain
21	1874 19 Jul	Series C/ MC	2	"took place an eruption of gases and ashes which killed all the livestock which were being raised on Volcano Island and withered or burned the entire vegetation on the western slopes of the crater" (Saderra Maso, 1911, p11; Worchester, 1912, p328)	Moderate PM	TF, G	Confined to TVI; complete destruction of flora & fauna	Confirmed
22	1878 12-15 Nov	Series C/ MC	2	"noises were frequently heard proceeding from the volcano which finally, from November 12 to 15, ejected a quantity of ashes sufficient to cover the entire island" (Saderra Maso, 1911, p11)	Moderate PH	TF	Affected entire TVI	Confirmed
23	1903	Series C/ MC	2		ND	ND	ND	Uncertain
24	1904 Apr to 5 Jul	Series C/ MC	1/2	"showered with mud, which burned viciously, not because it was hot, but because of the strong acid which it contained" describing the 5th July event (Worcester, 1912, p334)	Minor PH	TF, BP, G	Column about 150m high; absence of wind confining dispersal and deposition within the Main Crater	Confirmed

25	1911 27 Jan.	Series C/ MC	3/4	-"the volcano had been ejecting mud, ashes, and some rocks" (Saderra Maso, 1911, p.12); 26 volcanic earthquakes recorded, some felt in Metro Manila commencing at 1106PM	PM and/or PP	VE, TF, BP	Volume of ejecta ~80 million m^3; PDC affected 15 km of land including entire TVI, Talisay and other lakeshore barrios W of TVI; TF ~25-80 cm thick that affected entire TVI and towns N-NW-W-SW of the island (Talisay, Laurel, Tagaytay, Agoncillo) & can be seen 400 km away from Taal; accretionary lapilli was observed; fissures at Lemery & Taal; explosions heard in Manila (60km away);	Confirmed
	28 Jan.			-"huge column of black smoke" (Maso, 1911, p12); 197 volcanic earthquakes recorded by Manila Observatory	PM	VE, TF		
	29 Jan.			- "visited the volcano and found its top covered by recent mud and ashes" (Saderra Maso, 1911, p12); increased intensity of volcanic earthquakes with 113 recorded by Manila Observatory	PM	VE, TF, EA, F, SU, RS, SW		
	30 Jan.			-"explosions began to assume a terrific violence at 1o'clock in the morning"; "immense, threatening, black cloud, crossed by brilliant flashes of lightning" (Saderra Maso, 1911, p13)	PM or PP	VE, TF, EA, SU, AR, PDC, SW, G, VT, LIQ		

26	1965 28-30 September	Series D/ MT	3	- "incandescent material shooting high in the air from the general vicinity of the newly formed cinder cone"; "enormous Roman candle"; "directed towards the lake" observed at 02:00 AM on 28th September (Moore et al., 1966, p.955) - "continuous display of lightning in the eruption cloud accompanied by thunder" observed from 02:40-03:30 AM (Moore et al., 1966, p.955) - "at the base of the main cloud column a flat turbulent cloud spread out, radially transporting ejected material with hurricane velocity" (Moore et al., 1966; p958) - from 09:20AM 28th Sep. to 06:00AM of 30th Sep., eruptions	Strombolian PM Minor PM	LVFO, LVF, VE, TF RS, TF, BP, EA, PDC, SW, VT, G TF	PDC affected S of TVI from Balantoc (W) to Calauit (E), lakeshore barrios W of the island (from Gulod to Bilibinwang); TF deposited 20-50 cm as far as 60 km, affected entire TVI and towns S-SW of Taal; accretionary lapilli observed; 40 million m^3 of ejecta covering 60 square km; 200 fatalities	Confirmed
27	1966 5 Jul to 4 Aug	Series D/ MT	3	Center of activity was located on the southwest sector of the 1965 cinder cone; "122-meter high ellipsoidal tuff cone measuring 500x400 meters at its base" (DOST-PHIVOLCS, 1991, p.53) resulting from series of minor eruptions	Moderate PM	TF, BP, VE	TVI, formed a tuff cone; impact to houses & vegetation due to TF deposition	Confirmed
28	1967 16-18 Aug	Series D/ MT	1	Eruption created "a small doughnut-shaped cinder cone" (DOST-PHIVOLCS, 1995, p.51)	Minor PM	TF, BP, VE	Explosion centered at 1966 tuff cone; tephra column as high as	Confirmed
29	1968 31 Jan-1 Feb 2 Feb-28Mar 29 Mar-2 Apr	Series D/ MT	2	Centered within the 1966 eruption cone lake and a few meters from the 1967 conelet	Minor PM Moderate ST Minor PM	TF, VE LVF, LVFO TF	LV temperature about 1175°C; breached rim of 1966 cone; LV	Confirmed
30	1969 29 Oct 30 Oct to 10 Dec	Series D/ MT	1/2	Ejecta consisted of ash, steam and incandescent materials	PM Moderate ST	TF, VE LV	LV exceeded extent of 1968 LV; LVF moved	Confirmed
31	1970 9-13 Nov	Series D/ MT	1/2	"incandescent volcanic ejecta, ash and steam";	PH or PM	TF, VE	5-m explosion pit within 1969	Confirmed

32	1976 3 Sep-22 Oct	Series D/ MT	2	Activity centered at the southern foot of the 1966 cone; rhythmic explosions resulted in a 400m by 200m explosion crater	Minor PH	TF, VE	1500 m column drifted to SW	Confirmed
33	1977 3-4 Oct	Series D/ MT	1	Ejection ash producing tephra column with height of 500m	Minor PH	TF, VE	Centered at NE sector of 1976 crater	Confirmed

LEGEND:

(4) Eruption site: MC- Main Crater; BMA- Binintiang Malaki; BMU- Binintiang Munti; CAL- Calauit; PP- Pira-piraso; MT- Mt. Tabaro

(5) Volcano Explosivity Index – VEI

(6) Nature of eruptive activity: SA- solfataric activity; PH- Phreatic; PM- Phreatomagmatic; ST- Strombolian; PP- Phreatoplinian; SP-Sub-Plinian; PL- Plinian; ND- not determined/no description

(7) Eruptive processes/deposits: VE- volcanic earthquakes; RS- rumbling sounds; F- fissuring; SU- subsidence; EA- electrical activity (e.g. vent discharges, near-vent lightning, plume lightning); SW- shock waves; PDC- pyroclastic density current (e.g. pyroclastic flows, base surge); PF- pyroclastic flow; VT – volcanic tsunami/seiche; TF- tephra fall; LVF- lava flow; LVFO-lava fountaining; AR- acid rain; LIQ- liquefaction effects; FL- flooding; GE- geysering; G- toxic gases; ND- no description

(8) Eruptive impacts: TVI- Taal volcano island, N- north; S- south; E- east, W-west; SE- southeast; SW- southwest; ND- no description; UF- undertermined fatalities

APPENDIX C

Appendix C provides a summary of the tephra fall models that have been generated for various numerical modelling needs. The objectives, advantages, drawbacks and sample case studies are summarised. This comprehensive review of various models was needed in order to determine which tephra model best suited my research objective, that is to determine the eruption source parameters for the AD1754 eruptions of Taal, a Plinian/Sub-Plinian event that will be the basis for a maximum expected event scenario eruption at Taal.

Summary list of tephra fall models, objectives, advantages, drawbacks and sample case studies.

TYPE (1)	MODEL(S) (2)	OBJECTIVES (3)	ADVANTAGES (4)	DRAWBACKS (5)	EXAMPLES/ CASE STUDIES (6)	REFERENCES (7)
A. Particle settling & deposition in a wind field	Model of atmospherically transported volcanic dust in deep sea sediments	Predict mass and grain size of ash as a function of distance from source with known velocity profile & eruption height	Able to infer paleowind directions & velocities, & paleo-explosivities of eruptions recorded as tephra layers in deep-sea sediments	High cost of piston coring of deep-sea sediments; precision in design and selection of sites is important	South Pacific	Shaw et al. (1974)
	Theoretical model of clast dispersal from an eruption column	Predict sedimentation of tephra from eruption columns as a function of distance from source dependent on grain size and spread as gravity currents	Simple treatment of sedimentation process; thickness and grain size distribution can be estimated with identified grain size population in the column & known height of column	Eruption w/ fine particles (<1/2 mm) better studied using diffusion models	5000 years BP eruption from Agua de Pau volcano, Fogo, Sao Miguel, Azones	Bursik et al. (1992b)
	Koyaguchi Model	Develop two inversion model to reconstruct dynamics of eruption column from granulometric data of Plinian deposits	Volume, total height of eruption column and temperature of cloud top can be estimated, and can predict how close parameters are to actual condition of column collapse	The simplified model used does not consider some unknown factors such as varying eruption conditions, wind, & turbulence in the atmosphere	1991 eruption of Pinatubo volcano, Central Luzon, Philippines	Koyaguchi & Ohno (2001)
	FALLOUT - expanded model from Shaw (1974)	Construct a general quantitative predictive model that could be applied to any eruption	Good correlation of predicted and observed proportions of mafic crystals and lithics	Premature fallout of fine ash as small-particle aggregates strongly influenced ash deposition in distal environment	18 May 1980 eruption of Mount St. Helens, Washington, USA	Carey & Sparks (1986)
B. Advection-Diffusion Eulerian models	Suzuki model	Theoretical model that has become the framework of some of the other advection-diffusion models	Dispersal pattern independent of variation in total tephra mass; circular dispersion indicates low or absence of wind	Absence of field verification & comparative analysis	No field case study	Suzuki (1983)
	3-D Model	Predict thickness of tephra on the ground after dispersal and deposition	Complementary thicknesses of computed and observed measurements further from the vent; able to generate roof collapse risk map for Vesuvius modelling	Computed and observed near vent thicknesses do not correlate well	18 May 1980 eruption of Mount St. Helens, Washington, USA; 79 AD eruption of Vesuvius, Italy	Armienti et al. (1988b)
	HAZMAP	1^{st} order 2D model modified from Armienti; provide a simple semi-analytical model that can simulate tephra dispersal and deposition from a plinian or sub-	Assume constant, horizontally uniform windfield with negligible vertical advection diffusion; provides semi-analytical solutions and tephra thicknesses on the	Being a 2D model, inaccuracy might occur at lower atmospheric levels; cannot be applied to areas near the vent and limited	79 AD plinian eruption of Vesuvius; 1980 eruption of Mount St. Helens;	Macedonio et al. (2005); Macedonio et al. (1988); Pfeiffer, et al. (2005)

	plinian eruption at a shorter computing time	ground and isopach maps showing thicknesses in centimeters; simple with short computing time so can be effective as first approach to predicting dispersal	to application to areas at least 30-200 km away from the source; cannot be used to reconstruct tephra dispersal for a low column eruption	1992 eruption of Mt. Spurr	
Ash Dispersal Model	Modified version of Suzuki with varying wind speeds and directions in the atmosphere; predict the shape of tephra fallout dispersal; requires maximum height of eruption column, vertical velocity of erupted particles based on rate of accent of the column, total amount of erupted tephra, wind speed and direction, standard deviation of erupted particles & median diameter of particles	Generates isopach maps and isomass distribution maps; good correlation of isopach map generated from modelling with observed distributions for Hekla; while for Lascar, modelling results were nearly comparable with known dispersal	Acknowledge that further studies need to be conducted on the complex motion of small particles in turbulent eddies; need to combine models to be able to accurately describe medial and distal fallout	17 August 1980 eruption of Hekla in Iceland; 22 July 1980 eruption of Mount St. Helens, USA; 16 September 1986 Vulcanian eruption of Lascar, Northern Chile	Glaze & Self (1991)
FALL3D	Model tephra fallout for Plinian, a Sub-Plinian & violent Strombolian eruptions utilising past eruptions of Vesuvius; Input parameters include total erupted mass, tephra column height, bulk grain size, bulk component distribution, & wind profiles from NCEP/NCAR re-analysis.	Designed to forecast volcanic ash concentration in the atmosphere & ash loading at ground; can also be used to model the transport of any kind of airborne solid particles.	limitation of the model is that it requires larger computational times and resources	19 August 1992 eruption of Mt. Spurr, USA; 1998 & 2001 eruptions of Etna in Italy; Chaiten eruption, Chile; 26 February 2000 eruption of Hekla in Iceland	Macedonio et al. (2008); Folch et al. (2009)
Python FALL3D Model	Simplified model of FALL3D	Able to streamline FALL3D installation process, automated & simplified meteorological datasets in a single-step process, making it accessible to users with no modelling background	Need to enhance performance & speed; absence of block comments makes it difficult to check codes (code readable).	1994 eruption of Tavurvur in Papua New Guinea; probabilistic modelling of Gunung Gedein West Java, Indonesia; 1840 eruption of Guntur in Indonesia	Bear-Crozier et al. (2012)
ASHFALL	Predict tephra dispersal and how it will impact on the ground, mainly; probabilistic modelling to determine potential for an ashfall occurrence with particular thickness	Aimed at providing information for civil defence purposes including providing warnings and mitigation planning	Need to incorporate ASHFALL with meso-scale atmospheric models to acquire more accurate and automated wind forecast for tephra fall dispersion prediction	79 AD eruption of Vesuvius; North Island area in New Zealand; 1995 & 1996 Ruapehu eruptions	Hurst & Smith, 2004; Jenkins et al., 2012; Hurst & Turner (1999)

	TEPHRA	Combines various modelling theories & methodologies; aims to predict expected thicknesses in specific areas	Can perform probabilistic simulations; reduce computational time; output includes hazard curves and probability maps for tephra accumulation with variable conditions for hazard assessment run either for a specific locality, area or eruptive scenarios	Topography is not fully accounted in TEPHRA, nor is the model sensitive to grid resolution	1315 A.D. Kaharoa eruption at Tarawera, New Zealand; 17 June 1996 andesitic sub-plinian eruption of Ruapehu, New Zealand	Bonadonna et al. (2005)
	TEPHRA2	Improved and optimised version of TEPHRA; aims to generate tephra fall hazard maps for mitigation & provides estimates of amount of tephra that can potentially affect a specific location, determine extent of particle size distribution; aimed at providing fast GIS-based risk assessment for tephra fallout	Predicted geometry of tephra dispersal complements well with observed geologic data	Some identified constraints are: 1) does not consider effects of agglomeration of erupted materials; 2) underestimates near-vent (<13km) accumulation of tephra where additional sources may come from ballistic projectiles, pyroclastic flows and fallout from plume margins; 3) simplified wind assumption 4) distribution of diameter of particles simplified to one single mode	Cerro Negro Volcano in Nicaragua; 1963 eruption of Irazu Volcano in Costa Rica; basaltic-andesite vulcanian eruption of Colima, Mexico; small volume plinian eruption of Chaiten, Chile; 2450 BP plinian eruption of Pululagua Volcano near Quinto, Ecuador; Cotopaxi Volcano in Ecuador; 1707 Hoei eruption of Mount Fuji, Japan	Biass et al. (2012); Courtland et al. (2012); Volentik et al. (2010); Magill et al. (2015)
C. Particle dispersal from umbrella clouds	A mushroom cloud model	Predict ash deposition from discrete high-altitude disk-shaped cloud transported by prevailing wind	Simplified, qualitative physical model; incorporates particle aggregation to account for presence of coarse and fine particles near source	Ash thickness maps show single thickness, maximum near but not directly at source and tapering of isopach widths farther downwind	Genung Kalut eruption, Java, Indonesia	Slaughter & Hamil (1970)
D. Lagrangian particle-tracking	VAFTAD (Volcanic Ash Forecast Transport and Dispersion) by NOAA Air Resources Laboratory	Emergency response focusing on hazards related to aircraft flight operations; determine ash location in time and space	Rapid computation results in just 2 minutes with the output ready for automatic facsimile distribution to pre-designated stakeholders	Does not compute for absolute ash concentrations or deposition; very few validations	27 June 1992 eruption of Mt. Spurr	Heffter & Stunder (1993)
	MLDPO (Modele Lagrangian de Dispersion des Particules) developed by	Developed as emergency response measure focused on providing data on dispersal mainly for aircraft flight operations			Tuya Volcanic Field	http://www.ssd.noaa.gov/VAAC/vaac.html

Montreal Volcanic Ash Advisory Centre (VAAC)					
PUFF (Volcanic Ash Tracking Model) by Anchorage VAAC	Simulate movement of airborne tephra particles in near real-time following an eruption, predicting location of tephra cloud and spatial dimension for a given period of time	Intended use of the model is mainly for tracking upper-level airborne ash well away from boundary effects	Does not take into consideration topographic information when tracking ash particles	27 June 1992 Mount Spurr/Crater Peak eruptions; October 1994 eruption of Klychevskoy volcano	Searcy et al. (1998)
NAME (Numerical Atmospheric-dispersion Modelling Environment) by London VAAC	Utilised in prediction of transport and dispersal of pollutants in the atmosphere, particularly radioactive substances from nuclear accidents	Provided a system for asynchronous reading of meteorological data reducing runtime	Considerable number of source codes & complex data structure making memory transfer difficult; rewriting parts of code necessary	Chernobyl disaster; spread of volcanic ash in European & North Atlantic airspace after Eyjafjallajokull eruption & May 2011 eruption of Grimsvon in Iceland	Müller et al. (2013)
HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) by Washington VAAC	Tool that helps provide information on where, when, and how potentially hazardous materials could be transported and dispersed to the atmosphere, and later deposited; can track & forecast release of radioactive materials, wildfire smoke, and pollutants (e.g. mercury) from various stationary emission sources	Ideal for single point sources, and can even be applied to nearby volcanoes with similar meteorology			Draxler et al. (2005)
VOL-CALPUFF	Mixed Eulerian-Lagrangian formulation that can simulate 3D transport & deposition of tephra using realistic meteorological & volcanological conditions during entire eruption	Also forecast ash dispersal in proximal areas	Sensitive to meteorological conditions & atmospheric thermal stratification on plume height	Weak explosive events at Mount Etna	Barsotti, Neri, & Scire (2008)
CANERM (Canadian Emergency Response Model)	Simulate dispersion of ETEX cloud to test viability of model	Able to simulate main features of the cloud dispersion	Overestimation of surface concentration	ETEX (European Tracer Experiment) release on 23 October 1994	D'amours (1998)
MEDIA (Model for Dispersion in the Atmosphere)	Used by Toulouse VAAC			Calculates trajectories of volcanoes several times a day including Etna	

APPENDIX D

Appendices D-1 and D-2. Summary of review of global and Philippine-based case studies related to the emerging field 'social volcanology', including studies in the Philippines that provide on the objectives, concepts, actions/adjustments, impacts/observations/factors that influence risk awareness & preparedness, sampling method(s) and size. The different philosophical views, modes and topics of inquiry of previous risk perception studies helped me determine key questions to ask for my own research.

Appendix D-1. Summary review of published 'social volcanology' case studies from around the world.

VOLCANO AREA/ COUNTRY/DATE OF ERUPTIVE ACTIVITY	OBJECTIVE(S)	CONCEPT(S)/ THEORY/ PARADIGM/ASSUMPTIONS/ LIMITATIONS	ACTIONS/ ADJUSTMENTS DONE OR NEEDED	IMPACT(S)/ OBSERVATIONS/ FACTORS IDENTIFIED THAT INFLUENCE RISK AWARENESS, PREPAREDNESS & EVACUATION	SAMPLING METHOD/ SIZE	REFERENCE(S)
Kapoho/USA/13 Jan-1 Feb 1960	Questionnaire survey administered to most of the evacuees & a control group in same rural community but distant from volcanic activity seeking response to "security seeking" behavior & DRR information	"*security seeking*" behaviour (e.g. beliefs, rituals, related behaviour	1) Offer of prayers & gifts; 2) evacuated prior to and during the eruption; 3) construction of dikes to contain or divert lava started on 5th day of eruption	In time of stress, people seek security in supernatural beliefs, rituals and related behavior	No specific no. of evacuees; observation method	Lachman & Bonk (1960)
Mount St. Helens/ Washington, USA/27 Mar-18 May 1980	Key points for analysis: "Citizens' beliefs about volcano-related threat, sources of information about the hazard, citizens' evaluation of personal risk & appropriate protective measures to mitigate risks"	"*proximity to the volcano is related to the dangers from specific threats such as lava flows, mudflows and ash fall and that proximity should play a role in citizens' perceptions of danger from the volcano*" (p.51)	March - roadblocks; Federal Aviation Admin (FAA) banned planes from 5-mile radius; evacuation issued; hazard information distributed	"*before an individual begins making any adjustment to an environmental hazard, he/she must be aware of its existence and believe that it poses some level of real danger*" (p.51); 81.2% of respondent from Cougar, 87.4% from Woodland and 84.8% from Longview answered "unlikely" to be affect by volcanic activity	Probability sample of 230 with 174 telephone interviews partially or fully completed (76% completion rate); 10 min questionnaire administered over the phone	Greene et al. (1981)
Mauna Loa & Hualalai volcanoes /Kona/USA	"Evaluate experience with hazardous events & education programs; knowledge of emergency warning system; level of hazards awareness; perception of volcanic risk; level of preparedness; identify underlying causes and influences"	No theory mentioned	No adjustments identified; experience in hazardous events related to age & more adults take more household preparedness measures for frequent emergencies	Direct experience low; low knowledge of threat due to lack of exposure, even with participation in hazard education program; awareness of volcanism is extremely high but preparedness low (issue of transfer of responsibility); awareness is high but did not translate to knowledge & preparedness for future threat; lack of perceived need for personal preparedness resulting from transfer of responsibility; perception of risk linked to proximity to hazard source	Questionnaire survey; High school students (236) and parents or guardians (226) (n=462)	Gregg et al. (2004)

Mount St. Helens; USA/1980 & North Island, New Zealand	Look into oral traditions (cosmologies and mythologies) as an important component of community resilience to natural hazards	Cultural Theory?	Adaptation to volcanic hazards include coping mechanisms like engineering solutions (e.g., Sabo dam technology of Japan and lava flow barriers in Italy), monitoring systems, evacuation plans, and land-use restrictions (p. 407)	Resilience to disasters through coping mechanisms such as transfer of responsibility or religious or cultural belief of higher power causing the event; oral traditions often provide information on coping mechanisms of communities	Information tapped from spontaneous narrative and responses of people to disastrous events; no specified number of respondents	Cashman & Cronin, (2008)
Mt. Shasta in Northern California, USA/ last erupted in late 1700s	Examine relationship among risk perceptions & adjustment decisions related to each of the 3 threats -volcanic activity, seismicity & wildfires	Information seeking –to increase hazard knowledge; Experience-"most recent, frequent or intense is more likely to be retained and used in decision-making (Burton, 1993)	Volcano insurance; knowledge of volcano threat alert; breathing protection; structural countermeasures; defensive tools; complete evacuation plan	Higher level of risk perception and level of adjustment for wildfires rather than earthquakes and volcanic eruptions; perceived risk is not a strong predictor of hazard adjustment; self-protection and experience parallel to adjustment measures	No specified number of respondents	Perry & Lindell (2008)
North Island/New Zealand/Sep-Oct 1995 eruption of Ruapehu	"Evaluate individuals' hazard knowledge, perceptions of volcanic risk and documented individuals' sources of volcanic hazard information & perceived credibility of sources"	Perceived risk linked to proximity to the volcano; impact of ashfall will be translated to increased threat knowledge and perceived risk	Explore implications of direct and indirect experience of volcanic eruptions for knowledge threat, risk perception & preparatory adjustments; determine if perceived risk translated to hazard adjustment & increased level of protective measures	Direct impact translates to knowledge of threat & shift in hazard knowledge	Survey conducted in Hastings (H) & Whakatane (W) in May 1995 & November 1995; questionnaire distributed to 450 households in each centre with return rates of 45%(W) & 48% (H)	Johnston et al. (1999)
Mount Cameroon volcano/Africa	To obtain information on hazard knowledge and threat, past eruption experiences, importance of traditional beliefs, level of hazard education and communication, hazard preparedness and responsibility	Cultural and economic influences	Greatest perceived threat is destruction of farmland; 94.3% of respondents judged that hazard education is very important so government initiative on hazard education was recommended; trust in scientific authorities to provide accurate and reliable information; improvement of volcano monitoring system;	"*Adaptation & protection is poor; residents likely to shift responsibility for their protection to experts; little knowledge of existing emergency plan; little or no educational outreach activities, but a high perceived need for information and implementation of emergency plans; knowledge of natural threats found to directly related to past exposure to hazard; media is most accessible channel for hazard communication,*	Survey conducted Aug & Dec 2008; 70 responses to 34 item risk perception questionnaire w/ questions being hazard-centered; population concentration, perceived risk & eruption history as guide for selection of villages	Njome et al. (2010)

			utilisation of media & internet for hazard information dissemination	*& internet is a growing information source that should be used to reach out to younger generation*"; "*personal experience of volcanic hazard & a short time span since last event increases awareness and perception*"		
Santorini volcano complex (Nea Kameni, Mt. Columbo-1960 AD)/ Greece	Investigate risk perception of volcanic hazards on Santorini; determine level of awareness & knowledge of volcanic hazards and risk;	Low number of respondents which may not be considered representative but the number of respondents from the local government (14) is found to be significant	Need for the development of local evacuation and emergency plan and risk management strategy; more educational campaigns; develop risk management structures; establishment of a permanent Santorini Volcano Observatory	Absence of evacuation and emergency plans; no land-use zoning and geological assessment not a requirement for proposed construction on the caldera rim; insufficient emergency staff (e.g. doctors, firemen, etc.); lack of education campaign; residents believe the greatest impact would be on buildings and tourism.	57 permanent residents (14 local officials, 43 island residents); respondents of *different age groups- school children & elder members-*	Dominey-Howes & Minos-Minopoulos (2004)
Furnas, Sao Miguel, Azores/Portugal	Examine vulnerability of people to natural hazards	Vulnerability to volcanic hazards framework	Having resources or access to livelihood away from the volcano might reduce vulnerability	Identified susceptibilities & basic needs satisfaction that can facilitate social participation; destructive volcanic eruptions only have slight influence on community, limited to period of activity & the aftermath; exploitable resources as a result of the eruption is deemed more important	In-depth interviews/50 permanent residents	Dibben & Chester (1999)
Merapi Volcano/ Indonesia	To compare & contrast views of volcanic hazards	'culture of hazard'	Domestication of volcanic hazards; /adaptation to volcanic environment	Gov't resettlement efforts, interest & intervention peak after a major eruption; volcanic hazard considered beyond normal social order; villagers view government's resettlement intervention as another hazard.	Not mentioned/90 household in Turgo, Central Java	Dove (2008)
Mt. Merapi/ Central Java, Indonesia	Examine cultural reactions to volcanic hazards	Social volcanology- "*creative discipline focusing on reducing volcanic risk by examining the local societies*"	Cultural beliefs & socio-economic needs found to be interdependent influence; need to identify areas of cultural vulnerability and work with community to develop preparedness plans where they have a voice	Local traditions & belief systems found influential in motivating reactions during & prior to a crisis; livelihood as a key motivating force to behaviour during an eruptive crisis; perception of being safe either through belief of protection of supernatural creatures or	Semi-structured interviews (80), observational micro-ethnographic techniques (Bryman, 2004), participatory-based workshops (2), Participatory Rural Appraisal-based	Donovan (2010)

				knowledge gained from past eruptions	activities including daily & seasonal timelines, community hazard mapping, village emergency plans, storytelling, general discussion	
Katla Volcano, southern Iceland	Explores social dimensions of hazard, risk & emergency response procedures related to Katla Volcano; provide social framework for disaster risk reduction through in-depth social assessment combined with physical information	Adhere to the concept of social volcanology	Volcanic risk mitigation measures must consider each stakeholder groups	key influential issues to adaptation of recommended protective action include knowledge & perception of hazard & risk, livelihood connections, attachment to place & level of trust	Mixed method research; open/closed questioning using face-to-face delivery; representative sampling technique through non-probability sampling/101 respondents	Bird (2009); Bird et al. (2010)
The Caribbean island of Montserrat	Understanding of risk perception of Montserrat communities for improvement of risk communication & risk reduction	Development of schematic overview of risk communication process	'public' respondents split to 3 factions: those satisfied w/ current level of interaction, 2nd group wants more involvement (more influential locals) & 3rd group who quietly returns to take care of their livelihood (Montserratians); trying to bridge the gap between experts and the public through dialogue; need for understanding people's day to day survival	Scientists & authorities believe racial and political issues greatly affected the risk communication & management of volcano crisis; method of dissemination of information important; issue of trust in relation to source of information	Semi-structured interviews; 'public' respondents (35) interviewed in snowball fashion with consideration of demographic & geographic representation; 'elites' included scientists & authorities (31)	Haynes et al. (2008)
Vesuvius/ Italy	Determine volcanic risk perception related to Vesuvius of communities living in the identified Red and Yellow zones	None identified	Major education-information effort needed to improve public's knowledge, confidence and self-efficacy that is essential to enhance coping capacity during eruptions	Realistic views of risk: know eruption is likely, have serious consequences to community, worried about the threat; social, economic & security-related issues raised that are often considered more pressing than Vesuvius	2655 of 3600 questionnaires w/ 45 items distributed to students, parents & general population (2812 in Red Zone) were returned; response rate=73.7%	Barberi et al. (2008)

Popocatépetl/ San Pedro Benito Juarez (SPBJ), Puebla, Mexico	Examines how situational and cognitive variables associated with chronic (Popocatépetl) & acute (floods in Tezuitlán) hazardous conditions affect risk perception	None identified	Prior experience & risk perception is the major predictors of intended future evacuation in SPBJ (chronic site); emergency management could target those who perceive a low level of risk because of their high levels of well-being, as well as people with strong economic ties/place attachments, & past experience of residents; need to tailor-fit public awareness & evacuation efforts	Identified 4 measures of risk perception: 1) concern about living close to a hazard- more people worried in Tezuitlán; 2) perceived danger from hazards- greater in Tezuitlán (84%) than SPBJ; 3) perceived health risk from hazards- 90% in Tezuitlán & 53% in SPBJ; 4) concern about health in general-no difference	Two survey instruments used: short questionnaire (294 household) & more detailed impact & well-being survey (200 respondents randomly selected adult); response rate =79%	Tobin et al. (2011)
Soufriere Hills/ Montserrat, The Caribbean	Investigated how verbal & numerical probabilities affected decision making on the issue of evacuation amid uncertainty of when eruption will occur	Discussed Epstein's theory for two parallel processing systems that steers decision making: 1) *analytic* approach that applies computational processes & rules in analysing data; 2) *affective* approach, also known as *experiential* system that provides rapid, unconscious & immediate action.	Greater number of participants more inclined to evacuate when presented with numerical probability statement than with verbal. While numerical probabilities play an important role to decisions to evacuate, different time windows were not considered	Some considerations for decision making: management of uncertainty (e.g. paralysed or unable to decide because of the uncertainty), 'wait & see' attitude including search for more volcano information that will increase certainty of an eruption; normalization bias, fatigue and related issues especially for eruptive events of long duration; fear of non-compliance to warnings & evacuation related to issue of trust; issues of evacuation procedures; use of cost-benefit approach.	Utilised snowball approach through email with 179 respondents (92 scientists & 85 non-scientists) from physical & social science community, & emergency managers & civil defence officials from various countries; used online survey administered using Qualtrics Survey Research Suite software	Doyle et al. (2014b)
Tungurahua/ Ecuador/ 2006 & 2014	Examined how communities adapted to change in volcanic activity	Restructured & decentralised DRM system have greatly improved risk management.	Adaptation in response to volcano warning communication & evacuation that included voluntary evacuation system while maintaining their livelihood during volcanic activity; use of 'shadow networks' that greatly improved hazard knowledge & information	With the application of 'shadow networks', communication between informal institutions and risk managers improved such communities learned to believe & respond positively to scientific information & evacuation processes	Review of secondary literature & 130 semi-structured interviews from July 2013 to December 2014 with respondents from national, provincial & local level government officials, scientists, community	Armijos et al. (2017)

	exchange; trained 35 community-based volcano observers that assist in monitoring the volcano and provide early warning during emergencies.		leaders & residents; utilised purposive & snowballing sampling

Appendix D-2. Summary review of published Philippine based 'social volcanology' case studies.

VOLCANO AREA/ COUNTRY/DATE OF ERUPTIVE ACTIVITY	OBJECTIVE(S)	CONCEPT(S)/ THEORY/ PARADIGM/ASSUMPTIONS/ LIMITATIONS	ACTIONS/ ADJUSTMENTS DONE OR NEEDED	IMPACT(S)/ OBSERVATIONS/ FACTORS IDENTIFIED THAT INFLUENCE RISK AWARENESS, PREPAREDNESS & EVACUATION	SAMPLING METHOD/ SIZE	REFERENCE(S)
Taal Volcano/ southern Luzon	Describe the dominant social organisation in the Philippines in crisis situations; seek insights into human behaviour revealed during critical situations (e.g. 1965 Taal eruption)	None identified	Suggestion of a system whereby evacuees are provided the option of staying with relatives/friends while availing themselves of public relief rather than staying in very cramped evacuation centers; need for better organisation of relief and evacuees	Family provides greatest influence as far as leadership, behaviour and responses to volcanic crisis is concerned; leadership often connotes seniority in the Philippine setting; dominant social organisation in the Philippines is family-centered with attached commitment to mutual support and loyalty	Questionnaire surveys and interviews of 'ordinary' and 'key' informants	Carroll & Parco (1966)
Taal Volcano/ southern Luzon	Assess the development potential of the area & the constraints posed by the volcano; develop a framework plan for development directions for resource utilisation, preservation or conservation	None indicated	Absence of information on preparedness & response to emergencies; provided needs assessment for TVI (e.g. primary education, medical facilities, lifelines, livelihood training, roads)	Influencing factors include livelihood, attachment to place, self-efficacy, issue of trust	Semi-structures & free-wheeling interviews; respondents include barangay leaders, coastal communities, volcanologists, municipal & provincial officials (66)	Tayag et al. (1988)
Taal Volcano/ southern Luzon	Provide a summary of the historical eruptions of Taal and describe sources of livelihood of residents at Taal Volcano Island (TVI)	None indicated	Key social unit to concentrate on for disaster mitigation is the family; continuous volcano monitoring & intensive multidisciplinary studies aimed at reducing volcanic disasters	Residents at TVI profess to recognise signs of imminent eruption such as intense heat, rumbling sounds, ground shaking, and unusual animal behaviour; many affirm confidence in evacuation warning being provided by DOST-PHIVOLCS; at the time interviews were conducted, the number of boats at TVI was only half the number required for evacuation	Observation method & free-wheeling interviews; no specified size of respondents	Oppenheimer (1991)

Pinatubo Volcano/ Central Luzon	Provide an overview of the social & psychological impacts of the 1991 eruption, as well as issues & problems of resettlement	None indicated	Information dissemination of research findings; structural countermeasures (e.g. catchment basins, sandbagging & dikes) to prevent lahars from affecting communities adjacent to lahar channels; need to have communities participate in the conceptualisation and development of resettlement plans; livelihood, psychological adjustments & attachment to place need to be addressed to make resettlement viable	Some perceive Pinatubo as 'leveller' or 'equalizer'; religious rituals prevalent where residents offer prayer sessions & processions in villages & river channels affected by lahars especially during the rainy season; previous experiences elevated risk perception; issue of mistrust in situations where victims initially moved to resettlement sites but livelihood and basic needs were not addressed, that ultimately pushed them to return to their affected communities.	Review of secondary data pertaining to socio-economic data, relief, rehabilitation & resettlement of affected communities; interview of key informants in government and non-government organisations & victims in evacuation centers & resettlement sites; workshop	Banzon-Bautista (1996)
Pinatubo Volcano/ Central Luzon	Post-eruption surveys conducted in 1991 & 1992 to assess if warnings were received, understood and utilised by communities to take protective action	None indicated	Failure to stimulate protective action from 18% of respondents who received warning; delay in receiving warning information in remote areas; caution or overreaction of some local officials to warning information	Influencing factors: livelihood, & protection of properties, cultural/religious beliefs, absence of knowledge about the volcano & explosivity	Open/closed questionnaire survey; respondents selected from barangays within the 10km, 10-20km, and 20-40km radius from the volcano (167 of 234 questionnaires distributed) -response rate of 71%	Tayag et al. (1996)
Various disaster experienced in the Philippines including 1991 eruption of Pinatubo Volcano/ Central Luzon	Determine perception of risk of communities adjacent to Pasig-Potrero River and behaviour related to threat of lahars	Looked into concepts of vulnerability, capacities and resilience	Structural intervention like diking system, sand bagging, raising houses on posts; other adjustments: seasonal relocation, early warning system	"choice of adjustment depends on how people perceive rare and extreme threats and the associated risks for themselves" (p. 39); high correlation between risk perception and personal experience of past lahars; religious & cultural beliefs identified as factors molding risk perception & behaviour during volcanic crisis	Questionnaire survey (40 items) & 220 interviews were done from Jan-Mar 1998 using probability sampling where 1 out of 300 residents is selected in 6 different study areas; 60 interviews conducted in two resettlement sites (Madapdap & Bulaon)	Gaillard et al. (2015)

Pinatubo Volcano/Central Luzon/1991 eruption & subsequent lahars	Determine importance of social construction of natural hazards in consideration of disaster preparedness, management and relief activities	None identified	"*Pakikisama*" (fellowship) & "bayanihan" (communal unity and cooperation for a common goal) as a coping mechanism; need to establish public confidence	Cultural interpretations have great influence in people's actions/behaviour during a crisis (e.g. people resort to prayers and procession to seek protection from hazards); "*people's resilience to withstand hazard lies in the intangible qualities generated by shared cultural attitudes & community spirit" (p. 110);* lack of trust in government service could hamper implementation of DRR activities	None written	Bankoff (2004)
Taal Volcano/ southern Luzon	Obtain general perception on volcanic risk, preparedness & response to volcanic activities and gather population data and socio-economic profile for TVI	None indicated	Self-efficacy as a preparedness action (e.g. 65% of TVI residents have their own motorboats); knowledge of Alert Level Scheme (93%); dependent on authorities for warning (85%); dependent on government assistance during evacuation (90%); need for continuous update on population growth at TVI and risk reduction initiatives in preparation for immediate evacuation of the island's inhabitants when volcanic activity escalates	Awareness of hazards posed by Taal but opt to stay at TVI for economic reasons	Key informant interviews with local disaster planners, barangay captains; 210 questionnaire forms distributed & 130 forms returned giving a response rate of 62%; only 100 forms used as basis for the results of the study	Saquilon & De Guzman (2005)
Pinatubo Volcano/ Central Luzon	Determine risk perception of population living near Pasig-Potrero river & assess their behaviour in response to the threat of lahars.	Two paradigms: 1) perception adjustment-choice of adjustment depends on how people perceive rare & extreme volcanic phenomena & associated risk; 2) vulnerability-people's behaviour in the face of natural hazards is constrained by social, economic and political	Technical adjustment to lahar threat: raise houses on concrete posts (53%), sandbagging, relocation on the eve of rainy season (38%), return to resettlement sites (28%), or rented houses (11%); some go to identified multi-purpose evacuation sites but 101 of 206 such sites are deemed not safe by DOST-PHIVOLCS;	Higher risk perception of Pinatubo & lahars in Bacolor (84%), aware that they can be affected in the event of another eruption & subsequent lahars, know that lahar may occur again in the next rainy season (90% of respondents from Bacolor & 96% from resettlement sites); despite high risk perception, respondents of Bacolor chose to remain & face the threat either because of lack of livelihood (poverty) or issue of attachment to place to original	Questionnaire-based (40 questions) surveys conducted in the vicinity of Pasig-Potrero river; 220 respondents with voting registration as sampling frame; complemented by interviews of civil and disaster management sector	Gaillard (2008)

		forces beyond their control (p. 315)	other coping mechanisms include *'active calculation of the odds', sense of 'communalness' & burden-bearing mechanism* (p. 322)	homes (loss of cultural heritage); television & radio was the widest source of information (69% -Bacolor; 75%- resettlement), others identified authorities, newspapers & word of mouth; religious influence, while not asked directly, often crop up in the interviews		
Mayon Volcano/ Bicol Region	Determine if exposure to volcanic hazards decreased without adding to vulnerability through loss of livelihood, community & culture, and exposure to new risks; investigated a resettlement program for communities affected by volcanic activities of Mayon	To ensure that participants are able to express their views clearly, local language was used with assistance of an interpreter.	Volcanic resettlement program needs to consider issues like livelihood security, house design, availability of public & lifeline facilities; need for consultation with affected communities & they should have a share in decision making; increased livelihood opportunities for female participants through microfinance scheme for small business enterprise (e.g. grocery shops known as 'sari-sari' stores, making handicrafts, beauty services, purchase small vehicles for hired transportation)- nor 100% successful; while resettlement sites offer safe homes, issue of sustainable life & livelihood security still needs to be addressed	Livelihood not taken into consideration in the resettlement process; male residents were farmers who had difficulty adjusting and subsequently returned & risk safety by staying in old settlement to continue farming; community social network took longer to re-establish because resident only live part-time in the resettlement sites & schools were not immediately established forcing students to continue schooling at old settlements	Mixed method qualitative approach; semi-structured interviews with government officials, emergency managers & donors, participant observations, participatory workshop & focus group discussions	Usamah & Haynes (2012)
Kanlaon Volcano/ Negros Oriental	Identification, analysis & evaluation of risk as basis for timely & well-oriented disaster prevention & essential key component of disaster management	'Naturalist' approach in the design of hazard maps using historical & geological data from past eruptions	Identification of 'hot spots' where exposures of high values (e.g. concentration of population, roads) are at risk (p. 95); need for scenario building in order to anticipate effects of potential eruption; Information & training	Need better understanding of the community's point of view on the disaster management process; Factors that may affect risk perception include hazard knowledge, frequency & intensity of personal experience, and local knowledge & beliefs (p. 131)	Not specified	MIA-VITA (2012)

			provided; preparedness/ evacuation exercises			
Kanlaon Volcano/ Negros Oriental	Identify general risk perception of people living close to Kanlaon Volcano; consider factors such as previous experience, education, attitude & beliefs that influence risk perception, & identify communication strategies that can strengthen resilience of the community	None mentioned	Adjustment measures: Information campaign, establishment of early warning device in the community in the form of indigenous materials, communication system test & volcano evacuation drill	Religious beliefs have great influence in people's lives & relate disasters with punishments & prayers for prevention of disasters; majority do not believe Kanlaon is capable of having an explosive eruption; residents rank typhoon first as primary hazard in their community while volcanic eruption only second; majority answered livelihood and attachment to place as reasons why they remain and live near Kanlaon; 90% expressed interest in participating in community activities related to disaster risk reduction	Rapid Rural Appraisal (RRA) (Librero et al., 1997), interviews with barangay officials (23) and residents (81), focus group discussions, community facilitation and participant observations in Brgy. Pula, Kanlaon City	Martinez-Villegas et al. (2013)
Taal Volcano/ Batangas	Identify determinant to behavioral responses or disaster preparedness, awareness, attitude & preparedness related to volcanic eruptions & related hazards	Conceptual framework of study based on Theory of Planned Behavior; four determinant factors of behavioral intentions: knowledge, attitude, subjective norms (e.g. social pressure, acceptance to preparedness & evacuation) & behavioral control (e.g. confidence on resources, competencies & institutions). Based disaster preparedness behaviors on Public Readiness Index.	Identified television, barangay announcements & radio as main sources of information related to volcano status; 72.8% willing to volunteer help during emergencies but 66.7% do not have necessary skills (e.g. first aid, basic life support); almost all have knowledge of their evacuation center within & outside their barangay	Never had a volcano evacuation drill; 83.7% believe they have sufficient support system (e.g. family, friends) in terms of disaster preparedness, 77.6% believe their barangay captains will provide assistance but only 55% admitted they do not have enough knowledge on disaster risk management.	Used stratified sampling method; 147 participants consisting of household heads of families in Barangay Gulod, Laurel, Batangas; used online sample size calculator with two stakeholder groups: survey group & key informant group.	Del Monte-Sanico (2018)

APPENDIX E

Appendix E provides copies of both English (Appendix E-1) and Filipino (Appendix E-2) version of the questionnaire form originally approved by the Human Research Ethics Committee (HREC). Selected questions were utilised as prompts for the qualitative discussions with respondents. Filipino version were provided to cater to participants who were more fluent and comfortable speaking, reading and writing in their native language.

