Managing Volcanic Hazards: An Actor-Network of Technology and Communication

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Abstract

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The scientific and socio-political dimensions of volcanic hazards have been realigned since the eruption of Eyjafjallajökull in 2010, and have highlighted the need for volcanic activity to be studied from interdisciplinary perspectives. By focussing on communication, adaptability and resilience, this research explains the links between hazard management and social constructivism. The research question asks how Iceland's networked approach to managing volcanoes can be understood by analysing the development of communication channels between human stakeholders and non-human technical devices and systems. Fieldwork was conducted in both Iceland and the UK, and a mixed methods approach was used to engage with the network. Research methods consisted of semi-structured interviews, participant observations and archival research.

Findings explain the evolution of knowledge exchange, the value of technical innovation, and the need for interactions between local, national and international stakeholders. The study concludes that actors are increasingly empowered by the use of participatory technologies within hazard management, and the development of collaborative engagements between stakeholder communities from scientific and socio-political backgrounds. This research is relevant as it illustrates how the adaptive capacity of hazard networks can be expanded, potentially influencing the approaches that are taken to manage volcanic hazards in less economically developed contexts. In addition, this study can encourage continued interaction between scientists, at-risk communities and the aviation industry in multi-hazard environments such as Iceland.

Keywords: Actor-Network, Communication, Co-production, Information, Resilience, Translation

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List of Acronyms and Translations

ANT: Actor-Network Theory

AT: Assemblage Theory

ATC: Air Traffic Control

AVOID: Airborne Volcanic Object Identifier and Detector

BGS: British Geological Survey

CAA: Civil Aviation Authority (UK)

COBR: Cabinet Office Briefing Room

CP: Civil Protection (Iceland)

DfT: Department for Transport

EASA: European Aviation Safety Agency

ERCC: Emergency Response Coordination Centre

FMI: Finnish Meteorological Institute

Höfn: Höfn í Hornafirði

ICAO: International Civil Aviation Organization

ICE-SAR: Icelandic Association for Search and Rescue

IMO: Icelandic Meteorological Office

Isavia: Icelandic Aviation Service

LIDAR: Light Detection and Ranging

London VAAC: London Volcanic Ash Advisory Centre

MOCCA: Meteorological Office Civil Contingencies Aircraft

NAME: Numerical Atmospheric-dispersion Modelling Environment

NASA: National Aeronautics and Space Administration

NERC: Natural Environment Research Council

NHP: Natural Hazards Partnership

NILU: Norwegian Institute for Air Research

SAGE: Scientific Advisory Group for Emergencies

SCOT: Social Construction of Technology

SIGMET: Significant Meteorological Information

SSK: Sociology of Scientific Knowledge

STREVA: Strengthening Resilience in Volcanic Areas

STS: Science and Technology Studies

TRL: Technology Readiness Level(s)

UoI: University of Iceland

USGS: United States Geological Survey

VALS: Volcano Alert Level System

VAORG: Volcanic Ash Observations Review Group

VAR: Volcanic Ash Reports

VEI: Volcanic Explosively Index

Vík: Vík í Mýrdal

VolcIce: VOLcanic ash exercise in ICEland

WOVOdat: World Organization of Volcano Observatories

List of Icelandic translations

Department of Civil Protection: Almannavarnir

Environment Agency of Iceland: Umhverfisstofnun

Icelandic Association for Search and Rescue: Slysavarnarfélagið Landsbjörg

Icelandic Met Office: Veðurstofa Íslands

Icelandic Police: Lögreglan

Icelandic Red Cross: Rauði krossinn

Laki: Lakagígar

University of Iceland: Háskóli Íslands

Disaster risk reduction needs theory in order to make sense of apparently chaotic events. In effect, theory is the road map of mitigation, response and recovery.

David E. Alexander

Chapter One: Introducing the research

Hazard management can increasingly be defined by networked infrastructures, both within and beyond affected regions. Networked infrastructures consist of dynamic and interwoven channels of communication and resources (Graham and Marvin, 2001); their design and flexibility are integral to explaining stakeholder connections, and this has been illustrated in a natural hazards context by leading scientific institutions connecting with stakeholder communities from socio-political backgrounds. This thesis argues that the management of volcanic hazards can be studied from the perspective of networked infrastructures; for example, in Europe and North America, sophisticated networks of communication can exist in areas where volcanic activity both originates and impacts. These networks include the services and programs of the United States Geological Survey, and Iceland's approach to managing volcanic hazards.

Infrastructures were transformed following three major volcanic eruptions in Iceland between 2010 and 2014. The first of these eruptions, Eyjafjallajökull in April 2010, exposed the fragility of socio-political systems to Icelandic volcanism. For instance, the susceptibility of the aviation community illustrated the extent to which volcanic activity remained understudied (Miller and Casadevall, 2000; Donovan and Oppenheimer, 2012). The notoriety of the 2010 eruption undoubtedly influenced the deployment of a more flexible approach to hazard management (Eiser *et al.*, 2015), evident in the heightened sense of alert to the Grímsvötn (2011) and Bárðarbunga (2014-2015) eruptions. Following these tumultuous events, the intertwining of knowledge in the physical and social sciences has become integral to improving socio-economic resilience.

Therefore, a greater volume of research needs to approach hazard management from interdisciplinary perspectives. Volcanic events in Iceland have led to the construction of a networked infrastructure that can resonate with sociology. Iceland is a unique and multi-hazard environment, and it requires a network of communication that emerges from the interrelationship between science, society and technology (Donovan and Oppenheimer, 2015; Loughlin *et al.*, 2015). This PhD research is predicated on this constructivist approach to volcanic hazard management, and multiple theoretical frameworks are used to interpret socially embedded understandings of Iceland's networked infrastructure. This introductory chapter illustrates the authenticity of the research by outlining the relevant subject areas of interest, and highlighting the approaches that academics have previously used to study volcanic hazard networks from sociological perspectives. The research question and rationale are then outlined before a brief overview of the thesis structure is provided.

1.1: Research background

Hazard networks are ideally configured to reduce the vulnerability of relevant publics, whilst maximising the efficiency of measures taken to mitigate risk. This thesis uses an interdisciplinary approach to address the subject areas of information management, science and society, hazard communication and systematic approaches to disaster risk reduction. From a theoretical perspective, both Actor-Network Theory (Latour, 1993; 2005; Law, 1992; 1999; Callon, 1999) and Co-production (Jasanoff, 2004; Whatmore, 2009; Lane *et al.*, 2011; Landström *et al.*, 2011) are mobilised to explain the constructivist elements of hazard management. When analysing volcanic hazard networks in the context of the social sciences, previous research has tended to focus on either the impact of geoengineering and land management (Cutter and Zoback, 2013; Pierson e*t al.*, 2014), or the perceived contestation between science, technology and culture (Gaillard, 2008; Lavigne *et al.*, 2008; Mercer *et al.*, 2012; Mei *et al.*, 2013).

The research outlined in this thesis differs as it analyses a dynamic and evolving network, using sociological approaches to explain adaptability and resilience. Whilst not discrediting previous interpretations of hazard networks, this thesis seeks to cultivate a more interdisciplinary approach. For example, understandings of hazard management have rarely accounted for the dynamic evolution of the space or network within which a hazard is managed. In addition, there has been an inadequate focus on the importance of communication and the need for accessibility to increasingly autonomous and mobile technologies. In the context of volcanic hazards, Webersik *et al.* (2015), Leonard and Potter (2015) and Nayembil *et al.* (2016) renegotiated the relationship between science and society, enabling it to be perceived through collaboration and unity rather than conflict and contestation. However, this research is unique in that it not only penetrates a sophisticated and dynamic network such as Iceland, but does so through the lens of multiple sociological concepts. Constructivist narratives such as co-production have previously been applied to flood risk management (Jasanoff, 2004; Whatmore, 2009; Lane *et al.*, 2011; Landström *et al.*, 2011) and volcanic hazards (Donovan and Oppenheimer, 2015), but this thesis also draws comparisons with the application of Actor-Network Theory (Latour, 1993; 2005; Callon, 1999; Law, 2009a). The incorporation of both approaches into a field of research, traditionally dominated by the physical sciences, allows the thesis to analyse valuable connections and exchanges of knowledge between science and society. Theorising networks enables them to be approached by social scientists, and widens their scope of interpretation.

Unlike many previous explorations of hazard networks, this PhD research has a greater level of epistemic centrality; for example, the interdisciplinary premise encourages subjective analysis and critical discourse. This holistic approach to hazard management has stemmed from the researchers' past analysis of volcanic activity. For example, previous research has examined the visualisation and representation of natural hazards, specifically analysing how volcanic events and geological environments can be perceived and explained through art and the varied use of technology. Whilst the research documented in this thesis cannot be directly related, these past explorations built a cultural, interdisciplinary and humanistic perception of volcanic activity. Furthermore, the extraordinary impact of volcanic events such as the Eyjafjallajökull eruption, occurring during the years preceding this research, highlighted the neglect of sociology in studies of volcanic hazard management.

1.2: Research question

The dynamism of Iceland's networked infrastructure can be explored by analysing transitions in stakeholder communication, many of which were induced by the volcanic events between 2010 and 2014. For example, conscientious efforts were made to strengthen links between scientists and socio-political communities since the eruption of Eyjafjallajökull. Technical innovation has been essential to this process and has brought together aspects of both the physical and social sciences. In accordance with these transformations, this study provides responses to the following research question:

> **How may developing communications between human and non-human 'actors' be explored to theorise and manage a volcanic hazard network in Iceland?**

By not referring to the specific approaches discussed in this thesis (namely actor-networks and co-production), the research question is kept broad and acknowledges the diversity of 'actors' within hazard networks. In addition, the question refers to actors rather than monitoring and response agencies; this reflects the intention to rigorously deconstruct Iceland's network to the level of individual stakeholders, tools and components. Finally, this research question views hazard networks as processes that continually develop and evolve.

1.3: Research objectives and location

As this study adopts an interdisciplinary approach to interpret volcanic hazard management, the research question is supplemented by the following objectives:

> 1) To analyse the process through which a hazard network is furthered in its capability to mitigate risk by adapting the roles and positions of the actors within it.
>
> 2) To use Actor-Network Theory and co-production to speculate on the extent to which the development and effectiveness of hazard management can be attributed to technologies that are virtual and participatory.
>
> 3) To identify how the representation, mediation and negotiation of hazard knowledge can be explained through sociological narratives.