Appendix E-1. Sample Questionnaire Form (English)

THE UNIVERSITY OF SYDNEY

School of Geosciences
Faculty of Science

QUESTIONNAIRE SURVEY
General and Specific

Original Research Title: Geological and Social Dimensions of Volcanic Hazard and Risk Assessment/Management: Taal Volcano, Philippines as a Case Study

PARTICIPANT NO: ________________
BARANGAY/VILLAGE: ______________________________________
MUNICIPALITY: ____
PROVINCE: ____

NOTE: Submission of the completed questionnaire will be taken as consent for use of the data for research.

1. Participant's age:

   ☐ Less than 18 (*If less than 18, cannot participate in the study)*

   ☐ 18-24

   ☐ 25-39

   ☐ 40-55

   ☐ 56-65

   ☐ 66-79

   ☐ 80+

2. Participant's gender:

   ☐ Male

   ☐ Female

   ☐ Other (please specify) ____________________________

3. Marital status:

   ☐ Single

☐ Married or Defacto

☐ Married or Defacto with dependent children

☐ Separated with dependent children

☐ Widowed

☐ Widowed with dependent children

4. My highest level of education is:

☐ Elementary or lower

☐ High School

☐ Undergraduate Degree

☐ Vocational

☐ Postgraduate Degree

5. Participant's current occupation:

☐ Full time- What time: ________________

☐ Farmer ☐ Fisherman ☐ Office worker ☐ Other: ______________

☐ Part time/casual- How many hours: ______ What time: ______________

☐ Studying

☐ Daily commute ☐ Weekly ☐ Monthly

☐ Not working

☐ Retired with no pension

☐ Retired with pension

Questions 6 to 15 are being asked to have knowledge about your attachment to your current place of residence.

6. Participant's present address: (check more than one if necessary)

☐ Own land and house

☐

Rented

☐ Live with parents and/or relatives

☐ Others: please specify

____

7. Length of time in participant's present address: (check more than one if necessary)

☐ Lived here since birth

☐ More than 10 years

☐ 6-10 years

☐ 1-5 years

☐ Less than a year

8. Participant living with:

☐ Spouse or partner

☐ Spouse or partner and children

☐ Alone

☐ Children

☐ Immediate family (parents, siblings, etc.)

☐ Other relatives (grandparents, aunts, uncles, cousins, etc.)

☐ Friends

☐ Other: (Please specify)

____

9. Actively participate in social and/or religious activities: (Check more than one if necessary)

☐ Social/Recreational activities

☐ Religious activities

☐ Cultural activities

☐ Other: (Please specify) ________________________________

10. Existing dependents who live with participant:

☐ Yes (if Yes, go to Question 11)

☐ No (if No, go to Question 12)

11. If Yes, dependents are: (check more than one if necessary)

☐ Children under 18 years

☐ Relatives (parents, siblings, grandparents etc.)

☐ Friends

☐ People with special needs; please specify how many ____________

☐ Other: (Please specify) ________________________________

12. Please describe your life in your community (contented, discontented, constantly moving from place to place for livelihood, etc.) Please specify why.

____

____

13. Do you frequently travel to other places for livelihood, social/community service, recreation, etc?:

☐ Yes: (Please specify) ____________

☐ Daily ☐ Weekly ☐ Monthly ☐ Yearly

☐ Not very often

☐ No, never left the community

14. Is your family actively involved in community activities (e.g. religious, health-related activities, social, etc)?

☐ Yes: (check frequency below)

☐ Daily ☐ Weekly ☐ Monthly ☐ Yearly

☐ No, never participated in community activities

15. How many times have you moved within your lifetime?

☐ More than once: (check reason below)

☐ education ☐ livelihood ☐ spouse/family ☐ religious

☐ Never moved, been staying in my residence since birth

Questions 16 to 29 are being asked to understand your perception of the volcanic threat, your reactions and adaption measures, and to qualify for further interview.

16. I have experienced an eruption of Taal Volcano or anywhere in the Philippines:

☐ Within the past 40 years

☐ Within the past 50 years

☐ No, never

17. If you have experienced an eruption, were you given prompt warning for evacuation?

☐ Yes

☐ No

18. Who gave the warning information?

☐ Community leaders

☐ Local/national government unit(s)

☐ PHIVOLCS

19. If you have experienced an eruption, did you evacuate promptly when given warning?

☐ Yes

☐ No

20. If you answered NO to Question 19, why did you not evacuate immediately when given warning?

☐ I have to take care of my properties

☐ I did not believe the warning

☐ My neighbors did not believe the warnings so I did not evacuate

☐ Our community leader/barangay captain did not tell us to evacuate

☐ Others: (Please explain)

____

21. Do you think you will directly be affected if an eruption occurs again?

☐ Yes: check more than one if necessary

- ☐ Direct hazard (e.g. pyroclastic flow, base surge)
- ☐ Ash/tephra fall
- ☐ Lahars (during rainy season)
- ☐ Other volcanic hazards: (please specify)

____

☐ No, we will not be affected: (Please specify why not)

____

____

22. Who do you go to for information about volcanic hazards, disaster preparedness (please rank from 1 to 7 according to preference/priority:

☐ Consult with community or religious leaders

☐ Consult with relatives/close friends

☐ Consult with neighbors in my community

☐ Listen to radio/TV/social media

☐ Text or call PHIVOLCS

☐ Text or call local/national government officer

☐ Other: (Please specify)

____

23. During a volcano emergency, your decisions will be based on (please rank from 1 to 7 according to preference/priority:

☐ Past experience(s) and gut feeling

- ☐ Consultation with my family
- ☐ Consultation with my community/community leaders
- ☐ Consultation with PHIVOLCS contact officer
- ☐ Consultation with local/national government contact officer
- ☐ Reports heard on radio/TV or other social media: (Please specify) ___________
- ☐ Other: (Please specify) ____________________________________

24. How do you get information about impending eruption:

- ☐ Personal experience/visual signs
- ☐ Information from my family/relative/friends
- ☐ Listening to radio/TV
- ☐ From PHIVOLCS contact officer
- ☐ From local/national government contact officer(s)
- ☐ Other: (Please specify) ____________________________________

25. In the event that PHIVOLCS issues warning of impending eruption, how would you react:

- ☐ Believe and immediately move away from the volcano
- ☐ Consult with my family
- ☐ Consult with my community/community leaders
- ☐ Consult with local/national government contact officer and wait for their action
- ☐ Wait and see

26. Do you have knowledge of volcano emergency preparedness measures/training in your community in the event of an imminent eruption?

- ☐ Yes: check more than one if necessary

☐ I have independent preparedness plans for my family and relatives

☐ We, as a community meet regularly for community-based preparedness plans

☐ I rely on our community leaders for guidance

☐ I rely on national/local government leaders for emergency actions

☐ No, we do not have volcano emergency measures/trainings.

☐ I don't know of any existing emergency plans.

27. If you volcano emergency preparedness measures/trainings in your community, how often do conduct these training?

☐ Yearly

☐ Semi-annually

☐ Quarterly

☐ Monthly

☐ Never since it was planned

28. If eruption occurred and you evacuated, would you return to your residence even if it was severely impacted by the eruption and if so why?

☐ Yes: check more than one if necessary

☐ Our livelihood

☐ Our possessions are there

☐ No other place to go

☐ No, will not go back

29. If you were provided with housing and livelihood, would you consider moving far from the threat of Taal Volcano?

☐ Yes, I will move

☐ No: check more than one if necessary

☐ My family and friends are there

☐ I do not want to give up my properties even with the threat of another eruption

☐ I do not believe the government can give the housing and livelihood I need.

Questions 30 to 33 are being asked for some specific details on livelihood. The purpose of the questions is to determine general planting and harvesting season (for the farmers) and raising fingerlings and harvesting (for fishermen) in relation to potential eruptions at Taal Volcano.

30. I am a farmer, and my main source of livelihood is:

☐ Raising livestock: (please specify type)
____

☐ Rice production

☐ Coconut production

☐ Corn production

☐ Coffee/black pepper, rootcrops production

☐ Vegetable production

☐ Fruit production including pineapple, etc.

☐ Not applicable (not a farmer) (PROCEED TO QUESTION 32)

31. If farming, best season for: Check more than one if necessary.

a. Planting

☐ January	☐ July
☐ February	☐ August
☐ March	☐ September
☐ April	☐ October
☐ May	☐ November
☐ June	☐ December

b. Harvesting

☐ January	☐ July

☐ February ☐ August
☐ March ☐ September
☐ April ☐ October
☐ May ☐ November
☐ June ☐ December

32. I am a fisherman, and my main source of livelihood is:

☐ Raising tilapia

☐ Raising other types of sea or fresh water food: ____________________

☐ Not applicable (not a fisherman) (PROCEED TO QUESTION 33)

33. If fisherman, best time for:

c. Raising fingerlings

☐ January ☐ July
☐ February ☐ August
☐ March ☐ September
☐ April ☐ October
☐ May ☐ November
☐ June ☐ December

d. Harvesting

☐ January ☐ July
☐ February ☐ August
☐ March ☐ September
☐ April ☐ October
☐ May ☐ November
☐ June ☐ December

34. If an eruption advisory was given, with lead time of a few weeks, would you harvest earlier than planned in order for your crops not be destroyed/damaged by the eruption?

- [ ] Yes
- [ ] No: (Specify why)
    - [ ] Do not believe early warning given by the government
    - [ ] Harvesting not yet possible/appropriate
    - [ ] No available warehouse to keep stocks that would be safe from the impacts of the eruption
    - [ ] Other reason(s): ______________________________

35. Finally, if an eruption occurs with enough lead time, do you think you, your family, and your community are prepared?

- [ ] Yes
- [ ] No: Specify why ______________________________

Thank you for taking time in answering all the questions. Your input in this study will be invaluable and important in providing us with your insights to volcanic threat and how it

Appendix E-2. Sample Questionnaire Form (Filipino)

THE UNIVERSITY OF SYDNEY

School of Geosciences Faculty of Science

QUESTIONNAIRE SURVEY
Pangkalahatang at Patukoy
(General and Specific)

Paaaral ukol sa potensiyal na panganib ng pagputok ng Bulkang Taal sa mga komunidad at paano ito masosolusyunan at mapaghahandaan
(Original Title: Geological and Social Dimensions of Volcanic Hazard and Risk Assessment/Management: Taal Volcano, Philippines as a Case Study)

BILANG NG KALAHOK: _______________
PANGALAN NG BARANGAY_____________________________
MUNISIPYO: ____
PROBINSIYA: ____

PAALALA: Ang pagsusumite ng nakumpletong palatanungan (questionnaire) ay pahiwatig ng iyong pagsangayon at pagbibigay pahintulot upang lumahok sa pag-aaral.

1. Edad ng kalahok:

   ☐ Mas bababa sa 18 (Kung mas mababa sa 18, hindi maaaring lumahok sa pag-aaral)

   ☐ 18-24

   ☐ 25-39

   ☐ 40-55

   ☐ 56-65

   ☐ 66-79

   ☐ 80+

2. Kasarian ng kalahok:

   ☐ Lalaki

   ☐ Babae

   ☐ Iba pa kasarian (mangyaring tukuyin)___________________________

3. Marital status/Katayuan:

☐ Walang asawa

☐ May asawa

☐ May asawa at anak

☐ Hiwalay at may umaasang mga anak

☐ Balo

☐ Balo at may umaasang mga anak

4. Pinakamataas na antas ng pinag-aralan:

☐ Elementarya

☐ High School

☐ Nakatapos ng kolehiyo

☐ Bokasyonal

☐ Masterado o Doktoral na digri

5. Kasalukuyang trabaho ng kalahok:

☐ Full time- What time/Anong oras: _______________

☐ Magsasaka ☐ Mangingisda ☐ Nagtatrabaho sa opisina ☐ Iba pa:______

☐ Part time/casual: Ilang oras ______ Anong oras:________

☐ Nag-aaral

☐ Araw-araw bumibyahe ☐ Linguhan ☐ Buwanan

☐ Hindi nagtatrabaho

☐ Retirado ngunit walang pensiyon

☐ Retirado na may pensiyon

Ang ika-6 hanggang 15 na katanungan ay para malaman ang patungkol sa kahalagahan ng inyong kasalukuyang lugar ng tinitirahan.

6. Kasalukuyang tirahan ng kalahok: Maaring magcheck ng higit isa kung kinakailangan)

☐ Sariling pag-aari ang bahay at lupa

☐ Paupahan

- ☐ Natira kasama ang magulang at/o kamaganak
- ☐ Iba pa: pakitukoy ___________________________

7. Tagal ng paninirahan sa kasalukuyang adres: (check more than one if necessary)
   - ☐ Nakatira mula ng ipanganak
   - ☐ Mahigit sampung taon
   - ☐ 6-10 taon
   - ☐ 1-5 taon
   - ☐ Wala pang 1 taon

8. Kasamang kalahok sa bahay:
   - ☐ Asawa
   - ☐ Asawa at anak
   - ☐ Mag-isa
   - ☐ Mga anak
   - ☐ Pamilya(magulang, kapatid, atbp.)
   - ☐ Ibang kamag-anak
   - ☐ Kaibigan
   - ☐ Iba pa: pakitukoy____________________________

9. Aktibong lumalahok sa mga aktibidad na komunidad (Pwedeng lagyan ng tsek ang higit sa isang kung kinakailangan
   - ☐ Gawaing panglibangan
   - ☐ Gawaing pangrelihiyon
   - ☐ gawaing pangkultura
   - ☐ Iba pa: pakitukoy _______________________________

10. May kasambahay na umaasa sa kalahok:
    - ☐ Meron (Pumunta sa pang-11katanungan)
    - ☐ Wala (Pumunta sa pang-12 katanungan)

11. Kung mayroon, sila ay: (pwedeng sumagot ng mas marami sa isa)

- ☐ Mas bata sa 18 taon
- ☐ Kamag-anak
- ☐ Kaibigan
- ☐ Mga taong may espesyal na pangangailangan: (Pakitukoy kung ilan) ___________________
- ☐ Iba pa: pakitukoy ____________________________

12. Mangyaring ilarawan ang iyong buhay sa inyong komunidad (nasisiyahan, nayayamot, patuloy sa paglipat para sa kabuhayan, atbp) Mangyaring tukuyin kung bakit.

____
____

13. Madalas ba kayong maglakbay sa ibang lugar para sa kabuhayan, serbisyong pangkomunidad/pangrelihiyon, libangan, atbp:

- ☐ OO: pakitukoy

  ☐ Araw-araw ☐ Linguhan ☐ Buwanan ☐ Taunan
- ☐ Hindi madalas
- ☐ Hindi umaalis sa komunidad na tinitirahan

14. Ang inyong pamilya ba ay aktibo sa mga aktibidad ng komunidad (hal. pangrelihiyon, mga aktibidad na may kaugnayan sa kalusugan, panlipunan, atbp)?

- ☐ OO: Pakitsek gaano kadalas

  ☐ Araw-araw ☐ Linguhan ☐ Buwanan ☐ Taunan
- ☐ Hindi kailanman lumahok sa mga aktibidad ng komunidad

15. Maka-ilang paglipat na ang naranasan ninyo?

- ☐ More than once: (check reason below)/Mahigit isang beses: (Itsek ang dahilan)

  ☐ Edukasyon ☐ para sa kabuhayan ☐ dahil sa asawa/ pamilya ☐ relihiyon
- ☐ Hindi pa umaalis ng komunidad mula ng ipanganak

Ang ika-16 hanggang 29 na katanungan ay tinatanong para maunawaan ang inyong pagtingin banta ng panganib dulot ng bulkan, inyong reaksyon at anukala para sa paghahanda, at upang malaman kung marapat bang magkaroon ng karagdagang pakikipanayam.

16. Nakaranas na ako ng isang pagsabog ng Bulkang Taal o kahit anong aktibong bulkan sa Pilipinas:

- ☐ Sa loob ng nakalipas na 40 taon
- ☐ Sa loob ng nakalipas na 50 taon
- ☐ Hindi pa nakaranas ng pagputok ng bulkan

17. Kung ikaw ay nakaranas na ng isang pagsabog, naibigay ba sa iyo ang babala para sa paglisan ng tama sa oras?

- ☐ Oo
- ☐ Hindi

18. Sino ang nagbigay ng babala?

- ☐ Mga punong barangay/komunidad
- ☐ Lokal o nasyonal na pamahalaan
- ☐ PHIVOLCS

19. Kung ikaw ay nakaranas na ng isang pagsabog, lumikas ba kayo kaagad alinsunod sa babala?

- ☐ Oo
- ☐ Hindi

20. Kung kayo ay sumagot ng HINDI, bakit hindi kayo lumikas kaagad?

- ☐ Kailangan ko munang asikasuhin ang aming ari-arian
- ☐ Hindi ako naniwala sa babala
- ☐ Hindi naniwala ang mgakapitbahay ko sa babala kaya hindi ako limisan kaagad
- ☐ Hindi nag-utos ang mga lider ng aming komunidad /Punong Barangay na lumikas nakami
- ☐ Iba pa: pakitukoy ______________________________

21. Sa inyong pananaw, kayo ba ay direktang maaapektuhan kung sakaling pumutok muli ang Bulkang Taal?

- ☐ Oo: pakitukoy, maaaring mas marami ang –tsek kung kinakailangan
  - ☐ Direktang panganib tulad ng *pyroclastic flow*, *base surge*

- ☐ Abo
- ☐ Lahars (Kung umulan/tag-ulan)
- ☐ Iba pang panganib: ___________

☐ Hindi kami maaapektuhan ng pagputok: (Pakitukoy bakit)
____
____
____

22. Who do you go to for information about volcanic hazards, disaster preparedness (please rank from 1 to 7 according to preference/priority:/ Sino ang inyong pinupuntahan para sa impormasyon tungkol sa peligro ng bulkan, isyu ng pagkahanda (mangyaring iranggo ng 1-7 ayon sa inyong kagustuhan o priyoridad)
    - ☐ Mga lider ng komunindad o relihiyon
    - ☐ Kamag-anak at/o kaibigan
    - ☐ Mga kapitbahay
    - ☐ Makikinig sa radio/Telebisyon o iba pang mga social media
    - ☐ Magtext o tumawag sa PHIVOLCS
    - ☐ Magtext o tumawag sa local/nasyonal na pamahalaan
    - ☐ Iba pa: pakitukoy ___________________________

23. Sa oras ng kagipitan, ang inyong mga desisyon ay ibabatay nyo sa (mangyaring iranggo 1-7 ayon sa kagustuhan o priyoridad)
    - ☐ Nakalipas na (mga) karanasan at pakiramdam
    - ☐ Konsultasyon sa aking pamilya
    - ☐ Konsultasyon sa mga lider ng aming komunindad (Hal. Punong Barangay, etc.)
    - ☐ Konsultasyon sa kawani ng PHIVOLCS
    - ☐ Konsultasyon sa kawani ng local/nasyonal na pamahalaan
    - ☐ Ulat na narinig sa radyo / TV o iba pang mga social media (Mangyaring tukuyin) _____________________________________
    - ☐ Iba pa (Pakitukoy)________________________

24. Paano ka kumukuha ng impormasyon tungkol sa nagbabadyang pagsabog? (Itesk ang higit saisa kung kinakailangan)

- [ ] Personal na karanasan at/o biswal na mga palatandaan
- [ ] Impormasyon galing sa kapamilya o kaanak o kaibigan
- [ ] Pakikinig sa radio o pagpanood sa telebisyon o iba pang mga social media
- [ ] Sa kawani ng PHIVOLCS
- [ ] Sa kawani ng local/nasyonal na pamahalaan
- [ ] Iba pa (Pakitukoy)___________________________

25. Ano ang inyong magiging reaksyon kung magpalabas ng babala ang PHIVOLCS ukolsa posibleng pagputok ng Bulkang Taal?

- [ ] Maniwala at agad na lilikas layo mula sa bulkan
- [ ] Konsulta sa pamilya
- [ ] Konsultasyon sa mga lider ng aming komunindad (Hal. Puning Barangay, etc.)
- [ ] Konsultasyon sa kawani ng local/nasyonal na pamahalaan at antayin ang kanilang aksiyon
- [ ] Mag-antay at magmatyag

26. Mayroon ka bang kaalaman sa pagkahanda/pagsasanay sa niyong komunidad patungkol sa Bulkang Taal?

- [ ] Oo: maaring higit sa isang kung kinakailangan
  - [ ] Mayroon akong independiyenteng paghahanda para sa aking pamilya at mga kamag-anak
  - [ ] May paghahanda ang aming komunidad at may regular na pagsasanay
  - [ ] Umaasa sa gabay ng mga lider ng aming komunidad
  - [ ] Umaasa sa gabay ng mga opisyales ng aming local/nasyonal na pamahalaan at antayin ang kanilang aksiyon
- [ ] Hindi, wala kaming paghahanda/pagsasanay ukol krisis pangbulkan.
- [ ] Hindi ko alam ng tungkol sa anumang mga umiiral nang paghahanda ukol sa krisis pangbulkan.

27. Kung kayo ay may pagkahanda sa inyong komunidad, gaano kadalas isinasagawa ang mga pagsasanay?

- [ ] Taunan
- [ ] Dalawang beses sa isang taon
- [ ] Minsan sa tatlong buwan
- [ ] Buwanan
- [ ] Hindi nagkaroon ng pagsasanay mula ng ginawa ang plano

28. Kung naganap ang pagsabog at kayo ay lumikas, gugustuhin nyo pa bang bumalik sa inyong tinitirahan kahit na malubha ito napinsala ng pagsabog? Bakit?

- [ ] Oo: (maaring higit sa isa ang sagot kung kinakailangan)
    - [ ] Dahil sa aming kabuhayan
    - [ ] Dahil sa aming ari-arian
    - [ ] Wala ng ibang mapupuntahan
- [ ] Hindi na babalik

29. Kung kayo ay mabibigyan ng alternatibong kabahayan at kabuhayan, nais nyo bang lumipat sa lugar na malayo mula sa banta ng pagputok ng bulkan?

- [ ] Oo, lilipat ako
- [ ] Hindi: (maaring higit sa isa ansagot kung kinakailangan)
    - [ ] Nandoon and aking pamilya, kaanak at mga kaibigan
    - [ ] Hindi ko nais limipat at iwan ang aking pag-aari kahit na may banta ng isa pang pagsabog
    - [ ] Hindi ako naniniwala na magbibigay ang pamahalaan magandang alternatibong pabahay at kabuhayan.

Ang tanong na ika-30 hanggang 32 ay tinatanong para makuha ang nga ilang detalye sa kabuhayan. Ang layunin ng katanungan ay upang matukoy ang pangkalahatang panahon ng pagtatanim at pag-aani (para sa mga magsasaka) at ang panahon ng pagpapalaki ng fingerlings at pag-aani (para sa mga mangingisda) na may kaugnayan sa mga potensyal na pagsabog sa Bulkang Taal.

30. I am a farmer, and my main source of livelihood is/ Isa akong magsasaka, at ang aking pangunahing pinagmumulan ng kabuhayan ay:

- [ ] Raising livestock: (please specify type) / Pagaalalaga ng baka atbp ____________
- [ ] Rice production/Pagtatanim ng bigas

- [ ] Pagtatanim ng buko
- [ ] Pagtatanim ng mais
- [ ] Pagtatanim ng kape/paminta/rootcrops
- [ ] Pagtatanim ng gulay
- [ ] Fruit production including pineapple, etc./Pagtatanim ng prutas
- [ ] Hindi naaangkop, hindi magsasaka (Tumuloy sa ika-32 Tanong)

31. Kung pagsasaka ang kabuhayan, pinaka-angkop na panahon sa pagtatanim: Pumili ng higit sa isa kung kinakailangan)
    a. Pagtatanim

- [ ] Enero
- [ ] Pebrero
- [ ] Marso
- [ ] Abril
- [ ] Mayo
- [ ] Hunyo
- [ ] Hulyo
- [ ] Agosto
- [ ] Septembre
- [ ] Octubre
- [ ] Nobyembre
- [ ] Disyembre

    b. Pag-ani

- [ ] Enero
- [ ] Pebrero
- [ ] Marso
- [ ] Abril
- [ ] Hunyo
- [ ] Mayo
- [ ] Hulyo
- [ ] Agosto
- [ ] Septembre
- [ ] Octubre
- [ ] Disyembre
- [ ] Nobyembre

32. I am a fisherman, and my main source of livelihood is/ Isa akong mangingisda, at ang aking pangunahing pinagmumulan ng kabuhayan ay:

- [ ] Pag-aalaga ng tilapia
- [ ] Pag-aalaga ng ibang uri ng isda: (Maaring tukuyin)
  ____
- [ ] Hindi naaangkop, hindi mangingisda (Tumuloy sa ika-34 Tanong)

33. Kung mangingisda, pinaka-angkop na panahon sa pagpapalaki/pag-ani ng isda at ibang lamang ilog: Pumili ng higit sa isa kung kinakailangan)

a. Pagpapalaki

☐ Enero	☐ Hulyo
☐ Pebrero	☐ Agosto
☐ Marso	☐ Septembre
☐ Abril	☐ Octubre
☐ Mayo	☐ Nobyembre
☐ Hunyo	☐ Disyembre

b. Pag-ani

☐ Enero	☐ Hulyo
☐ Pebrero	☐ Agosto
☐ Marso	☐ Septembre
☐ Abril	☐ Octubre
☐ Mayo	☐ Nobyembre
☐ Hunyo	☐ Disyembre

34. Kung ang babala ng pagsabog ay binigay ilang lingo sa posibleng pagsabog, kayo ba ay magkukusang-loob na mag-ani ng mas maaga upang hindi masira o mapinsala inyong pananim sa pagsabog?

☐ Yes/Oo

☐ Hindi: Pakitukoy kung bakit hindi

- ☐ Hindi naniniwala sa babala
- ☐ Hindi angkop ang panahon para anihin ang tanim/pinapalaking isda
- ☐ Walang pasilidad na ligtas na pwedeng pagtaguan ng ani

35. Panghuling katanungan, kung ang pumutok ang bulkan at may sapat na panahon mula sa pagbigay ng babala, sa palagay ninyo kayo at ang inyong pamilya at komunidad ba ay handa?

☐ Oo

☐ Hindi: (Maaring tukuyin) ____

Salamat sa inyo paglalaan ng panahon sa pagsagot sa lahat ng mga katanungan. Ang iyong paglahok at kontribusyon sa pag-aaral na ito ay napakahalaga para sa mas malalim at malawak na pang-unawa sa pananaw ninyo ukol sa nagbabantang panganib ng pagsabog ng bulkan at kung paano ito nakakaapekto sa inyong buhay.

APPENDIX F

Copy of the University of Sydney Human Resource Ethics Committee (HREC) approval letter granted 21 July 2014 for this research entitled “Geological and Social Dimensions of Volcanic Hazards and Risk Assessment /Management: Taal Volcano, Philippines as a Case Study”.

THE UNIVERSITY OF SYDNEY

Research Integrity
Human Research Ethics Committee

Monday, 21 July 2014

Assoc Prof Dale Dominey-Howes
Geosciences; Faculty of Science
Email: dale.dominey-howes@sydney.edu.au

Dear Dale

I am pleased to inform you that the University of Sydney Human Research Ethics Committee (HREC) has approved your project entitled "**Geological and Social Dimensions of Volcanic Hazard and Risk Assessment/Management: Taal Volcano, Philippines as a Case Study**".

Details of the approval are as follows:

Project No.: **2014/560**

Approval Date: **1 July 2014**

First Annual Report Due: **1 July 2015**

Authorised Personnel: **Dominey-Howes Dale; Delos Reyes Perla;**

Documents Approved:

Date Uploaded	Type	Document Name
11/06/2014	Participant Info Statement	A1_Participant Information Statement in English
11/06/2014	Participant Info Statement	A1B_Participant Information Statement in Filipino language
11/06/2014	Participant Consent Form	A2_Participant Consent Form in English
11/06/2014	Participant Consent Form	A2B_Participant Consent Form in Filipino language
11/06/2014	Recruitment Letter/Email	C1_Letter of Introduction from Chief Investigator for Govt/NGO
11/06/2014	Recruitment Letter/Email	C2_Letter of Introduction from Director/PHIVOLCS for Governor
11/06/2014	Recruitment Letter/Email	C3_Letter of Introduction from Director/PHIVOLCS for Mayors
11/06/2014	Recruitment Letter/Email	C4_Letter of Introduction from PHIVOLCS for Barangays_English
11/06/2014	Recruitment Letter/Email	C4B_Letter of Introduction from PHIVOLCS for Barangays_Filipino
11/06/2014	Questionnaires/Surveys	D1_Questionnaire in English
11/06/2014	Questionnaires/Surveys	D1B_Questionnaire in Filipino language
11/06/2014	Interview Questions	D2_Interview Themes/Topics in English
11/06/2014	Interview Questions	D2B_Interview Themes/Topics in Filipino language

Research Integrity
Research Portfolio
Level 6, Jane Foss Russell
The University of Sydney
NSW 2006 Australia

T +61 2 8627 8111
F +61 2 8627 8177
E ro.humanethics@sydney.edu.au
sydney.edu.au

ABN 15 211 513 464
CRICOS 00026A

HREC approval is valid for four (4) years from the approval date stated in this letter and is granted pending the following conditions being met:

Condition/s of Approval

- Continuing compliance with the National Statement on Ethical Conduct in Research Involving Humans.
- Provision of an annual report on this research to the Human Research Ethics Committee from the approval date and at the completion of the study. Failure to submit reports will result in withdrawal of ethics approval for the project.
- All serious and unexpected adverse events should be reported to the HREC within 72 hours.
- All unforeseen events that might affect continued ethical acceptability of the project should be reported to the HREC as soon as possible.
- Any changes to the project including changes to research personnel must be approved by the HREC before the research project can proceed.
- Note that for student research projects, a copy of this letter must be included in the candidate's thesis.

Chief Investigator / Supervisor's responsibilities:

1. You must retain copies of all signed Consent Forms (if applicable) and provide these to the HREC on request.
2. It is your responsibility to provide a copy of this letter to any internal/external granting agencies if requested.

Please do not hesitate to contact Research Integrity (Human Ethics) should you require further information or clarification.

Yours sincerely

Dr Stephen Assinder
Chair
Human Research Ethics Committee

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007), NHMRC and Universities Australia Australian Code for the Responsible Conduct of Research (2007) and the CPMP/ICH Note for Guidance on Good Clinical Practice.

APPENDIX G

Appendix G summarizes the chronology of the AD1754 eruption of Taal with interpretations of eruptive styles, processes and products. Sources of information include Saderra Masó (1904, 1911); Pratt (1911); Worcester (1912); Moore et al. (1966); Ruelo (1983); Masigla and Ruelo (1987); Oppenheimer (1991); DOST-PHIVOLCS (1991, 1995, 2016); Smithsonian (2016); Delos Reyes et al. (2018).

The Chronology of the AD1754 Eruption of Taal Volcano, Philippines with interpretations of eruptive styles, processes and products.

DATE/ TIME	SIGNIFICANT DESCRIPTION OF ACTIVITY	NEW INTERPRETATION OF ERUPTIVE ACTIVITY	ERUPTIVE PROCESSES/ DEPOSITS	IMPACT(S)	REFERENCE(S)
Phase 1: 15 May (between 9 or 10PM) up to 02 Jun 1754	*"the volcano quite unexpectedly commenced to roar and emit, sky-high, formidable flames intermixed with glowing rocks which, falling back upon the island and rolling down the slopes of the mountain, created the impression of a large river of fire*"	Plinian/Sub-Plinian with column collapse leading to generation of PDCs	TF, BP, VE, PDC	Tephra column reaching maximum height of ~40m; pumice fragments observed in the lake; volcanic ejecta were propelled to the NW that destroyed Bayuyungan, Laurel	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 9; Worcester, 1912, page 319
Phase 2: 02 June-26 Sep 1754	*"volcano never ceased to eject fire and mud of such bad character that the best ink does not cause so black a stain"; "the fire emitted was quite extraordinary and accompanied by terrifying rumblings. The strangest thing was, that within the black column of smoke issuing from the volcano ever since June 2, there frequently formed thunderstorms, and it happened that the huge tempest cloud would scarcely ever disappear during two months."*	Phreatomagmatic events; continuous ejection of volcanic materials that resulted in darkening of lake water; volcanic tremors, lightning flashes; tephra clouds continuously observed but height of tephra column could not be determined	TF, PDC, VE, EA	Houses made of non-concrete materials collapsed under the weight of the tephra load; about 45 centimeters of tephra deposited; damage to plants/trees/crop s;	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 9; Worcester, 1912, page 319
Quiescenc e: 26 Sep to 30 Oct 1754	Daybreak of 26 Sep- "*After this the volcano calmed down considerably, though not sufficiently to offer any prospect of tranquility.*"	Volcano quieted down enough that people were able to assess impact of the eruptive activity.			Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 9
Phase 3: 1-15 Nov 1754	"*resumed its former fury, ejecting fire, rocks, sand, and mud*"; "*vomited enormous bowlders which rolling down the slopes of the island, fell into the lake and caused waves*"	Plinian/ Sub-Plinian or Phreatomagmatic	TF, PDC, VE, VT	Occurrence of volcanic tsunami on 15 November	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 9; Worcester, 1912, page 319
Phase 4: 1754 28 Nov to 02 Dec	At 0700PM of 28 Nov- "*columns of fire and smoke ascended higher than ever before*"; "*accompanied by terrific lightning and thunder above, and violent shocks of earthquake underneath*"; "*the cloud of ejecta, carried on by the wind, extended itself toward west and south with the result that we saw already stones fall close to our shores*"	Plinian/Sub-Plinian and Phreatomagmatic events; tall ash column, well-defined umbrella cloud, and tephra fall; eruption reached its peak; volcanic tsunami possibly produced by pyroclastic materials exceeding shoreline and entering into the	TF, PDC, VE, EA, SW, FL, AR, F, G	Tephra columns formed with electrical activity; greatest volume ejected; tephra fall drifted west and south of Taal volcano	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, p.9; Worcester, 1912, page 319-320

		lake; lightning flashes			
	"*waves of the angry lake began already to flood the houses nearest to the beach*"; "*in other parts of the lakeshore have likewise opened many cracks*"	Occurrence of volcanic tsunami	VT, LIQ	Inundation of houses near lakeshore; waves swept away objects it its path	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, p.10-11
	On 28 to 29 Nov from late evening to dawn- "*volcano subsided almost suddenly*"	Lull/quiescence		Lull/quiescence	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 10; Worcester, 1912, page 320
	From 0800AM 29 Nov to 02 Dec- *"heard a crash and then I noticed that the smoke was rising from the point of the island which looks towards the east"; "it began to rain mud and ashes at Caysasay (12 miles) from the volcano and this rain lasted three days. The most terrifying circumstance was that the whole sky was shrouded in such darkness that we could not have seen the hand placed before my face, had it not been for the sinister glare of the incessant lightnings"; "the 1st of December broke somewhat clear and our eyes contemplated everywhere ruins and destruction. The layer of ashes and mud was more than 5 spans (1.1m or 43 inches) thick, and it was almost a miracle that the roofs of the church and convento sustained so great a weight."*	Intense Phreatomagmatic activity with fissure-controlled flank eruptions; base surges and co-surge ash were generated; ash column generated with subsequent ashfall about 1.1m thick at Old Taal; fissuring at the Fracture Zone trending NE-SW; earthquake-induced landslides	TF, PDC, EA	Tephra fall at Caysasay (SW) that is 19.3 meters from the volcano; aggradation blocked the mouth of Pansipit River resulting in inundation of Old Lipa and Old Tanauan; change in wind direction on 2nd of December carried tephra fall materials up to Balayan, Batangas (28km southwest of Taal) and tephra reached Manila (~60km north of Taal)	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 10; Worcester, 1912, page 320-321
Cessation of activity: 3-4 Dec 1754	"*we had a formidable typhoon, and therefore the volcano quieted down*"	Passage of typhoon			Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 10; Worcester, 1912, page 321
Summary Impacts/ Aftermath	Upon return to Taal, Fr. Buencuchillo said "*nothing was left of it except the walls of the church and convento. All the rest, the government house, the walks of the rope factory, the warehouses, everything was buried beneath a layer of stones, mud, and ashes more than 10 spans thick"; "twelve persons are known to*	Pyroclastic density currents and tephra fall deposits destroyed most infrastructures in Old Taal, now part of San Nicolas; thickness of deposits estimated to be about 2.2m; 12 casualties were reported	PDC, TF	Only about 700 of 6000 inhabitants remained in Old Taal after the eruption	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 10 & 26; Worcester, 1912, page 327

have perished- some carried away by the waves of the lake, others crushed beneath their collapsing houses."				
"*In other parts of the lake shore have likewise opened many cracks and occurred very extensive slides*."	Lateral spreading & mudslides (liquefaction effects)	F, LIQ	Location of phenomena not identified	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 10-11; Worcester, 1912, page 327
"*mouth of the river Pansipit having been blocked, the lake is rising and invading the towns of Lipa and Tanauan, both being on the lowest level, and inundating their buildings*"	Flooding resulting from damming of river mouth	FL	Old towns of Tanauan and Lipa flooded	Fr. Buencuchillo of Taal *In* Saderra Masó, 1911, page 11; Worcester, 1912, page 327
"an eruption of Mount Taal caused waves on Lake Taal which together with the volcanic ejecta destroyed the nearby towns of Taal, Lipa, Tanauan and Sala. These waves also washed out the road to Balayon on the west side of the lake (referencing Masó and Worchester)."	Volcanic tsunami		Volcanic tsunami impacted Taal, Lipa, Tanauan and Sala	Berninghausen, 1969, page 295

1. Eruptive processes/deposits: VE- volcanic earthquakes; RS- rumbling sounds; F- fissuring; SU- subsidence; EA- electrical activity (e.g. vent discharges, near-vent lightning, plume lightning); SW- shock waves; PDC- pyroclastic density current (e.g. pyroclastic flows, base surge); PF- pyroclastic flow; VT – volcanic tsunami/seiche; TF- tephra fall; LVF- lava flow; LVFO-lava fountaining; AR- acid rain; LIQ- liquefaction effects; FL- flooding; GE- geysering; G- toxic gases; ND- no description
2. Eruptive impacts: TVI- Taal Volcano Island, N- north; S- south; E- east, W-west; SE- southeast; SW- southwest; ND description; UF- undertermined fatalities

APPENDICES H-1 TO H-38

Appendix H-1 to H-38 provides results of the geologic mapping activities undertaken including lithologic identification, stratigraphic logging and measurement of thickness of each stratigraphic layer. Map locations, photo documentation, and stratigraphic columns are provided for each of the outcrops. While 41 exposures were identified, mapped and the thickness of the tephra layers were measured, some outcrops do not have stratigraphic logs (e.g. (Outcrop #5 and #34). This is because some are poorly exposed or because previously identified exposures (e.g. Outcrop # 27, #28 and #36) had been covered over by local government engineering offices and regional offices of the Department of Public Works and Highways (DPWH) to reduce landslide potential. In general, exposures of the AD1754 deposits were found where past and present quarrying and road cutting was being undertaken at the time of the surveys.

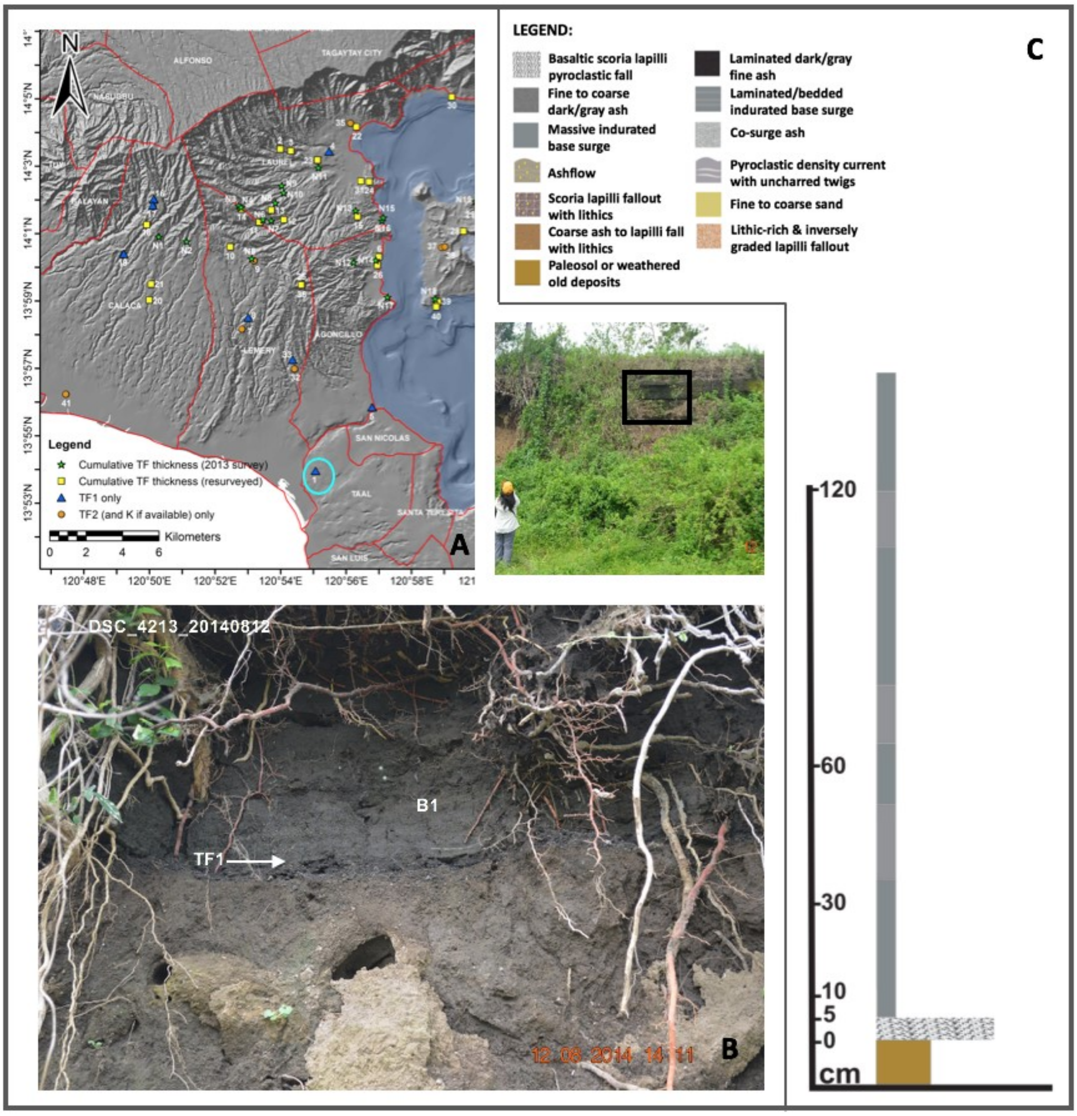
A total of 25 of the 41 exposures have both *TF1* and *TF2* tephra deposits present. Eight outcrops only had *TF1* and another eight outcrops only had *TF2*. The very thin key bed unit (*K*) is generally found underlying *TF2* and the thicknesses of the key beds are added to the total thickness of the *TF2* units. Keybeds or marker beds, are chronostratigraphic markers readily recognisable because of their distinct physical characteristics and are generally found over a large area.

The AD1754 event spanned from 15 May to 2 December with four main phases that included: a) a plinian/sub-plinian phase that started on 15 May and lasted until 2 June; b) a phreatomagmatic phase from 2 June until 26 September; c) a plinian/sub-plinian or phreatomagmatic phase from 1 to 15 November; and d) a plinian/sub-plinian and phreatomagmatic phase that commenced on 28 November and lasted until 2 December. Detailed descriptions of the AD1754 eruption are provided in Chapter 4, Section 4.1.2.3 and Appendix A. Out of the four phases, only two were deemed to be represented by exposed deposits: the 15 May to 2 June phase tephra deposit identified as *TF1* in this study, and the tephra deposit identified as *TF2* correlated to the November phase.

In general, the outcrops included a base layer of paleosol that served as marker that had sharp contact with the base of the tephra deposit. The *TF1* layer was identified as scoria lapilli fall that was observed to be dark, brittle and highly vesiculated. On top of *TF1*, a massive and indurated to cross-bedded base surge layer were logged. The massive *B1* beds appear to have no internal structure and stands out as one coherent single unit. The observed cross bedding in the base surge layers of the AD1754 exposures are more likely small-scale trough bedding that were inclined when compared to base or top of the bed. The *TF2* unit that consisted of thick, often graded, dark lapilli fall units were likely ejected and deposited during the November plinian/sub-plinian phase. The total thickness for the November phase combines *TF2* and *K* (hereafter, referred to as simply *TF2*), as it is assumed that they were ejected and emplaced during the same eruptive phase. The uppermost unit, *B2*, is a plane-bedded to massive base surge layer that is likely the eruptive product of a phreatomagmatic eruptive phase of the AD1754 event.

APPENDIX H-1.

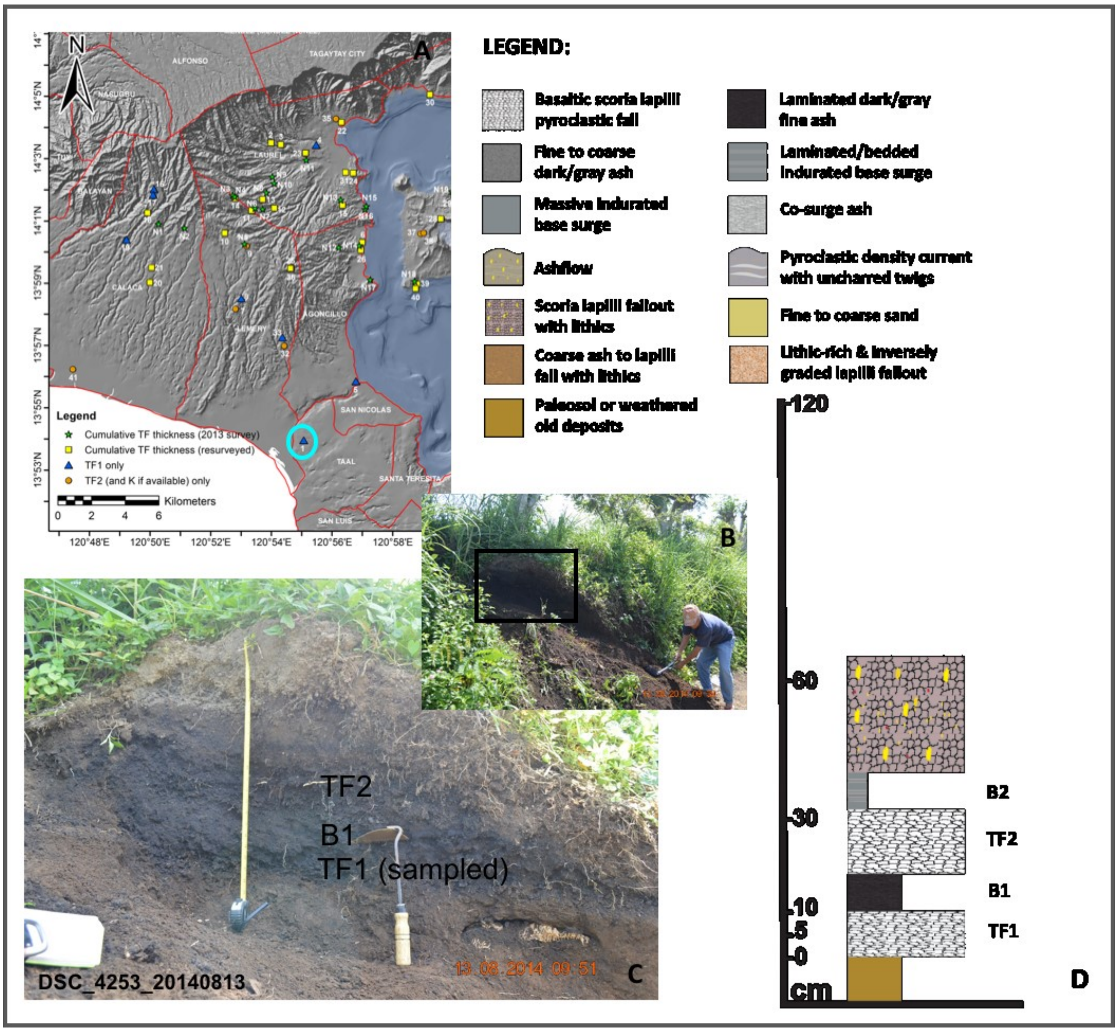
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #1 at Barangay Cawit, Municipality of Taal, Batangas Province. An AD1754 exposure located southwest of Taal. A) map showing location of the outcrop, a distance of ~15.5 km from the volcano, highlighted by a blue circle; B) close-up picture of the outcrop with a layer of massive to bedded base surge deposit *(B1)*, on top of dark, brittle and vesiculated tephra fallout (*TF1*) deposits; C) detailed stratigraphy of the outcrop with *TF1* having thickness of 5 cm and *B1* having thickness of 140 cm.

APPENDIX H-2.

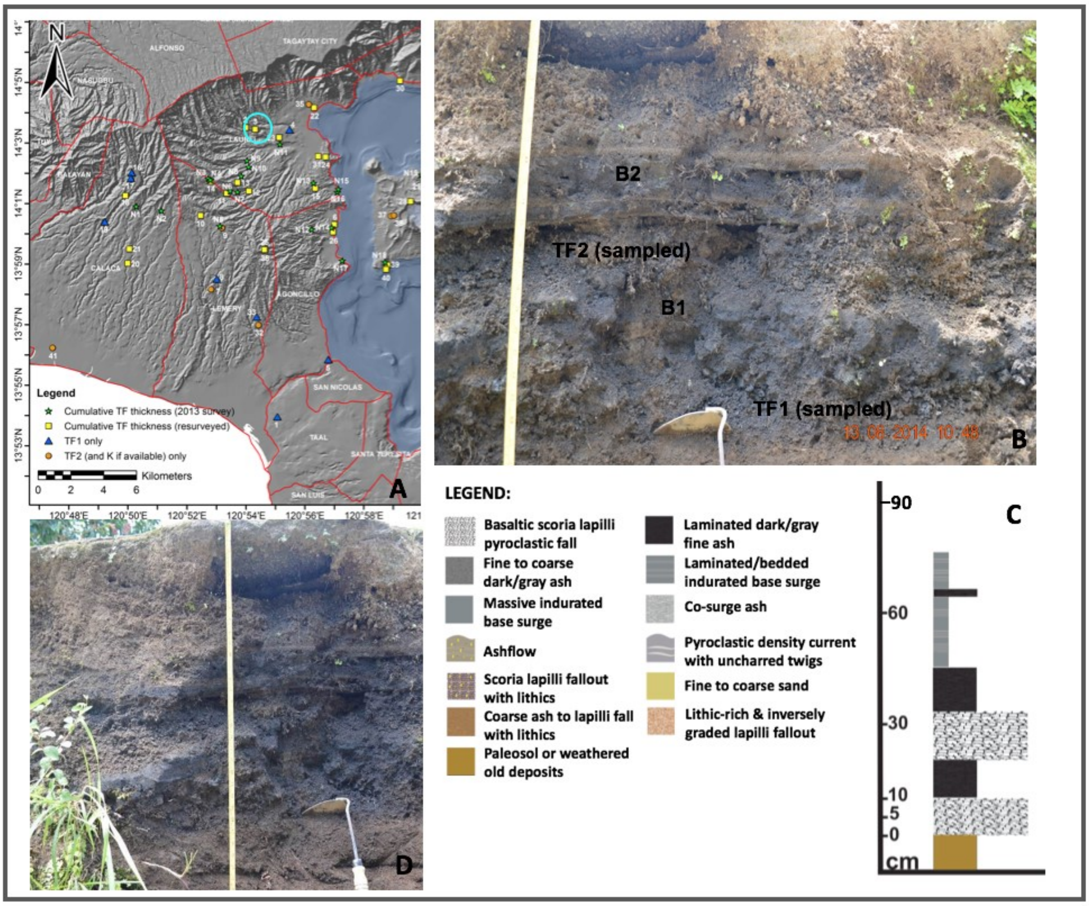
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #2 (WP443) at Barangay As-is, Municipality of Laurel, Batangas. An AD1754 exposure located southwest of Taal. A) map showing location of the outcrop, about 12 km from the volcano, highlighted by a blue circle; B) general location of outcrop; C) close-up photo of the outcrop with alternating layers of massive to bedded base surge deposit, identified as B1, and dark, brittle and vesiculated tephra fallout (*TF1* and *TF2*) deposits; D) detailed stratigraphy of the outcrop with *TF1* having a thickness of 24 cm and *TF2* having a thickness of 25 cm.

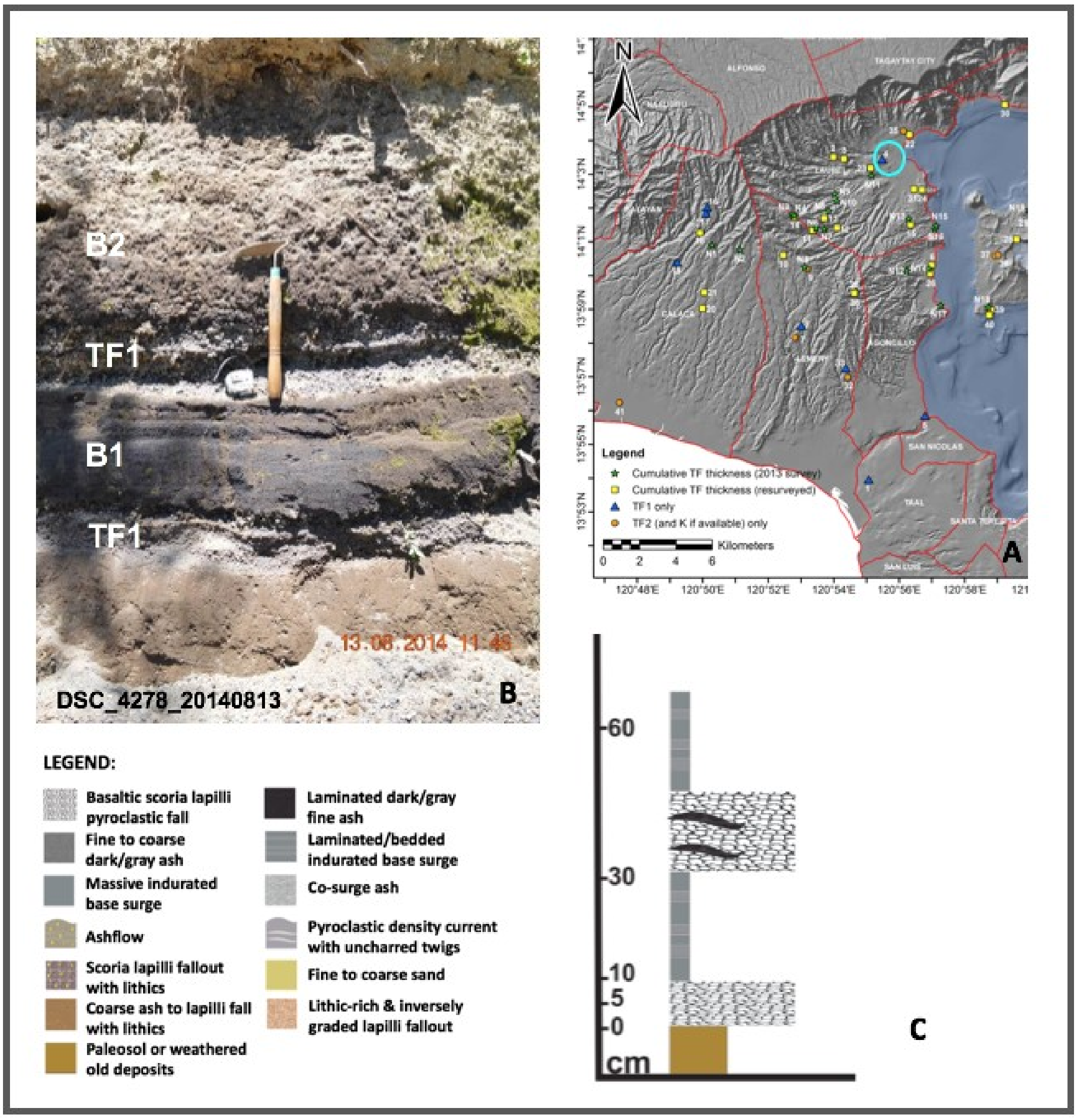
Appendix H-3.

Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #3 (WP444) at Barangay As-is, Municipality of Laurel in Batangas Province. An AD1754 exposure located southwest of Taal. A) map showing location of the outcrop, a distance of 12 km from the volcano, highlighted by a blue circle; B) close-up picture of the outcrop with alternating layers of dark, brittle and vesiculated tephra fallout deposits (*TF1* and *TF2*) and massive to bedded base surge deposit (*B1* and *B2*); C) detailed stratigraphy of the outcrop with *TF1* having thickness of 23 cm and *TF2* having thickness of 24 cm.

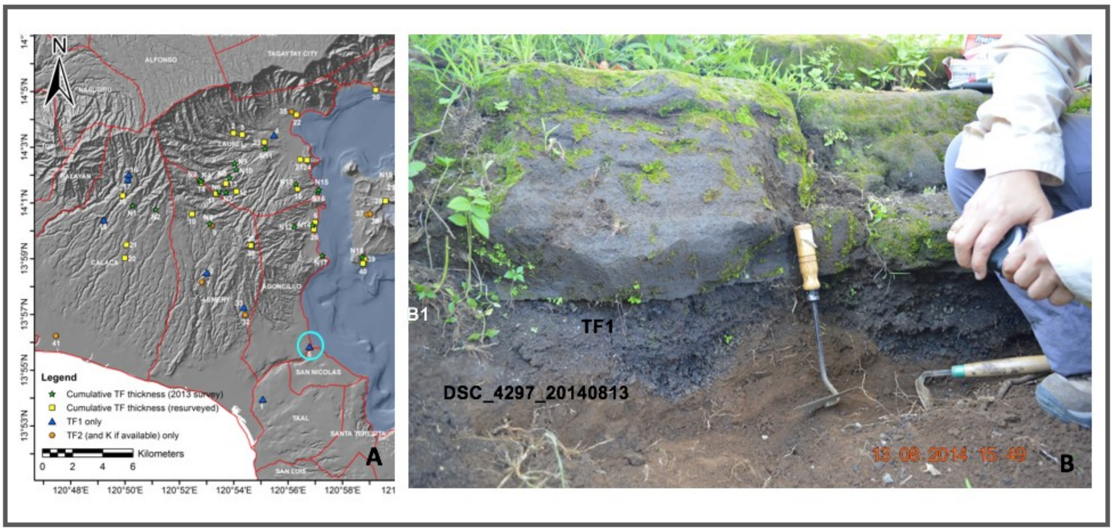
APPENDIX H-4.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #4 (WP445) at Barangay As-is, Municipality of Laurel, Batangas. An AD1754 exposure located southwest of Taal. A) map showing location of the outcrop, a distance 8.5 km from the volcano, highlighted by a blue circle; B) close-up picture of the outcrop consisting of (bottom to top): paleosol with erosional contact with dark, brittle and vesiculated tephra fallout (*TF1*) deposits followed by a layer of massive to bedded base surge deposit (*B1*), then overlain by another basaltic tephra fallout deposit but with cross laminatio n of dark fine ash (*TF1*) topped by another surge deposit (*B2*); C) detailed stratigraphy of the outcrop with *TF1* having thickness of 27 cm, *B1* with thickness of 23 cm, and *B2* with thickness of 6 cm.

APPENDIX H-5.

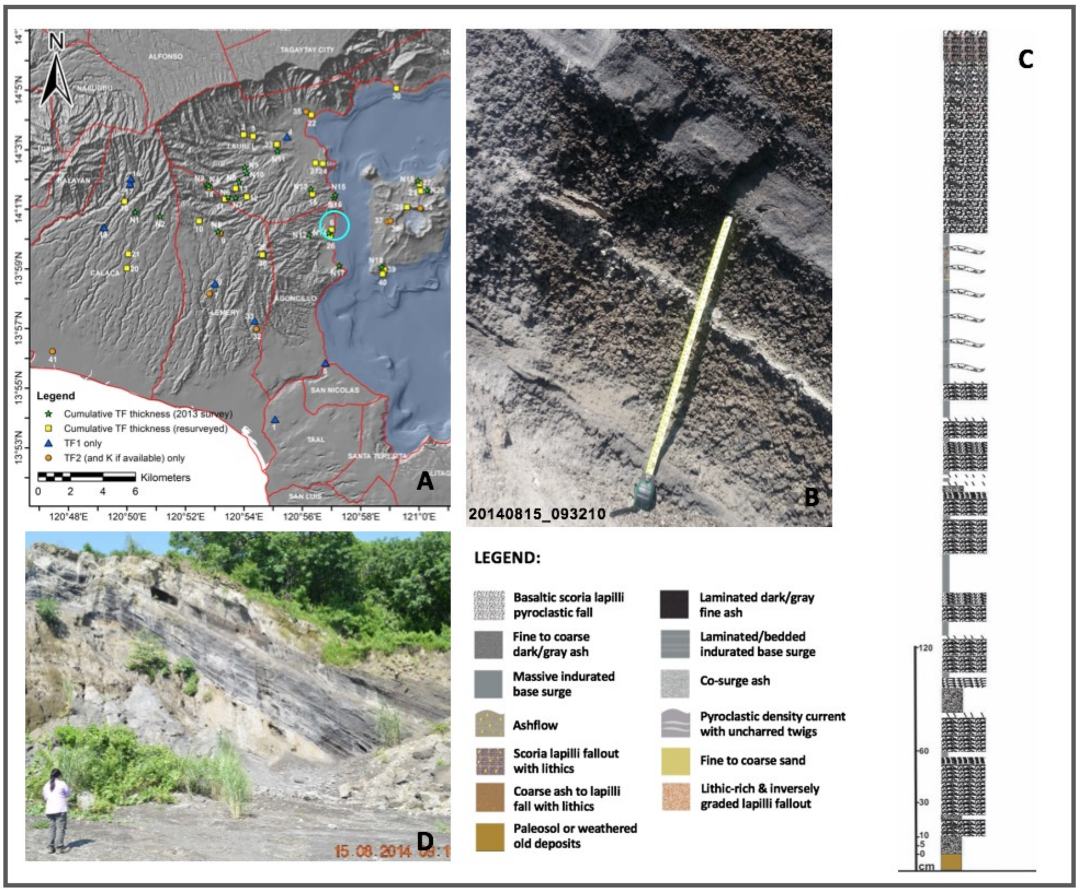
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #5 at Barangay Pansipit, Municipality of San Nicolas, Batangas Province. An AD1754 exposure located southwest of Taal Volcano. A) map showing location of the outcrop highlighted by a blue circle; B) close-up picture of the outcrop with a layer of massive to bedded base surge deposit, identified as *B1* having thickness of 50 cm on top of dark, brittle and vesiculated tephra fallout (*TF1*) deposits with thickness of 16 cm.

APPENDIX H-6.

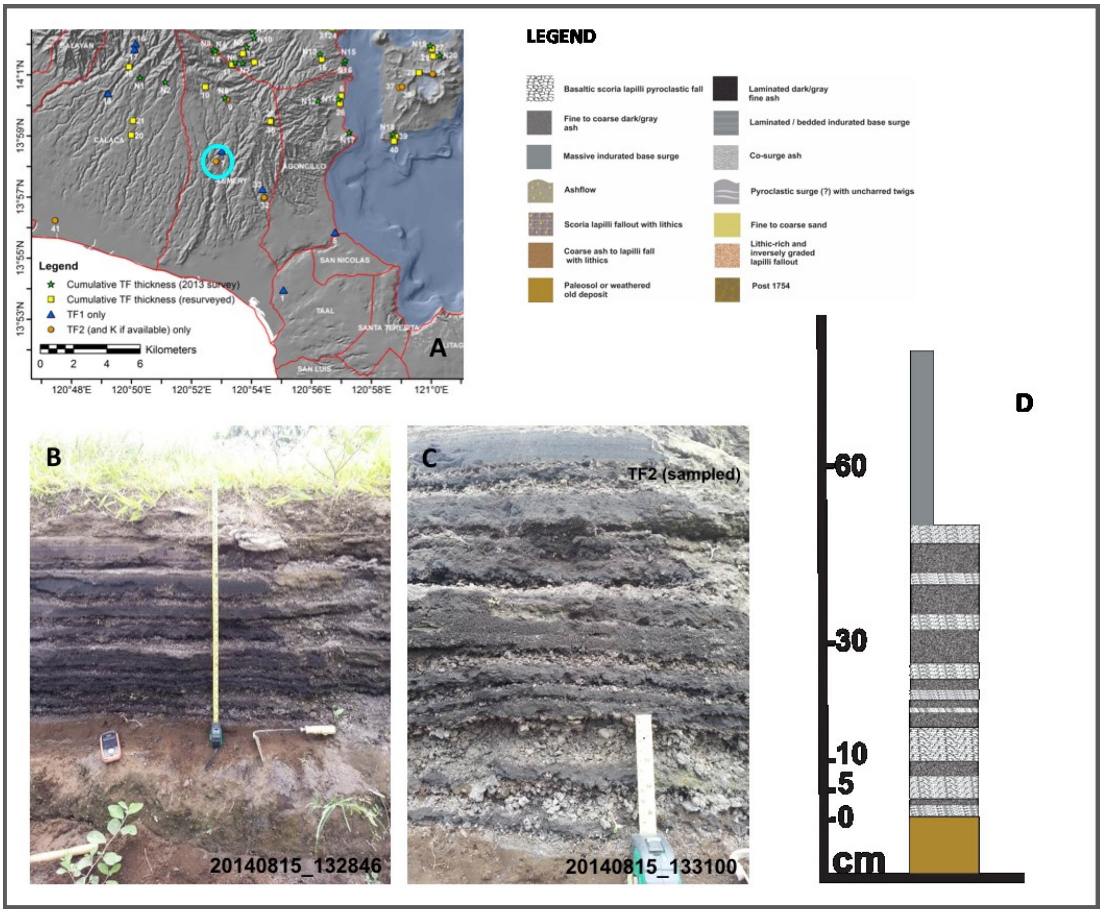
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #6 (WP 451) at Barangay Banyaga, Municipality of Agoncillo, Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of 6 km from the volcano, highlighted by a blue circle; B) close-up picture of the outcrop with alternating layers of tephra fall (*TF1* and *TF2*) and surge deposits; C) detailed stratigraphy of the outcrop; and D) profile picture of the outcrop. Thickness of *TF1* ~190 cm and *TF2* ~124 cm.

APPENDIX H-7.

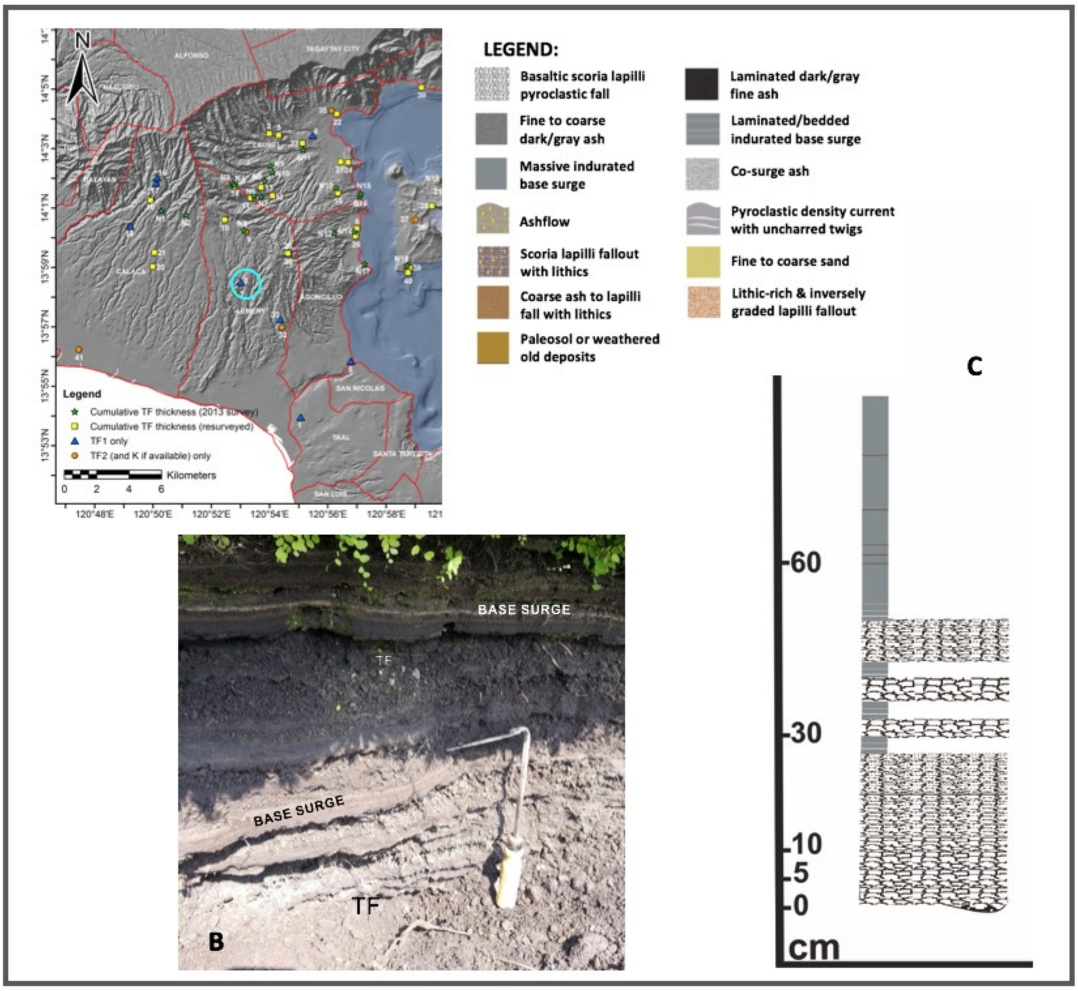
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #7 (WP452) at Barangay Masalisi, Municipality of Lemery, Batangas. An AD1754 exposure located southwest of Taal. A) map showing location of the outcrop, a distance of ~13.5 km from the volcano, highlighted by a blue circle; B) profile picture of the outcrop; C) close-up picture of the outcrop with alternating layers of tephra fall (*TF2*), surge, and base surge deposits; and D) detailed stratigraphy of the outcrop. Thickness of *TF2* ~33 cm.

APPENDIX H-8.

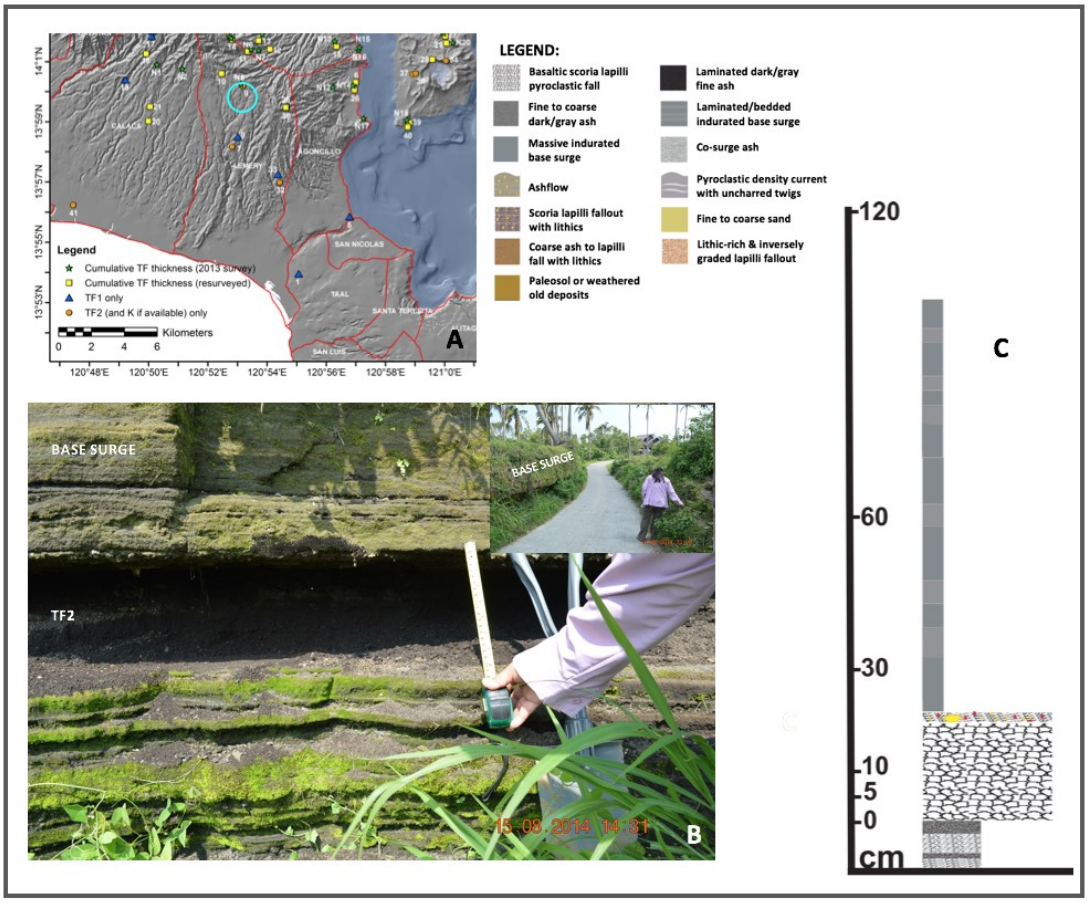
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #8 (WP453) at Barangay Masalisi, Municipality of Lemery, Batangas Province. An AD1754 exposure located southwest of Taal. A) map showing location of the outcrop located 13.5 km from the volcano, highlighted by a blue circle; B) profile photo of the outcrop; C) close-up photo of the outcrop with alternating layers of massive to bedded base surge deposit (B), and dark, brittle and vesiculated tephra fallout (*TF1*) deposits with total thickness of 17.5 cm.

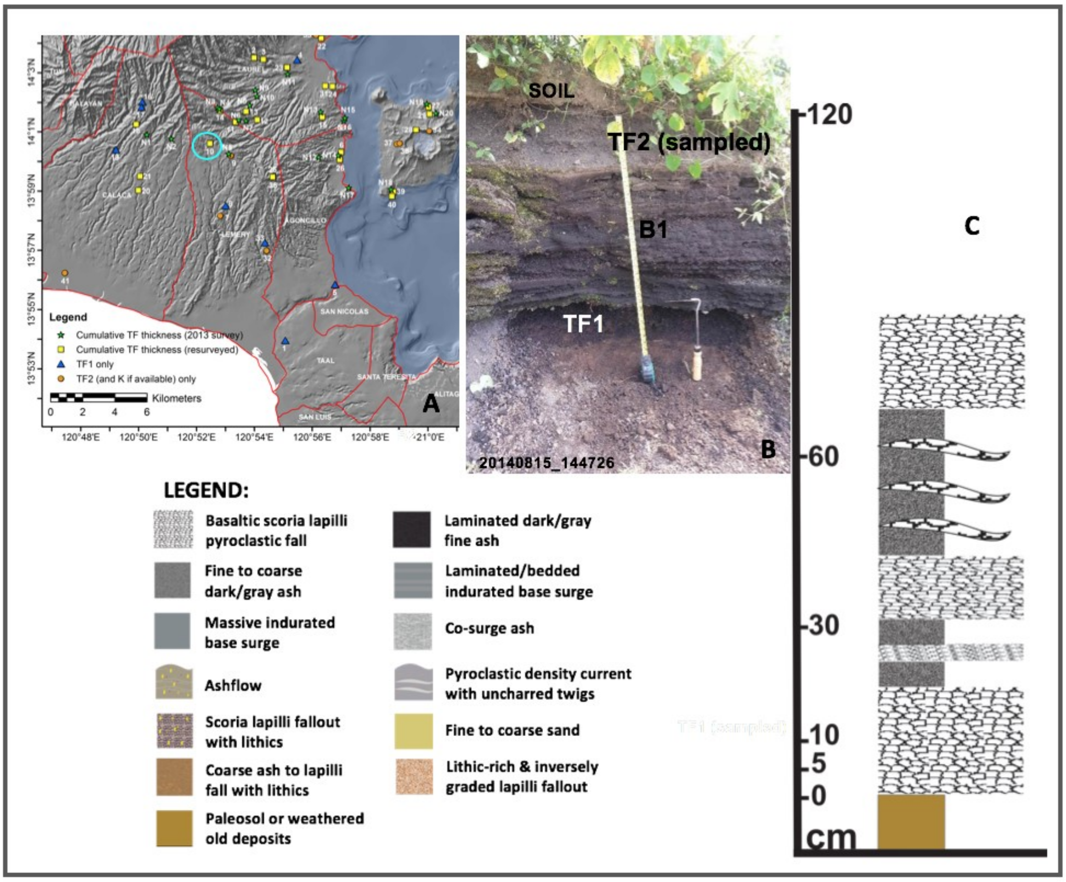
APPENDIX H-9.