By adhering to these objectives, this PhD research can recognise the evolution of Iceland's hazard network and establish transformations in methods of communication. Furthermore, the interdisciplinary element of each objective reflects the extension of the study across multiple stakeholder communities.

However, the scope of this study is not necessarily reflective of the knowledge gap between science and society in other hazard networks; for example, the fieldwork focuses almost exclusively on Iceland, the UK and Europe. Therefore, the outcomes are likely to be largely irrelevant to less economically developed regions, where the use of innovative technology and the resilience of a network infrastructure is typically more constrained. Whilst the contextual focus on Iceland and the UK is potentially problematic, it is a direct result of economic and temporal constraints. An extensive overview of the fieldwork sites is provided in Chapter Three and the contextual setting is outlined at length in Chapter Four.

1.4: Rationale for conducting the research

This study of Iceland's network follows an interdisciplinary trend in hazard research, influenced by the work of Fearnley (2013), Donovan and Oppenheimer (2015) and Webersik *et al.* (2015). The value of this PhD research can be derived from its application of geographical knowledge and sociological theory. For example, this thesis theorises how stakeholders and institutions, attached to the physical sciences, can actively connect with communities from non-scientific backgrounds. This approach is relevant to hazard management as there is a universal need for the binaries of scientific and social knowledge to be mutually appreciated rather than resented (Tierney, 2012; Cvetkovich and Lofstedt, 2013). Furthermore, the interdisciplinary position of the research enables it to relate to a vast array of stakeholders in networks that are modelled on a similar trajectory to Iceland. This PhD research can consolidate post-structural perceptions of hazard networks and renegotiate conceptual understandings of adaptation and resilience.

Recent seismic activity has highlighted the geological, social and political sensitivities of hazard management in European contexts, with examples including the recurrent volcanic episodes in Iceland between 2010 and 2014, and the powerful earthquakes in Italy in 2009 and 2016 (Donovan and Oppenheimer, 2014a; Heiðarson *et al.*, 2014; De Marchi, 2015). This study is relevant as the risk posed to humanity by natural hazards remains both considerable and unsustainable. For example, the impact of the Eyjafjallajökull eruption on the aviation industry (Bonadonna, 2014; Parker, 2015) demonstrated the vulnerability of socio-economic systems and the need for continued expansion in interdisciplinary research. The importance of the study is highlighted by how it seeks to address these continuing concerns. Furthermore, the findings can be used for both academic and non-academic purposes; for example, they can influence how hazard management is taught, as well as explain how mitigation strategists and policymakers can negotiate knowledge.

Despite innovative technologies and the expansive outreach of scientific communities, volcanic activity continues to exhibit hazards that are unpredictable and unforeseen, even in the most sophisticated of networks. The rationale for choosing Iceland as a study site is based on the international notoriety it has gained from recent events, and the serious and cumulative threat posed to the aviation industry, both within and beyond Europe (Eiser *et al.*, 2015). This study expands on previous hazard research conducted in Iceland, primarily because it accepts that the management network is continually evolving. For example, the introduction of cross-sector initiatives, projects and task forces (Sigmundsson *et al.,* 2013a; Palma *et al.,* 2014; Hicks *et al.,* 2014) continue to provide windows through which the infrastructure of the network can be observed. Finally, Iceland allows this PhD research to trace how the technical age has redefined the structure of hazard management in Europe, analysing the impact of virtual and multimedia technologies on the communication process.

1.5: Thesis structure

The next section of the thesis presents a comprehensive literature review (see p.24), firstly addressing the precedent on which interdisciplinarity can be applied to hazard management. The review then ventures into sociology and explains both Actor-Network Theory and co-production by referring to the influential approaches of Bruno Latour (1993; 2005) and Sheila Jasanoff (2004; 2005) respectively. Chapter Three presents the methodology (see p.64) and explains the rationale for a mixed methods approach that consists of semi-structured interviews, participant observations and archival research. The fourth chapter then describes the context in which the study is carried out (see p.91); firstly, it alludes to the scientific and social dimensions of Icelandic volcanism, and then documents the attempts that have been made since Eyjafjallajökull to improve communication. The empirics consist of three chapters tailored to the subsidiary research questions (see p.63); Chapter Five is the most holistic as it analyses the power dynamics, channels of communication and collaborative practices within Iceland's network. Chapter Six then looks in considerable depth at the concept of scale and demonstrates how the use of technology has weakened the existence of boundaries between different stakeholder communities. Finally, Chapter Seven is more theoretically attuned, with an emphasis on the positionality of the actors and institutions that form Iceland's network; this chapter directly associates hazard management with various aspects of social theory.

Chapter Two: A review of volcanic hazards, Actor-Network Theory and co-production

This PhD research explains how knowledge is constructed and communicated within Iceland's hazard network. By studying knowledge exchange from a sociological perspective, this thesis presents a subjective analysis of the interconnections that bind stakeholder communities. The first section of this review assesses contemporary trends in hazard management, and highlights the relevance of technical infrastructures, networks and interdisciplinarity (Donovan, 2012; Barclay *et al.,* 2008; Loughlin *et al.*, 2015). The second section then introduces understandings of social constructivism and directly relates them to the subject matter, namely hazard networks. The third section of the review discusses theoretical interpretations of Actor-Network Theory (ANT), and accounts for how it has emerged as a prominent framework within the social sciences (Latour, 1993; 2005; 1996a; Law, 1999; 2002; Callon and Blackwell, 2007). Finally, the fourth section discusses co-production, and focuses primarily on the management and resolution of knowledge controversies (Jasanoff, 1996; 2004; Slovic, 2000; Whatmore, 2009; Landström *et al.*, 2011).

2.1: Transforming hazard and risk management: A sociological perspective

A succession of catastrophic events in recent decades, such as Hurricane Katrina in August 2005 (Schneider, 2005; Bankston *et al.*, 2010), the Haiti Earthquake in January 2010 (Bilham, 2010; Williams and Shephard, 2016), and Iceland's Eyjafjallajökull eruption in April 2010 (Guffanti *et al.*, 2012; Bonadonna, 2014;

Parker, 2015), appear to have instigated greater sociological research into extreme natural hazards. Each of the cases exposed the social and infrastructural weaknesses that continue to prevail in the management of meteorological and seismic hazards. Academics and strategists alike have taken the view that hazardous environments cannot be managed by scientists alone, largely because of the potential impacts on the sociological composition of a place or region. For example, De Marchi (2015) provides a rather critical commentary of scientists' limitations in forming and activating mitigation policies:

> The distinction between risk assessment and risk management was traditionally based on the pretended exclusively scientific nature of the former vs. the politically and value constrained character of the latter. Risk communication, the last phase of a linear process, was customarily devoted to correct the distorted perceptions of lay people, unable or unwilling to accept the verdict of the experts… An open discussion on the role of scientific inputs in policy decisions progressively became to be perceived as both legitimate and urgent. Moreover it was not limited to risk issues but moved across disciplinary fields and policy issues (De Marchi, 2015, p.150).

De Marchi accounts for a wholescale transformation in how hazard networks need to function; management practices require holism and need to expand beyond the realms of science. The sentiments referred to by De Marchi echo those of Blaikie *et al.* (2005) and Wachinger *et al.* (2013), emphasising the need for hazard networks to broaden communication and venture beyond disciplinary boundaries.

2.1.1: Performing hazard discourse through the construct of a network

Network infrastructures allow voices to be incorporated from more diverse backgrounds, and can be designed to enhance the interconnectedness of stakeholder groups (Paton and Johnston, 2006; Palliyaguru *et al.*, 2014). Whilst success is often dependant on the economic development and socio-political stability of a hazardous region, networks have previously demonstrated how communication can be enhanced and resilience can be improved. For example, Donovan and Oppenheimer imply that network infrastructures can strengthen connections between stakeholders, literary artefacts and technological devices:

> Models, methods, reports, laws, social, political and scientific networks are all linked through their collective role in managing an eruption (Donovan and Oppenheimer, 2015, p.156).

Writing in the context of Montserrat, Donovan and Oppenheimer refer to actors being united by their association with risk. Furthermore, the extract also draws attention to the weakening of boundaries and portrays a hazard network as a convergent space.

Therefore, academic literature acknowledges how a network can shape the inclusion of actors and stakeholder communities from non-scientific backgrounds. Whilst the involvement of socio-political stakeholders has previously been explained through socially constructed understandings of risk, exhibited in publications such as Beck's "Risk Society" (Beck, 2014, in Etkin, 2015), less attention has been attributed to the concept of a network aggregating communication channels by using technology. Infrastructure dynamics are relevant as hazard networks are messy and unpredictable, largely because their components are diverse and constantly evolving (Cronin *et al.*, 2004a). The longevity and resilience of any network configuration is undermined unless it can be adjusted in-situ (Blaikie *et al.*, 2005).

However, when explaining how hazard networks are reactive to changing compositions and demands, a greater emphasis should be placed on nodal points. These are positions at which communication channels intersect and agencies both provide and receive data (Mukherjee, 2014). The process of establishing and identifying nodal points is defined by Beech (2015):

> As hazard networks become more collaborative, the number of channels through which to communicate data and information expands. The network itself become so interconnected that nodes form… Data nodes are rarely stable and can be repositioned in response to crises or technical innovation (p.4).

As documented in the literature, nodal points can enhance the adaptation and resilience of communication channels within a network. The multiplicity of channels passing information through nodal junctures can safeguard against potential disconnects between stakeholders, agencies or technical devices (Doyle *et al.*, 2015). The nodal points within Iceland's hazard network are relevant to this PhD research as such positions can be indicative of decision-making power and network stability. This narrative reflects Cavallo and Ireland's (2014) views on the significance of power relations within networked infrastructures:

> Networked effects are very different to effects in hierarchical systems and generally follow power laws (Cavallo and Ireland, 2014, p.12).

Nodal points are significant to explaining and representing the configuration of hazard networks such as Iceland. Data nodes can be interpreted as being purposefully designed and constructed in a manner that allows appropriate information to be conveyed at the most critical points (Wang and Guo, 2012).

Previous research has tended to study data nodes in the relatively confined context of geospatial probability, primarily in relation to the occurrence of seismic risks in urban areas (Carreño *et al*., 2012). A broader view of nodes facilitating knowledge exchange across national and international levels of communication has rarely been touched on. In addition, when explaining the composition of nodes, academics have often been ambiguous or contradictory. For example, studies of wireless or algorithmic data (Pereira *et al*., 2014; Fernandez-Steeger *et al*., 2015) have referred to the presence and functioning of technical nodes such as "automatic sensor nodes" in "Environmental Sensor Networks" (Hart and Martinez, 2006, p.177). In contrast, other nodes are interpreted as individuals or institutions whose authority enables them to have nodal responsibilities (Patwardhan and Ajit, 2007; Samarajiva and Waidyanatha, 2009). Regardless of form, researchers appear to unanimously attribute value to nodes based on their consolidation, maintenance or adjustment of a network's infrastructure (Werner-Allen *et al.,* 2006; Zook *et al*., 2010). Nevertheless, there is a need for greater consistency in how nodes are interpreted; the performativity of a node not only provides a lens through which to grasp how a network operates, but also has the capacity to explain how stakeholder coordination can be better understood (Chen *et al*., 2008, in Bharosa *et al*., 2009, p.50).

The L'Aquila earthquake in Italy (2009) and the Eyjafjallajökull eruption in Iceland (2010) can both be viewed as seismic events that demonstrated nodal limitations within European networks. For example, the L'Aquila earthquake exposed the contentious failure to communicate adequate scientific information to the public (Alexander, 2014), whilst the Eyjafjallajökull eruption highlighted the breakdown of communication and the failure to ensure the correct protocol was followed (Bolic and Sivcev, 2012). However, Cavallo and Ireland relate mismanagement, inaction and mistrust to an inability to contend with uncertainty:

> Many institutions refuse to manage complex risks as they do not think to be able to cope with the complexity and uncertainty involved (Cavallo and Ireland, 2012, p.162).

In a similar manner to Cavallo and Ireland, academic literature explaining the L'Aquila earthquake has rarely questioned or analysed communication failures from nodal perspectives. The network designed to manage seismic hazards in the L'Aquila region had nodal characteristics, but these have only been studied in relation to data science (Cirella *et al.,* 2009; Marzocchi *et al.,* 2012) and the internal dynamics of civil protection centres in Italy (Alexander, 2010). Whilst uncertainty is likely to have played a significant role in the breakdown of communication, the broader failings that occurred at nodal junctures could be covered to a much greater extent. There is a need to consider nodes not only in the transient context of where data is aggregated or converged, but also in the holistic context of a broader network infrastructure.

Throughout this PhD research, the terms "institution" and "institutionalised" are defined as collective actuarial clusters with an in-built synergy to work together, and a legal or moral obligation to act (Cornelissen *et al.*, 2013; Fuenfschilling and Truffer, 2014). Selected examples include the Icelandic Association for Search and Rescue (ICE-SAR), the Icelandic Met Office (IMO) and the London Volcanic Ash Advisory Centre (London VAAC). This study assesses the extent to which the configuration of a hazard network is determined by the culture and power relations of institutional entities:

> Institutional theory attends to the deeper and more resilient aspects of social structure. It considers the processes by which structures, including schemas, rules, norms, and routines, become established as authoritative guidelines for social behavior. (Scott, 2005, p.460).

Recognising institutional theory allows this research to evaluate the impact of organisational structures on the management of volcanic hazards. Grossetti (2004) highlighted the commanding influence of institutions on the actions, communications and mobilisations of networks. By incorporating aspects of the social sciences, this thesis applies Grossetti's narrative to Iceland's hazard management community. However, this PhD research does not view institutions as superficial or rigidly bounded, but explores their complexity, outreach and evolutionary capabilities.

Institutional frameworks are actively deconstructed in this thesis so that the individual human and technical actors within them can be subjectively analysed. Many influential teachings of deconstruction, most notably those of Derrida, have strengthened post-structuralism by establishing difference in the meaning of language and text (Derrida, 1976; Derrida and Caputo, 1997). This research has applied deconstruction to hazard data, as well as to the mobility and characteristics of actors within complex entities such as the IMO and the London VAAC. Therefore, a deconstructive narrative is used to identify difference in the meanings and features of literary commands, oral interactions, human actors and uses of technology. Iceland's approach to hazard management spans various stakeholder communities, so deconstruction is valuable when applying and analysing aspects of social theory.

The continual evolution of Iceland's network means that its structure can be viewed as fragmented and contestable. Therefore, the complexity of the network is increasing as the actions of stakeholders and institutions are rarely predictable:

> In a complex system… the interaction among constituents of the system, and the interaction between the system and its environment, are of such a nature that the system as a whole cannot be fully understood simply by analysing its components (Cilliers, 1998 viii, in Florêncio, 2011, p.76).

Cilliers' quote highlights the need for network analysis to focus on the changing dynamics of stakeholder interactions. Volcanic hazard networks can generally be applied to this interpretation of complexity as many are not "strategically ordered" (Law, 1999). Furthermore, technology has also led to Iceland's network becoming increasingly complex; for example, stakeholder relations can be made sense of by recognising how participatory devices can further fragment the actions of communities and institutions (Pérez-González and Susam-Saraeva, 2012; Cupples and Glynn, 2014; Khorram-Manesh *et al.*, 2015).

2.1.2: The interdisciplinary expansion of hazard management

As academics have strived for greater interdisciplinarity, particularly since the end of the science wars and the beginning of the 21st century, closer collaboration between the sciences and the humanities has been encouraged (Ashman and Barringer, 2005), notably by C.P. Snow in the Rede Lecture titled 'The Two Cultures' (Snow, 1959). As a result, the scientific knowledge upon which understandings of natural hazards are predicted has also been transformed, a process that has been further aided by the flexibility of monitoring institutions and more techno-centric fieldwork practices. As interdisciplinary motions require the "integration of one or more academic disciplines" (Hoffmann *et al.*, 2013, p.1), research that has been conducted into the management of natural hazards has needed to realign itself by being more openly engaging, postmodern and post-structural (McEntire, 2007; Donovan and Oppenheimer *et al.*, 2012; Blaikie *et al.*, 2005). These approaches to hazard management are viewed in a positive manner by many academics:

> It is now relatively widely acknowledged that advances in volcanic risk reduction research are contingent on the integration of social and physical science based knowledge and approaches, and tailored communication methods (Hicks *et al.*, 2014, p.1871).

The extract alludes to a more balanced approach to hazard research, inclusive of knowledge from across several disciplines. The approaches of mitigation strategists therefore require effective and frequent communication between various stakeholder communities.

Understandings of hazard management have traditionally emerged from the sub-disciplines of the physical sciences (geology, physics, chemistry, etc.), but academics have instigated an expansion into epistemically softer subjects such as sociology, geopolitics and psychology. This transition in how hazards can be explained is evident in research related to risk communication:

> The key factors that led to the standardisation of the USGS (United States Geological Survey) VALS (Volcano Alert Level System) were only marginally related to the current scientific understanding of volcanic behaviour and hazards, and how to best represent these in a warning, and more driven, ultimately, by the social context of the post-9/ 11 U.S., which shaped the broader emergency management policy (Fearnley *et al.*, 2012, p.2031).

> Datasets (of monitoring data), like our understanding of the physical process, are incomplete and the resulting uncertainty requires a

> strong subjective element of judgement in the output information (Barclay *et al.*, 2008, p.165).

Whilst Fearnley *et al.* (2012) use a socio-political narrative to explain what has influenced the standardisation of risk, Barclay *et al.* (2008) refer to the relevance of subjectivity. Both extracts therefore demonstrate links to sociology by exploring and evaluating the representation of data and information. Standardisation allows for greater interdisciplinarity as it regulates communication practices in a manner that furthers knowledge and flattens disparities between stakeholder communities. For example, hazard knowledge becomes universally accessible and can be shared by actors from both scientific and socio-political backgrounds.

However, when analysing the VALS, Fearnley *et al.* (2012) also draw attention to the undermining of context in standardised representations:

> (Difficulties) relate to the simplification of what are complex volcanic events and systems, such that more targeted response efforts are hindered, but also to an accompanying shift away from the description (and explanation) of particular events towards a set of warning icons and words that lend themselves to very particular (that is, aviation) communities (Fearnley *et al.*, 2012, p.2024).

The lack of specificity and negation of context therefore counter the positive aspects of approaching hazard management from an interdisciplinary perspective. With considerable variance between the hazards experienced in many volcanic environments, the role that context plays cannot be ignored. Whilst transitions to virtual iconographies are enabling hazards to be communicated in real-time, there is a need to prevent environmental and socio-political factors from being overlooked (Timmermans and Epstein, 2010). If standardisation can be attributed to the emergence of increasingly geospatial technologies (Soto *et al.*, 2014), then sociological understandings of networks are required to preserve socio-cultural diversity.

Researchers have begun to associate hazard management with humanistic and environmental disciplines. The role of science within geophysical environments is not discredited, but needs to renegotiate its positionality and readjust to a more collaborative and interdisciplinary field of research (Bursik *et al.*, 2014; Palma *et al.*, 2014; Leonard and Potter, 2015). Furthermore, focussing on the construction and exchange of knowledge represents a movement away from neoclassical views of risk. Hazard networks gain interdisciplinarity by extending risk beyond prediction and probability, instead furthering a processual approach that can be explained through sociological frameworks such as ANT and co-production. Following such a profound overhaul, academic literature implies that natural hazards have also needed to be re-envisioned, with greater attention attributed to the context and circumstance in which an event takes place:

> Disciplinary and cultural differences play a key role in the negotiation of dialogue during crisis advice, even where methods are deployed to harmonise the scientific opinion (Donovan and Oppenheimer, 2014b, p.159).

Donovan and Oppenheimer draw attention to the significant expansion of the hazard research community. For example, the extract illustrates how knowledge of volcanic hazards should not be confined to the tectonic activity that underpins them, but should also recognise "disciplinary and cultural differences". This allows research to be carried out by urban planners, psychologists, policymakers, ethnographers and sociologists. A more holistic approach to hazard research is likely to reduce conflicts and facilitate dialogue that is transient across stakeholder communities (Aspinall *et al.*, 2002).

The relationship between hazard management and interdisciplinarity can be defined by a socio-cultural layering of natural hazards (Webersik *et al.*, 2015). Amongst academics, both meteorological and geophysical hazards are now rarely viewed as the outcome of solely atmospheric and subterranean processes respectively (Paton, 2006; Barclay *et al.*, 2008). The value of scientific evidence has not been degraded or become obsolete, but neither are its potentialities necessarily determined within laboratories or monitoring stations. Despite scientific knowledge continuing to form the precipice upon which actions are taken to mitigate risk, information needs to be compatible with socio-cultural interpretations. Science must have the capacity to co-exist in accordance with the characteristics and ethos of affected communities (Paton, 2006). This mediated depiction of a hazards monitoring and response process allows the advantages of an interdisciplinary interface to be clearly recognised (Barclay *et al.*, 2008; Donovan and Oppenheimer, 2014b). For example, academics tend to agree that such set-ups are of significant value to the eradication of "knowledge gaps"

(Meyer *et al.*, 2013, p.1365), minimising the potential for risk perception to be skewed because of cultural mistrust or alienation.