Stratigraphic mapping of suspected AD1754 deposits at Taal



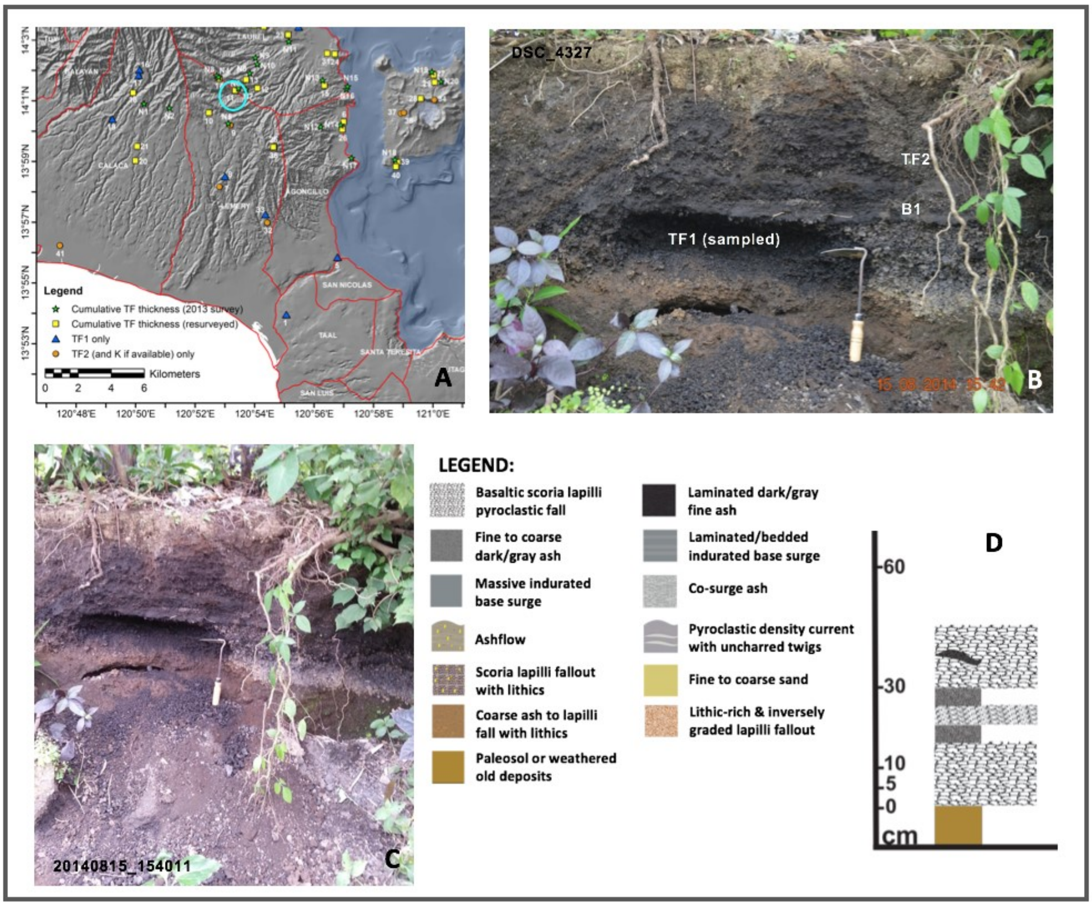
Outcrop #9 (WP454) at Barangay Payapa, Municipality of Lemery, Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of 12 km from the volcano, highlighted by a blue circle; B) close-up photo (with inset profile photo) of the outcrop with alternating layers of tephra fall (*TF2*), surge, and base surge deposits; C) detailed stratigraphy of the outcrop. Only *TF2* is exposed with a thickness of ~19 cm.

Appendix H-10.
Stratigraphic mapping of suspected AD1754 deposits at Taal



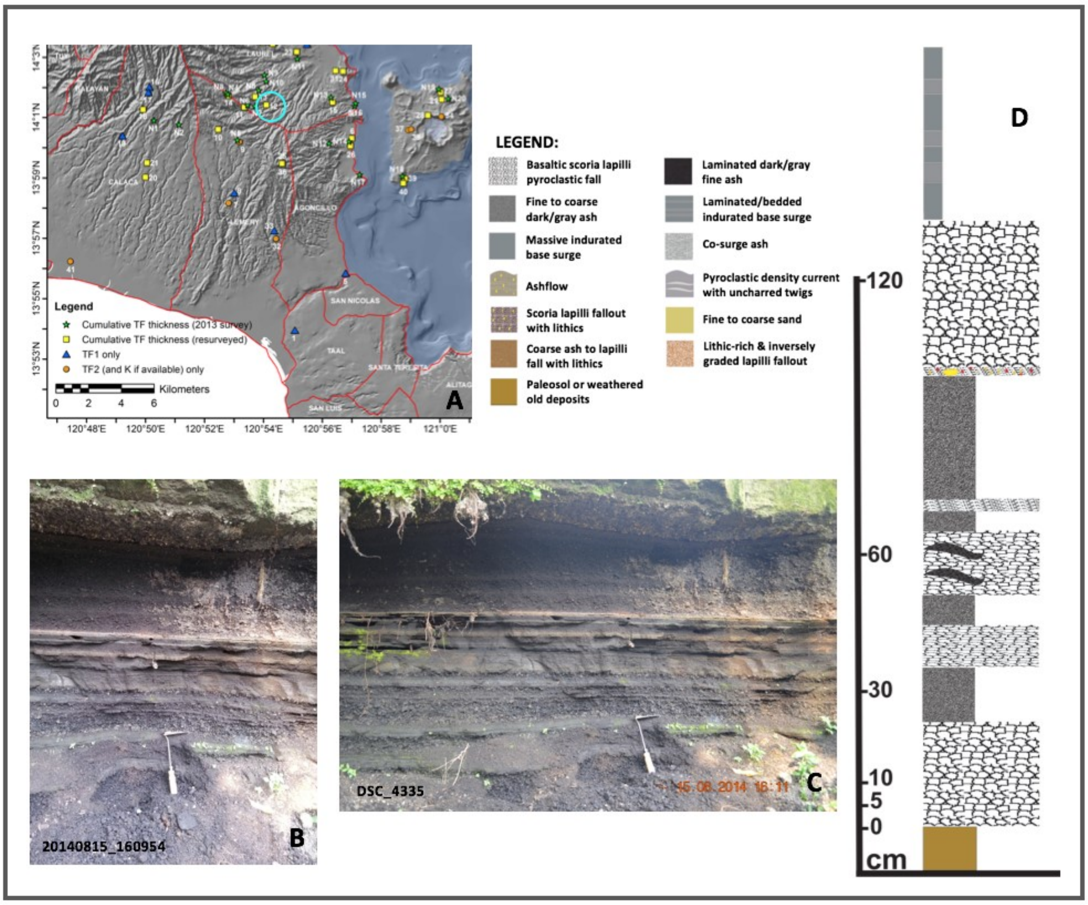
Outcrop #10 (WP455) at Barangay Niogan, Municipality of Lemery, Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of 13.5 km from the volcano, highlighted by a blue circle; B) and C) profile and close-up photos of the outcrop with alternating layers of tephra fall (TF2) intercalated with surge, and base surge deposits; D) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~33 cm and *TF2* ~16.5 cm.

APPENDIX H-11.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #11 (WP456) at Barangay Ticub, Municipality of Laurel, Batangas. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of 12km from the volcano, highlighted by a blue circle; B) close-up photo of outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with surge and base surge deposits; C) profile photo of the outcrop; D) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~21 cm and *TF2* ~16 cm.

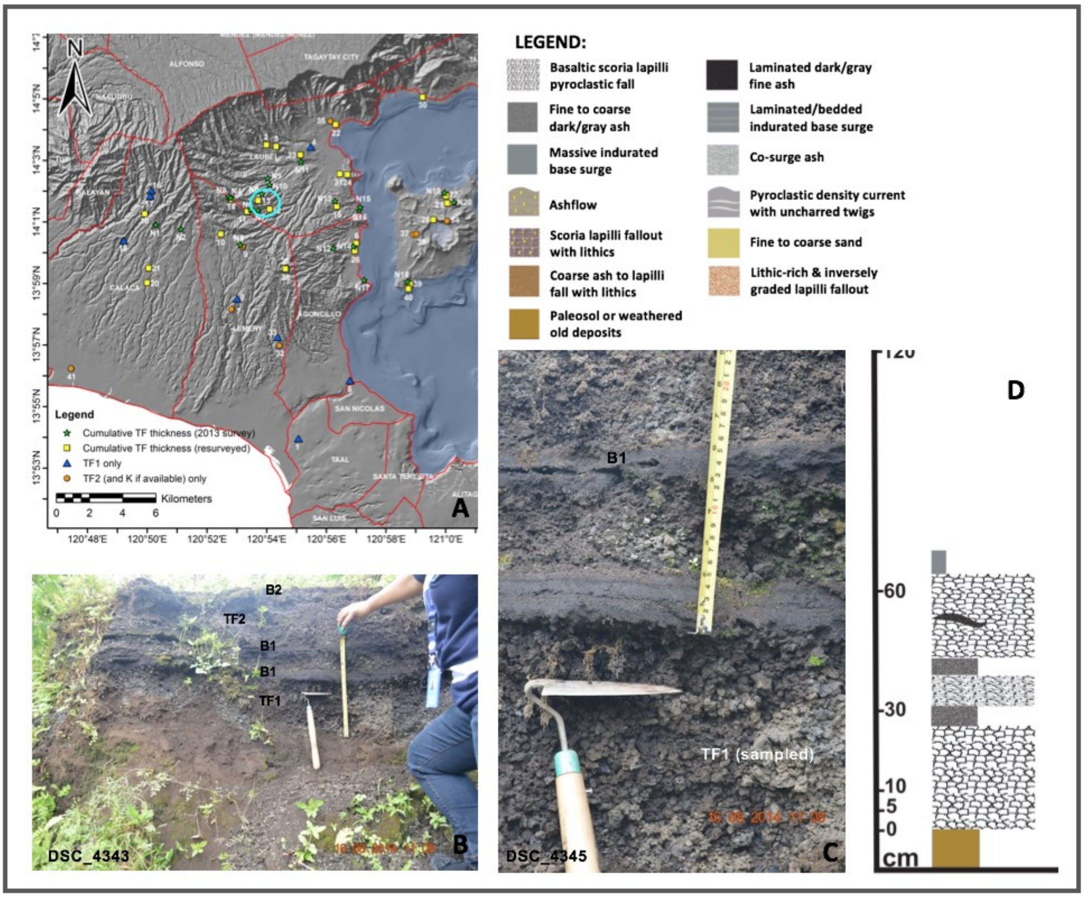
APPENDIX H-12.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #12 (WP457) at Sitio Matandang Gubat, Barangay Ticub, Municipality of Laurel, Batangas. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of 10.5 km from the volcano, highlighted by a blue circle; B) outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with surge and base surge deposits; C) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~51 cm and *TF2* ~34 cm.

APPENDIX H-13.

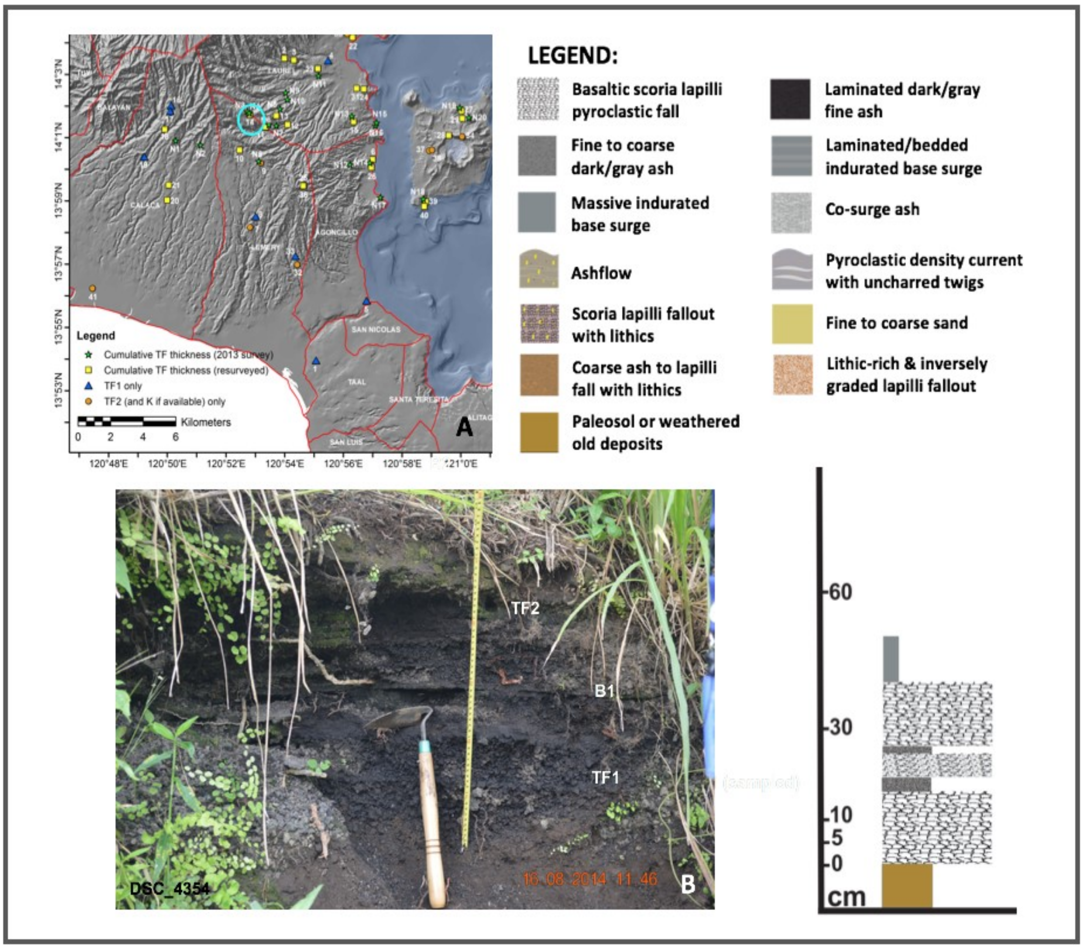
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #13 (WP459) at Sitio Culit, Barangay San Gregorio, Municipality of Laurel in Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of 12 km from the volcano, highlighted by a blue circle; B) and C) photos of outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with surge and base surge deposits; D) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~33.5 cm and *TF2* ~21 cm.

APPENDIX H-14.

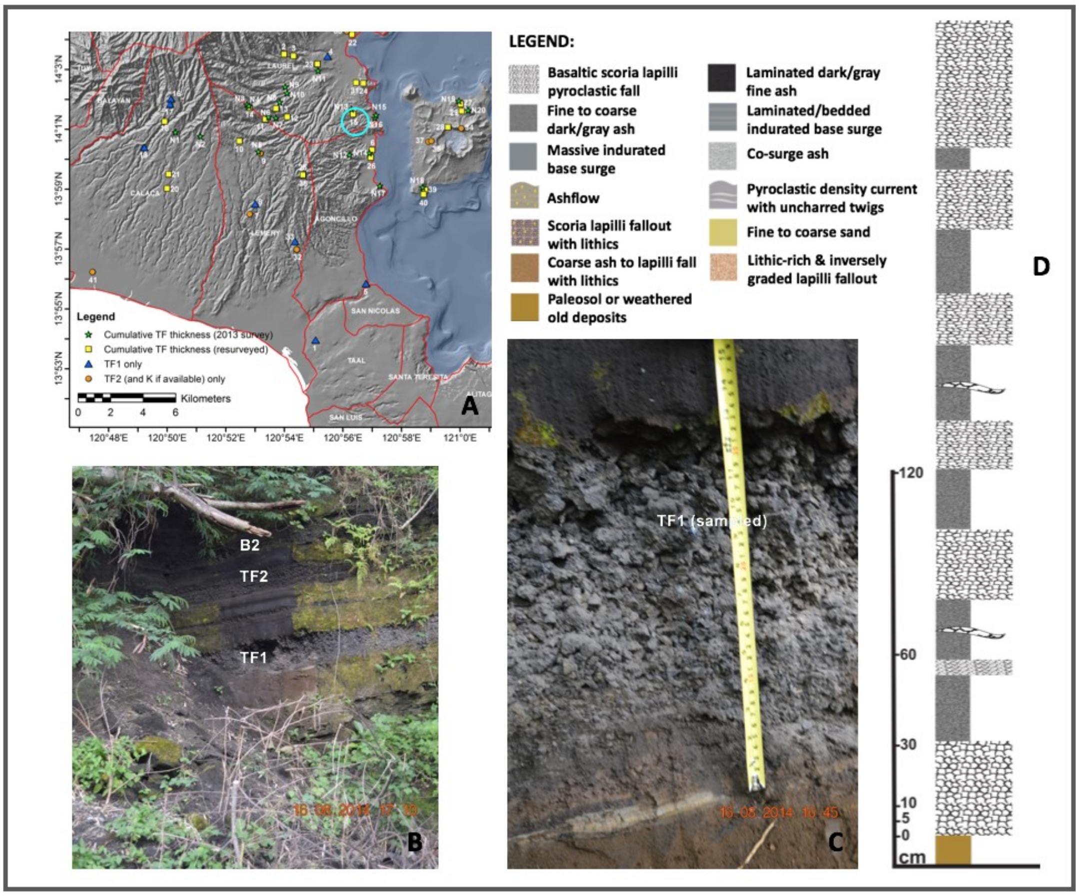
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #14 (WP459) at Sitio Culit, Barangay San Gregorio, Municipality of Laurel in Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of ~13.5 km from the volcano, highlighted by a blue circle; B) photo of outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with surge and base surge deposits; and C) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~21 cm and *TF2* ~14 cm.

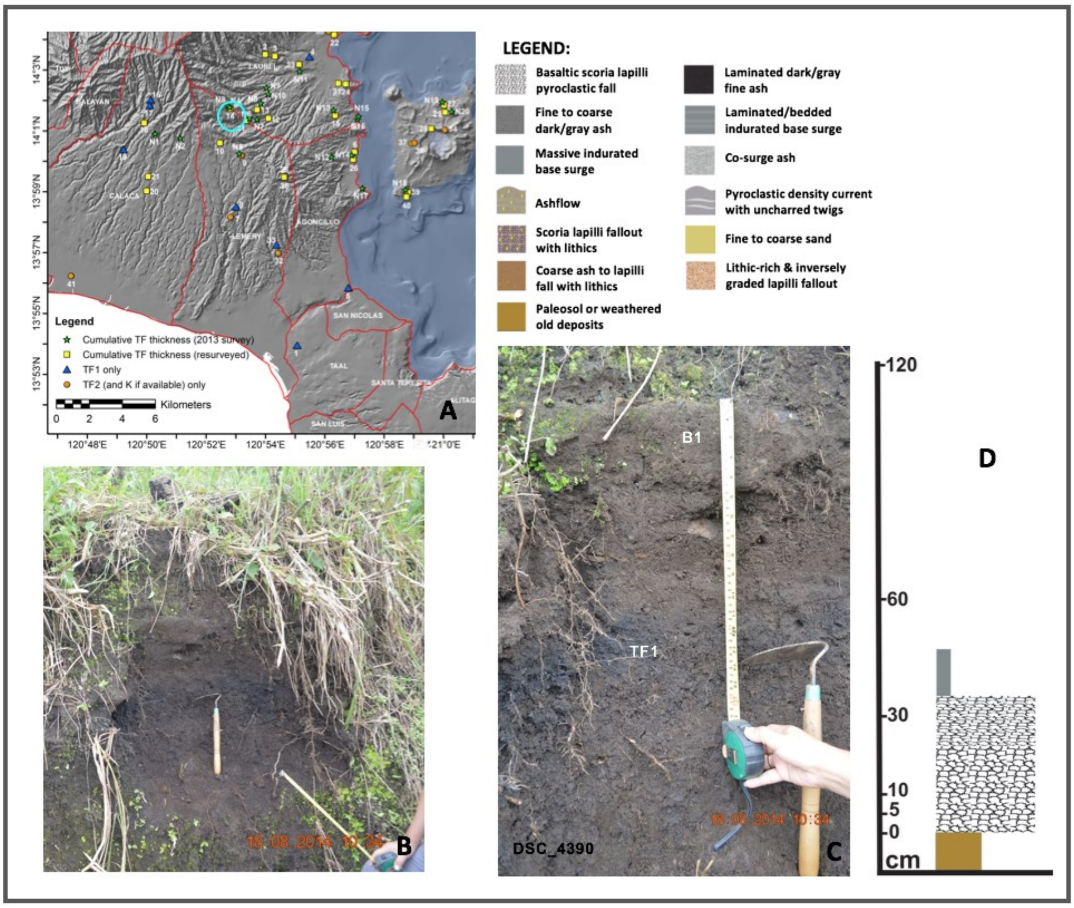
APPENDIX H-15.

Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #15 (WP460) at Barangay Buso-buso, Municipality of Laurel in Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of ~6.5 km from the volcano, highlighted by a blue circle; B) profile photo of outcrop; C) close up photo of outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with surge and base surge deposits; and D) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~92 cm and *TF2* ~62 cm.

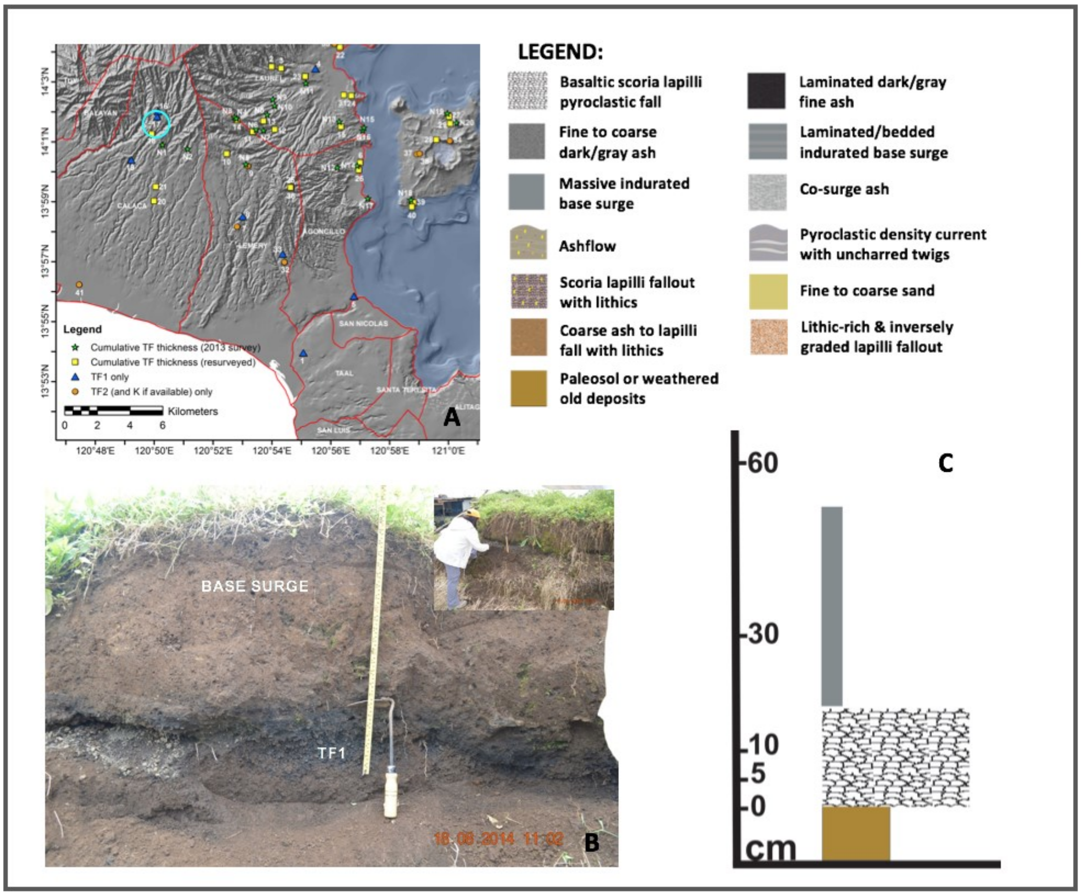
APPENDIX H-16.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #16 (WP461) at Barangay Cahil, Municipality of Calaca in Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of ~18 km from the volcano, highlighted by a blue circle; B) profile photo of outcrop; C) close up photo of outcrop showing a layer of tephra fall (*TF1*) intercalated with surge and base surge deposits; and D) detailed stratigraphy of the outcrop profile picture of the outcrop. Only *TF1* is exposed with a thickness of ~35 cm.

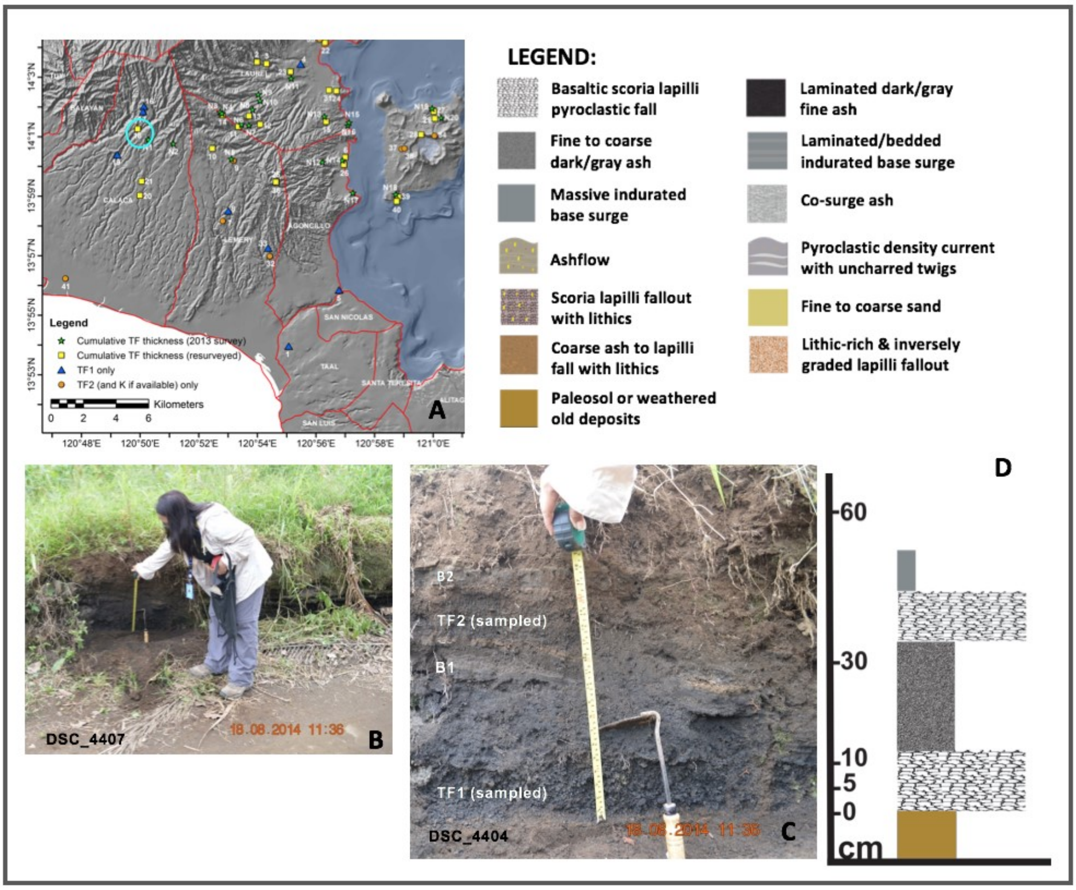
APPENDIX H-17.

Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #17 (WP462) at Sitio Matala, Barangay Cahil, Municipality of Calaca in Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of 18 km from the volcano highlighted by a blue circle; B) profile photo of outcrop; C) close up photo of outcrop showing a layer of tephra fall (*TF1*) intercalated with surge and base surge deposits; and D) detailed stratigraphy of the outcrop profile picture of the outcrop. Only *TF1* is exposed with a thickness of ~17 cm.

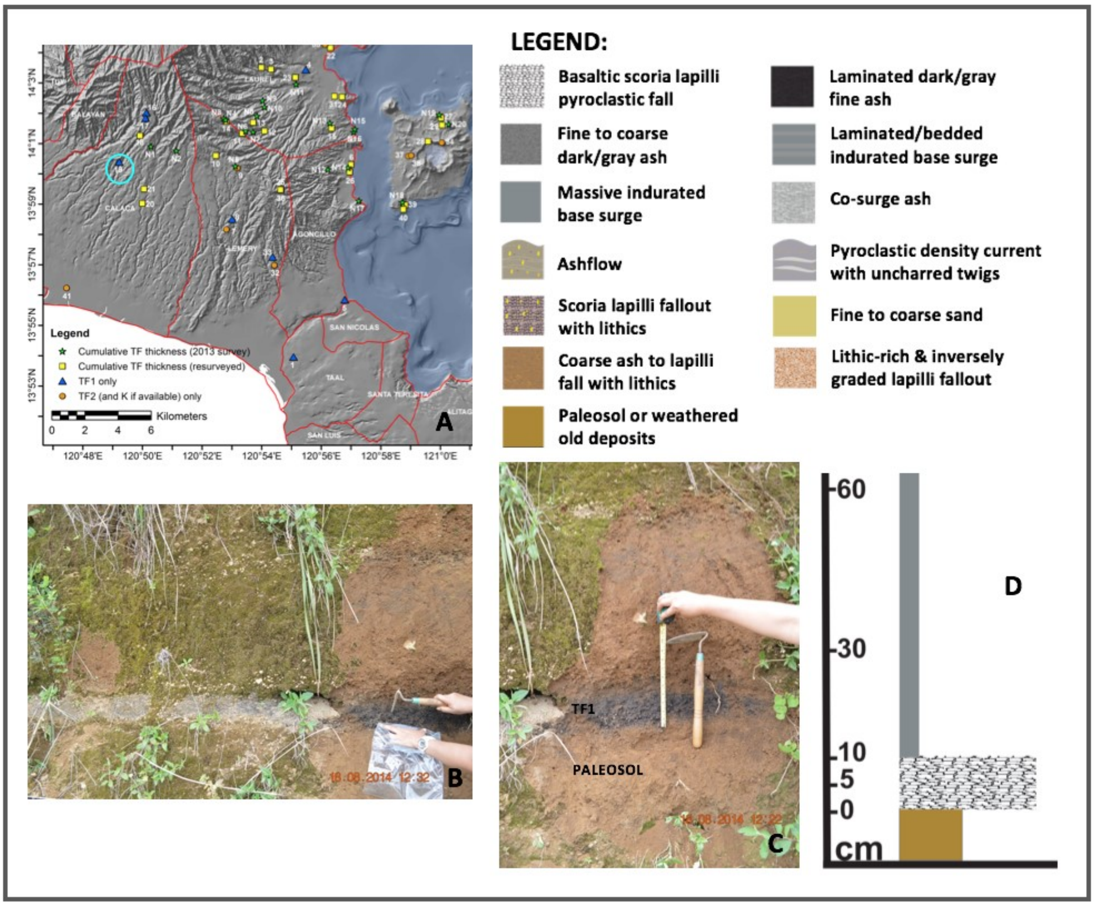
Appendix H-18.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #18 (WP 463) at Barangay Cahil, Municipality of Calaca in Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of 18 km from the volcano, highlighted by a blue circle; B) profile photo of the outcrop; C) close up photo of outcrop showing a layer of tephra fall (*TF1* and *TF2*) intercalated with surge and base surge deposits; and D) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~12 cm and *TF2* ~10 cm.

APPENDIX H-19.

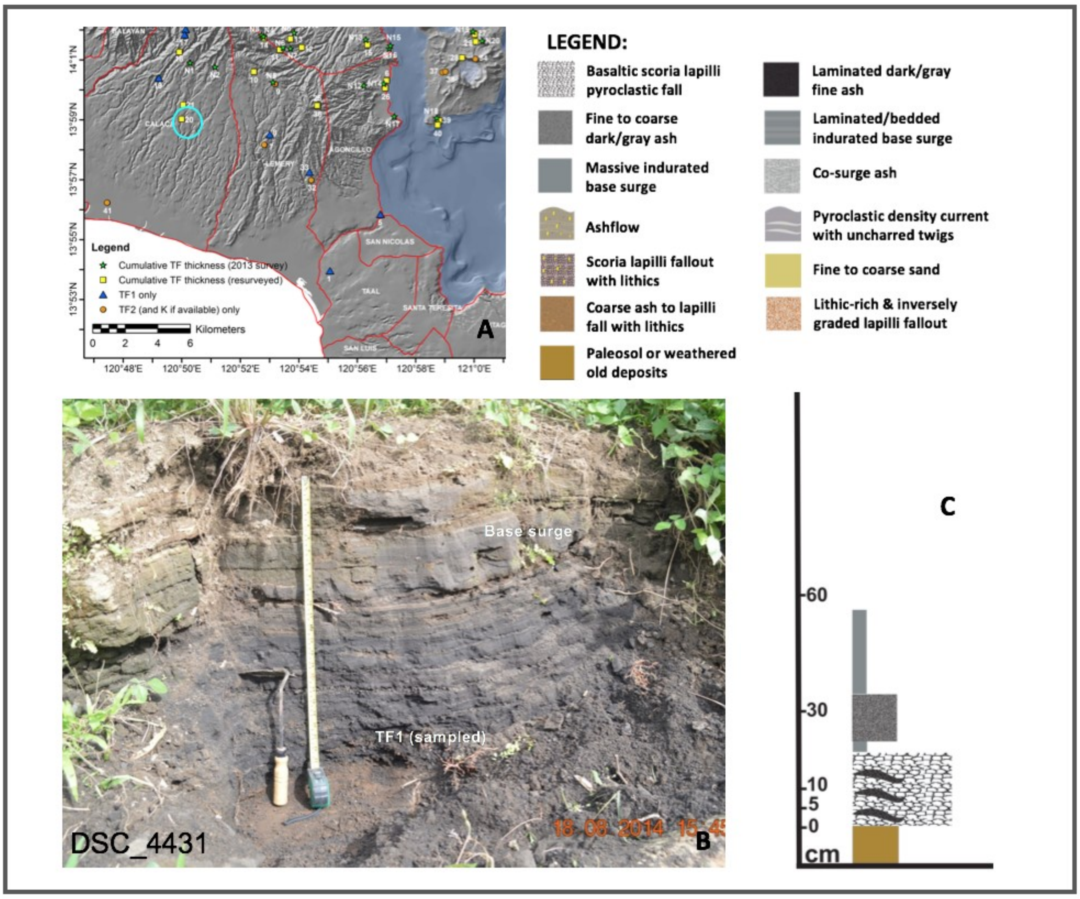
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #19 (WP464) at Barangay Loma, Municipality of Calaca in Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of ~18.5 km from the volcano, highlighted by a blue circle; B) and C) photos of the outcrop showing a layer of tephra fall (*TF1*) intercalated highly weathered base surge deposit; and D) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~10 cm.

Appendix H-20.

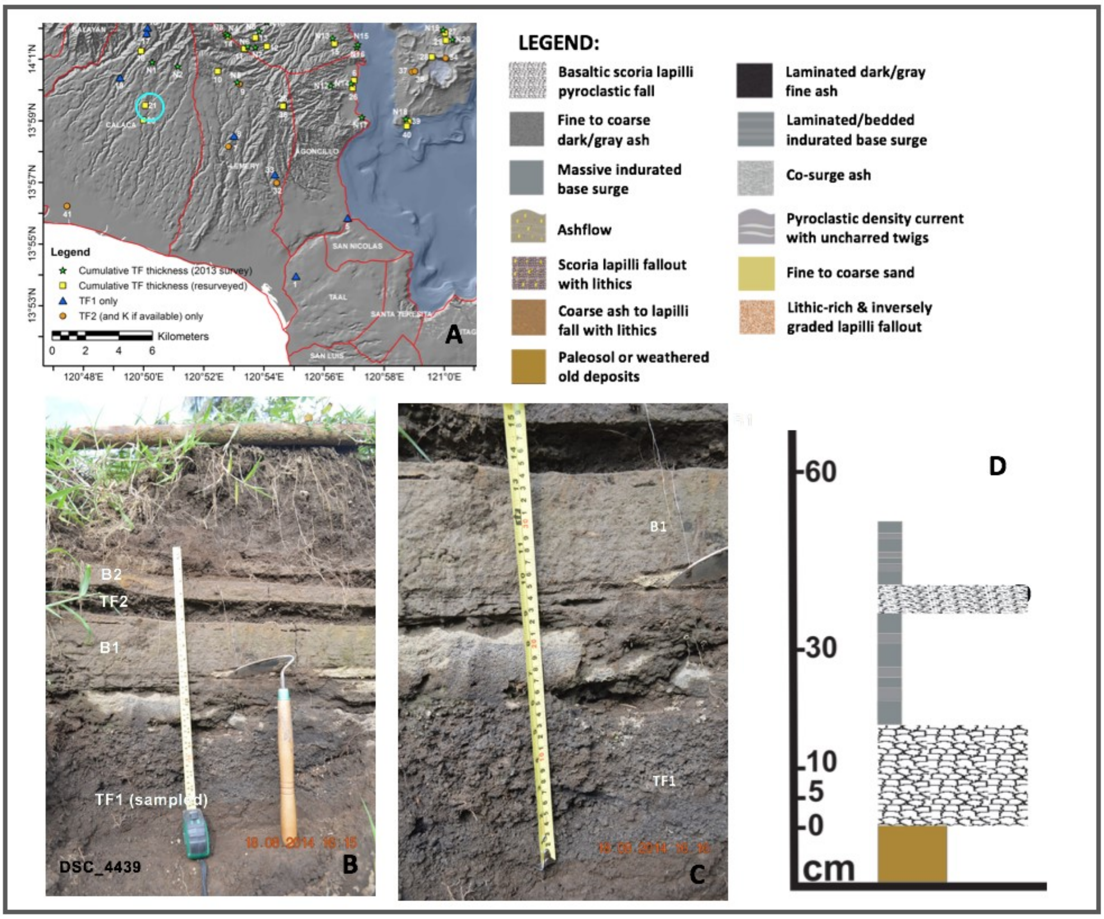
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #20 (WP465) at Barangay Madalunot, Municipality of Calaca in Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop found a distance of 18 km from the volcano, highlighted by a blue circle. B) outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with surge and base surge deposits; C) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~15 cm and *TF2* ~12 cm.