Disastrous events such as the Nevado del Ruiz catastrophe of 1985, when political ignorance shunned the legitimacy of scientific evidence (Naranjo *et al.*, 1986; Voight, 1990), have a greater chance of being avoided if an interdisciplinary narrative is constructed. Evidence for this claim is provided in analysis of the evacuation of the Faldas at Mt Tungurahua (Tobin and Whiteford, 2002), and the links between scientists and cultural communities near to Mt Pinatubo in the Philippines. In the case of the latter, Garcia and Fearnley estimate that closer links between stakeholder communities "generated the political will for the safe evacuation of over 60,000 vulnerable people" (Garcia and Fearnley, 2016, p.127). This event demonstrated not only the impact of an interdisciplinary approach on the acquisition of trust, but also the seemingly harmonious co-existence of science and culture in a less economically developed context.

However, when discussing collaboration and interdisciplinarity, the impact of institutional partnerships has been studied to a lesser extent. For example, the actions of monitoring and response agencies appear to be particularly powerful in preventing scientific hegemony:

> Institutional environments reward normative requirements for appropriateness and legitimacy and, in some cases, conformity to procedure, presentation, symbols and rhetoric (Fountain, 2001, p.12).

The extract refers to the collectivity, conformity and holism of many institutions; this culture allows institutional entities to contribute to interdisciplinary agendas as they are better able to prevent or lessen the detachment of scientific evidence from society (Nightingale, 2003). For example, the institutionalisation of hazard networks in Europe and North America has often improved the interdisciplinary credentials of civil protection services, primarily because it has facilitated stronger links between contrasting stakeholder communities.

Despite this review outlining interdisciplinary approaches to hazard management, many observations are not applicable to regions that are blighted by war and conflict, or where socio-political tensions are a predominant factor. For example, the struggles between scientists and cultural communities surrounding Mt Merapi in Indonesia have been extensively documented in academic literature

(Lavigne *et al.*, 2008; Donovan, 2010; Mercer *et al.*, 2012). Interdisciplinary action has been difficult to achieve in the region largely because of cultural vulnerability:

> Cultural vulnerability is a global indicator of risk that can produce unpredictable reactions beyond scientific logic (Donovan, 2010, p.118).

During past eruptions, the influential theological beliefs and cultural traditions of several Javanese communities have had a history of directly contradicting science. When conflated with a general distrust of the authorities, cultural vulnerability can manifest a deeply embedded and continued resistance towards scientific representations of risk (Donovan, 2010). Networks therefore need to be carefully managed; for example, attempts to extend interdisciplinary action in Montserrat are perceived to have provoked additional distrust by expanding communication between Montserratian communities and US scientists (Haynes *et al.*, 2008). Nevertheless, an interdisciplinary agenda has generally become workable in much of the economically developed world, where a technical infrastructure has transformed stakeholder communication.

2.1.3: Recognising the role and influence of a technical infrastructure

This literature review has so far covered two relevant aspects of contemporary hazard management, namely networks and interdisciplinarity. As forms of technology are continually evolving (Bourova *et al.*, 2016), researchers can only speculate on their future capability and purpose within hazard networks. However, technical innovation has undoubtedly encouraged interdisciplinary research of volcanic hazards:

> (Open access technologies) require supportive interdisciplinary networks, where scientists and social scientists are willing to work together to expose their disciplines to volcanic risk assessment and mitigation processes shaped and led by vulnerable communities (Barclay *et al.*, 2008, p.174).

Barclay *et al.* directly relate interdisciplinarity to technologies that widen participation and expand the research community. Therefore, devices and software packages are playing a significant role in encouraging a more holistic approach to volcanic hazard management in environments such as Iceland

(Donovan and Oppenheimer, 2012; Cadag and Gaillard, 2013; McCallum *et al.*, 2016).

Tools such as Geosocial, introduced by the British Geological Survey (BGS), provide further examples of how scientific institutions are increasingly using technology to strengthen their ties with the public (British Geological Survey - Citizen science: Geosocial, 2016). However, many researchers have studied the impact of these technologies from the perspective of the non-scientific end-user, rather than from the position of the scientific community that is seeking to expand its outreach. In addition, whilst researchers have studied the impact of technologies on hazard communication (Van Manen *et al.*, 2015; Bee *et al.*, 2014; Kar, 2015), they have rarely explored the process and discussions that lead to the innovation of new devices and systems, and the regulatory measures that ultimately determine their implementation into a hazard network.

Situational awareness has become an important consideration when communicating seismic hazards, and has influenced the development of technical infrastructures (Power *et al.*, 2014; Endsley and Jones, 2013). According to Huang and Xiao, situational awareness can be conceptually reduced to simply "knowing what is happening in space" (Huang and Xiao, 2015, p.1551). In the context of hazard management, the geotagging feature of social media messages can improve efficiency by enabling communication to be geospatially assigned (Rogstadius *et al.*, 2013). Huang and Cervone elaborate on this observation in their analysis of Twitter:

> A few attempts (Huang and Xiao, 2015; Vieweg, 2012) have been made to uncover and explain the information Twitter users communicate during mass emergencies. Information about causalities and damage, donation efforts, and alerts are more likely to be used and extracted to improve situational awareness during a time-critical event. (Huang and Cervone, 2016, pp.304-305).

The ability to overcome the challenges created by time and space therefore highlights the value of technology; for example, social media can be used to identify the geographical regions and end-users to whom mitigation or aid are most urgently required (Yin *et al.,* 2012). The participatory elements and real-time characteristics enable the hazard to be managed through a largely unstructured but well integrated network:

> Twitter communication is largely public and can be monitored, and members of the disaster-affected population can be employed as a sensor network (Rogstadius *et al.*, 2013, p.4:2).

The extract highlights how the inclusion of the public weakens the structure of networks, allowing them to be viewed as interoperable and allowing hazard information to be mediated at will (Gencturk *et al.,* 2015). Social media platforms such as Twitter effectively illustrate how technical infrastructures provide accessible spaces within which communication can be channelled and public engagement can be improved (Herfort *et al.*, 2015).

The ability to openly source information and practice citizen science are key to understanding technical infrastructures in networks such as Iceland. For example, Barclay *et al.* (2008) outlined how open source data has led to greater transparency and trust through the development of "deliberative and inclusive processes" (Barclay *et al.*, 2008, p.172). These approaches to hazard communication influence policy frameworks and actively encourage participation from non-scientific stakeholders. Whilst geospatial software's now appear to be well established in this regard (Alam *et al.*, 2015; Rossi *et al.*, 2015), methods of "crowdsourced human-based computation" (Rogstadius *et al.*, 2013, p.4:2) have been studied to a lesser extent in Icelandic or European contexts. Furthermore, the success of "Volunteered Geographic Information" (Zook *et al.*, 2010; Dransch *et al.*, 2013) during the Canterbury earthquake in New Zealand in 2010 (Doyle *et al.*, 2015), and the Tōhoku earthquake and tsunami in Japan in 2011 (Peary *et al.*, 2012), highlights the need to further expand real-time communication and participatory technologies.

Technical infrastructures have dual purposes within hazard management; for example, they are intended to renegotiate "knowledge management" (Yates and Paquette, 2011, p.7), whilst also improving the methods used to source data. The uptake of user-orientated technologies such as social media is "making peer-to-peer communications and public participation more visible" (Sutton *et al.*, 2008, p.624). This has improved the transparency of hazard information and expanded the outreach of scientific institutions. A technical infrastructure should not be viewed in its entirety through the capability of a device or software package, but should be assessed on its links to a plethora of end-users (Scolobig *et al.,* 2015; Thierry *et al.,* 2015), and ability to reflect the holism of a hazard network. This section of the review has intended to demonstrate how networks and interdisciplinarity form conceptual bridges between volcanic hazards, innovative technologies and stakeholder communities.

2.2: Constructing and communicating knowledge

When explaining how knowledge is constructed and communicated, academics such as Demeritt and Slovic have both focussed on the importance of circumstance and "social negotiation" (Demeritt, 1998, p.176). Several subject areas ranging from nanotechnology (Schillmeier, 2015) to globalisation (Teschke and Heine, 2016), and geopolitics to risk management, have either reinforced or criticised the concept of knowledge being socially shaped. Constructivist explanations of knowledge have emerged from diverse and sporadic disciplinary backgrounds:

> Social constructionism draws its influences from a number of disciplines, including philosophy, sociology and linguistics, making it multidisciplinary in nature (Burr, 2015, p.2).

As a result, academics have often struggled to define and explain constructivism in a coherent manner. Boghossian (2001) arguably provides the clearest and most widely applicable definition:

> To say of something that it is socially constructed is to emphasize its dependence on contingent aspects of our social selves (Boghossian, 2001, p.1).

Constructionism cannot solely be applied to how knowledge is shared, but can also relate to why particular knowledge strands exist. Therefore, constructivist approaches have the potential to improve understandings of trust in complex hazard networks, largely because they can be used to explain the social construction of information flows.

2.2.1: Defining Social Constructionism: Links to science and technology

In one of the most influential texts on social constructionism, Knorr-Cetina (2008) claimed that the process of constructing "knowledge-centred practices" (p.195) can be assimilated to the "relational dynamics" (p.196) that exist between objects. Knorr-Cetina (1983) had earlier outlined the links between social constructionism and science, highlighting the transformation of several dichotomies:

> The constructive operations with which we have associated scientific work can be defined as the sum total of selections designed to transform the subjective into the objective, the unbelievable into the believed… and the painstakingly constructed into the objective scientific fact (Knorr-Cetina, 1983, p.122).

Therefore, science is viewed as the objective and factual imprint of knowledge, minus the subjectivity of social constructionism. Whilst both Knorr-Cetina and Bruno Latour have drawn on the epistemic background from which social constructionism has emerged (Latour and Woolgar, 1979), there are significant tensions in how constructivist movements are interpreted. Nevertheless, both social constructionism and ANT accept that scientific knowledge cannot be isolated from processes and networks.