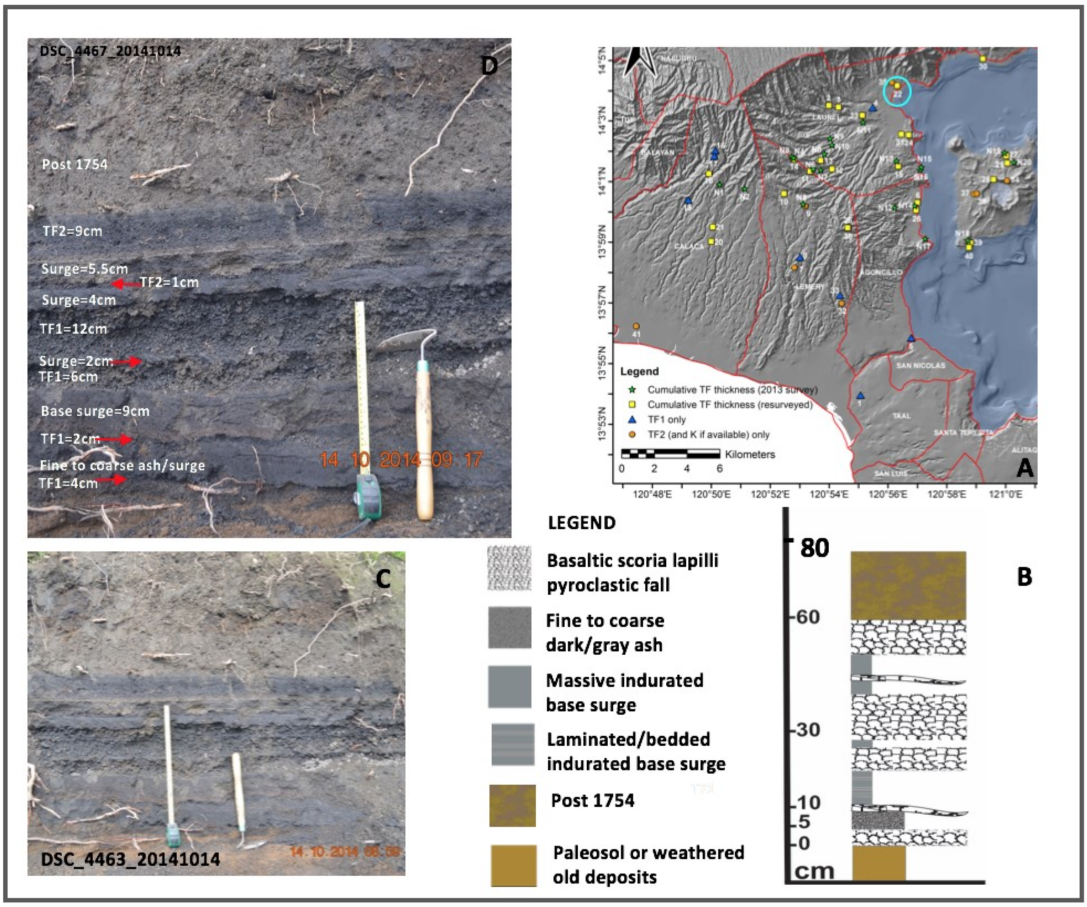
APPENDIX H-21.

Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #21 (WP466) at Barangay Matipok, Municipality of Calaca, Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop, a distance of ~18 km from the volcano, highlighted by a blue circle; B) photo of the outcrop showing the layers of tephra fall (*TF1* and *TF2*) intercalated with highly indurated base surge deposits; and C) close up photo of *TF1* layer; and D) detailed stratigraphy of the outcrop profile picture of the outcrop. Thickness of *TF1* is ~15 cm and *TF2* is ~45 cm.

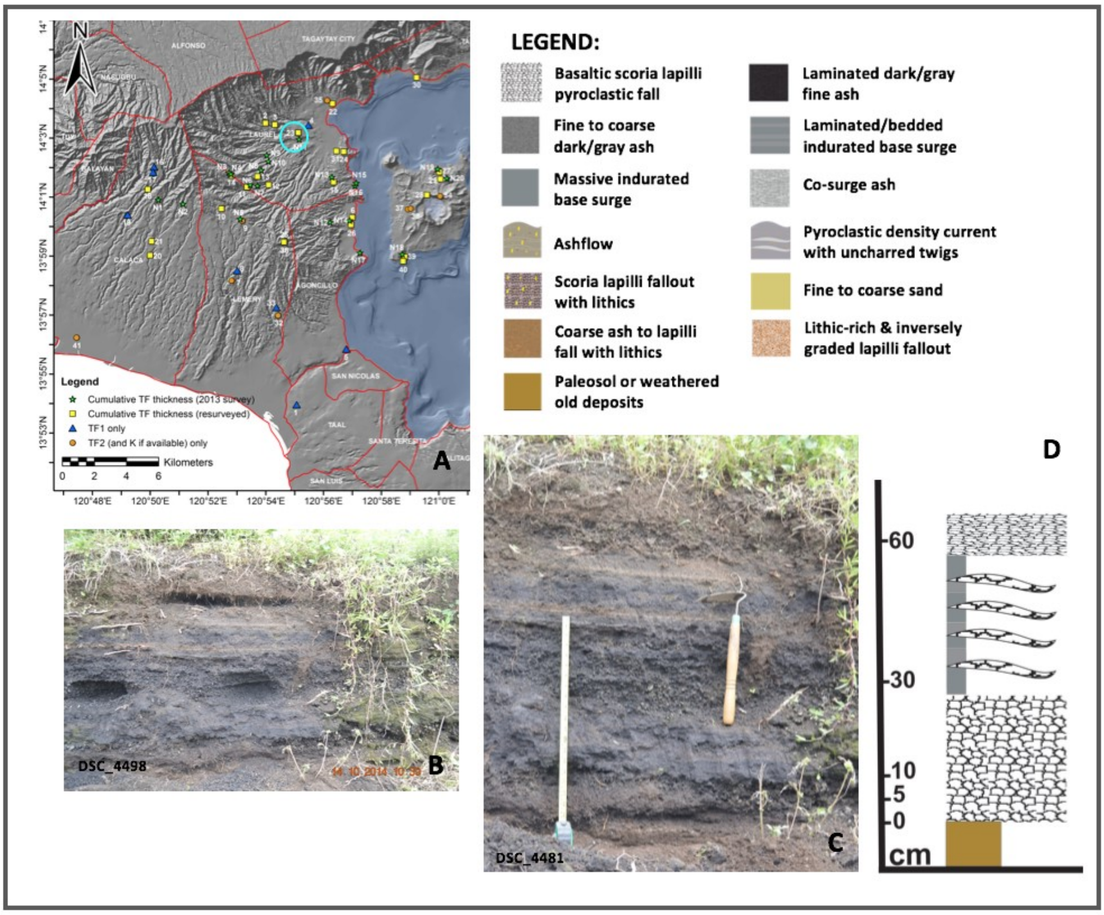
APPENDIX H-22.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #22 at Barangay Leviste, Municipality of Laurel in Batangas Province. An AD1754 exposure located northwest of Taal. A) map showing location of the outcrop found a distance of 9 km from the volcano, highlighted by a blue circle; B) detailed stratigraphy of the outcrop; C) profile photo of the outcrop; and D) close up photo of the outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with highly laminated surge deposits. Thickness of *TF1* is ~24 cm and *TF2* is ~9 cm.

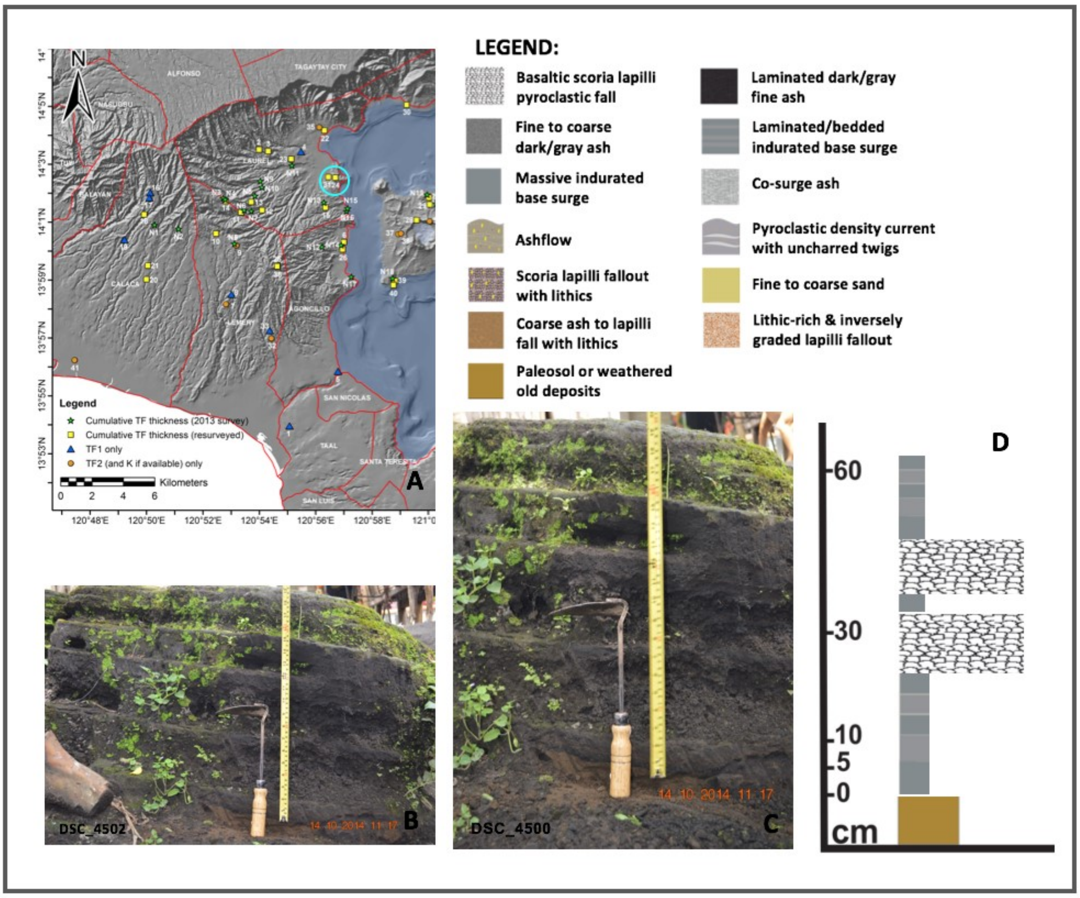
APPENDIX H-23.

Stratigraphic mapping of suspected AD1754 deposits at Taal



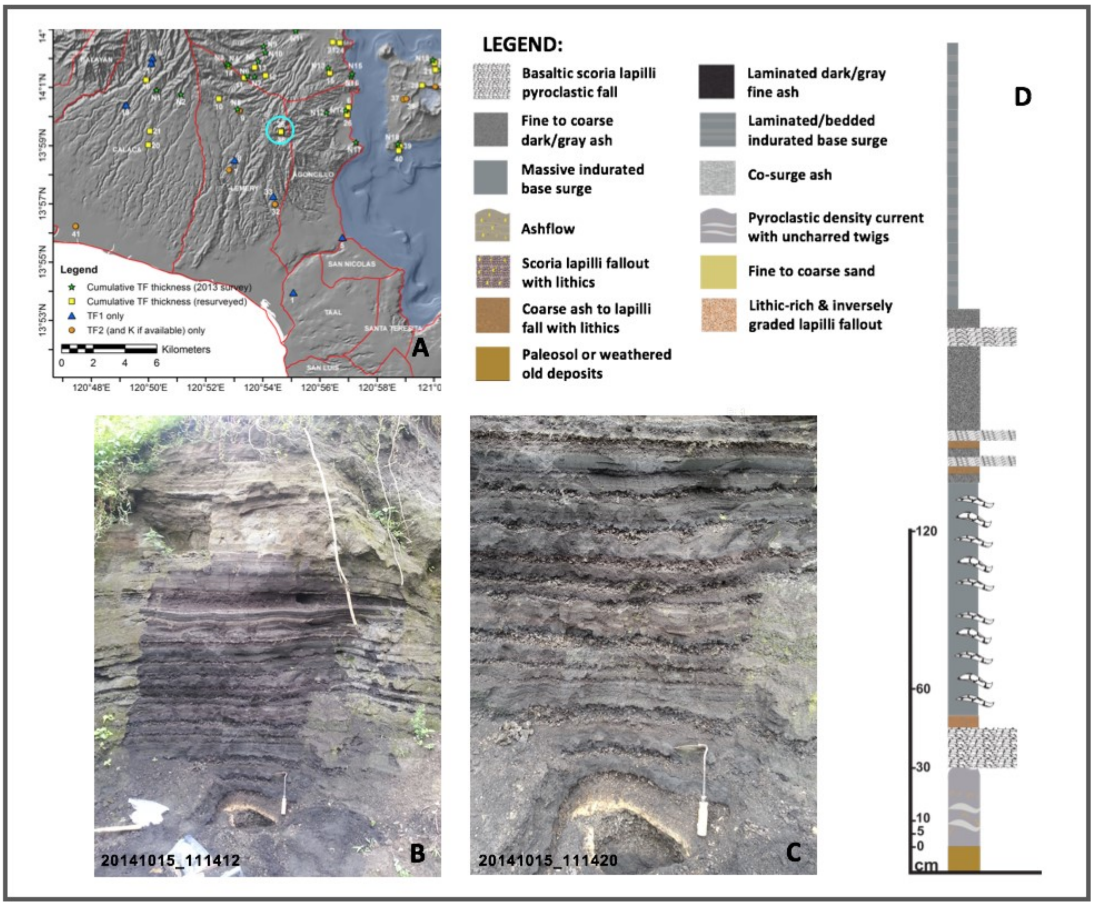
Outcrop #23 at Barangay As-is, Municipality of Laurel in Batangas Province. An AD1754 exposure located northwest of Taal. A) map showing location of the outcrop found a distance of 9 km, highlighted by a blue circle; B) profile photo of the outcrop; C) close up photo of the outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with highly laminated surge deposits; and D) detailed stratigraphy of the outcrop. Thickness of *TF1* is ~27 cm and *TF2* is ~9 cm.

APPENDIX H-24.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #24 at Barangay As-is, Municipality of Laurel. An AD1754 exposure located northwest of Taal. A) map showing location of Outcrop #24 found in highlighted by a blue circle; B) profile photo of the outcrop; C) close up photo of the outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with highly laminated and indurated surge deposits; and D) detailed stratigraphy of the outcrop. Thickness of *TF1* is ~1 cm and *TF2* is ~9 cm.

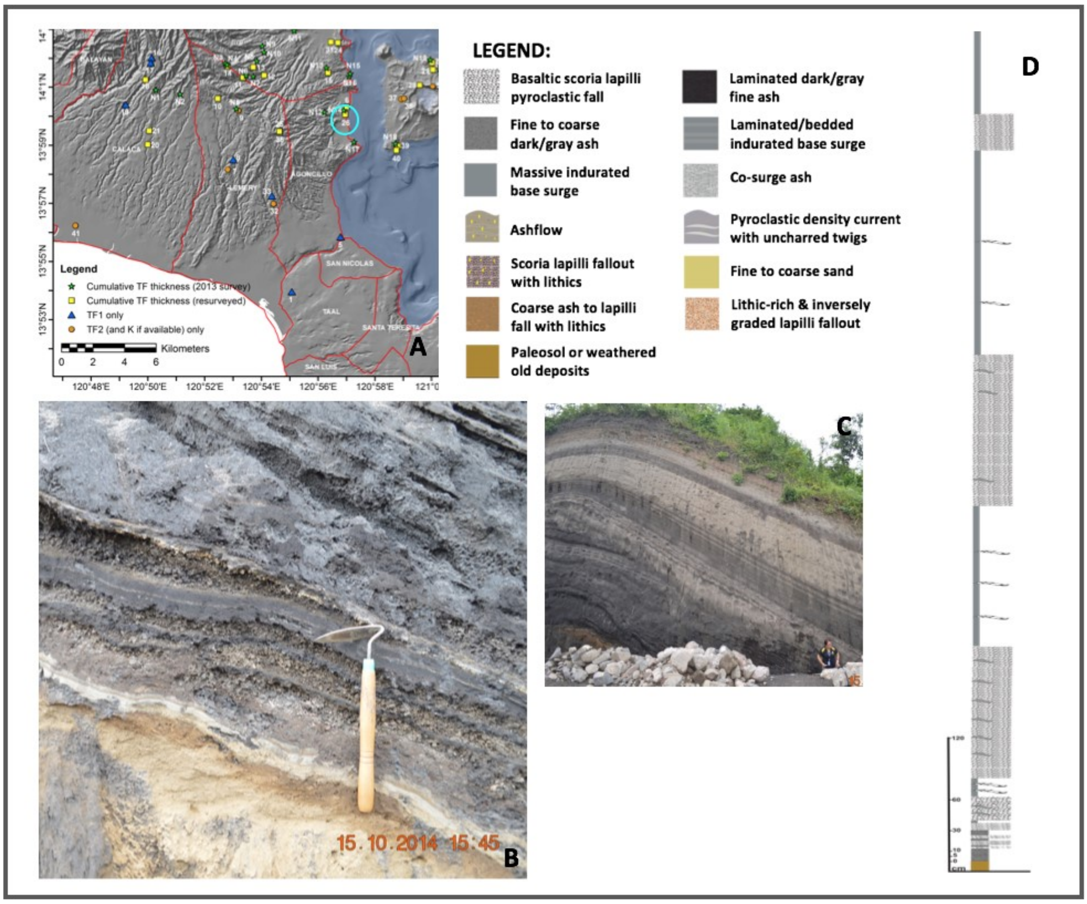
APPENDIX H-25.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #25 at Barangay Barigon, Municipality of Agoncillo in Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop found 9 km from the volcano, highlighted by a blue circle; B) profile photo of the outcrop; C) close up photo of the outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with highly laminated and indurated surge deposits; and D) detailed stratigraphy of the outcrop. Thickness of *TF1* is ~69 cm and *TF2* is ~102 cm.

APPENDIX H-26.

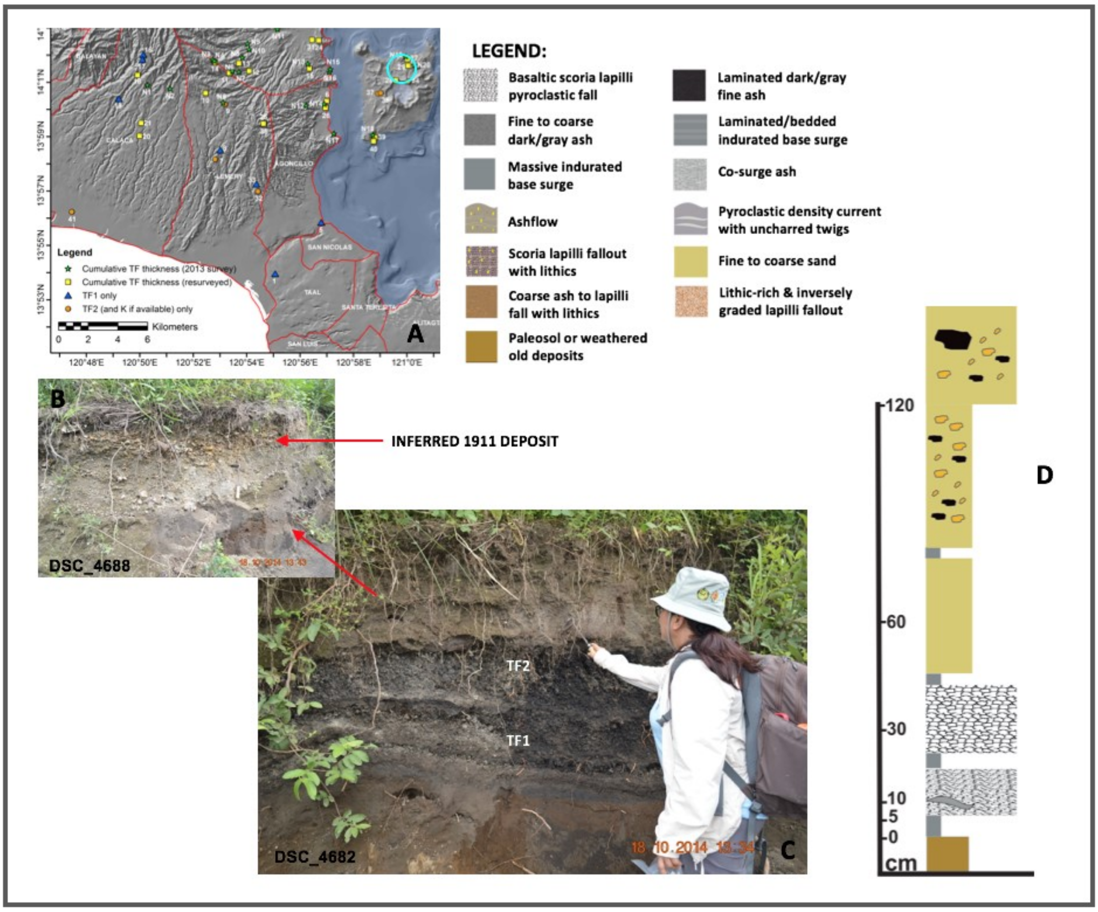
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #26 at Barangay Bilibinwang, Municipality of Agoncillo. In Batangas Province. An AD1754 exposure located west of Taal. A) map showing location of the outcrop found 6 km from the volcano, highlighted by a blue circle; B) close up photo of the outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with highly laminated and indurated surge deposits; C) profile photo of the outcrop; and D) detailed stratigraphy of the outcrop. Thickness of *TF1* is ~57 cm and *TF2* is ~130 cm.

APPENDIX H-27.

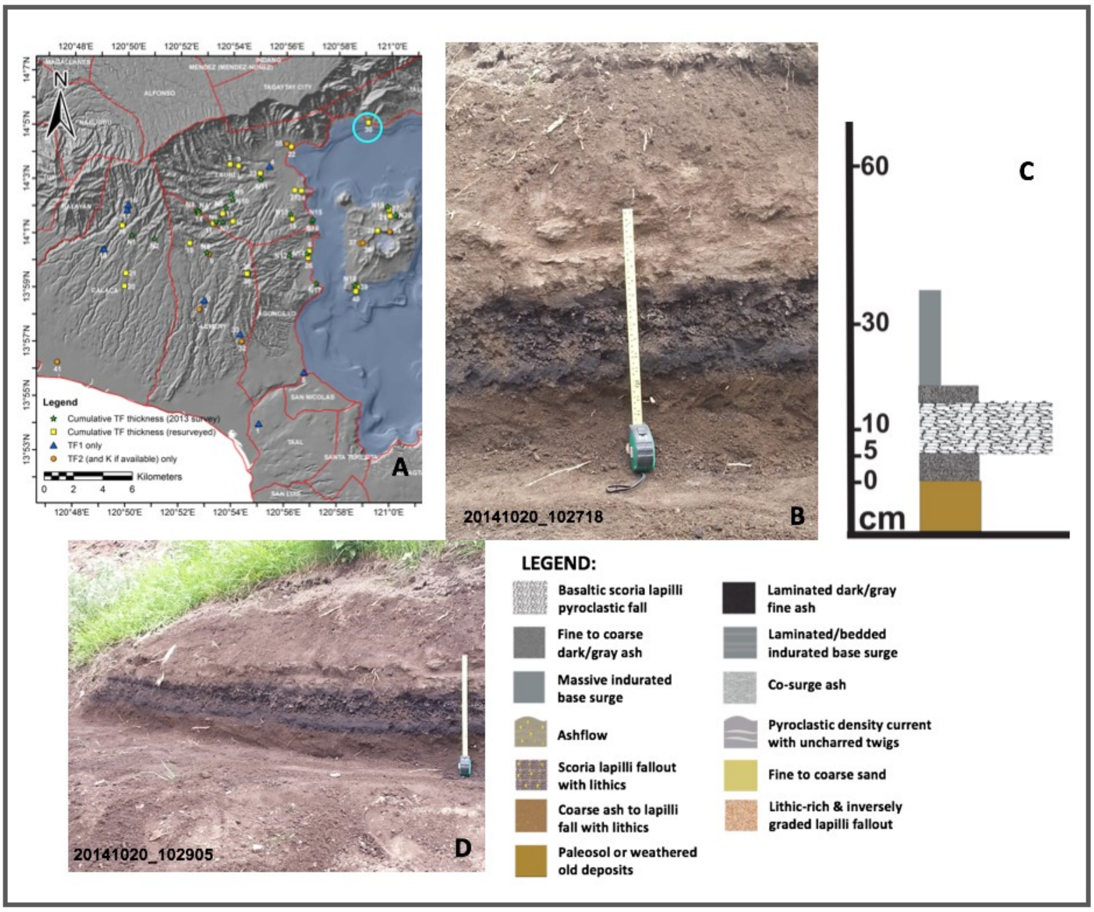
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #29 at Daang Kastila, TVI, Municipality of Talisay in Batangas Province. An inferred AD1754 exposure located at TVI. A) map showing location of the outcrop found 2 km from the vent, highlighted by a blue circle; B) profile photo of the outcrop with inferred AD1911 eruption deposit overlying inferred AD1754 materials; C) close up photo of the outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with highly laminated and indurated surge deposits; and D) detailed stratigraphy of the outcrop. Thickness of *TF1* is ~7 cm and *TF2* is ~33 cm.

APPENDIX H-28.

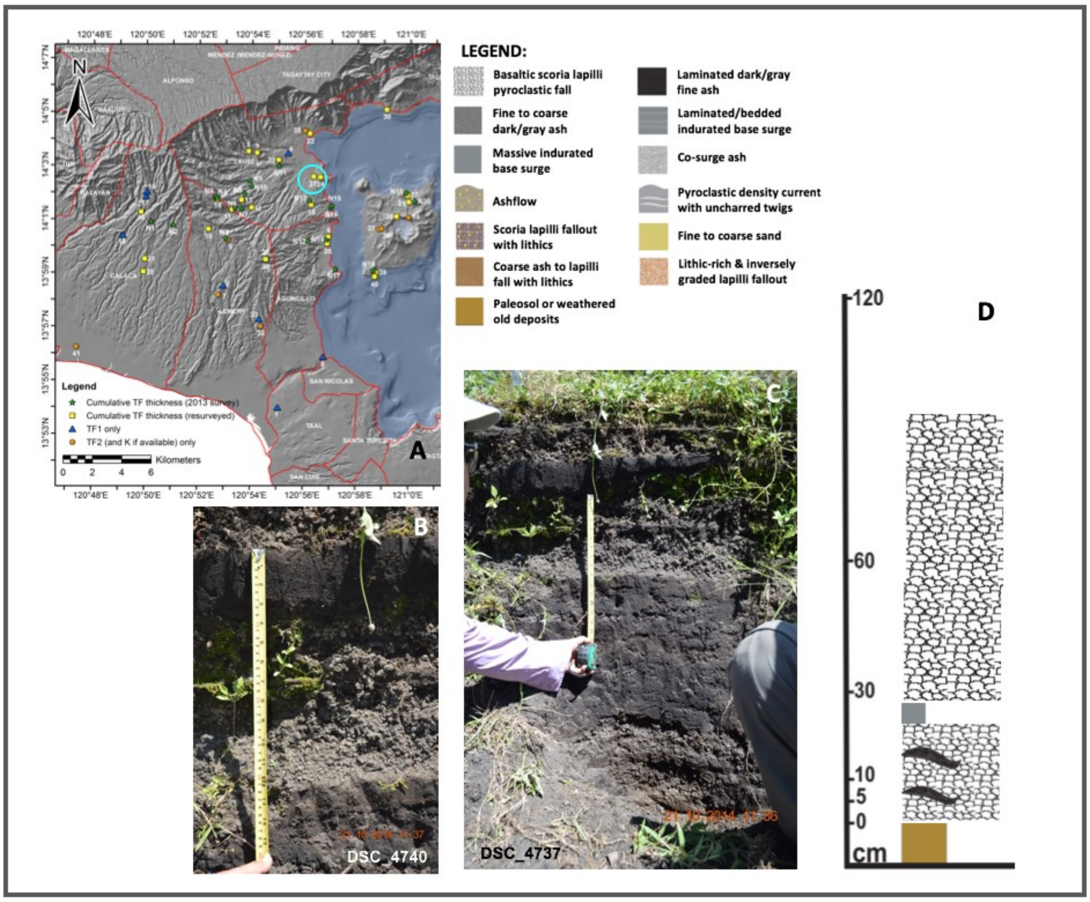
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #30 at Taal Volcano Observatory in Barangay Buco, Municipality of Talisay., Batangas Province. An inferred AD1754 exposure located north of Taal. A) map showing location of the outcrop found at the, highlighted by a blue circle; B) close up photo of the outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with highly laminated and indurated surge deposits; C) detailed stratigraphy of the outcrop; and D) profile photo of the inferred AD1754 outcrop. Thickness of *TF1* is ~10 cm and *TF2* is ~3 cm.

APPENDIX H-29.

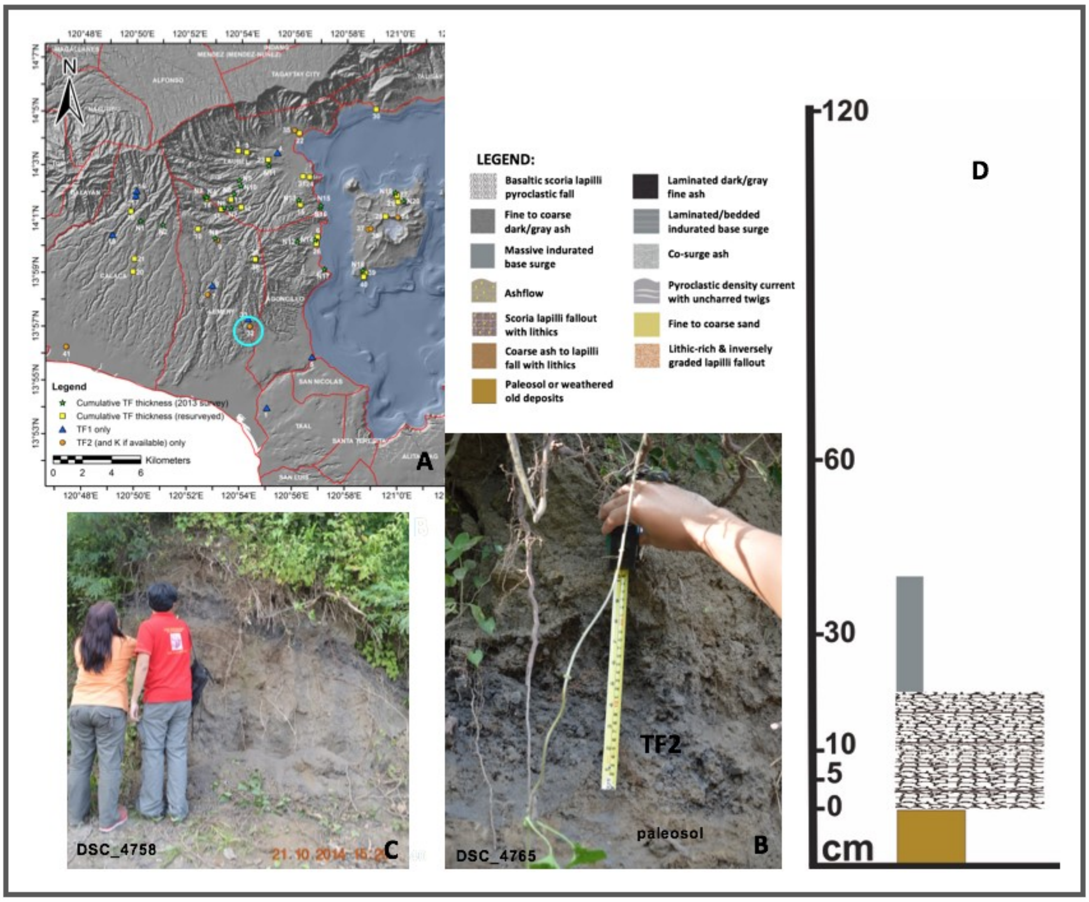
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #31 at Barangay Bugaan, Municipality of Laurel in Batangas Province. An inferred AD1754 exposure located northwest of Taal. A) map showing location of the outcrop found highlighted by a blue circle; B) close up photo of the outcrop showing layers of tephra fall (*TF1* and *TF2*) intercalated with highly laminated and indurated surge deposits; C) detailed stratigraphy of the outcrop; and D) profile photo of the inferred AD1754 outcrop. Thickness of *TF1* is ~24 cm and *TF2* is ~69 cm.

APPENDIX H-30.

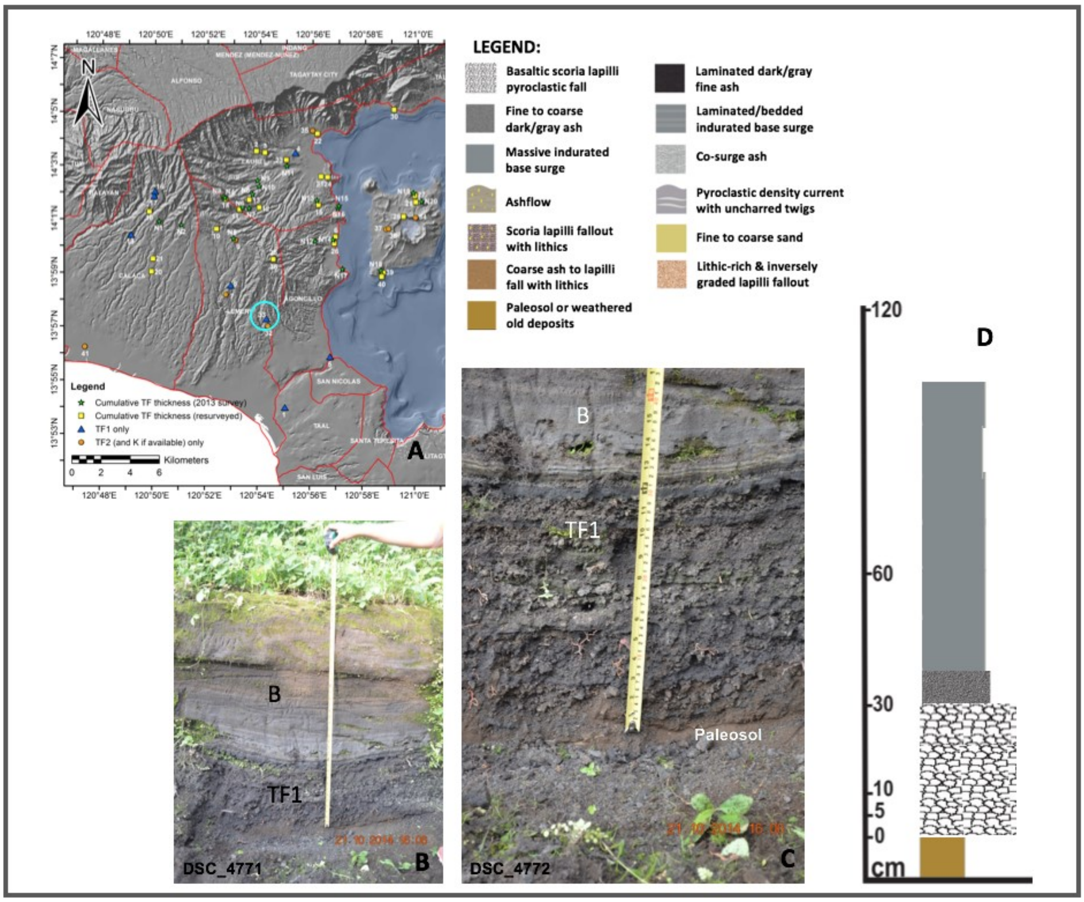
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #32 at Barangay San Jacinto, Municipality of Agoncillo in Batangas Province. An inferred AD1754 exposure located southwest of Taal. A) map showing location of the outcrop found ~6.5 km from the volcano, highlighted by a blue circle; B) close up photo of the outcrop showing a layer of tephra fall (*TF2*) on top of paleosol; and C) and D) profile photos of the inferred AD1754 outcrop. Thickness of *TF2* is ~20 cm.

APPENDIX H-31.

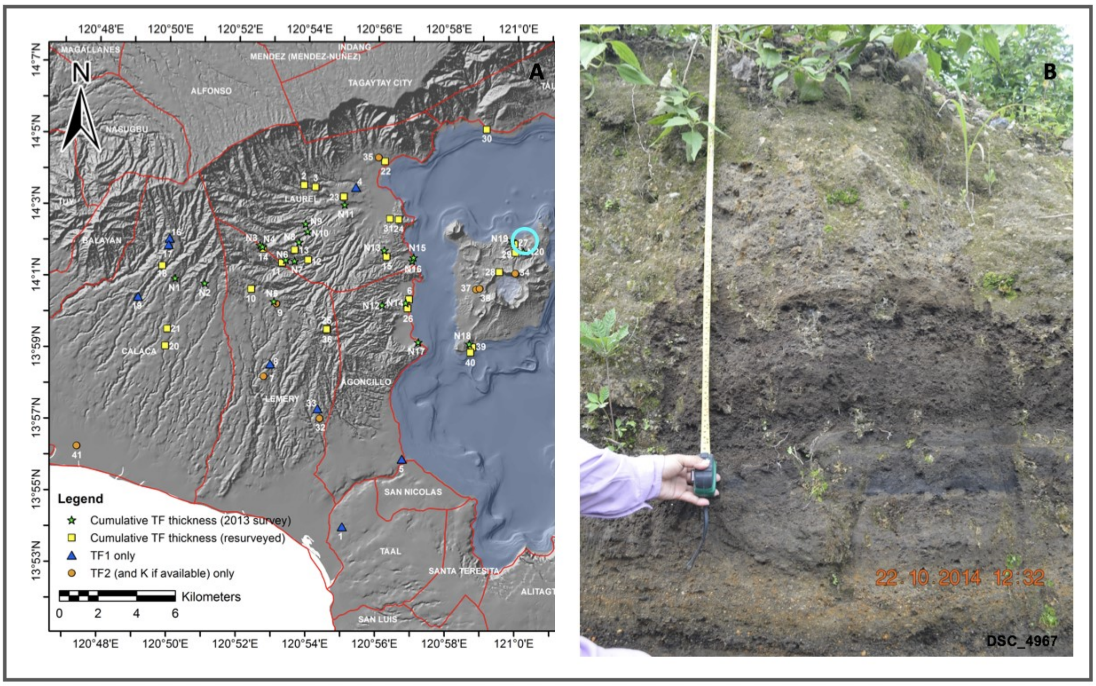
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #33 (WP493) at Barangay San Jacinto, Municipality of Agoncillo in Batangas Province. An inferred AD1754 exposure located southwest of Taal. A) map showing location of the outcrop found ~6.5 km from the volcano, highlighted by a blue circle; B) profile photo of the inferred AD1754 outcrop; C) close up photo of the outcrop showing a layer of tephra fall (*TF1*) on top of paleosol and overlain by indurated base surge layer. Thickness of *TF1* is ~35 cm.

APPENDIX H-32.

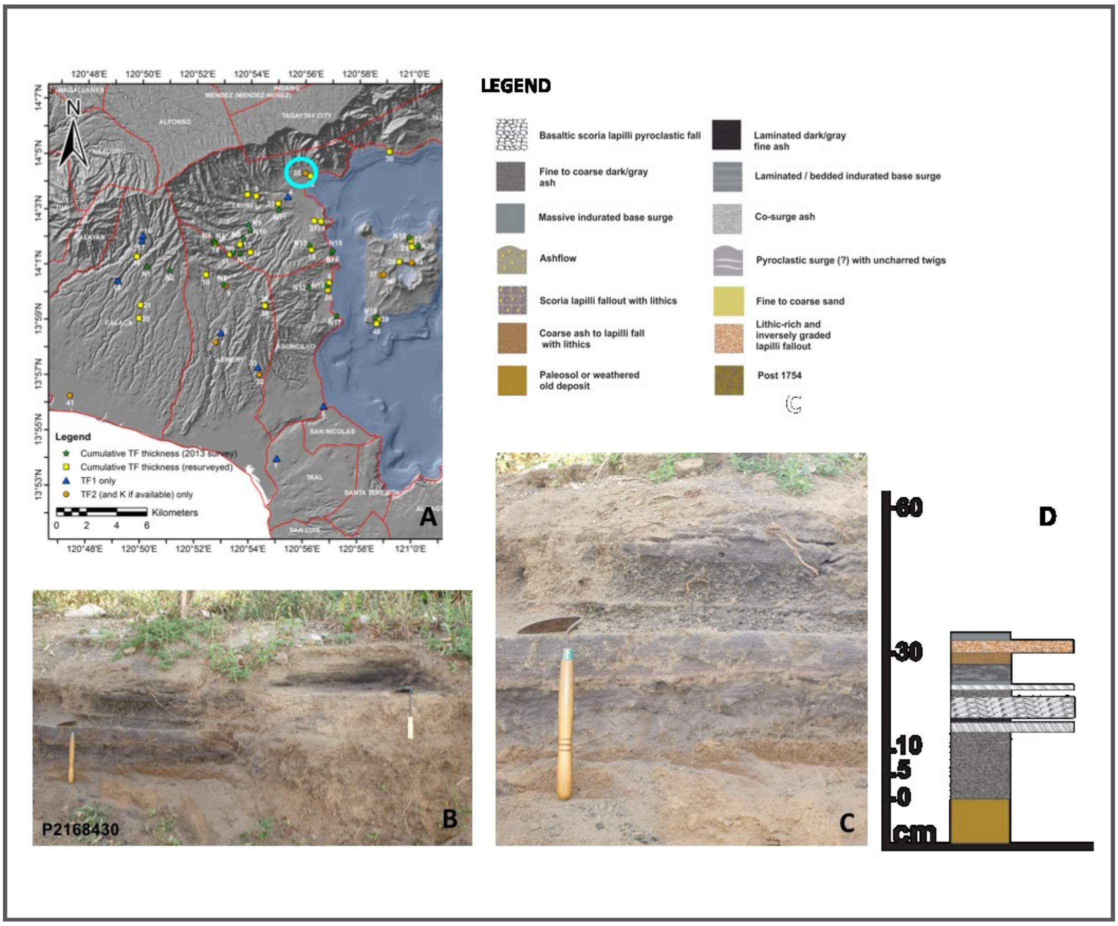
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #34 at Daang Kastila, Taal Volcano Island (TVI), Municipality of Talisay in Batangas. An inferred AD1754 exposure located at Taal Volcano Island. A) map showing location of the outcrop found ~2 km from the vent, highlighted by a blue circle; B) photo of an inferred AD1754 tephra outcrop (presumed to be *TF2*) overlain by inferred layer of AD1911 deposit. Thickness of *TF2* is ~41 cm.