ANT and co-production have both been influenced by the Strong Programme of scientific knowledge (Bloor, 1983), and the debates stemming from the Sokal Hoax (Weinberg, 1996). These movements addressed the concept of knowledge being a unifying force and highlighted how postmodernism contradicts the more traditional descriptions and understandings of science:

> Critics of constructivism claim that viewing scientific discovery this way opens the gate to non-scientific influences and arguments, thereby undermining factuality (Racovita, 2013, p.676).

The Sokal Hoax and the Strong Programme both expanded on the rejection of positivism and reductionism. In the case of the Sokal Hoax, mathematical physicist Alan Sokal, carried out an academic hoax that challenged the postmodern tendencies of a journal (Weinberg, 1996; Sokal, 2000). Sokal wholly opposed the removal of fact and objectivity from the physical sciences. On the other hand, David Bloor's development of the Strong Programme was an attempt to strengthen the profile of sociology within the sciences (Bloor, 1984; Sismondo, 2010), primarily through the four tenets of causality, impartiality, symmetry and reflexivity (Manicas and Rosenberg, 1985). The programme was heavily criticised but strengthened the profile of social constructivism (Woolgar, 1981; Lynch, 2000) and aided the development of the field of Science and Technology Studies (STS). The Sokal Hoax and the Strong Programme therefore approached constructivism from contrasting perspectives, but enriched its standing in both the physical and social sciences.

The holistic scope of constructivism allows ANT and co-production to have tenuous links with "technoscience" (Patton, 2004, p.67). Whilst knowledge has previously been associated with the politicisation of science, academic literature increasingly refers to the interdependence of science and technology (Lawhon and Murphy, 2012; Wesselink *et al.*, 2013):

> Technological innovation would not be possible without scientific problem-solving; nor could scientific discovery be imagined without technological means to enable new experimental methods and approaches (Jasanoff, 2010, in Frodeman, 2010, p.194).

Jasanoff outlines the intrinsic relations and interactions that allow science and technology to be viewed as co-existing and wholly inseparable. The combination of scientific and technical processes defines a constitution of knowledge, rather than an exchange of information.

However, technical devices are shaped not only by the physical science that leads to their engineering and construction, but also by the influences of socio-political communities. Therefore, approaches such as the Social Construction of Technology (SCOT) are also relevant to this study:

> If it is accepted that a variety of relevant social groups are involved in the social construction of technologies and that the construction processes continue through all phases of an artefact's life cycle, it makes sense to extend the set of groups involved in political deliberation about technological choices (Bijker, 2010, p.72).

Bijker illustrates how the construction of technical "artefacts" and knowledge need to be explained through the co-evolution of society and technology. Constructivism cannot be viewed as one-dimensional, but can be interpreted through the creation and strengthening of "shared mental models" (Levine *et al.*, 1999, p.270). These ensure that knowledge is co-constructed and "socio-political contestations" (Nightingale, 2003, p.80) have a better chance of being negotiated. Both knowledge management and the construction of technology are therefore significant when exploring the complexity and technical infrastructure of hazard networks

2.2.2: Applying constructivism to hazard management

Academic literature has mobilised constructionism to explain the extension of hazard management beyond the physical sciences (Alexander, 2013b; Jasanoff, 1998; Renn, 1998; Wilkinson, 2001; Horlick-Jones and Sime, 2004; Weichselgartner and Pigeon, 2015). Whilst not dismissing realism, Beck demonstrates the need for risk to be constructed in the context it is situated:

> According to Beck himself, "[t]he decision whether to take a realist or constructivist approach is… a rather pragmatic one… I am both a realist and constructivist" (Beck, 2000: 211-2). With this somewhat puzzling statement Beck means to say that while risks are out there (realist ontology), it depends upon cultural, subjective and social categories which risks are selected for treatment (Aradau and Van Munster, 2007, p.96).

Aradau and Van Munster recognise that a realist approach is insufficient in the context of many situations where a society or stakeholder community is perceived to be at risk. Connections can be made to the views of Latour and Woolgar (1979), whose illustration of the need for science to become socially inclusive theorised the construction of postmodern networks.

Furthermore, Renn claims that risk perception is accountable for "socially mediated consequences" (Renn, 1998, p.57); this draws attention to the pivotal role played by circumstance. The construction of risk allows scientific knowledge to be repositioned so that it has no epistemic superiority over society:

> Concepts come from experts and are subject to subjective alteration or manipulation. Most of these ideas emphasize the active role that people play in constructing the meaning of risk and in the role of communication as a transforming power, indicating the need to consider risk as an appreciation, a reading or a 'imaginary' and not as something external to people. It is important to consider perceptions, attitudes and motivations both individually and collectively (Cardona, 2004, p.44).

Focussing on the subjective characteristics of risk enables constructivist narratives to be applied in a manner that transforms, but does not remove, science (Jasanoff, 1998; Renn, 1998). However, in the context of volcanic hazards, Donovan (2012) found that scientific information can be opposed rather than mediated, with negative impacts on the society affected. For example, constructing risk in accordance with communities near to Mt Merapi in Indonesia has proven to be an arduous task, and one that has not significantly reduced social vulnerability or the conflict between science and culture.

However, writing in relation to Mt Pinatubo in the Philippines, Gaillard (2008) highlights the need for a co-construction of knowledge that allows risk perception to be positioned in the context of the everyday. This would allow representations of risk to not only respect cultural traditions, but to also relate to the socio-economic uncertainties of local actors. The co-construction of knowledge, as well as "inter-agency" trust (Salter, 1997, p.64), are reliant on the implementation of technologies that can encompass multiple stakeholder communities (Steelman and McCaffrey, 2013). These include the Google Crisis Response platform (Gibson *et al.*, 2015), the construction of which exhibits key aspects of both technoscience (Brown and Rappert, 2000; Echeverría, 2003) and the SCOT approach (Bijker, 1990; Pinch, 1996; Klein and Kleinman, 2002).

Social constructionism can arguably influence the evolution of hazard networks in less economically developed regions, where the social shaping and uptake of innovative technologies are currently in their infancy (Chipangura *et al.*, 2016). Furthermore, in many European and North American contexts, "artifactual constructivism" (Instone, 2004, p.133) can be used to examine the widening of decision-making practices. For instance, artifactual constructions are relevant to hazard management as they allow conventions and instruments to either adapt or expand channels of communication. This improves the exchange of knowledge between science and society, and provides an effective means of communicating scientific facts. Admittedly, it would be a bold assumption to apply all natural hazards and technologies to this constructivist doctrine, but nevertheless it highlights an approach to hazard management that remains largely unexplored.

2.3: Actor-Network Theory: Applying sociology to hazard management

This next section of the review focuses on a sociological approach that is deeply embedded within network geographies. Emerging from the field of STS, the ANT framework has developed to tackle complexity and lessen the epistemic gap between modernism and postmodernism (Stalder, 1997). It's broad understanding is defined in the following extract:

> …a disparate family of material-semiotic tools, sensibilities and methods of analysis that treat everything in the social and natural worlds as a continuously generated effect of the webs of relations within which they are located. It assumes that nothing has reality or form outside the enactment of those relations. Its studies explore and characterise the webs and the practices that carry them (Law, 2009a, in Banks, 2011).

ANT therefore seeks to analyse the associations that create knowledge and constitute networks. Value is attributed to use of language and dialogue, and their ability to weaken the epistemic binary of nature and culture.

As networks are deconstructed, ANT refers to their individual components as "actors", regardless of their human or non-human characteristics:

> Actors (1) construct common definitions and meanings, (2) define representativities, and (3) co-opt each other in the pursuit of individual and collective objectives (Bardini, 1997, p.516).

ANT can be used to analyse the construction and evolution of information channels, explaining how knowledge is transformed between actors. Therefore, the concept of actors is integral to understanding the flexibility of networks (Callon, 1999) and the formation of agency structures (Murdoch, 1998). For example, the dynamics that exist between actors can define the dichotomies of science and society, human and non-human, modern and postmodern. However, whilst these dualisms will be explored in this review, there are considerable variations in how ANT can be understood as a sociological framework. For instance, academics have used numerous approaches to study and define technical actors, translation and "black-boxed" knowledge (Goodman, 1999, p.27). How can ANT relate to sociality? Where does the translation and mediation of knowledge begin and end within a complex network? What is the role and power of technical objects?

2.3.1: Geographical engagements with Actor-Network Theory

This review primarily covers Bruno Latour's understanding of ANT, considering the predominant aspects of his interpretation at length, before applying them to

Iceland's hazard network. In seminal papers titled "We Have Never Been Modern" (1993) and "Reassembling the Social" (2005), Latour denies modernity has existed. This approach has influenced many geographical engagements with ANT; for example, Nick Bingham's expansion of technological determinism and social constructionism referred extensively to Latour (1993). Bingham recognised technology's place in a world where material objects and humans are intrinsically connected (Bingham, 1996; 1999). Therefore, Bingham and Latour both theorise networks in a manner that transcends modernity, with mediated forms of communication providing new methods of following or travelling with the world.

Furthermore, Bingham and Thrift (2000) approach ANT from the perspective of time and space, and analyse the work of Serres and Latour (1995) to explain the partiality and circulation of space within networks. By perceiving space to be fluid and evolving, Bingham and Thrift (2000) are able to recognise and describe relativity. However, Thrift also draws attention to the weaknesses of ANT, highlighting how Latour's interpretation downplays human capability (Thrift, 2000), conflicts with understandings of complexity (Thrift, 1999), and redefines the local and the global according to networked connections (Thrift, 1996). Other geographical engagements with ANT have included those of Steve Hinchliffe, who refers to Latour when explaining practices of embodiment and representation (Hinchliffe, 1996).

Hinchliffe focuses to a lesser extent on the creation of knowledge and describes human and non-human relations through power, ontology and the denaturalising of boundaries between nature and culture. Writing in the context of relational ethics, Sarah Whatmore also addresses the work of Latour when referring to these ontological divisions. For example, Whatmore analyses the relativity of nature and culture in the text titled "Hybrid Geographies" (2002), and focusses on the configuration of networks and spaces. Both Hinchliffe and Whatmore approach ANT from an environmental perspective, but their work varies as Whatmore has also referred to mediation, expertise and context when explaining how knowledge is constructed (Whatmore, 2006). Therefore, ANT can span multiple branches of geography, and Latour's ideology can be approached from technological, ontological and environmental perspectives.

2.3.2: Understanding the emergence of Actor-Network Theory

ANT has risen from an ethnographic base and has developed into an analytical framework that explains the construction and mobilisation of knowledge. Latour's rejection of modernity allows his understanding of actor-networks to theorise the development of a middle ground between nature and society:

> (Nature and culture) are both premature attempts to collect in two opposite assemblies the one common world. This is what I have called the Modern Constitution (Latour, 2005, p.254).