APPENDIX H-33.

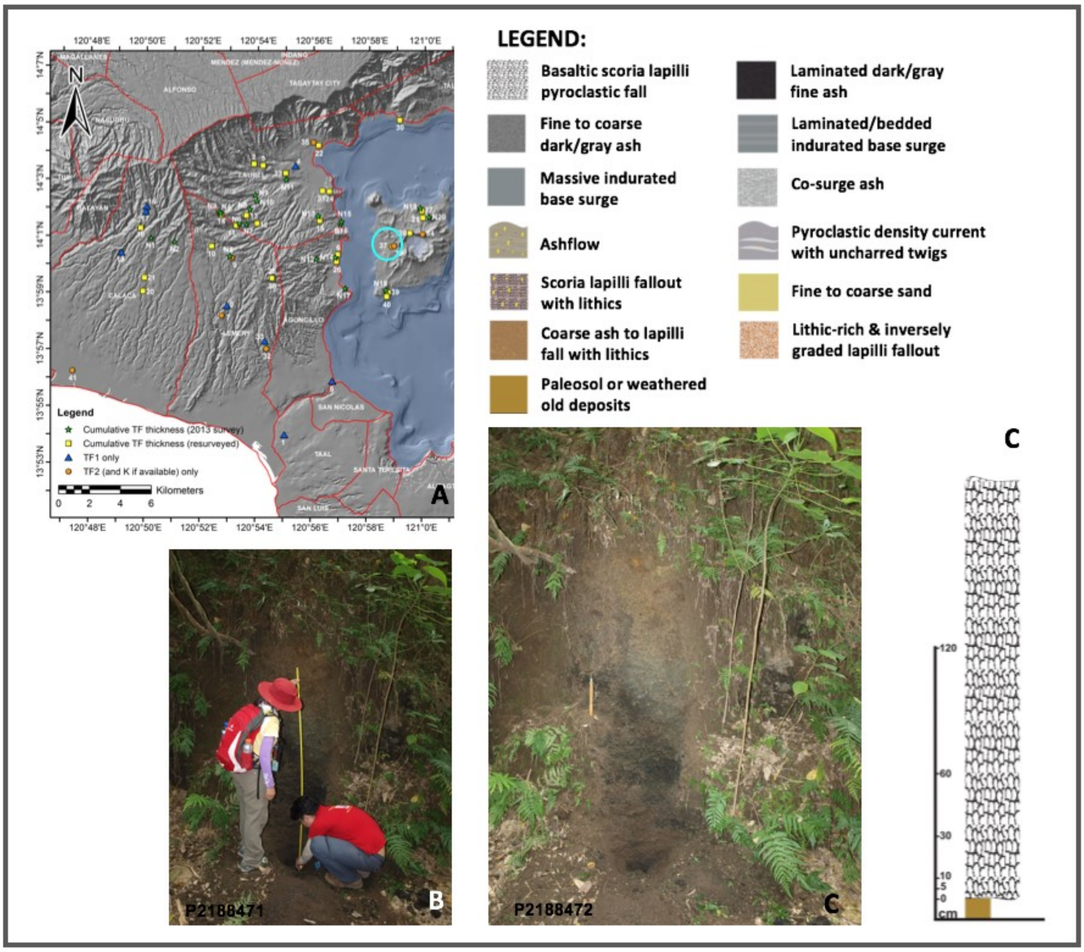
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #35 (WP74) at Barangay Balaquilong, Municipality of Laurel in Batangas Province. An inferred AD1754 exposure located northwest of Taal. A) map showing location of the outcrop found 9 km from the volcano, highlighted by a blue circle; B) profile photo of the inferred AD1754 outcrop; C) close up photo of the outcrop showing layers of tephra fall (*TF1* + *K*) on top of paleosol and intercalated with surge and base surge layers; and D) detailed stratigraphy of the outcrop. Key bed (*K*) layer is lithics-rich and generally inversely graded fallout deposit that is usually identified with *TF2* tephra deposits. Thickness of *TF2* is ~65 cm and *K* ~10 cm.

APPENDIX H-34.

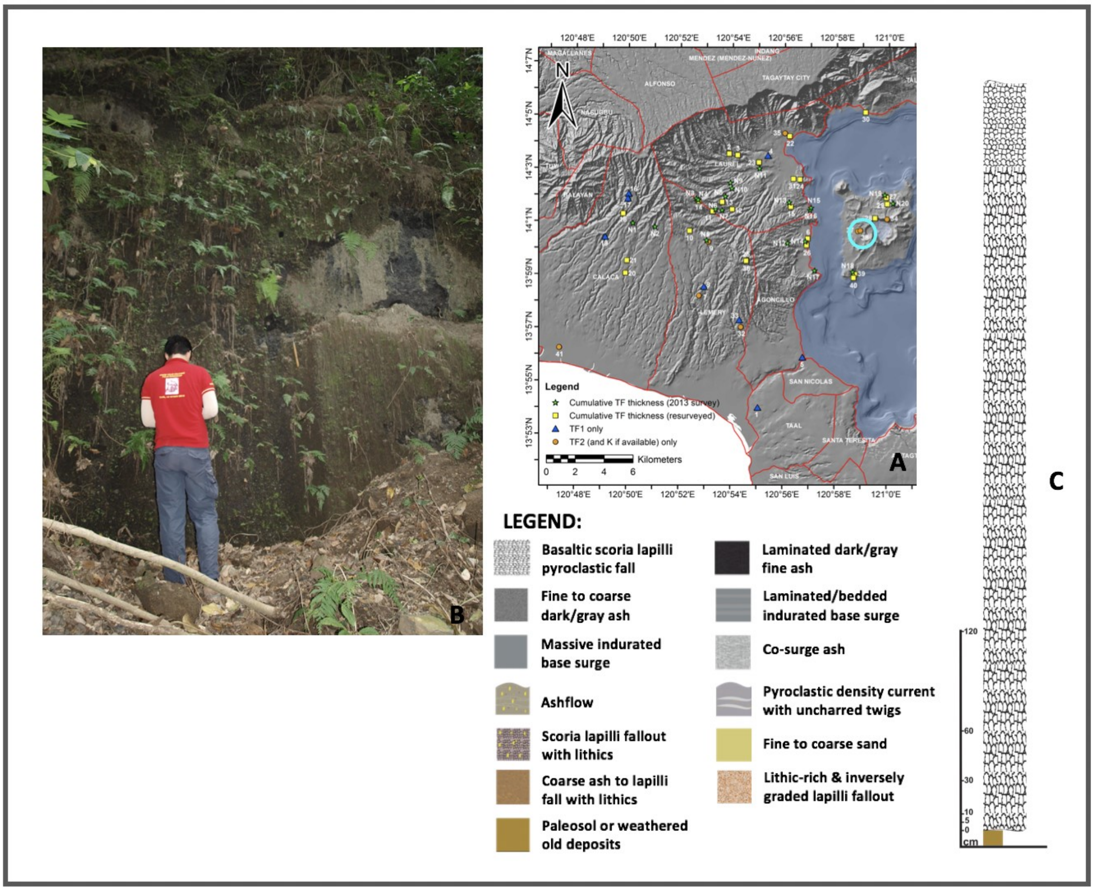
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #37 (WP79) at Barangay Alas-as, TVI, Municipality of San Nicolas, Batangas Province. An inferred AD1754 exposure located at TVI. A) map showing location of the found ~2 km from the vent, highlighted by a blue circle; B) and C) photos presumed to be *TF2* tephra deposit; and D) detailed stratigraphy of the outcrop. Key bed (*K*) layer is lithics-rich and generally inversely graded fallout deposit that is usually identified with. Thickness of *TF2* is ~200 cm.

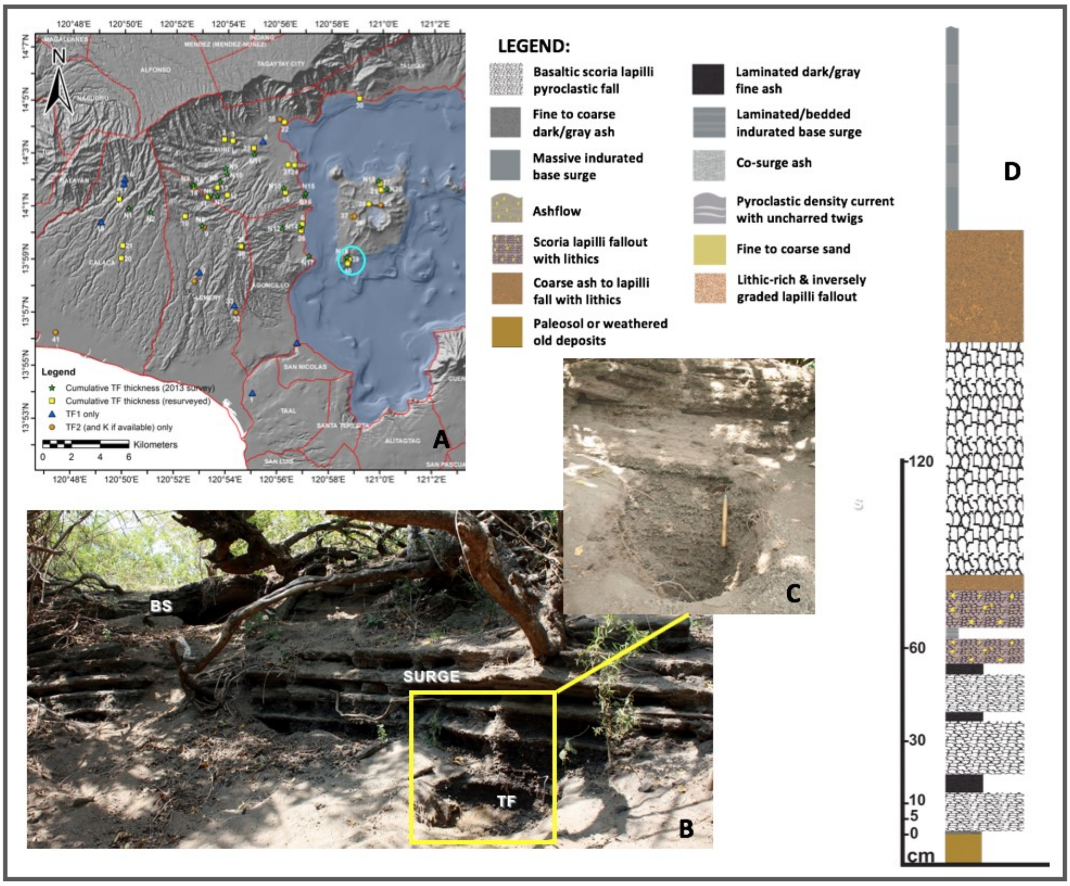
Appendix H-35.

Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #38 (WP80) at Barangay Alas-as, Taal Volcano Island, Municipality of San Nicolas, Batangas Province. An inferred AD1754 exposure located at Taal Volcano Island. A) map showing location of the outcrop found ~2 km from the vent, highlighted by a blue circle; B) photo showing an inferred *TF2* tephra deposit; and C) detailed stratigraphy of the outcrop. Thickness of *TF2* is ~450 cm.

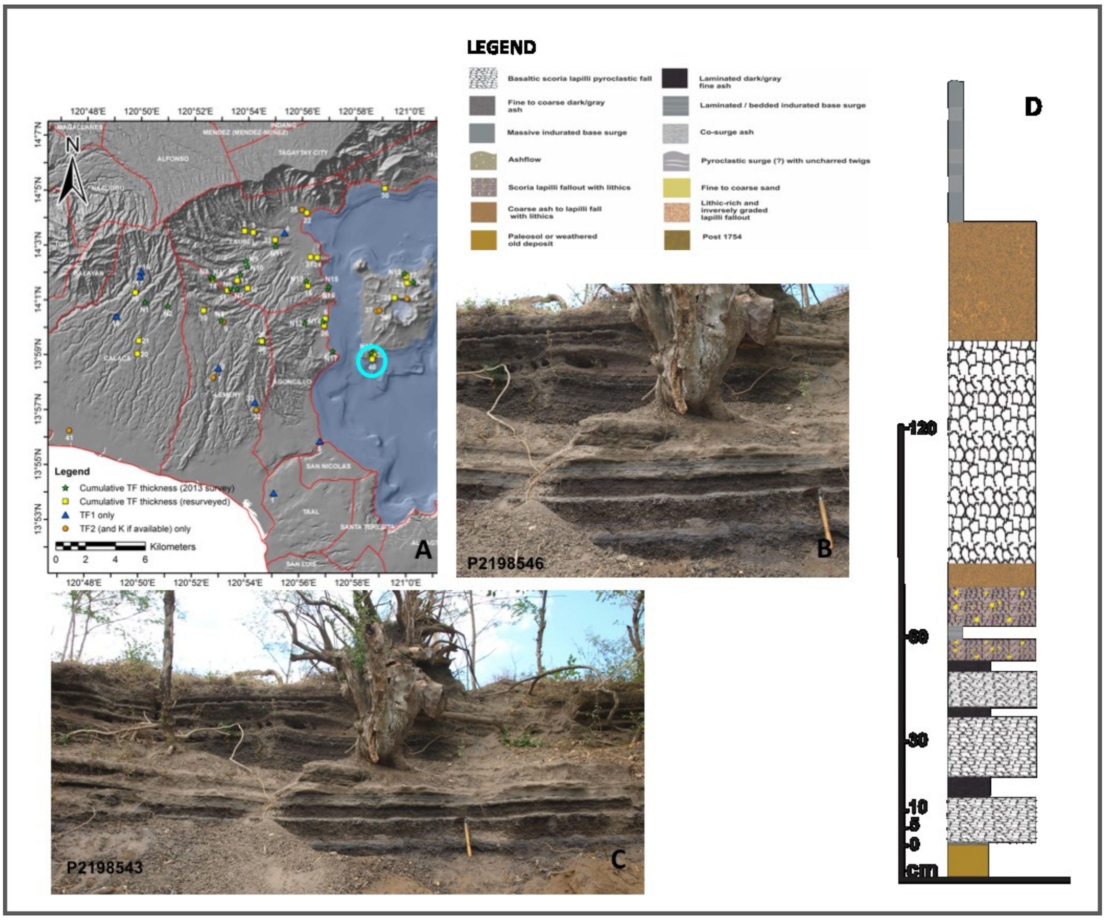
APPENDIX H-36.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #39 (WP84) at Sitio Saluyan, Barangay Alas-as, TVI, Municipality of San Nicolas, Batangas Province. An inferred AD1754 exposure located at TVI. A) map showing location of Outcrop #39 found ~4 km from the vent, highlighted by a blue circle; B) profile photo of the inferred AD1754 outcrop showing alternating layers of tephra fall (*TF1* and *TF2* + *K*) on top of paleosol and overlain by indurated base surge layer; C) close up photo of the base of the outcrop Thickness of *TF1* is ~51cm, *TF2* ~64 cm and *K* ~34 cm.

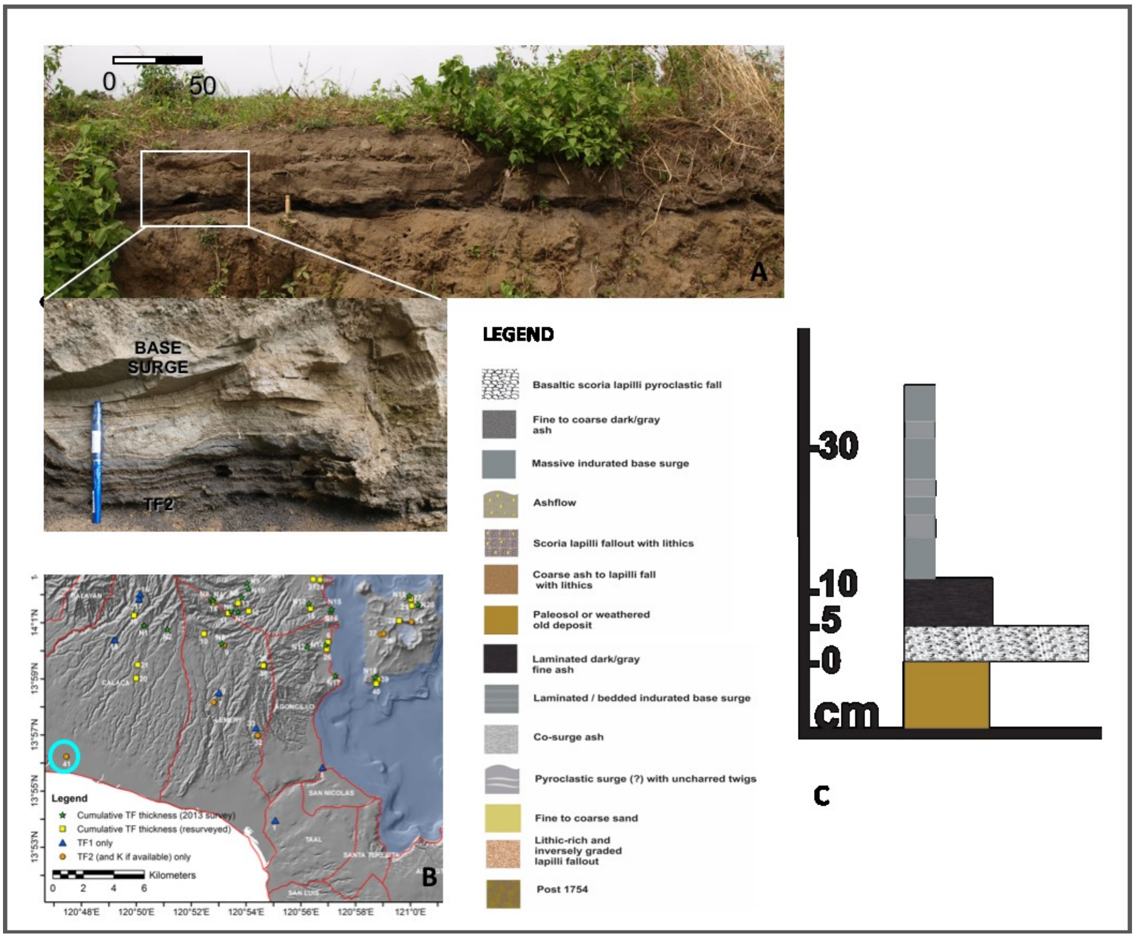
Appendix H-37.

Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #40 (WP86) at Barangay Alas-as, TVI, Municipality of San Nicolas, Batangas Province. A suspected AD1754 exposure located on the southwest sector of TVI. A) map showing location of the outcrop found ~4 km from the vent, highlighted by a blue circle; B) and C) photos showing an inferred *TF1*, *TF2* and *K* tephra deposit alternating with surge and base surge deposits; and D) detailed stratigraphy of the outcrop. Thickness of *TF1* is ~49cm, *TF2* ~64 cm and *K* ~34 cm.

APPENDIX H-38.
Stratigraphic mapping of suspected AD1754 deposits at Taal



Outcrop #41 (WP97) at Barangay San Rafael, Municipality of Calaca in Batangas Province. A suspected AD1754 exposure located on the southwest sector of TVI. A) photos showing an inferred *TF2* tephra deposit alternating with surge and base surge deposits; B) map showing location of the outcrop found 24 km from the volcano, highlighted by a blue circle; and C) detailed stratigraphy of the outcrop. Thickness of *TF2* ~115 cm.

APPENDICES I-1 TO I-13

Appendices I-1 to I-13 presents the results of the sieve analysis undertaken for selected samples of the identified *TF1* and *TF2* tephra. The grain size data are displayed using three graphical methods that include: A) grain size data tables; B) plotted frequency curves utilising the grain size data tables; and C) plotted cumulative curves where median phi is represented as the 50th percentile diameter of the tephra samples. Aside from median ϕ values, mean ϕ, standard deviation and skewness values obtained using formulas by Folk & Ward (1957) described in Boog (2006) and discussed in detail in Chapter 5. The computed values are likewise provided in each of the figures. Normal distribution of grain size provides a bell-shaped frequency curve. A very steep cumulative curve indicates good sorting. Skewness provides preferential sorting in the tails of the frequency curves. *TF1* and *TF2* samples are listed from proximal to distal locations for easy comparison of grain sizes. Proximal distance: 0 to 4 km of the vent; medial distance: 4 to 6 km; distal distance: 6 to 20 km. Locations of the outcrops are shown in Figure 5.1 and listed in Table 5.4.

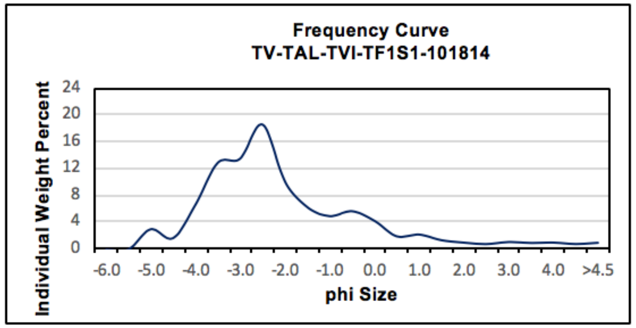
APPENDIX I-1.

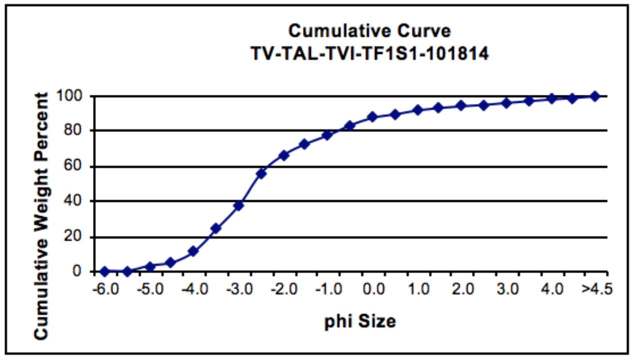
Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop # 29.

Sample Name: TV-TAL-TVI-TF1S1-101814
Waypoint No. 487
Location: Brgy Daang Kastila, Municipality of Talisay
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~2km (PROXIMAL REACH)3
Mode phi size: -2.5
Median phi size: -2.0
Mean phi size: -2.5
Standard deviation: 2.23863636 (VERY POORLY SORTED)
Skewness: 0.4926349 (STRONGLY FINE SKEWED)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
21.33	-5.0	3.01	-5.0	3.01
11.92	-4.5	1.68	-4.5	4.69
47.07	-4.0	6.64	-4.0	11.33
91.36	-3.5	12.89	-3.5	24.23
95.8	-3.0	13.52	-3.0	37.75
131.68	-2.5	18.58	-2.5	56.33
71.93	-2.0	10.15	-2.0	66.48
44.69	-1.5	6.31	-1.5	72.78
35.13	-1.0	4.96	-1.0	77.74
40.34	-0.5	5.69	-0.5	83.43
30.26	0.0	4.27	0.0	87.70
13.85	0.5	1.95	0.5	89.66
15.74	1.0	2.22	1.0	91.88
9.77	1.5	1.38	1.5	93.26
7.23	2.0	1.02	2.0	94.28
5.69	2.5	0.80	2.5	95.08
7.86	3.0	1.11	3.0	96.19
6.89	3.5	0.97	3.5	97.16
7.27	4.0	1.03	4.0	98.19
5.75	4.5	0.81	4.5	99.00
7.08	>4.5	1.00	>4.5	100.00
708.64		100.00		





Outcrop #29. Graphical plots for a *TF1* tephra sample located in Daang Kastila, TVI, Municipality of Talisay, Batangas Province with Sample No. TV-TAL-TVI-TF1S1-101814. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Mdϕ) is obtained that is represented as the 50th percentile diameter estimated as -2.0ϕ.

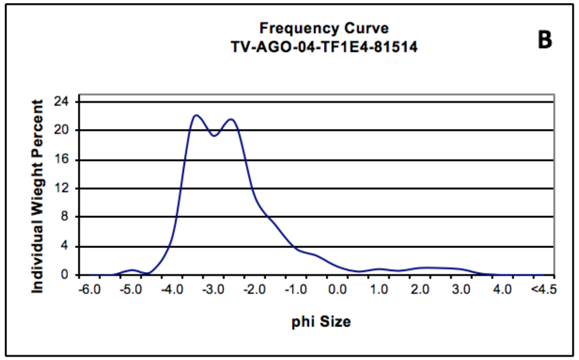
APPENDIX I-2.

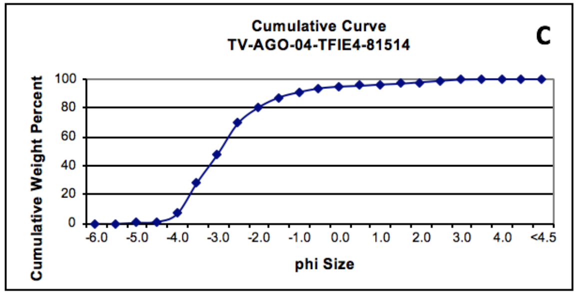
Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop #6.
Sample Name: TV-AGO-04-TF1E4-81314
Waypoint No. 451
Location: Brgy. Banyaga, Municipality of Agoncillo
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~6km (MEDIAL REACH)
Mode phi size: -3.5
Median phi size: -3.0
Mean phi size: -2.83
Standard Deviation: 1.306818182 (POORLY SORTED)
Skewness: 0.377777778 (STRONGLY FINE-SKEWED)

A

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
6.5	-5.0	0.71	-5.0	0.71
5.19	-4.5	0.57	-4.5	1.28
50.04	-4.0	5.49	-4.0	6.77
198.9	-3.5	21.83	-3.5	28.60
176.49	-3.0	19.37	-3.0	47.97
194.6	-2.5	21.36	-2.5	69.33
99.7	-2.0	10.94	-2.0	80.27
63.51	-1.5	6.97	-1.5	87.24
33.82	-1.0	3.71	-1.0	90.96
24.69	-0.5	2.71	-0.5	93.67
11.18	0.0	1.23	0.0	94.89
4.71	0.5	0.52	0.5	95.41
7.81	1.0	0.86	1.0	96.27
5.62	1.5	0.62	1.5	96.88
9.22	2.0	1.01	2.0	97.89
9.14	2.5	1.00	2.5	98.90
7.72	3.0	0.85	3.0	99.75
2.01	3.5	0.22	3.5	99.97
0.3	4.0	0.03	4.0	100.00
0.01	4.5	0.00	4.5	100.00
0	>4.5	0.00	>4.5	100.00
911.16		100.00		





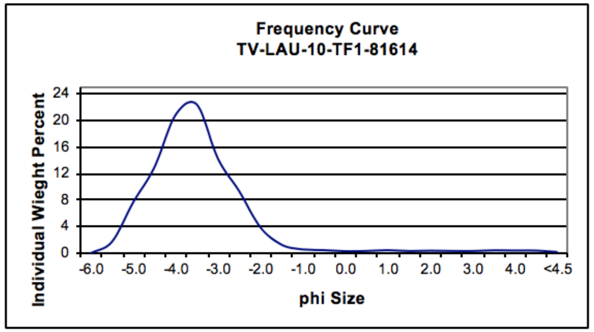
Outcrop #6. Graphical plots for a *TF1* tephra sample located at Barangay Banyaga, Municipality of Agoncillo, Batangas Province with Sample No. TV-AGO-04-TF1-81514. (A) grainsize data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Mdϕ) is obtained that is represented as the 50th percentile diameter estimated as -3.0ϕ. The frequency curve is nearly bell shaped indicating normal grain size distribution. The computed skewness provided values indicating that the deposit is strongly fine-skewed that is validated by the tail of the graph in the frequency curve having excess fine particles. The frequency plot is also unimodal with a near-bell-shaped appearance indicating that the tephra sample has normal grain size distribution.

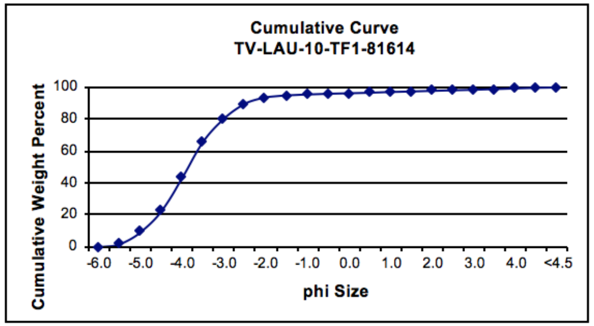
APPENDIX I-3.

Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop #15.
Sample Name: TV-LAU-10-TF1-81614
Waypoint No. 460
Location: Brgy. Buso-buso, Municipality of Laurel
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~6.5km (MEDIALREACH)
Mode phi size: -3.5
Median phi size: -3.5
Mean phi size: -3.67
Standard deviation: 1.20833333 (POORLY SORTED)
Skewness: -0.03030303 (NEAR SYMMETRICAL)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
10.36	-5.5	1.75	-5.5	1.75
45.6	-5.0	7.71	-5.0	9.46
77	-4.5	13.02	-4.5	22.48
123.98	-4.0	20.96	-4.0	43.44
133.43	-3.5	22.56	-3.5	66.00
84.87	-3.0	14.35	-3.0	80.35
55.75	-2.5	9.43	-2.5	89.77
23.41	-2.0	3.96	-2.0	93.73
7.69	-1.5	1.30	-1.5	95.03
3.39	-1.0	0.57	-1.0	95.60
2.75	-0.5	0.46	-0.5	96.07
1.83	0.0	0.31	0.0	96.38
2.0	0.5	0.34	0.5	96.72
2.73	1.0	0.46	1.0	97.18
1.97	1.5	0.33	1.5	97.51
2.27	2.0	0.38	2.0	97.90
2.02	2.5	0.34	2.5	98.24
1.97	3.0	0.33	3.0	98.57
2.58	3.5	0.44	3.5	99.01
2.41	4.0	0.41	4.0	99.41
2.35	4.5	0.40	4.5	99.81
1.12	<4.5	0.19	<4.5	100.00
591.48		100.00		





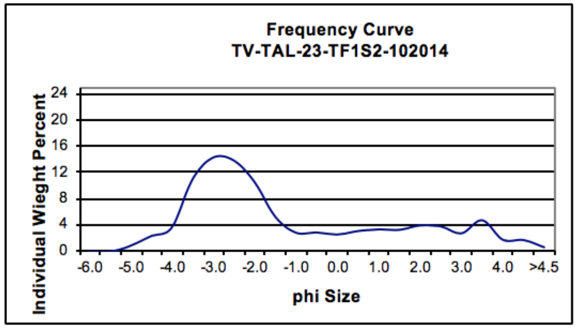
Outcrop #15. Graphical plots for a ***TF1*** tephra sample located in Barangay Buso-buso, Laurel, Batangas Province with Sample No. TV-LAU-10-TF1-81614. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Md ϕ) is obtained that is represented as the 50^{th} percentile diameter estimated as -3.5ϕ. The frequency curve is unimodal and bell shaped indicating normal grain size distribution. The computed skewness provided values indicating that the deposit is strongly fine-skewed that is validated by the tail of the graph in the frequency curve having excess fine particles.

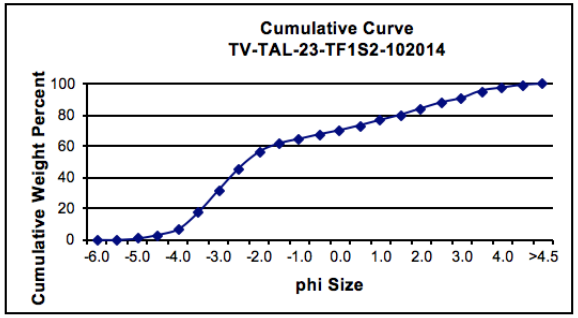
Appendix I-4.

Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop #30.
Sample Name: TV-TVO-TAL-23-TF1S2-102014
Waypoint No. 490
Location: Brgy. Buco, Municipality of Talisay
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~9km (DISTAL REACH)
Mode phi size: -3.0
Median phi size: -2.5
Mean phi size: -1.33
Standard deviation: 2.51136364 (VERY POORLY SORTED)
Skewness: 0.61818182 (STRONGLY FINE SKEWED)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
9.37	-5.0	0.93	-5.0	0.93
23.98	-4.5	2.38	-4.5	3.31
37.13	-4.0	3.69	-4.0	7.00
110.26	-3.5	10.95	-3.5	17.95
143.6	-3.0	14.26	-3.0	32.22
138.98	-2.5	13.80	-2.5	46.02
106.27	-2.0	10.56	-2.0	56.58
53.57	-1.5	5.32	-1.5	61.90
29.22	-1.0	2.90	-1.0	64.80
29.53	-0.5	2.93	-0.5	67.73
26.46	0.0	2.63	0.0	70.36
31.7	0.5	3.15	0.5	73.51
34.22	1.0	3.40	1.0	76.91
33.58	1.5	3.34	1.5	80.25
40.24	2.0	4.00	2.0	84.24
38.71	2.5	3.85	2.5	88.09
28.29	3.0	2.81	3.0	90.90
48.09	3.5	4.78	3.5	95.68
18.49	4.0	1.84	4.0	97.51
18.03	4.5	1.79	4.5	99.30
7.02	>4.5	0.70	>4.5	100.00
1006.74		100.00		





Outcrop #30. Graphical plots for a *TF1* tephra sample located in Barangay As-is, Laurel, Batangas Province with Sample No. TV-TAL-23-TF1S2-102014. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (*Md*ϕ) is obtained that is represented as the 50th percentile diameter estimated as -2.5ϕ. While the frequency curve is generally bell-shaped, a significant amount of fines in the tail of the plot was observed. Cumulative curve is gentle indicating that the tephra sample is poorly sorted.

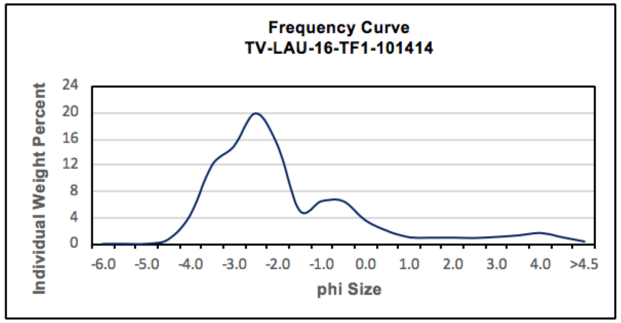
APPENDIX I-5.

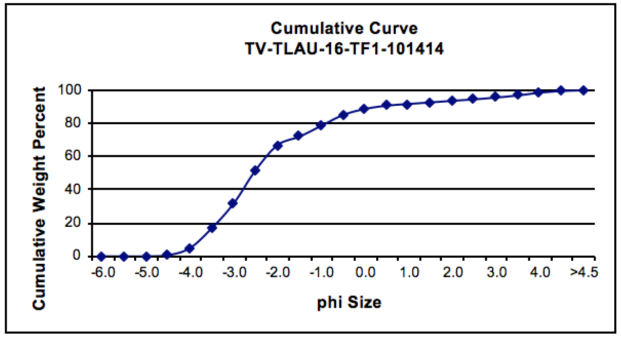
Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop #22.

Sample Name: TV-LAU-16-TF1-101414
Waypoint No. 467
Location: Brgy Leviste, Municipality of Laurel
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~9km (DISTAL REACH)
Mode phi size: -2.5
Median phi size: -3.0
Mean phi size: -2.33
Standard deviation: 1.73484848 (POORLY SORTED)
Skewness: 0.67948718 (STRONGLY FINE SKEWED)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
0	-5.0	0.00	-5.0	0.00
4.03	-4.5	0.67	-4.5	0.67
26.12	-4.0	4.35	-4.0	5.02
72.19	-3.5	12.01	-3.5	17.02
89.85	-3.0	14.95	-3.0	31.97
120.28	-2.5	20.01	-2.5	51.98
90.55	-2.0	15.06	-2.0	67.04
30.74	-1.5	5.11	-1.5	72.16
39.28	-1.0	6.53	-1.0	78.69
39.21	-0.5	6.52	-0.5	85.22
21.74	0.0	3.62	0.0	88.83
11.98	0.5	1.99	0.5	90.83
6.06	1.0	1.01	1.0	91.83
5.67	1.5	0.94	1.5	92.78
5.7	2.0	0.95	2.0	93.73
5.38	2.5	0.89	2.5	94.62
6.4	3.0	1.06	3.0	95.68
7.81	3.5	1.30	3.5	96.98
9.99	4.0	1.66	4.0	98.65
5.99	4.5	1.00	4.5	99.64
2.15	>4.5	0.36	>4.5	100.00
601.12		100.00		





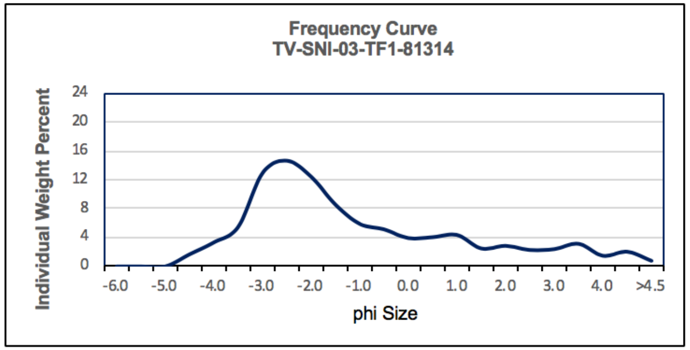
Outcrop #22. Graphical plots for a *TF1* tephra sample located in Barangay Leviste, Municipality of Laurel, Batangas Province with Sample No. TV-LAU-16-TF1-1-1414. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Md ϕ) is obtained that is represented as the 50th percentile diameter estimated as -3.0ϕ. The plot of the frequency curve for this outcrop showed a slightly bimodal grain size distribution but most of the particle sizes still provide a bell-shaped appearance and I still consider the plot as unimodal and having a normal grain size distribution. The slope of the cumulative curve gentle indicating that the sample is poorly sorted.

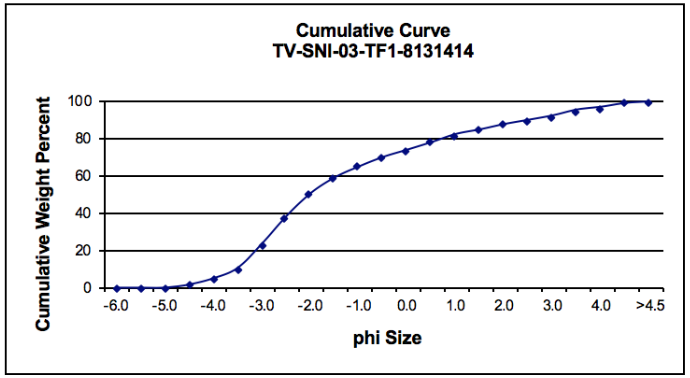
APPENDIX I-6.

Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop #5
Sample Name: TV-SNI-03-TF1-81314
Waypoint No. 446
Location: Brgy Pansipit Municipality of San Nicolas
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~10.5km (DISTAL REACH)
Mode phi size: -2.5
Median phi size: -2.0
Mean phi size: -1.5
Standard deviation: 2.18560606 (POORLY SORTED)
Skewness: 0.38095238 (STRONGLY FINE SKEWED)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
0	-5.0	0.00	-5.0	0.00
7.27	-4.5	1.68	-4.5	1.68
14.43	-4.0	3.34	-4.0	5.02
23.8	-3.5	5.50	-3.5	10.52
55.96	-3.0	12.94	-3.0	23.46
63.42	-2.5	14.67	-2.5	38.13
53.8	-2.0	12.44	-2.0	50.57
37.06	-1.5	8.57	-1.5	59.14
25.53	-1.0	5.90	-1.0	65.05
22.22	-0.5	5.14	-0.5	70.19
17	0.0	3.93	0.0	74.12
17.54	0.5	4.06	0.5	78.18
18.86	1.0	4.36	1.0	82.54
10.77	1.5	2.49	1.5	85.03
12.35	2.0	2.86	2.0	87.88
9.86	2.5	2.28	2.5	90.16
10.37	3.0	2.40	3.0	92.56
13.56	3.5	3.14	3.5	95.70
6.4	4.0	1.48	4.0	97.18
8.82	4.5	2.04	4.5	99.22
3.38	>4.5	0.78	>4.5	100.00
432.40		100.00		





Outcrop #5. Graphical plots for a *TF1* tephra sample located in Barangay Pansipit in the Municipality, Batangas Province with Sample No. TV-SNI-03-TF1-81314. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Md ϕ) is obtained that is represented as the 50th percentile diameter estimated as -2.0ϕ. While the frequency curve is generally bell-shaped, a significant amount of fines is noted in the tail of the plot. Cumulative curve is gentle indicating that the tephra sample is poorly sorted.

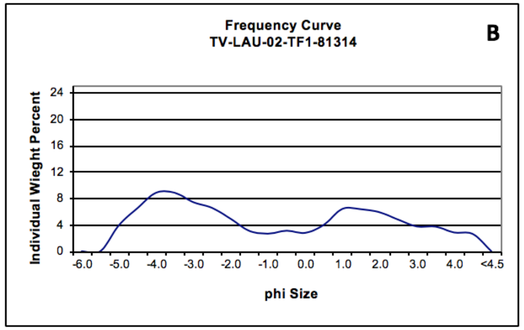
APPENDIX I-7.

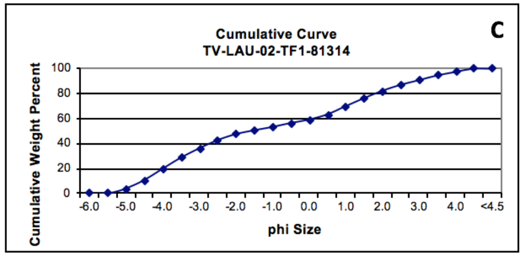
Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop #3.
Sample Name: TV-LAU-02-TF1-81314
Waypoint No. 444
Location: Brgy. As-is, Municipality of Laurel
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~12km (DISTAL REACH)
Mode phi size:-4.0
Median phi size: -2.0
Mean phi size: -1.5
Standard deviation: 2.83712121 (POORLY SORTED)
Skewness: 0.36538462 (STRONGLY FINE SKEWED)

A

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
23.33	-5.0	3.98	-5.0	3.98
38.69	-4.5	6.60	-4.5	10.57
52.47	-4.0	8.94	-4.0	19.52
52.37	-3.5	8.93	-3.5	28.45
43.93	-3.0	7.49	-3.0	35.93
38.86	-2.5	6.62	-2.5	42.56
29.07	-2.0	4.96	-2.0	47.52
18.28	-1.5	3.12	-1.5	50.63
15.72	-1.0	2.68	-1.0	53.31
18.4	-0.5	3.14	-0.5	56.45
16.46	0.0	2.81	0.0	59.25
23.65	0.5	4.03	0.5	63.29
37.95	1.0	6.47	1.0	69.76
37.66	1.5	6.42	1.5	76.18
34.89	2.0	5.95	2.0	82.12
28.31	2.5	4.83	2.5	86.95
22.2	3.0	3.78	3.0	90.73
22.08	3.5	3.76	3.5	94.50
16.81	4.0	2.87	4.0	97.36
15.46	4.5	2.64	4.5	100.00
	>4.5	0.00	>4.5	100.00
586.59		100.00		





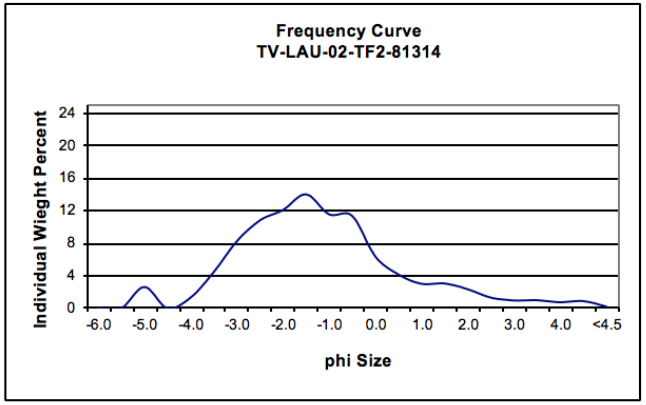
Outcrop #3 located at Barangay As-is, Municipality of Laurel, Batangas Province with Sample No. TV-LAU-02-TF1-81314. The tephra sample is identified as *TF1* tephra deposits from the initial phase (plinian/sub-plinian phase that started on 15 May and lasted until 2 June) of the AD1754 eruption. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Mdϕ) is obtained that is represented as the 50th percentile diameter estimated as -2.0ϕ. The frequency curve is nearly bell shaped indicating normal grain size distribution. The plot of the frequency curve for this outcrop showed a bimodal grain size distribution, with two plotted modes, the steepest or inflection points in the frequency curve. This indicates that there are two different groups of grain sizes. One inflection is in the coarser side while the other inflectio n is in the finer side of the grain size plot. One possible reason for the distinct bimodal plot could be that different types of eruptive products were deposited at the same time (e.g. lapilli tephra fallout deposits coinciding with the emplacement of co-ignimbrite ash), or two tephra fall events that may have occurred one after the other such that the fall and accumulate at the same time.

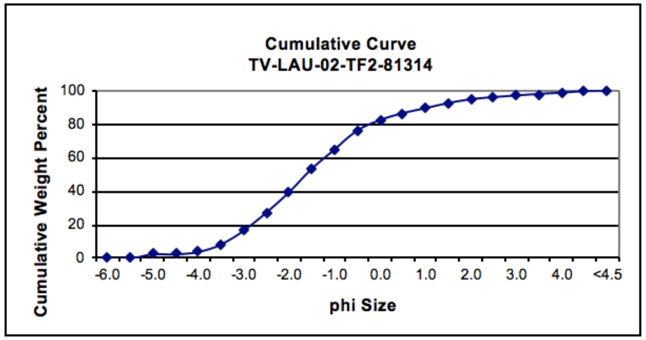
APPENDIX I-8.

Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF2*)

Outcrop #3.
Sample Name: TV-LAU-02-TF2-81314
Waypoint No. 444
Location: Brgy. As-is, Municipality of Laurel
Description: AD1754 Tephra Fall Deposit (TF2)
Distance from the vent: ~12km (DISTAL REACH)
Mode phi size: -1.5
Median phi size: -1.5
Mean phi size: -1.5
Standard deviation: 1.65909091 (POORLY SORTED)
Skewness: 0.8333333 (NEAR SYMMETRICAL)

sed (g)	phi	ind wt %	phi	cum wt %	pan (after)
0	-6.0	0	-6.0	0	473.33
0	-5.5	0.00	-5.5	0.00	462.79
12.39	-5.0	2.59	-5.0	2.59	461.73
0	-4.5	0.00	-4.5	2.59	485.66
6.2	-4.0	1.30	-4.0	3.89	514.18
21.11	-3.5	4.42	-3.5	8.31	491.48
39.12	-3.0	8.19	-3.0	16.50	459.02
51.46	-2.5	10.77	-2.5	27.27	441.59
57.57	-2.0	12.05	-2.0	39.32	437.86
66.75	-1.5	13.97	-1.5	53.29	411.28
55.05	-1.0	11.52	-1.0	64.81	427.94
54.05	-0.5	11.31	-0.5	76.13	393.82
30.36	0.0	6.35	0.0	82.48	375.24
19.78	0.5	4.14	0.5	86.62	359.23
14.29	1.0	2.99	1.0	89.61	341.68
14.5	1.5	3.03	1.5	92.65	334.05
11.09	2.0	2.32	2.0	94.97	314.56
6.23	2.5	1.30	2.5	96.27	311.25
4.52	3.0	0.95	3.0	97.22	304.15
4.69	3.5	0.98	3.5	98.20	304.99
3.47	4.0	0.73	4.0	98.93	299.8
4.16	4.5	0.87	4.5	99.80	294.14
0.97	>4.5	0.20	>4.5	100.00	279.55
477.76		100.00			





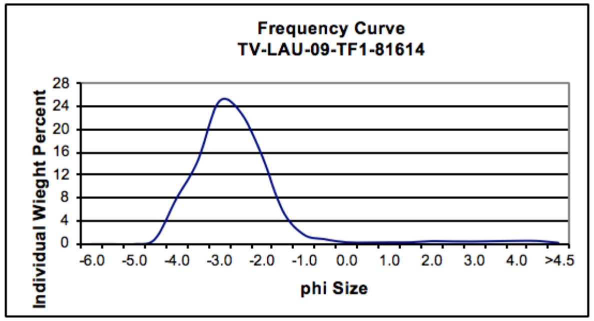
Outcrop #3 located at Barangay As-is, Municipality of Laurel, Batangas Province with Sample No. TV-LAU-02-TF2-81314. The tephra sample is identified as *TF2* tephra deposits (November phase) of the AD1754 eruption. Graphical plots for the *TF2* tephra sample include: (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Md ϕ) is obtained that is represented as the 50th percentile diameter estimated as -1.5ϕ. The frequency curve shows a nearly bell-shaped form indicating nearly normal grain size distribution.

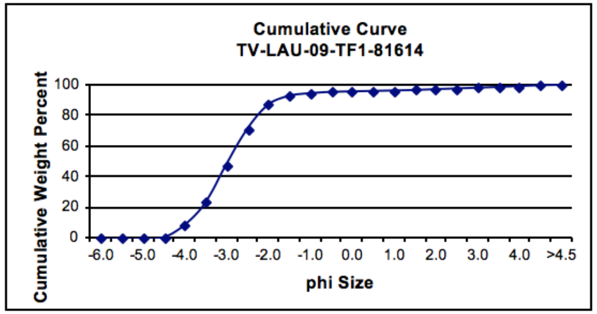
APPENDIX I-9.

Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop #13.
Sample Name: TV-LAU-09-TF1-81614
Waypoint No. 458
Location: Brgy. San Gregorio, Municipality of Laurel
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~12km (DISTAL REACH)
Mode phi size: -3.0
Median phi size: -3.0
Mean phi size: -2.83
Standard deviation: 1.13257576 (POORLY SORTED)
Skewness: 0.46666667 (STRONGLY FINE SKEWED)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
0	-5.0	0.00	-5.0	0.00
5.15	-4.5	0.93	-4.5	0.93
44.01	-4.0	7.91	-4.0	8.84
80.31	-3.5	14.44	-3.5	23.28
137.99	-3.0	24.81	-3.0	48.09
128.54	-2.5	23.11	-2.5	71.20
87.67	-2.0	15.76	-2.0	86.96
32.94	-1.5	5.92	-1.5	92.88
9.35	-1.0	1.68	-1.0	94.56
4.76	-0.5	0.86	-0.5	95.42
1.81	0.0	0.33	0.0	95.74
1.53	0.5	0.28	0.5	96.02
1.74	1.0	0.31	1.0	96.33
1.79	1.5	0.32	1.5	96.65
2.9	2.0	0.52	2.0	97.18
2.66	2.5	0.48	2.5	97.65
2.56	3.0	0.46	3.0	98.11
2.88	3.5	0.52	3.5	98.63
3.15	4.0	0.57	4.0	99.20
3.11	4.5	0.56	4.5	99.76
1.35	>4.5	0.24	>4.5	100.00
556.20		100.00		





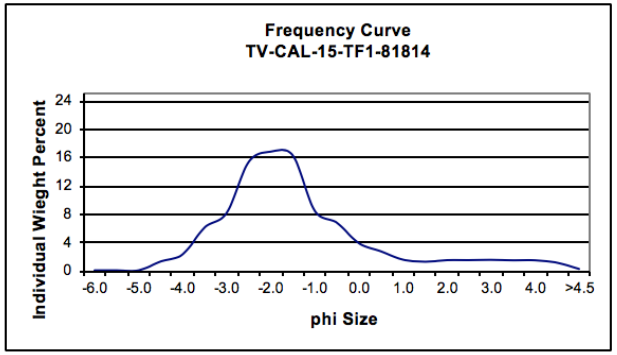
Outcrop #13. Graphical plots for a *TF1* tephra sample located in Barangay San Gregorio, Municipality of Laurel, Batangas Province with Sample No. TV-LAU-09-TF1-81614. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Md ϕ) is obtained that is represented as the 50th percentile diameter estimated as -3.0ϕ. The frequency curve for the tephra sample indicates a unimodal/normal grain size distribution.

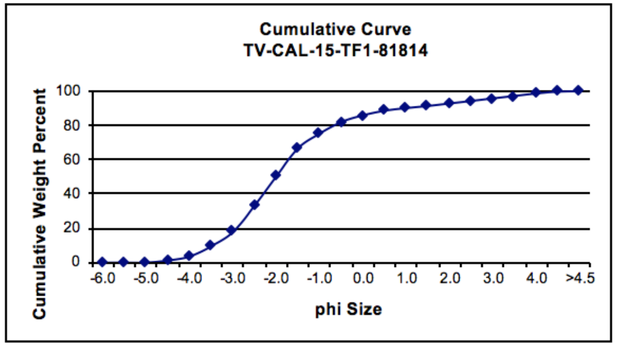
APPENDIX I-10.

Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop #21.
Sample Name: TV-CAL-15-TF1-81814
Waypoint No. 466
Location: Brgy Matipok, Municipality of Calaca
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~12km (DISTAL REACH)
Mode phi size:-2.0
Median phi size: -2.0
Mean phi size: -1.67
Standard deviation: 1.81060606 (POORLY SORTED)
Skewness: 0.38095238 (STRONGLY FINE SKEWED)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
0	-5.0	0.00	-5.0	0.00
5.31	-4.5	1.26	-4.5	1.26
9.62	-4.0	2.29	-4.0	3.56
25.72	-3.5	6.13	-3.5	9.68
34.53	-3.0	8.23	-3.0	17.91
65.02	-2.5	15.49	-2.5	33.40
71.17	-2.0	16.95	-2.0	50.35
68.89	-1.5	16.41	-1.5	66.76
35.69	-1.0	8.50	-1.0	75.26
28.57	-0.5	6.81	-0.5	82.07
16.29	0.0	3.88	0.0	85.95
11.4	0.5	2.72	0.5	88.66
6.42	1.0	1.53	1.0	90.19
5.17	1.5	1.23	1.5	91.42
6.11	2.0	1.46	2.0	92.88
6.13	2.5	1.46	2.5	94.34
6.3	3.0	1.50	3.0	95.84
6.02	3.5	1.43	3.5	97.27
6.03	4.0	1.44	4.0	98.71
4.56	4.5	1.09	4.5	99.80
0.85	>4.5	0.20	>4.5	100.00
419.80		100.00		





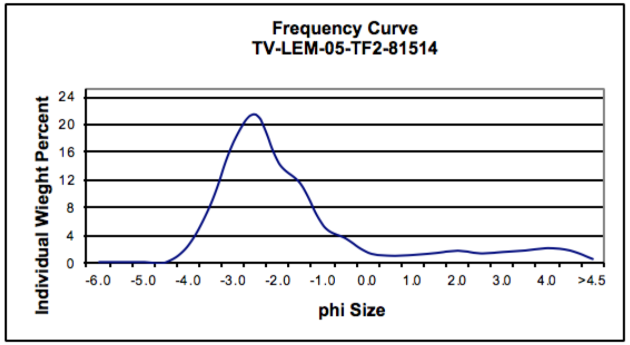
Outcrop #21. Graphical plots for a *TF1* tephra sample located in Barangay Matipok, Municipality of Calaca, Batangas Province with Sample No. TV-CAL-15-TF1-81814. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Mdϕ) is obtained that is represented as the 50th percentile diameter estimated as -2.0ϕ. Frequency curve shows a unimodal, bell shaped appearance indicating normal grain size distribution. The slope of the cumulative curve is gentle indicating poor sorting.

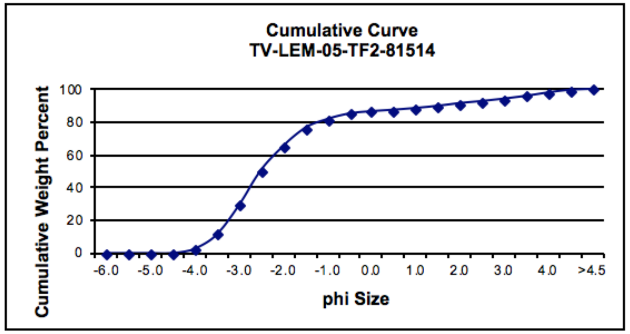
APPENDIX I-11.

Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF2*)

Outcrop #7.
Sample Name: TV-LEM-05-TF2-81514
Waypoint No. 452
Location: Brgy. Masalisi, Municipality of Lemery
Description: AD1754 Tephra Fall Deposit (TF2)
Distance from the vent: ~13.5km (DISTAL REACH)
Mode phi size: -2.5
Median phi size: -2.5
Mean phi size: -2.17
Standard deviation: 1.81060606 (POORLY SORTED)
Skewness: 0.45238095 (STRONGLY FINE SKEWED)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
0	-5.0	0.00	-5.0	0.00
0	-4.5	0.00	-4.5	0.00
14.88	-4.0	2.56	-4.0	2.56
50.58	-3.5	8.69	-3.5	11.24
102.79	-3.0	17.65	-3.0	28.90
125.52	-2.5	21.56	-2.5	50.46
84.6	-2.0	14.53	-2.0	64.99
66.05	-1.5	11.34	-1.5	76.33
30.84	-1.0	5.30	-1.0	81.63
20	-0.5	3.44	-0.5	85.06
7.91	0.0	1.36	0.0	86.42
5.39	0.5	0.93	0.5	87.35
6.09	1.0	1.05	1.0	88.39
7.71	1.5	1.32	1.5	89.72
9.69	2.0	1.66	2.0	91.38
7.4	2.5	1.27	2.5	92.65
8.61	3.0	1.48	3.0	94.13
9.89	3.5	1.70	3.5	95.83
11.89	4.0	2.04	4.0	97.87
9.8	4.5	1.68	4.5	99.55
2.6	>4.5	0.45	>4.5	100.00
582.24		100.00		





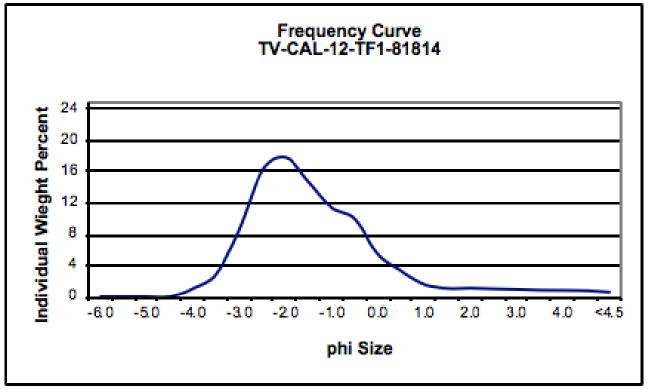
Outcrop #7. Graphical plots for a *TF*2 tephra sample located in Barangay Masalisi, Municipality of Lemery, Batangas Province with Sample No. TV-LEM-05-TF2-81514. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Md ϕ) is obtained that is represented as the 50th percentile diameter estimated as -2.5ϕ. Frequency plot is unimodal and nearly bell-shaped indicating normal grain size distribution.

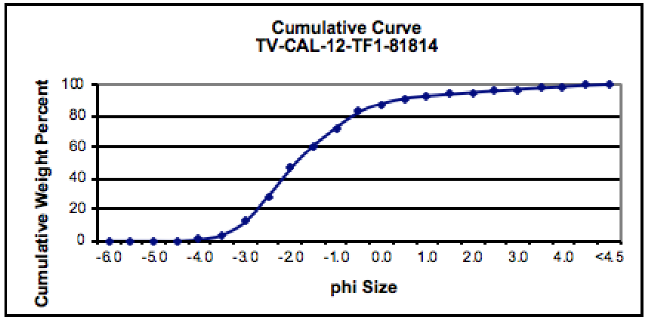
APPENDIX I-12.

Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF1*)

Outcrop #18.
Sample Name: TV-CAL-12-TF1-81814
Waypoint No. 463
Location: Brgy. Cahil, Municipality of Calaca
Description: AD1754 Tephra Fall Deposit (TF1)
Distance from the vent: ~18km (DISTAL REACH)
Mode phi size: -2.0
Median phi size: -2.0
Mean phi size: -1.83
Standard deviation: 1.45833333 (POORLY SORTED)
Skewness: 0.8333333 (STRONGLY FINE SKEWED)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
0	-5.0	0.00	-5.0	0.00
0	-4.5	0.00	-4.5	0.00
4.92	-4.0	1.06	-4.0	1.06
13.54	-3.5	2.91	-3.5	3.97
39.8	-3.0	8.56	-3.0	12.53
74.83	-2.5	16.09	-2.5	28.62
82.68	-2.0	17.78	-2.0	46.39
68.12	-1.5	14.65	-1.5	61.04
52.88	-1.0	11.37	-1.0	72.41
46.09	-0.5	9.91	-0.5	82.32
25.2	0.0	5.42	0.0	87.74
15.31	0.5	3.29	0.5	91.03
7.43	1.0	1.60	1.0	92.63
5.08	1.5	1.09	1.5	93.72
5.26	2.0	1.13	2.0	94.85
4.85	2.5	1.04	2.5	95.89
4.51	3.0	0.97	3.0	96.86
4.05	3.5	0.87	3.5	97.73
3.93	4.0	0.84	4.0	98.58
3.73	4.5	0.80	4.5	99.38
2.89	>4.5	0.62	>4.5	100.00
465.10		100.00		





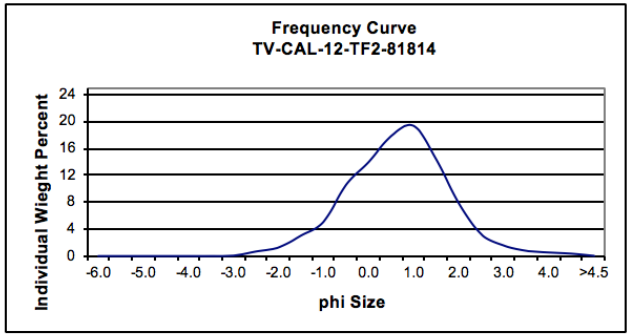
Outcrop #18. Graphical plots for a *TF1* tephra sample located in Barangay Cahil, Municipality of Calaca Batangas Province with Sample No. TV-CAL-12-TF1-81814 (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Mdϕ) is obtained that is represented as the 50th percentile diameter estimated as -2.0ϕ. Frequency plot is unimodal and nearly bell-shaped indicating normal grain size distribution. Cumulative curve has a gentle slope that indicate that the sample is poorly sorted.

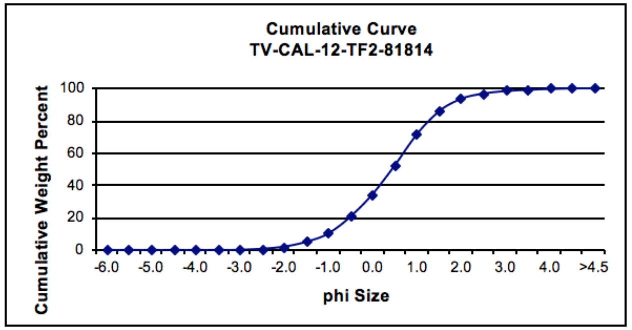
APPENDIX I-13.

Graphical plots of grain size analysis of an AD1754 tephra fallout deposit (*TF2*)

Outcrop #18.
Sample Name: TV-CAL-12-TF2-81814
Outcrop #18/Waypoint No. 463
Location: Brgy. Cahil, Municipality of Calaca
Description: AD1754 Tephra Fall Deposit (TF2)
Distance from the vent: ~18km (DISTAL REACH)
Mode phi size: 1.0
Median phi size: 0.5
Mean phi size: 0.5
Standard deviation: 1.03030303 (POORLY SORTED)
Skewness: -0.07142857 (NEAR SYMMETRICAL)

sed (g)	phi	ind wt %	phi	cum wt %
0	-6.0	0	-6.0	0
0	-5.5	0.00	-5.5	0.00
0	-5.0	0.00	-5.0	0.00
0	-4.5	0.00	-4.5	0.00
0	-4.0	0.00	-4.0	0.00
0	-3.5	0.00	-3.5	0.00
0.5	-3.0	0.06	-3.0	0.06
5.5	-2.5	0.67	-2.5	0.73
10.38	-2.0	1.27	-2.0	2.01
24.76	-1.5	3.03	-1.5	5.04
41.48	-1.0	5.08	-1.0	10.12
86.08	-0.5	10.54	-0.5	20.67
113.45	0.0	13.90	0.0	34.56
144.82	0.5	17.74	0.5	52.30
156.96	1.0	19.23	1.0	71.53
116.34	1.5	14.25	1.5	85.78
63.45	2.0	7.77	2.0	93.55
26.22	2.5	3.21	2.5	96.76
12.65	3.0	1.55	3.0	98.31
6.29	3.5	0.77	3.5	99.08
4.29	4.0	0.53	4.0	99.61
2.9	4.5	0.36	4.5	99.97
0.28	>4.5	0.03	>4.5	100.00
816.35		100.00		





Outcrop #18. Graphical plots for a *TF1* tephra sample located in Barangay Cahil, Municipality of Calaca, Batangas Province with Sample No. TV-CAL-12-TF2-81814. (A) grain size data table; (B) frequency curve plotted from the data in (A); and (C) cumulative curve, where median phi (Md ϕ) is obtained that is represented as the 50th percentile diameter estimated as 0.5ϕ. Fine particles dominate in this tephra sample. Considering the distance of the outcrop from the volcano, a fines-dominant grain size distribution seems reasonable. Frequency plot is unimodal/bell-shaped indicating normal grain size distribution. Cumulative curve has a gentle slope that indicate that the sample is poorly sorted.

APPENDIX J

Appendix J summarises the results of the vignette study undertaken through the process of structured interviews of ten selected Barangay Captains to gauge their level of education, knowledge, experience, risk perception, awareness and preparedness for supporting their communities during a volcanic emergency. I opted for purposive non-probability sampling rather than probability sampling because participants are selected purposively based on their community roles. I chose to interview some selected Barangay Captains of communities on or close to Taal, with one participant further away from the volcano to gain a perspective of those living a considerable distance from the volcano. My sampling was purposive and my selection of respondents (Barangay Captains) was based on proximity to Taal. Appendix E-1 and Appendix E-2 are the HREC approved questionnaire forms that I developed at the start of my research. I progressed through the survey questions, using them as prompts for the structured interviews and qualitative discussions. I further expounded on each of the questions with follow-up questions.

From the results of the vignette study, recommendations will be offered on how Barangay Captains could be supported to enhance their DRR activities and governance. The interviews were structured in the sense that the questions were divided into themes. The five factors for my structured interviews (e.g. level of education, knowledge and understanding of volcanic hazards and risk, direct or indirect experience of an eruption, influencing factors to behaviour and responses related taking the volcanic risk seriously, and level of preparedness) were identified as recurring themes in the literature review I conducted related to social volcanology and other hazard related DRR research. Further, the emphasis given to the five factors seemed appropriate in the context of the Philippines and my prior experience working on volcano and earthquake related hazards and risk.

Summary of the responses of the Barangay Captains on key elements of the hypothesis. Text written in BLUE are actual/official facts. Text in GREEN Italics are verbatim quotes from the respondents. Respondent number identified in the Table also corresponds to number in Table 7.1 and Figure 7.2. In relation to "education", additional learnings (e.g., specific training, information sessions about or study etc) related to volcano hazard and risk are considered positive. Text in RED are my interpretations and comments. Acronyms: TVI- Taal Volcano Island; PDC- pyroclastic density currents; MDRRMO- Municipal Disaster Risk Reduction and Management Office; DRR- disaster risk reduction; SW- southwest; N-NW- north-northwest; BC- barangay captain; SSB- single side band; CDRRMO- City Disaster Risk Reduction and Management Office; BH- Barangay Hall; MH- Municipal Hall; LGU- local government unit; MCL- Main Crater Lake; ES- Elementary School.

Respondent Code/ Respondent #	Educated	Knowledgeable	Experienced	Take risk seriously & are prepared	Other issues, themes and salient points
GE01/#1	***Positive:*** Participated in one preparedness training session conducted by DILG in 2010	• Know they are located in an area at high risk to volcanic hazards including PDCs and tephra fall.	• Was told stories about the 1965 eruption by parents/relatives Inherited memories • Said they evacuated during the eruption *"base sa kwento ng mga magulang"* (*based on parents' story*)	• Knows where accurate/reliable information on volcano condition can be obtained Trust in relevant government authorities • Has existing alert system where at Alert 2, they provide warning by doing house-to-house; if evacuation is necessary, all boats will be used; knows where they are going (Talisay ES) when they evacuate TVI	• Has lived in their community since birth. • He believes the government will provide what is promised. Trust in government
GE01/#1	***Negative:*** Highest level of education: High school graduate only. In available statistics- 2010, 34.31% of population in Batangas only reached Elementary education while 35.66% reached High School level.	• Does not think they will be affected by lava flows • Have not identified lahars (Community is located on the foot slopes of Taal) and tsunami (same community is along the shoreline)	• Could not remember anything because he was only 2 years old when Taal erupted in 1965: *"Wala po basta, palibhasa ano eh batang isip pa kami nasa bundok"* (Not much, since we were	• Claims he has independent preparedness plans for family but they have no BDRRM Plan Not proactive with DRR related activities. • Minimal preparation on emergency actions including knowledge of action at Alert Level 2 considering they are living at TVI.	• Intends to return to TVI & his home even if it is severely damaged by an eruption and would not avail of an alternative option like housing and livelihood far away from the volcano. • Worked part time as fish cage owner & travels to other places daily

	Compared to national statistics, these levels serve as the average highest level of education for most Filipinos.	• Even knowing they are located in an area at high risk to volcanic hazards including pyroclastic density currents (PDCs) and tephra fall, they still stay there and was not even proactive with DRR measures	just kids staying in the mountains).	• Rely on local government and wait for their action Trust in government can also be negative in the sense that they may have become too complacent and have not prepared alternative action if assistance from the LGU fails, like provision of boats for residents at TVI during evacuation. There is absence of self-reliance.	Implies he may not be there when an eruption occurs. • GE01 was interviewed in 2014 but respondent died in a boat accident in 2016.
GE02/#2	***Positive:*** In terms of DRR, respondent has attended trainings/seminar-workshops for different hazards including Taal.	• Know they can be affected by tsunami based on 'inherited memories' *"Parang yung mga lolo ko po noon ang nagsabi na mas malala noon yung mga putok na mga nauna (likely the 1911 eruption) dahil may kinukwento po dito na yung ang mga bahay po dito nakapatong sa bato ang haligi... ang sabi eh nagkapalit palit ang mga bahay-'Aba bakit ka lumapit? Bakit nandito na bahay mo?'- Nung pagdating na ang tubig, nailipat ang kanilang mga bahay. Nung una pa, hindi 1965." (I remember our grandfather told us that the impact of the previous eruption of Taal was worst. He said that the houses built over there with wall leaning on the* stone, they said the houses	• *"Ash lang. Kaunti lang po ang ashfall na pumaroon. Lumikas pa din po kami. Palibhsa naman po nung panahon na yun eh kakaunti pa lang ang sasakyan. Kanya-kanya pa naman lakarin noong panahon na yun. Bale tatlong buwan po kami sa Tagaytay. Tumira sa mga kamag-anak"* (*Ash only. Very little ash came that way We still evacuated to Tagaytay. During those times, there were very few vehicles. People went their own way walking during that time. We stayed in Tagaytay for three months. We stayed with relatives.)* • While only 8 years old during 1965, remembered experiencing ashfall. *"Kaunti lang po ang ashfall na pumaroon." (Very little ash came that way)*	• Knowledgeable in terms of barangay actions on Alert Levels: *"Ehh sa ngayon ho talagang unang una nga basta yung nag alert level 3 eh talagang automatic na yun." (As of now, if Alert level 3 is raised, we will automatically evacuate.)* • Knows where to get information on hazard warning (SOP is from MDRRMC but since TVO is just beside the barangay hall, they try to get information/ confirmation directly from DOST-PHIVOLCS • Has BDRRM Plan & have existing DRR committees; mentioned they have several L-trucks in the community that they intend to use during evacuation; identified initial meet up/pick up point including Barangay hall & barangay chapel; they	• Inherited memories: *"Mabuti nga noon ganoon lang. Sabi ng matatanda, yung Sistema ng pagputok nya, talagang dito nakaharap ang... yung mga bato…talagang dito ang punta" (It was good that during that time we only experienced minor impact. Our elders told us that before the eruption was directed here… the ejected stones were going this way)* • Description of Alert Level 2 warning as *"umiinit ang ulo ng ating bulkan" (literally means the volcano's head/top is heating up).* • *He and his family have good community relationship. Mention of neighbors mostly consisting of relative in whatever consanguinity- "Dahil sa barrio ho eh bihirang bihira ang hindi*

moved. And they said – 'Why did you house become closer? Why is your house here?' -He said when the waves came in, the houses moved, during the earlier eruption, not the 1965)

- He got the estimated time of eruption (2AM) right.

"Ay, sa personal na karanasan, nung primero kami nun eh tuwang tuwa tingin mo maliwanag. Siyempre bata pa, kala namin kung ano lang. Eh di nung masabing mga magulang namin na delikado di lumikas na kami (*Personal experience, initially we were very happy because it was so bright. We did not think much of it. Of course, we were young. But when our parents said it was dangerous, we evacuated).*

- Stayed in the ridge area in their farm in the north; later walked/ evacuated to Tagaytay; when asked what he remembers during the eruption:

"Wala po, basta,palibhasa ano eh batang isip pa kami nasa bundok" (Not much, since we were just kids staying in the mountains);

"Eh palibhasa naman po nung panahon na yun eh kakaunti pa lang ang sasakyan Kayang kaya pa naman lakarin noong panahon na yun. Bale 3 months po kami sa Tagaytay"

(During those times, there were very few

will do house to house to relay eruption warning.

- If warning of impending eruption is provided by DOST-PHIVOLCS (e.g. Alert 3), he will believe and immediately move away from the volcano.
- Their practice is at Alert Level 3, they will evacuate.
- Use church bells for warning (continuous ring 3x means emergency).
- There are committee members who are residents, not just barangay officers.
- In a year since he held office, had one assembly meeting (March or April 2014) and one will be held in November).

He follows the legally required number of assemblies. Local Government Code provision- Chapter 6, Section 397- Barangay assembly should meet at least twice a year composed of registered residents of the barangay); have confidence that LGU will contact them immediately during emergencies.

ninyo kamag-anak." (Here in the barrio, it is unusual if your neighbours are not related to you.)

			vehicles. It was very easy to walk during that that time. We stayed 3 months in Tagaytay). • they observed that the ballistics were going towards the north (their side) but then observed the change in wind direction so the ash was dispersed to the SW; also recounted that his grandfather told them the past eruption (likely 1911) was more explosive, describing occurrence of tsunami moving house further away by the waves; since he was BC, experienced the 1977 eruption		
GE02/#2	***Negative:*** • Highest level of education: High school graduate only **"*High School lang ho.*** *Apat na buwan akong nag college. Bata akong nag-asawa*" (*High school only. Stayed in college for four. months. Got married early.*)	• Do not think they will be directly affected but they will still evacuate This perception of absence of direct threat may be influenced by what the old people say. • BC mentioned that a lot of the elderly residents are generally the hardest to convince because they believe Talisay is safe –	• Too young to remember (only 8 years old-Grade 2) "*Wala po basta, palibhasa ano eh batang isip pa kami nasa bundok*" (*Not much, since we were just kids staying in the mountains*). • Only experienced ash; evacuated to Tagaytay (~10AM) when the eruption (~2AM) was already ongoing. Initially enjoyed seeing the brightness coming from the eruption in the vent. • Never experienced Alert Level reaching 3 and no	• Have never experienced Alert level being raised to 3 but said "*Lilikas sakaling pumutok*". (*Will evacuate if it erupts*) • Know the importance of drills but have not conducted one up to the time of interview and do not know specific place they are going: "*Tingin ko maganda ang epekto ng pagsasanay namin dahil kasi ho yung di ka na maninibago kung sakali may nangyari nga. Alam mo na yung gagawin.*" *(I think our efforts are good, we will be used to it and if the eruption*	• Priority duty: "*Peace and order. Yun po ang number one dito sa barrio*" (Peace and order- *That is the number one priority here in the barrio*). • They have difficulty inviting residents to barangay assemblies, even the ones where they did an echo seminar of what they learned in a seminar workshop organised by DOST-PHIVOLCS. • Problem dealing with hard-headed &

	"*Matitigas ang ulo ditong matatanda, laging ang sabi basta pumutok daw ang bulkan na yan, ang Talisay libre*" (*The hard-headed elderly people here keep saying that if Taal erupts, Talisay is safe.*)	direct experience of a volcano emergency as a BC.	*happens, you know what needs to be done.*) and said further: *"Sa ngayon ho ang nakukuha ko sa seminar, yun lang mayroon na hong evacuation center pero wala pa ho akong pagsasanay. Ang lagay ho, ang nasabi nga ng MDRRMC (Municipal Disaster Risk Reduction and Management Council) na hanggang sa nakipagcoordinate kami sa Tagaytay na talagang doon ang punta namin in case nga na pumutok. Basta yun lang sigurado lang yun evacuation center... di ko pa din alam saan doon."* *(Right now, based on the seminars I have attended, I know we have existing evacuation centers but still do not have drills. MDRRMC told to go there, and that we should coordinate with Tagaytay for confirmation that we are going there. The only thing that is sure is the evacuation center in Tagaytay. I still do not know where.)* • Talisay MDRRMO gave instruction that they will proceed to Tagaytay. They themselves should confirm with Tagaytay City government about this evacuation procedure. Unfortunately, respondent was not able to ask if they confirmed with Tagaytay City government but from the way he talked, he just took it as is- "*Basta sinabi ho nilang*	uncooperative residents that sometimes they let the police handle them and when asked how many were uncooperative he answered about 50%: "*Syempre ho ang pinakamahirap po nating laging gagawin eh yung may matitigas na ulo sa barrio ho. Hindi ho nawawala yun. Yun ang lagi ho naming problema. Naging plano ho namin dyan sa mga matitigas ang ulong yan, pulis na lang ang kukuha sa kanila. .Eh paano ho sasabihin 'hindi ako aalis, baka mawala ang aking ganito... ganon!' Hindi nila alam mam kaya nagsasakripisyo kami ganyan, kanilang buhay ang nakataya.*" (*Of course, one of the most difficult problem in handling evacuation is when you have hard-headed residents in your community. There will always be one in the community. Our plan for the hard-headed residents, we will have the police pick them up. They often say 'We will not go because our properties may be stolen!'- They do not realise that we doing this because their lives are* at *stake.*) •No warning system except house to house

		Tagaytay" (*They just told us we proceed to Tagaytay*.) • Never discussed permanent resettlement and alternative livelihood.	using patrol bike/tricycle and ringing of church bells: *"Wala pa ho kame. Medyo kasi ho ang mabigat ngayon sa ating gobyerno, yung kagaya naming maliit na barrio- kunwari may pondo kame sa calamity. Bakit yun ehh hindi magalaw. Sabi ko nga makaranas nga ng bagyong Glenda, ehh may calamity fund kami banda siguro mga PhP 65,000. Sabi ko ipamili natin to ng gamit. Halimbawa mega phone, itong gamot, yung pagkain, yun mga dilata para kung sakali nga hong pumutok yung bulkan para may makain ang tao. Eh ang problema bakit yung pondo hindi mailabas? Ang Calamity Fund ay sampung porsiyento based sa income ng barrio. Ang mangyayari ho sa 10% na yun, ang magagalaw pa rin ho doon eh yung 70%. Yung 30% ititira nyo pa yun. Hindi pepwedeng ubusin. Yun ay in case lang may kalamidad na dumating tsaka mo lang mawiwithdraw yun."* (We still do not have any. The problem with the system of our government, we experienced Typhoon Glenda and we have calamity fund, around PhP65,000-AUD1950. I said we should buy some

					equipment like megaphones, food like canned goods. So that just in case Taal erupts people will have food to eat. The problem is why can't they release the funds? That is 10% of the barangay income. Out of the 10%, you can only use 70%. The remaining 30% cannot be used. You can only get that if there is a calamity.) Calamity fund - 10% of barangay revenue; 70% of this fund for DRRM activities & 30% as Quick Response Fund. • Reluctance to leave their barangay even if it experiences great impact from an eruption - *"Ayy babalik… kung saan kayo nakasanayan… ehhh di dun!" (Will return…You will go to the place you are used to).* Issue of attachment to place
GE03/#3	***Positive:*** Has attended trainings related to DRR	• Believe they will only be affected by ashfall. *"Abo, ayy yun po sigurado!" (Ash, we will be surely affected by it!)* A barrio named Bayuyungan was written in Saderra Masó (1911) as having been destroyed by the AD754 eruption, now within the barangay boundaries of their community.	• Was 14 years old during the 1965 eruption; no major impact in the community except minor ashfall *"Kami ho nung 1965 di naman kami masyadong. Nagkaroon kami ng konting abo lamang. Hindi ho malaki. Natatandaan ko pa nga ho nun, noong naglalakad kami diyan paakyat ng bundok na*	• Have BDRRM Plan and existing DRR committees; know protocol that volcano information & warning come from MDRRMO sourced from DOST- PHIVOLCS; Alert system includes doing house-to-house using megaphones, 2-way radios, sirens & church bells will be activated from the barangay.	• They evacuated to higher grounds instinctively, with others going to Tagaytay. Issue of inherited memories provided by their elders who experienced eruptions in the past • Trust in DOST- PHIVOLCS for accurate warning information. • Have lived in their community since birth, participates in community

yan nakatapat saming ganun yung maitim na usok. Naisip ko lang ngayon, kung kako yun ay bumagsak sa amin mga naglalakad, marami hong mamatay. Maitim talaga, ang kidlat nun talagang kitang kita ninyo. Parang walang hangin. Ang usok talagang nakatapat samin diyan, oh paakyat sa bundok sa Tagaytay na yan. Nagiging ilaw lang namin noon ay yung kidlat maya't maya eh kidlat sa taas." (Yes, we were not affected. Even during the 1965 eruption, we were only affected by small amount of ashfall. Not a significant amount of ash. I remembered back then when we were hiking towards the mountain, the black ash cloud was right above us. Thinking about it now, realised that if those ash fell on us while where walking, a lot of people would have been killed. It was really dark, and the lightning was really very bright. I think there was no wind. The ash cloud was directly on top of us when we were towards the mountain to Tagaytay. Our only source of light that time were the lightning flashes that frequently illuminated the sky.) (Provided

- Have evacuation plan/map locating pick-up points (chapel, covered court).