Social theorists have used the Modern Constitution to account for the erosion of pure and "distinct ontological zones" (Latour, 1993, p.10), and to describe the circulatory process that allows knowledge to "crisscross ideologies" (Latour, 1993, p.3). For example, Latour refers to the division between natural and cultural binaries in his outline of the "first dichotomy" [see Figure 2.1, p.44] (Latour, 1993, p.11); as knowledge is translated with the development of an actor-network, this dichotomy is progressively weakened.

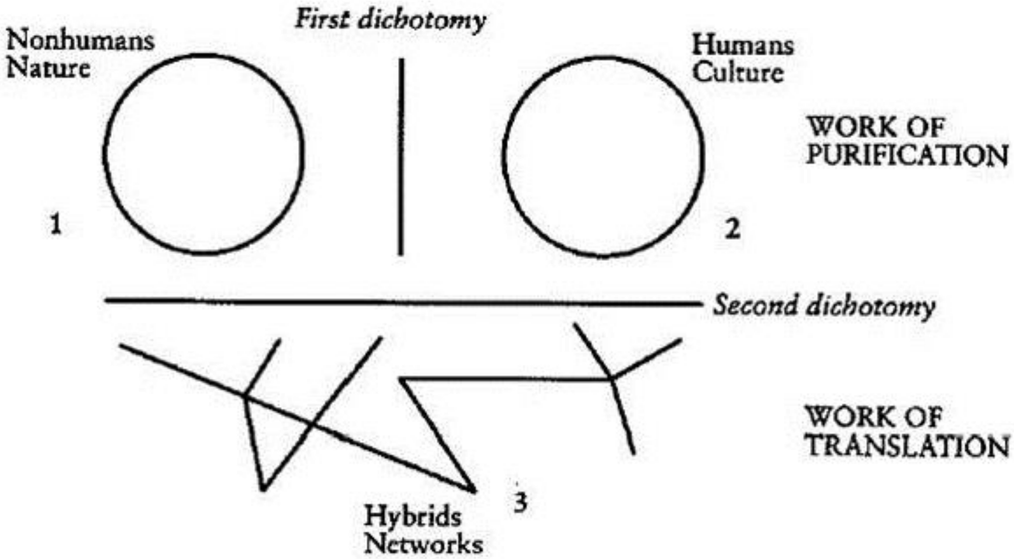

Figure 2.1: *An illustration of the epistemic transition and evolution of knowledge within actor-networks (Source: Latour, 1993, p.11).*

In the second dichotomy, the mediation and translation of knowledge form hybrid networks between nature and culture, nonhumans and humans. These networks lack stability and emerge from the evolution of alliances, connections and communication channels. However, the dichotomies outlined by Latour are wholly interdependent, and this has been explained in Van Krieken (2002):

> Without translation, hybridification and mediation, 'the practices of purification would be fruitless or pointless'. Without purification, 'the work of translation would be slowed down, limited or even ruled out' [Latour, 1991/1993: 11] (Van Krieken, 2002, p.263).

Therefore, as actor-networks develop, they do so as a result of purification and translation existing simultaneously; one dichotomy does not precede or have superiority over the other.

In one of the most notable works to cover ANT, Callon (1984) illustrates the insecurity of networks when studying the science of scallops at St. Brieuc Bay. Callon's understanding of translation is explained by Law (2009a):

> (The science of scallops is) a web of relations that makes and remakes its components. Fishermen, scallops, and scientists are all being domesticated in a process of translation that relates, defines, and orders objects, human and otherwise. Callon adds that they hold themselves together but they do so precariously. All it takes is for one translation to fail and the whole web of reality unravels… translation is always insecure, a process susceptible to failure (Law, 2009a, p.145).

By deconstructing the science of scallops, Callon outlines the transformation of natural, ecological and scientific laws on the one hand, and anthropogenic, social and technical acts on the other. Callon does not distinguish between the non-human and human components of the network, but draws attention to the evolutionary nature of interactions. Therefore, whilst the weakening of purified binaries can be understood relatively easily, explaining the process of translation and the durability of alliances proves to be arduous as relations are unstable.

Latour referred to translation in the context of science being extended beyond the laboratory. As scientific knowledge is communicated between actors, the purified elements are eroded to the extent that the boundary between science and society is transcended:

> By the end of the story "no one can say where the laboratory is and where society is" (Latour, 1983, p.154, in Murdoch, 1997, p.736).

Latour has been eager to draw attention to the dissolution of dualisms (Demeritt, 1998); the legitimacy, truth and boundaries of knowledge are instead determined by connections between natural and social communities. Academic literature has supported Latour's interpretation and has applied it to the translation of knowledge within economic, organisational and logistical contexts (Farias and

Bender, 2012). Latour has also described how knowledge is mediated by distinguishing between mediators (actants that initiate, transform or translate knowledge) and intermediaries (actants directing or transporting knowledge without making modifications). However, Latour's understanding has also been criticised on numerous occasions:

> Latour provides an "asymmetrical reading of the mediation process, which is overly oriented towards the contribution of things to the production of the social order, almost neglecting the reverse, that is, the 'sociality' of the stability of things (Habers, 1995, p.273, in Walsham, 1997, p.472).

In his review of 'We Have Never Been Modern', Habers questions Latour's account of how mediation takes place. Latour focuses on interaction between the non-human and the human, whereas Habers recognises the situational context (the sociality) in which knowledge is mediated. Therefore, approaches to ANT can often be viewed as contrasting, particularly in relation to how humans and objects (things) are perceived.

However, from a technological perspective, a Latourian approach views a device or system as an influential "agent" that provides "mobilized" and "connected lines" of communication (Latour, 1993, p.118). The technical components of actor-networks therefore manifest traceable channels of connectivity:

> Every branching, every alignment, every connection can be documented, since it generates tracers (Latour, 1993, p.118).

Latour's interpretation is supported by Callon (1999) and Law (2009a), who also describe how technology explains the translation of knowledge in complex and evolving networks. The mobility of technical actors is key to understanding how knowledge can be mediated (Lowe, 2001), regardless of an objects' mundanity or sophistication. Furthermore, technology can also explain why Latour's approach is predicated on power equity; the hierarchical elements of networks are flattened as human and non-human engagements construct hybrids (see Figure 2.1, p.44). Technological objects play a significant role in neutralising the balance of power within actor-networks.

The conceptual positioning of technology and power is further reflected in Latour's seminal publication titled "Aramis":

> In connecting together all kinds of things, what we then have are 'hybrids' formed from the mixing up of subjects and objects, humans and nonhumans… Aramis duly raises up the (nonhuman) 'poor objects' of the world for our (human) 'attention and respect' as coequal 'social' agents. (Laurier and Philo, 1999, p.1048)

The extract relates to how both the non-human and the human can be united under the umbrella term "actors" (Latour, 1996b, p.374), essentially components of a networked constitution that have powers defined by their connectivity (Law, 1999; Callon, 1999; Allen, 2003). Aramis refers to a subordination of the human from a position of perceived dominance to one equal to that of a non-human object. For instance, power is neutralised as human actors depend on technology for the provision of communication channels; this prevents the non-human from being subsumed. However, Latour's approach implies that human actors are not accountable for their own actions, rendering "impossible" any degree of responsibility (Banks, 2011).

When analysing Iceland's hazard network, the research presented in this thesis deviates from Latour's views as it approaches ANT from a less ideological perspective. For example, it does not deny the existence of sociality or define interactions by connectivity alone. Furthermore, despite remaining loyal to the broad and post-structural elements of Latour's approach, this study rejects power equity and assesses the extent to which power dynamics are influenced by specific actors and institutional entities. Nevertheless, the inclusion of ANT and recognition of Latour is justified as the construction and mediation of knowledge within Iceland's network is seldom attributed solely to human actors. The research explores the connectivity and remit of partnerships, objects and technological systems, reflecting Latour's approach to the non-human elements of networks.

Pyyhtinen and Tamminen (2011) are amongst the many academics who have explained the conflict between Latour and Foucault's (1982; 2007) use of sociality to define power relations:

> While Foucault focused exclusively on games of truth where the object of knowledge is man, Latour's concerns are not confined to the boundaries of the human sciences. Instead, he characteristically studies the 'hard sciences' by focusing on laboratories, microbes, technology and the like (Pyyhtinen and Tamminen, 2011, p.136).

Whilst the extract refers to the stark contrasts between the Latourian and Foucauldian interpretation, both approaches take the view that power is determined and problematised at a holistic scale (Collier, 2009). This thesis approaches power dynamics and knowledge management from multiple philosophical perspectives; the interdisciplinary scope and contextual focus of the research ensures aspects of both Latour and Foucault can be appreciated.

Writing in the context of Vanuatu and Montserrat respectively, researchers such as Cronin *et al.* (2004b) and Haynes *et al.* (2008) have previously used ethnography to illustrate how power and knowledge can be purposely structured in hazard networks. These interpretations of power conflict with the post-structural lens of Latour's approach to ANT. For example, Haynes *et al.* (2008) and Earle (2010) associate power with levels of trust between scientific and socio-political stakeholder communities. Earle (2010) illustrates how power dynamics are influenced by egalitarian attitudes, inequalities and segregation. On the other hand, Latour (2005) argues that trust and context cannot be separated; trust itself contextualises the lived experiences of networks, as well as the human and non-human actors within them (Wright and Ehnert, 2010). Therefore, conceptual gaps exist between interpretations of power within hazard networks, and the broad parameters of Latour's explanation of ANT.

Differentiating between the human and the non-human has become increasingly contentious in networks that are influenced by sophisticated technologies (Murdoch, 1998; Law and Mol, 2001). For example, as devices and systems (objects) have become participatory and inclusive of the human, it is increasingly difficult to position them as part of a human or non-human dichotomy. This point has been contextualised by both Callon (1984) and Cresswell *et al.* (2010) in their application of ANT to electric vehicles and healthcare respectively. In addition, Latour claims that "no technology is first and foremost technological" (Latour, 1996a, p.32); this implies a dynamic level of human or non-human agency is ever present from the point at which a device is entrained into a network. Furthermore, artificial intelligence has proven that technology can become self-sufficient and adapt to environmental or circumstantial changes (Del Casino, 2015; Tatnall and Davey, 2015). The programming and self-determination of objects, devices and robots therefore allows them to be positioned in the grey area between the human and the non-human (Avgerou *et al.,* 2004). This enables the technological constitution of networks to be critically explored and analysed. Haraway (1991) claimed the middle ground between dichotomies is manifested from technology that takes the form of cyborgs and tricksters, further illustrating the level of humanistic control possessed by devices and systems.

Establishing where humanistic elements of control begin and end are relevant to not only understanding the mobility of technical objects and networks, but also for studying the partiality of knowledge. For example, non-human actors are broadly characterised by malleability and transcendence (Dolwick, 2009); the non-human can be construed as the attributes of networks that undermine stability and act as transporters of knowledge that is only ever partial (Oppenheim, 2007). On the other hand, human components tend to be defined by "immanence" and materiality (Hillier, 2005, p.271). Human elements do not, therefore, migrate according to circumstance and are recipients of the partial knowledge communicated by non-human counterparts (Albertsen and Diken, 2004). The partiality of knowledge within actor-networks illustrates the need for this review to briefly address the process through which epistemologies are established.

Scientific knowledge is generally viewed as an abstract element that can only be defined once it becomes an accepted theory. Therefore, the philosophy of science (Kuhn, 1962; Bergmann, 1978) and the sociology of scientific knowledge (SSK) contradict the concept of partiality. Whereas logical positivism defines science based on its verifiability (Ayer, 1966; Bergmann, 1978), the philosophical approach of Thomas Kuhn (1962) viewed the revolution of scientific knowledge as a cyclical process, determined by the acceptance or rejection of a paradigm. The philosophy of science therefore provides little leverage for knowledge to be viewed as partial. Meanwhile, the SSK purports that evidence and facts are socially conditioned and develop according to social influences (Shapin, 1995; Bloor, 2004). Therefore, the SSK neglects the role of the non-human and does not allow for partiality; it is criticised for being too reductive by sociologists such as Law (2009b).

Hassard and Callon are amongst numerous scholars who have highlighted the role of partial knowledge in the development and evolution of actor-networks. By referring to the processual emergence and disconnection of actors, understandings of ANT generally imply that knowledge is partial and situated in relation to connections and objects:

> The situatedness of knowledge draws attention to the spatialities of knowledge: knowledge is always situated and because of this partiality it is always multiple. It is also territorialized through various forms of inclusion and exclusion, meaning that it can be to varying intensities in or out of the "proper" spaces [Law, 2000] (McFarlane, 2009, p.5).

However, Cole (1992) argues against these interpretations by claiming that knowledge can exist as a scientific whole without partiality or relativity. Different epistemologies therefore emerge from how the construction, mobility and aggregation of knowledge can be perceived. For example, Latour's defines knowledge through the construction of a "black box" (Latour, 1987, p.1), namely the position at which an actor-network stabilises and the components can "act as one" within a "wider organisational field" (Lagendijk and Cornford, 2000, p.10). The convergence of different partial strands of knowledge at these points temporarily constitute fact.

However, philosophers such as Manuel DeLanda have explained the convergence of partial knowledge through the lens of Assemblage Theory (AT). DeLanda focuses primarily on how knowledge can be renegotiated or exchanged by fluid and transitional power relations (DeLanda, 2006). As a realist, DeLanda's approach to social complexity and knowledge is influenced by the proliferation of material and territorial relationships. Whilst understandings of AT can be applied to the context of this PhD research, they are overlooked on the basis that its inclusion could make the study unmanageable. ANT and co-production are preferred as they offer an optimal contrast in sociological approaches to complex networks, whereas DeLanda's narrative is associated primarily with systems and bodies. Furthermore, ANT enables networks to be deconstructed to the level of each individual actor, object and channel of communication; it therefore facilitates a more rigorous exploration of Iceland's hazard network than could be afforded by AT. As the research covers both ANT and co-production, it is already conceptually dense and there is a need to maintain coherence and lucidity.

2.3.3: Establishing links between Actor-Network Theory and natural hazards

ANT can be of considerable value to studies of hazard management, primarily because it can explain the evolution and translation of knowledge. When scientific evidence is communicated through complex network infrastructures, translation can account for changes in how data and facts are represented:

> Science does not always provide simple "black and white" accounts of events that are amenable of smooth translation into law or policy (Drake, 2016, p.48).

Drake (2016) illustrates the critical role translation plays in ensuring that scientific knowledge can be deciphered by decision-makers from a broad spectrum of stakeholder communities. However, despite Drake writing in the context of an Indonesian mud volcano, many attempts to apply translation to hazard networks have overlooked geological and geophysical events, and have been tailored to manmade or technological hazards.

Potts (2009) reflected on the impact of translation when explaining how the London bombings were communicated in 2005. In the following extract, Potts describes how technologies such as Flickr have the capacity to translate photography into hazard information:

> In the case of the London Bomb Blasts Community on Flickr, Storey (group moderator) served as the researcher attempting to funnel information through the obligatory passage point of this photo pool… the focal actor is both Storey, as moderator, and Flickr, as the site of the obligatory passage point. Storey's ability to aggregate the images he found on Flickr and to encourage others to add them to the photo pool certainly was the first step toward transforming the community into a network. However, it is also the participants' understanding of Flickr that allows these translations to take place. (Potts, 2009, p.289)

Potts refers to the impact and effectiveness of engagement between technical and human actors during crisis situations. The extract outlines the construction of an information hybrid that is collectively composed of humans, objects and digital channels of communication (Whatmore, 1997). Potts' narrative also resonates with both Callon's account of translation (1984) and Latour's focus on the "collection of signs, language and texts" within actor-networks (Laurier and Philo, 1999, p.1053). Neither human nor non-human actors are privileged in Potts' description, and knowledge is synthesised across social and technical boundaries. Therefore, this example of how knowledge can be translated illustrates connections between contemporary methods of hazard communication, and multiple aspects of ANT.

Both Potts (2009) and Drake (2016) explain hazard communication in a post-structural context and refer to the transformation of boundaries. ANT can be used to analyse the mobility of "boundary spanners" (Owen *et al.*, 2013, p.9) within hazard networks; these can include individual actors or objects that have the capacity to collaborate across social, scientific and technological boundaries. Researchers have often approached boundary spanning from either an institutional or policy-orientated perspective (Alemanno, 2011; Neisser, 2014). However, there is a need to analyse the specific processes that fragment and weaken boundaries to the extent they become invisible within networks (Gieryn, 1983; 1999; Hackett *et al.,* 2008; Hård and Jamison, 2013). This requires taking a holistic view of boundary relations, and embracing ANT by recognising the diversity of human and non-human actors:

> If ANT has a project or a general ambition, it is first of all to highlight the frailty of the modernistic worldview (Latour, 1993) and underline how the making of society demands association of diverse elements (Van Der Duim *et al.*, 2013, p.5).

If applied to hazard management, ANT can explain the need for networks to be analysed from a post-structural perspective; this approach can undermine the existence of boundaries between stakeholder communities from scientific and social backgrounds.

However, Barron *et al.* (2014) appear to question the legitimacy of approaching hazard networks from relational standpoints. For example, when discussing hazard management in Papua New Guinea, Barron *et al.* (2014) identify a temporal contrast between the global media's representation of volcanic hazards and the relative confinement of the Papua New Guinea culture:

> The vulcanologists with their gases, and the ABC reporter with his map locate the volcanoes firmly within the global westernised scientific temporality of the arrow of time stretching along a single dimension to end at a definite conclusion; ring of fire, and consecutive, ordered eruptions; cause and effect…Papua New Guineans were denied access to this temporality. All the expert vulcanologists and seismologists were white. They located the volcanoes within a well-defined, global, scientific space, but the local space was trivialised (Barron *et al.*, 2014, pp.122-123).

The temporal gap implies a disconnect between local and global actors, undermining the relational approach to networks described by ANT. In regions where cultural or spiritual narratives can be less passive, such as Papua New Guinea, iconographic connotations of volcanic hazards contravene the western-centric approach to science. A holistic interpretation of networks therefore appears to lack both credibility and substance, primarily because developments do not lead to the mergence of scientific and social ontologies.

Unlike Potts (2009), Barron *et al.* (2014) focus on sociality rather than the presence or absence of technical actors. Potts recognised the impact of innovative technologies on the translation of knowledge following the London Bombings in 2005, but Barron *et al.* (2014) do not refer to the adoption or rejection of participatory devices in Papua New Guinea. Therefore, technology appears to be a determining factor when establishing how ANT can explain the adaptability of hazard networks. Technical actors play a significant role in mobilising knowledge, reconceptualising hazards and eroding the binary of nature and culture (Yamin *et al.*, 2005). In addition, technical devices provide communication channels that allow stakeholder interactions to be traced:

> Given our current technology and ability to trace the connections people make across multiple technologies, Web sites, and groups online, we can study the pathways and better understand how people find and exchange information in crisis situations (Potts, 2009, p.284).

The extract reflects on how technology has the capacity to facilitate and perform public engagement within hazard networks. Therefore, by studying the use of technical actors, researchers can assess how the complex elements of networks can be overcome, and how connections can evolve in a way that improves the resilience of various stakeholder communities.

A techno-centric approach to hazard management demonstrates the malleability of non-human actors, but the impact of technology is ultimately determined by the willingness of an educated and informed public to engage with communication devices and systems:

> Pure technical or structural solutions along with the demand for an 'absolute protection' against the negative impacts of natural hazards are hardly achievable (Kuhlicke *et al.*, 2011, p.806).

Here, Kuhlicke *et al*. illustrate how technology cannot act alone, and needs to be intrinsically related to multiple stakeholder communities. This view further reinforces the relevance of constructivist approaches such as ANT; for example, actor-networks theorise the development of connections and alliances between human and non-human actors. However, sociality cannot be ignored in the way Latour implies, largely because technical actors are situated within hazard networks, and their evolution primarily stems from contextual dynamics:

> Critical infrastructure is materialized in different ways, depending on how rationalities and technologies of risk management intra-act with other social and political practices, discourses, forms of knowledge and materialities (Aradau, 2010, pp.502-503).

Aradau (2010) illustrates the constructivist elements of hazard management, but deviates from Latour's approach by referring to the relevance of materiality. Hazard networks can resonate with understandings of ANT, but the links are often speculative and remain understudied in academic circles. For example, few researchers have studied the growth of real-time hazard information from a constructivist perspective.