Confirmed that their barangay had contingency plans submitted to MDRRMO/DILG.

- Mentioned the disabled and the elderly as priority.

activities (e.g. social, religious, cultural), happy in his community.

Issue of attachment to place

- Amenable to moving to an alternative housing and livelihood, if offered by the government-*"kung may mas magandang magiging option po ang pamahalaan"* (*If the government can provide us with better options*.)

  Livelihood issue in relocation

			experience of both ashfall and lightning flashes) • remembers that it happened at 2AM, that there was no steaming in the main vent (Main Crater); eruption he saw did not come from MC. The site of the eruptions from AD1965 to AD1977 was Mt. Tabaro located in the SW side of TVI. • no impact of the 1970's eruptions		
GE03/#3	***Negative:*** • 2nd year College only • He has participated in one volcano-related drill. However, the fact that he is not familiar with Alert Levels and parallel actions of LGU implies that the training he obtained was not sufficient.	• Not sure if PDC can affect them: *"Baka, hindi ko ho sigurado kung aabot dito eh." (Maybe, I am not sure if it will reach our side.)* • Do not think they will be affected by lahars: *"Baka naman po hindi na kami apektado ng lahar." (Maybe we will not be affected by lahars.)* • Believe if eruptive vent is not MC, they will not be affected & even if the eruption occurred at MC, believes they will only be affected by ashfall. (DOST-PHIVOLCS hazard maps show that their community is prone to PDC, tephra,	• While he already described some observation of the eruption, he then said he could not remember too clearly since he was still young. • Initially, they did not get the right information. News was that a gasoline station exploded)- this implies that the eruption warning information was not relayed to the community on time. I am confident that in AD1965, DOST-PHIVOLCS Resident Volcanologist provided early warning. He was a very reliable man who would not neglect his duties, so along the way, the flow of warning information from PHIVOLCS to the LGU failed.	• Initially seemed knowledgeable about alert system and LGU actions per Alert Level but gave confusing comment on what to do if Alert 3 is given: *"Mga 3 ganyan magsisimula na mag-handa." (At Alert Level 3, we will start to prepare.)* and *"Pag Alert 2, nagbibigay din po kami ng impormasyon para sila ay makapag-handa na kung ano ang kanilang dapat ihanda sapagkat talaga pong pumutok na, Alert 3, meron din po kaming ginagawang bahagi para malaman nila na puputok na talaga ang bulkan. Automatic na po yun na sila ay aming eevacuate." (We also give information so they can prepare their things because of a possible eruption. We also have our own plans to disseminate the information that there is strong possibility that the*	• Believes DOST-PHIVOLCS will be able to give warning as to where the impacts of an eruption will be directed- *"Siguro ay masasabi yun ng volcanologists kung saan pupunta". (Maybe the volcanologists at PHIVOLCS will be able to know where eruptive products will be directed.)* DOST-PHIVOLCS instrumentation detects where current seismic activity is concentrated; also monitor gas emission but not be able to warn residents of exact time and day of eruptions, much less where the impacts will be directed.) • GE03 was interviewed in 2014 but respondent was shot dead by riding-in-tandem suspects on 15 May 2016. Automatically, the 1st Councilor took over his place. I learned about

	shoreline communities prone to tsunami, those near river channels prone to lahars)	• They evacuated an hour after the eruption & stayed in his grandparents' farm in higher ground N-NW from Taal but others went to Tagaytay; does not remember any assistance from the barangay officials.	*volcano might erupt. We will make sure that the residents are automatically evacuated.)* • More prone to believe that they will not be directly affected by an eruption They are directly facing TVI. • Too much reliance on LGUs for emergency action & not familiar with routine/customary actions of LGU/communities especially for Alert Level3. • Confident they are prepared but have not conducted any volcano-related drills but confident they have preparedness plans. *"Di pa po kami nagkakaroon ng drill sa ganun"* and *"Sa pagsasanay po di kami masyado pero yung paghahanda meron po kami niyan*" • Not proactive in validating volcano information and too much reliance on LGU for warning & evacuation decisions; assumes LGU/ MDRRMO will inform them if there is a volcano emergency; will wait for orders of evacuation from LGU: *"Opo, konsultasyon sa local pag Alert 3. Kasi di naman po pwedeng likas agad." (Yes, consult with local government at Alert 3 because we cannot just evacuate immediately.).*	it after I already returned to Australia and was not able to interview the 1st Councilor (next-in-rank official of the barangay).

				• Identified their barangay gym as an evacuation site but rely on local government on where they will go if they need to go farther away from their community: *"Meron pong isang evacuation center dito yung amin pong gym. Meron po kami diyang basketbolan (covered court). Yun po yung aming pwedeng pagdalhan sa kanila. Mayroon pong plano kung kelangang lumayo dito. Yun po ay manggagaling na sa amin pong ano sa local."* *(Our gymnasium also serves as one of our evacuation centers. It's a covered court here that can also serve as an evacuation. We can assemble our residents there. We have evacuation plans if we need to leave. It will come from our local government.)*	
GE04/#4	***Positive:*** Knows about tsunami hazard (cited the 2011 Japan tsunami) & attended volcano-related seminars.	• "Know that if the eruption is big, they may be affected because he knows they are close to the volcano". *"Depende ho sa magiging sitwasyon, dahil pagka medyo malakas, mag-saboy siya ng gabok, maaabot talaga dito kasi malapit lang sa bulkan." (It will depend upon the situation, because if the eruption is explosive, it will reach our place here*	**Pinatubo experience:** • Experienced ashfall (~1 inch of sand & ash, more ash than sand); ash covered most surface outside (e.g. *"magabok ang mga batya"- tub was filled with ash*). **Taal experience:** • While he was still young (~11 in 1977) during the more recent eruptions of Taal (could not remember if the 1960's or 1970's eruption but likely 1976 or 1977)	• Familiar with Volcano Alert Levels and standard LGU actions for each level: *"Pag Level 2 ay di mag-iikot na at magbibigay ka na ng babala… bawa't bahay, magbigay ng kaalaman sa kanila na maghanda na at pag tinaas na sa Level 3 eh likas na." (Roam around and give warnings... every household will be provided with warning information and to be ready. Then when Level 3 is raised, evacuate.)* • Has activated BDRRM plans and committees	• Having stayed in his community since birth (never moved), reinforces his knowledge about the place and connection and attachment to the place • • Owning property and having their own farm means the person is attached or connected to their community. • Participate in community activities (e.g. social/

since we are close to the volcano) • Knows *'buga'* (*local name for tephra fall consisting of scoria*) & thinks they may be affected by them only (perhaps because of the 1991 ashfall experience related to Pinatubo.	• He remembered strong smell of sulfur in their area but no ashfall so he has knowledge of at least one volcanic hazard.	• Barangay use SSB radios for communication during emergencies. • He has contact information for DOST-PHIVOLCS but knowledgeable about the protocol (chain of command) related to relay of warning information, emanating from PHIVOLCS to local government to barangays and will consult LGUs for decisions during volcano emergencies. • Have identified assembly points (schools & chapel) for pick-up, have warning signals (bells, megaphones, SSB radio, house-to-house. • Have corresponding actions based on DOST-PHIVOLCS Alert levels and have emergency committees and BDRRM Plan including evacuation. Intend to use church bells for warning residents. *"Magiikot na at magbibigay ka na ng babala… bawat bahay, magbigay ng kaalaman sa kanila na handa na at pag dumating ang level 3, lilisan na at pupunta muna sa school at kapilya".* (*Roam around and give warnings... every household, give them information/ knowledge and be ready and if alert level 3 is given- evacuate to identified initial sites like the school & chapel.*)	recreational, religious). • If his community has been severely affected by an eruption, and the government will provide alternative housing and livelihood, he is willing to move to a safer location. Still believes the government will provide as promised. • BC has served the maximum 3 terms (8 years at the time of the interview). Issue of trust- His community clearly trust him.

				• If evacuation further away from Taal is needed, they will go to another neighboring barangay further east. • In the event of a larger eruption & there is a need to evacuate from their municipality, their next step would be to go to Batangas City. • Have identified who is responsible & vehicles to be used for pick-up of residents, provision of relief.	
GE04/#4	***Negative:*** • Completed 3rd year High School only. *"High School lang, third year high school"* *(High school only, third year high school.)*	• He has poor knowledge of volcanic hazards. He does not know '*pila*' (local name for surge deposits) & does not believe they will be affected by them. *"Hindi pa naapektuhan. Walang potensyal na maaapektuhan kami. Ang buga alam ko. Eh kasi nagagamit din ipader yun." (We have not been affected yet. (No potential to affect us. I know scoria fall deposit. It could be used for construction of walls.)* • Does not believe they will be affected by lahars: *"Lahar? Wala dito." (Lahar, there is no threat here.)* (DOST-PHIVOLCS hazard map shows that the shoreline portion of	• Have not experienced a major eruption at Taal. While he mentioned the smell of sulfur during the 1970's eruption, his response "*I just can't remember*" negates his positive response. • They did not evacuate because nobody told them to evacuate. •	• Also, mentioned that radio and tv were not yet popular so the information they receive is delayed. • He has very limited personal experience of an eruption but when ask how would he get information about impending eruption, he equally prioritised personal experience/visual signs with getting in touch with MDRRMO. He said "*magmamatyag muna*" (*will wait and see*) prior to evacuation. Visual signs like eruption columns, ballistic projectiles, etc. will only be observed during ongoing eruption. Being the barangay captain of his community, a 'wait and see' attitude may cause loss of lives, especially for parts of his community close to the shoreline that has been identified as prone to base surge.	• Asked to describe life in his community, he said he was generally happy but sometimes displeased with the problems in the barangay, mostly not volcano related like flooding. • Issue of poor memory about events related to volcanic crisis. • While he prioritised local DRRMO as #1 and DOST-PHIVOLCS as #2 for source of information to base his decision on evacuation, he also mentioned gut feelings as #3 source for decision making. • Decision to leave permanently tied to the intensity of the eruption: if the eruption is as big as the 1991 eruption of Pinatubo, they will leave-- "*E pagka talagang gaya sa Pinatubo noon,*

		their community is exposed to base surge hazard.) • Lahars are also not identified as a threat. • While aware that a neighboring sitio from another barangay is threatened by tsunami, not aware that shoreline areas of his community is also threatened. • Elder have not relayed stories of past eruptions. No oral histories or legends, absence of inherited memory. Other research shows oral histories are important for transferring knowledge about hazards.		• He mentioned that their evacuation depended on the severity of the eruption. Considering his lack of experience, who will determine severity? With his knowledge of information and warning protocol, it is hoped that he will follow decisions of higher local authorities that would most likely come from DOST-PHIVOLCS. • BDRRM Plans and committees exist but from the few chats I had with residents of the same community, they do not have knowledge of any volcano emergency preparedness. • Never conducted an actual drill yet he still believes they are ready- *"Sa totoo lang, wala pa, hindi pa. Pero handa na."* (In truth, we still have not done it.)	*alangan hindi ka umalis pero sa ngayon nama'y wala pa. ayoko umaalis". (If it's as big as the Pinatubo eruption, of course we will leave but at this point, it's not happening yet.)* For him to know if the eruption will be big means the eruption is already ongoing and evacuation action may be too late.
GE05/#5	***Positive:*** • Completed a college degree *"College po. BS Chem po tapos dine ako napasok".(BS Chemistry and then entered this profession.)* • Attended DRR related seminars.	• Know they may be affected by PDC: *"Opo, abot ng surge. Abot daw ho nung nag seminar kami noon eh." (Yes, base surge can affect us. Base surge can reach this place based on the seminar I attended before.)* • Know they can be affected by ashfall: *"Abo, oo." (Yes, ash.)* • Familiar with the tsunami in Japan in 2011 • While she had no experience of an	• Have not experienced an eruption; was only 5-6 years old during the minor eruptions of Taal in 1976 & 1977.	• Showed concern and provided monitoring of situation when they had false eruption warning. Barangay staff stayed overnight in the barangay office to monitor sitios of their community close to the shoreline and await word from CDRRMO -*"kaya kami kinabukasan na umuwi. Sinecure namin itong baybay dagat" (So we went home the next day. We made sure we monitor the lake shore areas)*.When asked where they would get volcano information-	• Lived in their community since birth. • Third term (maximum term of a barangay captain), almost 9 years, implies that the residents of their community have full trust & confidence in their community leader. • Active in social/cultural/ religious activities in the community. • *"Masaya, tulong tulog" (Happy in the*

		eruption, she remembered the information she gathered from the seminar on volcanic hazards she attended (“*abot daw ho nung nag seminar kami noon eh*”); Based on DOST-PHIVOLCS hazard maps, she correctly identified PDC and tephra fall as hazards that may affect their community.			responded that “*Yung una sabi nila ibabato sa City*” (*They said the information will be sent to the City Office*) • Showed interest (not sure if it was because of our interview) in having training/ seminar and coordinating with DOST-PHIVOLCS/LGU Our interview was conducted in November 2015 but as far as I know, no such request was received by our office. • Have identified initial evacuation area (covered court and chapel) which will be the pick-up area if volcano condition worsens & they need to evacuate further from the volcano. • They will be responsible for the transport of residents to town proper which is further away from the volcano.	*community; people help one another*)
GE05/#5	***Negative:*** • While knowledgeable about what a tsunami looks like, BC not familiar with generators of tsunami, and difference between tectonic/earthquake-generated and volcano-related tsunami. • Not knowledgeable about volcanoes and precursors to	• While BC mentioned ‘storm surge’ (meteorological hazard) as potentially reaching their place, she is not certain if a tsunami is a threat in their community; same with lahars when their community has volcanic slopes that may be eroded and remobilised during high precipitation. • Admit to not having enough knowledge	• Never experienced an eruption, was only told that an eruption occurred when they were not born yet, that a whole barangay was buried because of that eruption While a lot of parents have experienced the 1965 eruption of Taal, there seemed to be a general lack of knowledge transfer and absence of detail of the eruption on the inherited memories of offspring.	• While honest & admitted absence of knowledge about Alert Levels, this is not acceptable considering her position as the barangay captain. • They have no volcano contingency plans. BC was in office for 8 years already. • Will rely on LGU for instructions/ action on what to do when DOST-PHIVOLCS issues eruption warning information Placed this as negative because too much reliance on	• Respondent still did not have an idea where in the town proper near local government office they will be evacuating to if condition worsens --(“*Di ko lang alam kung anong barangay, pag yun talagang matindi na pero pag yang mga ganyan, pipick-upin namin dito, may list sila*”) (*I’m not sure which barangay we are going if the condition worsens but if it is not so*

	eruption considering she is a college graduate and mentioned she attended volcano-related seminars. "*Ang basis ng pagputok ng bulkan ay lindol?*" (*The reason why we have volcanic eruptions is the occurrence of earthquake?*)	about volcanoes-"*Oo pero hindi ganun ang knowledge ko sa bulkan syempre.*"(*Yes but my knowledge about volcanoes is very little.*) This statement is indeed worrisome. The fact that they are close to the volcano, and considering the history of Tanauan City (the town residents who survived the AD1754 eruption opted to move further away- to the current location of Tanauan).		LGU might mean their actions might be too late, especially if there is failure in communication. • while they have identified church bells as one way to inform the residents of the volcano emergencies, resident still do not know the warning signals. • Knows only that they will go to the town proper if things get worse, but until our interview, not aware where exactly are the residents going to be evacuated: "*Di ko lang alam kung anong barangay, pag yun talagang matindi na pero pag yang mga ganyan, pipick-upin namin dito. May list sila*"). (*I'm not sure which barangay we are going if the condition worsens but if it is not so strong, we will pick up them up here. They have a list.*) • No coordination with their school DRR coordinators when they are part of the community. • When I asked if the drill conducted by the school is earthquake drill or volcano related activities, here response was: "*Siguro parang, hindi ko alam eh.*" (*I think so, I'm not sure.*) Schools are part of BDRRM system.	*strong, we will pick up them up here, and they have a list.*) • On the issue of moving if the government offers alternative housing and livelihood, the respondent said "*Magbibigay? Di naman ganun ka-sustainable ang ibibigay…*" (*They will provide? Usually, the ones given are not that sustainable…*) • Even if severely affected by an eruption, will return- "*Ah bumalik. Kalimitan naman ganon…*" (*Will return. That's usually the case...*)
GE06/#6	***Positive:*** • Attended DRR related trainings and	• *Identified ashfall: "Abo laang ang nakarating dito." (Only ash reaches our area.)*	• While the respondent does not recognise base surge, his description of	"Have strong confidence in their Mayor related to promptness in relaying	• Residents, including parents and relatives of BC knows that going to

- seminars so expected to be knowledgeable and prepared.
- Was barangay councilor for 11 years before being a barangay captain (1st term of 3 years).

Assume to provide experience in handling DRR crisis.

the event confirmed its occurrence:

"Yun e parang ugong, parang sirena, malakas ang ugong. Tapos ang nararamdaman mo laang ay lagabok tapos sumabay na yung mga gabok. Syempre yung mga matatanda naman noong araw takot na takot." (Yes, the rumbling sound is similar to a siren and it was very loud. Then we just heard noise and felt dry earth and can see that ash fall is depositing. Our elders were very scare then.)

- the tephra was described as fine sandy texture and thickness about one "*dangkal*" (*distance between the tip of a man's thumb and the tip of his little finger when the hand is spread out, more or less 6 inches*).
- Tephra was described as dry but then it subsequently rained and resulted in severe damage to poorly built houses.

Loading of tephra increases when they are wet.

- Observed unusual 'animal behaviour' - different kinds of birds were seen close to their

DRR warnings, have direct contact with DOST-PHIVOLCS.

DOST-PHIVOLCS conducted several coordination with barangay officials for volcano related community activities & provided the contact information.

- Know protocol community action for alert levels (2- wait and prepare; 3- evacuation).
- Have BDRRM emergency committees and have warning system in place (have siren in the BH), and have tested it during Typhoon Glenda (July 2014).
- Each '*tanod*' (sergeant-at-arms) and councilor have their own areas to cover when warnings are to be disseminated.
- Along with various seminars and training on different hazards, they are the one who conducted a drill with tanods (sergeant-at-arms), kagawad (councillors) and police in 2014 conducted by the municipal office but with no residents:

"Nagtraining na ho rin kami noon kasama mga tanod namin. Oo dahil kami naman minsan ho, e sinasanay din kaming DENR, sinasanay

higher places provides safety.

Issue of inherited memories

- Will return even if his place is severely affected because he wants to protect his community:

hindi maaaring hindi kami babalik dito, gaya namin punong barangay natural laang poprotektahan ko ang aking nasasakupang barangay." (I need to return because as head of the community, it is natural for me to go back to my place and protect my barangay.)

Issue of concern for constituents & attachment to place

- Live in their community since birth, active in social/cultural/ religious activities in the community.
- Action passed on from the elders/ grandparents who have experienced past eruption of Taal (likely AD1911):

"Oho naman, oho. Nagkaroon ng abo. Ang ginawa po ng aming mga lola noon, mga ninuno namin noong araw, ang sabi ay mga nakaipon ang tubig so ang ginawa namin noon ay nag ipon ng tubig,

			community the day before the eruption, something that never happened before (TVI was one of the birds habitat). • Accurately remembered time of eruption (2AM). • His family evacuated to different places (Taal, Buson in Sta. Teresita located south)	*din dahil nga diyan sa pagputok na yan. Isang beses pa lang." (Yes, we already did it before together with my staff. Yes, sometimes the DENR also gives us trainings about volcanic eruption. Just once.)*	*mga inumin. Yung mga kulambo nung araw ay di naman gaya ngayon. Ang kulambo nung araw ay parang damit. Yun ay binasa siyang kinulambo sa amin para di makapasok ang gabok sa amin. Siyempre po naituro nila dahil sila'y naka-experience na noong una pang putok eh." (Yes, there was ash. Then our grandparents did what our ancestors taught us, store water for drinking. Our mosquito nets during those days are not like the ones bought now. They were fine like the texture of clothes. They (the mosquito nets) was soaked in water then covered around us so that ash would not be able to affect us. Of course, they taught us that because they have experienced it already since its first eruption* 'Inherited memories'
GE06/#6	***Negative:*** • High school graduate; 1 semester in college *"High School. Nag college, di naman naka isang sem eh."* (*High School. I have not finished my first semester in College.*)	• Does not think they will be affected by PDCs & believe that they are only threatened by ashfall and no tsunami. *"Dito pa lang ho sa amin ay abo. Abo laang ang nakarating dito." (In our place, it is only ash. Only ash reaches our area.)* Their MH is along the shoreline & their BH is very close to the MH.	• Was 10 years old during the 1965 eruption: *"Nakaranas na ho. Yung 1965. Maliit pa ko." (I experienced the 1965 eruption. was very young back then)* • Warning about the eruption came from neighbours, uncle and brother who lives close to the shoreline. 'Social network'/'shadow network' • Tephra fall was described as not	• While he believes they can be affected by an eruption, he thinks they are far enough from the volcano to be immediately and directly be affected (Considering the fact that San Nicolas, formerly the town of Taal that was devastated by the AD1754 eruption by base surge and tsunami, likewise affected by the same events during the 1911 and 1965 eruptions, this is a major flaw	• Strong belief in the power of prayers being able to keep them from harm. Believed that the wind shift during the 1965 eruption was because of their prayers: *"Sabi nang matatanda, nandiyan kasi ang patron (reason why they were safe from the effects of theAD1965 eruption) kaya ganoon na lang ang debosyon ng mga taga-rito sa Poong Sta.Cruz." (The elders said it's because the Patron Saint is there, that is*

		• Believes ashfall may affect them: "Abo laang ang nakarating dito." *(Only ash reaches our area.)* • Do not believe lahar will affect them: *"Wala namang lahar dito." (There is no lahar threat.)* DOST-PHIVOLCS hazard maps show that their barangay is prone to PDC/BS, tsunami, tephra fall & lahar hazards.	significantly thick, thus their belief that the ash was drifted elsewhere because of the prayers of the elderly.	that needs to be addressed immediately) • No inventory of who have vehicles to help support transport of residents, he said if residents have vehicles, "*kanya-kanya ho silang lilikas*" (*People will evacuate on their own- to each his own*) • While there was mention of potential evacuation sites, the fact as to where the actual sites are was not yet verified at the time of the interview: *"Diyan po sa school, yung pag talaga hong matindi na, lilikas na talaga sa mataas na lugar. Maghihintay na lang po kami ng go signal ng kung pupunta kaming Taal, kung pupunta kaming Calaca. Ngayon e parang ang tinatarget nila eh ang Nasugbu." (There, in the school. But in the event that the eruption escalates, we will move them to higher place. We will just wait for a go signal to where we will go, if in Taal or in Calaca. Right now, they are targeting Nasugbu.)*	*why everyone in the community is devoted to the Patron Saint Sta. Cruz.)* • Reasons provided why he will not opt for alternative housing and livelihood to a safer place is that his family and friends are there, does not want to leave his home and properties, and he does not believe the government can provide this option. Issue of ttachment to place
GE07/#7	***Positive:*** • No responses that could be considered positive related to education; no additional DRR related trainings attended.	• He knew the last eruption prior to the 1965 was in 1911; knows they can be affected by PDCs *"Maaapektuhan po tayo dito. Aba'y syempre ho!" (Yes, we will really be affected here. Of course!)*; tephra fall *"Meron nyan."* (Yes, there is); lahars &	• Accurately remembered the 1965 eruption was around 2AM; remembered that they packed & evacuated when the eruption was already ongoing because he remembered seeing incandescent materials -	• Know that volcano information & warning should come from DOST-DOST-PHIVOLCS through their MDRRMO. • Have at least identified the barangay chapel as assembly point for people and have identified the	•Was not able to extract any important responses that will serve positive response.

tsunami: *"Ang nakakatakot eh yung nasa tabi lang na yun (pointing to the shoreline) dahil syempre pag sumulong nga yung lake eh apektado sila." (It's really frightening especially our nearby lakeshore areas because if the lake water moves towards the shores, they will be affected)*	*"Kitang kita ko na apoy na eh, maapoy na eh" (I saw incandescent materials!)* • Also observed a very black ash plume right on top of the vent as seen from the 2nd floor window of their house prior to evacuation. • Immediately evacuated to Lemery (further SW) because they had their own vehicle. They experienced the ashfall in Lemery. • When they returned to their community, they had to clean their roof to remove 3 cm of fine sand & ash	church bells as part of the warning system

	Negative: • High school *"High school graduate lang po" (High school graduate only)*		• Was in Grade 3 (~10 years old) during the 1965 eruption so does not remember much. • Thought the eruption occurred on 11 September (poor memory) & admits he was too young to know if warning was provided by authorities. Only remembers warning came from his cousin.	• Not aware if they have BDRRM/ Contingency Plans for volcanic eruption. *"Parang wala pa ho ako dahil bagong kapitan palang ho ako dito eh." (It seems like I don't have one yet as I'm just a new captain here)* While I was able to acquire a BDRRM Plan for his barangay dated 2012, at the time of the interview in 2015, no updated information was available and BC was not sure if the document exists. He replaced the BC after he died. • Not proactive with DRR related activities; do not know where they are going if they have to evacuate the barangay in the event the eruptive activity gets worse. • While aware of the hazards, no volcano-related drills were held prior to my interview. • On the decision to evacuate, BC will 'wait and see' -"*Sa kasanayan po namin kung kailan na rin talaga na nakikita na pumuputok na ang bulkan*" (*Based on our experience, we only evacuate when we see the volcano is already erupting.*) • Even at the point of interview, he does not know where they should go, and did not even consider going towards Lemery (as his family did in 1965) until I raised the issue.	• Explanation for absence of warning or any notification of evacuation- *"dahil ang ganyan po ay kanya-kanyang likas na eh, nabibigla din ng putok ang mga tao. Syempre yan magkakanya kanya na rin yan dahil may mga pamilya rin yan eh na ililikas nila eh kaya ganun…"* *(People evacuated on their own because of course they were shocked by the eruption. Of course, they (the authorities) would be expected to also think about the safety of their families and take care of their evacuation to safety…)* • When ask about arrangements made with local authorities on provision of vehicles during evacuation, his response was *"Yun ang di ko pa nga naitanong sa kanila dahil ang pinag-usapan lang sa oras ng mga disaster kung anong gagawin ditong evacuation"* (*We have not yet asked them about that because we only discussed what we will do when there's disaster and the evacuation that will be done.*) • No fixed arrangements on where their barangay will be evacuated in the event that the condition of Taal worsens.

				• On the issue of preparedness plan, while we were able to obtain a BDRRM Plan dated 2012, no updated version is available. He just mentioned: "*Ang alam ko lang na paghahanda, syempre kami ay umaasa pa rin sa munisipyo para kung saan nga kami pwedeng pumunta*" (*The only preparedness I know is consultation with municipal authorities on where we are going*.)	• Poor attendance to barangay assemblies where DRR information are also relayed to residents; some are forced to attend-like 4Ps beneficiaries (Pantawid Pamilyang Pilipino Program-a conditional cash transfer program of the Philippine Government to eradicate extreme poverty)-"*pag di kayo umattend, di kayo pipirmahan*", "*e di naka 100% naman na naattend*" (*If you don't attend, we won't sign your documents, then we get 100% attendance*)
GE08/#8	***Positive:*** Remembers information from DRR trainings.	• When asked if they will directly be affected by volcanic hazards if an eruption occurs again, he said: *"Ay lahat po! napakalaking apektado!"* (*Yes, all hazard! We will greatly be affected*!). • Aware that there is potential for all volcanic hazards to affect them because they are at TVI: PDCs, tephra fall & lahars- "*Lalo na po ang lahar. Pag*	• Respondent described series of felt earthquakes, geysering at MCL & fissuring in 1991 prior to ashfall from the Pinatubo eruption. Beginning March to July 1991, Taal also showed signs of unrest coincident with Pinatubo activity. Earthquakes up to 45 per day w/ some felt at TVI & intense bubbling at MCL; geysering at NNE wall of MCL w/ temp. ranging from 97-100°C; more steaming vents formed	• Familiar with Volcano Alert Levels & standard LGU actions: *"Ang PHIVOLCS ay talagang alerto na nagbibigay po talaga pagdating po ng Level 2, ang mga yan nagbibigay ng babala na maghanda na."* *(PHIVOLCS is really very alert in giving warning information. When its Level 2, they give warning to prepare for evacuation)* • Respondent mentioned direct contact with DOST-PHIVOLCS or the LGU for accurate volcano information during emergencies & the information they will obtain	• Have high regard for their Talisay Mayor, Gerry Natanauan, popularly known as GDN and totally believe that his Office will prioritise their barangay for evacuation away from TVI (Issue of trust) • When I raised the issue that MRDDMO might forget, he firmly said *"Ay nako hindi po mangyayari yun"* (*No, that will not happen*); • While reliance and trust in government is good, too much dependence on

		umagos yang lahar sigurado!" (Especially lahars. When lahar flows are initiated, we will be affected for sure!)	due to fissuring along thermal area); • He remembered DOST-PHIVOLCS provided warning during the 1991 unrest of Taal; they evacuated to San Nicolas (mainland) before PV erupted.	will be the basis for their actions • Have identified 4 pickup points (Tourism Office, in front of the house of the barangay captain, chapel and ES). • They have (2) "*batingtings*" (bells) installed by the Taal Volcano Protected Landscape, an office (TVPL) of DENR & when these bells are rang continuously, people should assemble in the 4 designated pick-up points; Talisay Central School at the back of the Municipal Hall identified as evacuation site for the barangay; while he said most would wait and see, • He maintains that at Alert 2, they will be preparing for evacuation (and they expect DOST-PHIVOLCS will be going around TVI to warn people) but at Alert 3 they will evacuate from TVI and will not wait for DOST-PHIVOLCS to give them warning.	them could result in complacency and inaction and panic when the expected help is not delivered. However, the fact that they have made an inventory of 100 more boats ready to be deployed means that they have alternative action.
GE08/#8	***Negative:*** • High school graduate only.	• Not very sure about tsunami even though he knows what a tsunami is, thinks Taal Lake too small to generate a tsunami.	• Born in 1966 so too young to remember the 1966 to 1970 eruptions and the minor phreatic eruptions in 1976 & 1977.	• When asked if they have conducted a volcanic drill, the response was: *"Oo, alam ang gagawin. Kahit maam, kahit nagsanay ang tao lalo lalaki pag nangyari po eh lasing na lasing tulog*	• While the respondent jokingly said he will take the offer of housing and livelihood further away from Taal, he still insisted he will stay at TVI because life is good there- both in terms of

		"Delikado yan. Sabagay, dito naman ay walang tsunami dahil napakaliit ng dagat natin eh." *(Yes, that is really dangerous. Anyway, here, there will be no tsunami since our lake is so small.)* Even with attendance to DRR trainings which includes lectures and hands-on workshop on map understanding & contingency planning, BC still does not know there were historical tsunami events during the past eruptions of Taal.		*e di mas maganda pa po na hindi nagsanay na nakahanda naman sa pangyayari, mas maganda po yung alam nya ang gagawin" (Yes, we know what we need to do. However, even if we have drills, especially the males, if they are drunk and fall asleep? Better those who have not done drills but are prepared for any event… better that he knows what he needs to do)* • He further commented: "Ang ganyan po ay kanya-kanyang likas na eh. Nabibigla din ng putok ang mga tao. Syempre yan magkakanya kanya na rin yan (the authorities) dahil may mga pamilya rin yan eh, na ililikas nila eh kaya ganoon." *(In those situations, people evacuate on their own because of course they were shocked by the eruption. Of course, they (the authorities) would also think about the safety of their families and will take them to safety.)*	livelihood and the community. • Male members return to TVI even at the risk of being caught during an eruption-"*Sinasabayan po kasi ng magnanakaw yan eh pag umalis ang may ari" (Thieves usually take the opportunity to steal when owners leave TVI to evacuate.)* • Non-participation of residents in preparedness activities: *"Ngayon nga po medyo lumalakas pa mga loob ng mga taga-rito eh. Nung una pong pumutok ang bulkan, walang banka e ngayon po e halos tigi-tigisa na kayang kaya na po ang mga tao. Kampante po sila." (At present, with most families having their own boats, they have become more daring/fearless and feel they can easily leave when the time comes, unlike before when there were not enough boats. They have become complacent.)*
GE09/#9	***Positive:*** • Postgraduate degree holder *"Oo, Nakatapos ng kolehiyo. Doktor po, Doctor of Medicine" (Yes, finished college. Doctor of Medicine)*	• Know what PDC looks like and that they may be affected: • Have correctly identified threat of ashfall in their community *"Ay, di abo na lang, siguro ash na lang." (I*	• During the AD1965 eruption, he was told stories by evacuees from Agoncillo who moved to a school in their community that they observed live fishes swimming to the edge of the shores of Taal Lake	• Know that eruption warning information will come from DOST-PHIVOLCS but go through the LGU channels.	No positive data.

		think we can be affected by ash only)	because the water was hot. The observation was noted 2 weeks before the eruption. • The respondent only experienced ashfall in their community during that eruption.		
	Negative: • Admits needs more training to handle volcano related emergencies • Does not know basic information on volcanoes considering proximity to Taal and the eruption history of their town	• Do not perceive any major risk from volcanic eruptions except possible occurrence of ashfall. • Being in the medical profession, I would have thought he himself would have raised the issue of the health hazard due to long term exposure to ash, and infrastructure hazard related to ash loading. I had to provide some basic information on possible ash-related hazards.	• He does not remember the 1965 eruption even though he was about 14 during that time	• No preparedness plans for volcano emergencies: *"Wala kami, parang baha lang dito eh. Dahil nakaranas na kami dito eh." (We have none. It is always flooding that we frequently experience.)* • No movement outside Bauan; no existing alarm system & no existing BDRRM committees	•Problem of flooding more important because it frequently happens to them. Challenges that impede volcano related DRR activities •Have very strong faith in God, to the point that they entrust their safety to him; must have strong respect for church leaders
GE10/#10	***Positive:*** Recipient of volcano-related seminars/ trainings	• Asked if they will be directly affected by an eruption & which hazard might impact their community, he identified PDC- *"Ah yung matitigas po sa San Nicolas? Ahh, yun! Opo. Tingin ko po." (The ones that are hard in San Nicolas? Oh, that one! Yes, I think so.)*; tephra fall and lava/ballistic:	• The respondent experienced the AD1976 OR AD1977 eruption but was still too young to remember details of the eruption. • Remembers DOST-PHIVOLCS going around the island warning residents after a series of earthquakes felt in the island. He said his family	• Communities in at TVI generally follow evacuation orders because their elders say Taal eruptions always happen at night, and so many died during those eruptions. (Inherited memories). So now, they do not want that to happen to them. Very much aware of the hazards, so much so that when warning and order for evacuation is	• Have direct contact with DOST-PHIVOLCS personnel for but also know that information will be relayed to their MDRRMO who in turn will give the warning information to them. • Said that if provided with housing and livelihood, they will move but emphasises that without livelihood it will be useless to move.

		"Maaapektuhan po tayo dito. Aba'y syempre ho!" (We will really be affected here) (Yes, we can be affected here. Of course!). Identified most of the hazards except lahars. • He will base his decision on the issue of evacuation on information gathered from the authorities. Formal source of information	evacuated during the AD1976 or AD1977 eruption (not sure which one). • He also experienced ashfall from Pinatubo.	given, they will follow immediately: *"Aba'y lilikas na lang ako bago mamatay!"* (I will evacuate before I die!) and further added: *"E kasi po, sa ngayon po kaya po lumilikas na kaagad, nadala na daw po sila nung unang nangyari dahil yun daw naman po ay gabi kung pumutok e. ang dami daw po nun namatay." (Now, people immediately evacuate because they (the elderly) do not want to experience what happened during past eruptions that usually occur at night* (possibly the 1965). *A lot of people died.)* • Have assigned boats for particular areas but still expect their municipal office to provide boats for them. • Their Bulletin Board post "what to bring"; have 2 bells located in the Barangay Court and the Barangay Captain's house for their alert system; • Know what to do- evacuate to the mainland and travel by tricycle to their municipal office **but they do not know which particular school they are going.**	Livelihood on the issue of relocation • Cited the story of his elders about the 1965 eruption & emphasised on how traumatic the event was for his parents and relatives. *"Pero yung mga kinukwento sa amin sadya daw hong nakakatakot ang putok ng bulkan, yun daw pong di nakaka-experience pa ay baka sabihin gusto nila pero pag ka nakaranas na ay naku baka daw ho isumpa na lang yung pangyayari"* (*The stories our elders told us was that the eruptions were frightening… those who have not experienced an eruption would say they want to experience one, but if they have experienced what we experienced during the eruption having said that*). Issue of inherited memories
	Negative: • *High School lang po.* (High school only) • Not the barangay captain but the 1st	• Believe they are not exposed to tsunami threat.	• Was still too young to remember details of the 1976 and 1977 eruptions.	• Other than his complete trust in their MDRRMO to provide boats to ferry them to the mainland (which may not happen), I found no negative	• No additional data that might be considered negative.

	Barangay Kagawad or Councilor- the next in rank and acting Barangay Captain when BC is away. Frequent absence of BC was confirmed by residents as being very often. I myself have personal experience of his absence whenever I visited TVI and tried to set up an interview with the BC three times but the BC was always in the Mainland especially during the months before the election on May 2016.So I decided to interview the 1st Councilor.		data on the issue of taking risk seriously. • Confident that they are prepared just because they have boats available in the island "*Oo, may sariling sasakyan na naman*" (*Yes, we have our own boats*). • Mostly his confidence stems from individual preparedness, not community preparedness. • They do not have contingency plans to move further away if the condition at Taal gets worse and impacted areas become bigger especially if it reached Calangay.