Approaches such as ANT have the capacity to explain and analyse the evolution and mobilisation of knowledge; from a Latourian point of view, volcanic hazard networks can be interpreted as interdisciplinary hybrids. For example, the interactions within them amalgamate geology, technology, politics and culture. When outlining his approach to ANT, Latour (1993) referred to the hole in the ozone layer as a network that collectively instils natural and cultural elements. Latour's interpretation of the ozone layer also explained how scientific knowledge can be "absolutely and irreversibly transformed" (Latour, 1993, p.111) following engagement with human actors. If the same narrative is applied to volcanic hazards, then tectonic processes and physical landforms can be assimilated to what Latour termed the "hard parts of nature" (Latour, 1993, p.55). Once translated, descriptions and understandings become increasingly subjective and represent a fusion of relational elements from across multiple disciplines. From this perspective, Latour's interpretation of ANT can be used to explain how representations of risk evolve, and how a modernistic binary of nature and culture can be diminished in hazard networks.

However, whilst the evolving ontology of volcanic hazard networks can relate to Latour's approach to ANT, several constraints can be identified. Firstly, Latour's interpretation of actor-networks does not explain institutionalisation:

> For Latour, individual entities lie at the core of reality (Bryant *et al.*, 2011, p.294).

Latour accepts that actors can be clustered, but deconstructs networks to the level of individual components. Therefore, sufficient scope is not provided for institutional frameworks to be recognised. In contrast, researchers have often tailored explorations of volcanic hazard networks to the actions of meteorological organisations or civil protection departments (Paton *et al.*, 1998; Scott and Travers, 2009). Secondly, critics of ANT have claimed that Latour's interpretation overlooks the concept of scale (Corpataux and Crevoisier, 2016) and cannot be assimilated to the everyday. For example, Latour dismisses objectivity and refers to the core or nucleus of an actor-network as a "central vantage point" that is "incomprehensible" (Latour, 1993, p.13). The applicability of ANT can therefore be questioned as understandings of this unfathomable central position are vague and inconclusive. Despite these limitations, this section of the review has referred to numerous resonances between ANT and hazard networks such as Iceland.

Beth Greenhough has also explored the geographies of Iceland's scientific network, and has established epistemic links with ANT. From the perspective of her genome mapping project, Greenhough views Iceland as a "natural laboratory" for genetic research (2006a, p.226), and a scientific space with boundaries that are unstable and negotiable. Greenhough's approach to science studies recognised the human and non-human dichotomy, as well as knowledge exchange and boundary relations. Constructivist elements are also reflected in the following interpretation of Iceland's interconnected and evolutionary field site:

> The island-laboratory/field itself (Iceland) becomes increasingly complex, defined not only by the practice of genetic epidemiology, but by a whole series of other approaches which bring with them new means of entering and engaging with the field site/island-laboratory (Greenhough, 2006a, p.231).

Here, Greenhough refers to the scientific network being subjected to external influences and interdisciplinary engagements; these collectively remove the laboratory from isolation and allow the wider world to connect to its complex and unique characteristics (Greenhough, 2006a; 2006b).

This research resonates with Greenhough's approach as it also views Iceland as a field site with fragmented boundaries, and uses social science to analyse its complex and interdisciplinary evolution. Whereas Greenhough's study focussed on genetics, the research presented in this thesis tailors the island-laboratory to the management and communication of volcanic hazards. The impact of social science on the scope and expanse of the research space was discussed by Greenhough (2006a) through the metaphor of seascapes:

> The notion of seascapes and the disorder they evoke shift the grounds (or waters?) upon which we might imagine Iceland as a laboratory from a closed space of analysis to an open contested site of scientific and social exploration (Greenhough, 2006a, p.235).

Social interventions are considered disruptive to the field site, primarily because they add subjective narratives that can span multiple disciplines and research communities. However, before explaining the development of new research spaces, the ideology and characteristics of the island-laboratory need to be recognised beforehand.

Greenhough's study is relevant to this thesis as it explains how connective engagements prevent detachment and lead to the progressive destabilisation of Iceland's boundaries (Greenhough, 2006b). Furthermore, the approach of Greenhough (2006a; 2006b) can also be related to Whatmore's (1997; 2006) work on the exchange of knowledge and information. For example, by exploring biotechnology, Greenhough (2006b) addresses the resolution of knowledge gaps and the participation of diverse publics. Further links can also be identified between the island-laboratory concept and understandings of ANT. For instance, boundary objects were a key element of Latour (1993; 2005) and Callon's (1999) approaches; Greenhough explores boundary objects by analysing the construction, communication and consumption of medical records. Finally, Greenhough (2006b) acknowledges that she approached the field site from an external position, and had already developed an understanding and perception of the island-laboratory. The same principal applies to the research documented in this thesis, again reflecting the resonance between these studies of Iceland and their relations to ANT.

2.4: Understandings of co-production

Whilst the process of translating knowledge can highlight the links between ANT and hazard management, there is also a need to establish how knowledge is produced. Therefore, constructivist approaches such as co-production (Jasanoff, 2004; Whatmore, 2009) are also relevant to this thesis. Co-production conceptually expands on the generation and negotiation of knowledge; it can be succinctly defined by Jasanoff (2004) and Lane *et al.* (2011):

> Increasingly, the realities of human experience emerge as the joint achievements of scientific, technical, and social enterprise: science and society, in a word, are co-produced, each underwriting the other's existence (Jasanoff, 2004, p.17).
>
> Knowledge is co-produced through a process of dynamic, collective learning involving those for whom an issue is of particular concern (Lane *et al.*, 2011, p.18).

The value of co-production is derived from its ability to explain knowledge management. For example, in the context of volcanic hazards, co-production can be used to analyse the impact of stakeholder communities on the generation of both knowledge and technology. Co-production can also theorise how technical devices, models and systems are incorporated and used in complex networks such as Iceland.

From an interdisciplinary perspective, understandings of co-production can explain the relationship between science and society, and the process of resolving the tensions between them. Scientific, technical and social practices are not interpreted as individual façades of reality, but are engaging, experiential and interactive:

> The ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it. Knowledge and its material embodiments are at once products of social work and constitutive of forms of social life; society cannot function without knowledge any more than knowledge can exist without appropriate social supports (Jasanoff, 2004, pp.2-3).

Jasanoff refers to the interdependency and co-existence of knowledge and society; there is a need to simultaneously account for both when constructing devices and methods that are intended to resolve controversies. The extract also refers to the process of generating knowledge, and highlights the relevance of social dynamics.

Defined as “generative events” (Whatmore, 2009, p.588), knowledge controversies are central to the co-production of knowledge, and are explained in the context of climate change by Barry (2012):

> Consider the emergence of (knowledge) controversies around the idea of climate change. Certainly, there have been a whole series of efforts to develop appropriate transnational mechanisms and institutions to address the problem of climate change (Andonova *et al*., 2009; Bulkeley and Newell, 2010). However, these efforts have occurred in conjunction with burgeoning disputes about the urgency, extent, causes and consequences of the problem itself. The controversies surrounding the governance of climate change have not just been about issues of state sovereignty (Paterson, 1996), environmental justice (Adger *et al*., 2006; Roberts and Parks, 2007) or the design of carbon markets (Mackenzie, 2008), but also about the reliability of models and data (Barry, 2012, p.325).

Barry draws on the complex way in which climate change is governed and explains how controversies can only be addressed when knowledge is co-produced by scientific, technical and socio-political communities. In an influential account of co-production, Lane *et al.* (2011) use the example of flood risk management to demonstrate how controversies can be resolved by models that transform public involvement and representations of risk. Controversies are relevant to this thesis as they conceptualise the process through which epistemic divisions can be remedied, and conflicting interpretations of an event can be overcome (Whatmore, 2009). Furthermore, they have seldom been referred to directly in academic literature that relates to volcanic hazard management.

However, controversies do not only exist in the form of perception and knowledge, but also as technical controversies when there are compatibility issues between devices and end-users. The resolution of controversies can impact on networked infrastructures, and requires the redistribution of scientific and socio-political expertise:

> In the event of knowledge controversies public scrutiny of environmental expertise intensifies, foregrounding the technologies that transact between the knowledge production practices of environmental science and the regulatory protocols instituted by environmental policy agencies… At the heart of these accounts is a

> redistribution of expertise in the face of environmental (and other) uncertainties on two related fronts (Whatmore, 2009, pp.588-589).

Despite expertise being context-dependent and conceptually challenging to define, the extract demonstrates how it can be renegotiated to facilitate co-production. In addition, Whatmore (2009) recognises the critical role technology plays in mobilising expertise, and ensuring it has the ability to transcend scientific and socio-political communities.

Therefore, co-production accounts for the profound impact technical devices and models can have on knowledge management and the infrastructure of networks such as Iceland. This is reflected in the development of participatory approaches such as deliberative mapping:

> A participatory, multi-criteria, option appraisal process that combines a novel approach to the use of quantitative decision analysis techniques with some significant innovations in the field of participatory deliberation (Burgess *et al.*, 2007, p.299).

Here, the extract refers to how deliberative mapping is designed to improve participation and coalesce expertise (Jasanoff, 2004; Lynch and Cole, 2005; Stirling, 2006). The process purposely exploits the mobile and transparent attributes of innovative technologies, primarily to co-produce knowledge in a way that transforms the involvement of communities from both scientific and social backgrounds (Aspinall, 2006; 2010; Donovan, 2012).

2.4.1: Co-production and the management of hazards

Hazard research has intrinsic connections with how aspects of co-production are theorised; for example, the generation and resolution of knowledge controversies has been explained in the context of flood risk modelling and public engagement (Whatmore, 2009; Landström *et al.*, 2011; Lane *et al.*, 2011):

> The framing that we brought to the experiment was a wider context of trying out a different means of practising science, in which both academics and the public worked together to co-produce knowledge rather than starting out to address a particular flood risk problem using a particular sort of method (Lane *et al.*, 2011, p.25).

The extract draws on the collaborative engagement between science and the public, and describes an experiential approach to the remodelling of flood risk.

Jasanoff (2004) also implies that risk is compatible with co-production because it provides controversies to solve. However, in comparison to flood risk management and climate change, the process of co-producing knowledge has rarely been applied to geological and geophysical hazards.

Nevertheless, when co-production and knowledge controversies have been studied in the context of volcanic activity, boundary relations and liminality have been the subject of much discussion. For example, Donovan and Oppenheimer (2015) refer to co-production in their work, and focus on the weakening and transcendence of epistemic boundaries:

> Political factors affect the ways in which scientific reports are framed, for example, just as politicians' interpretation of scientific information will affect the decisions that are made (e.g. Jasanoff, 1990, 2004, 2005): scientific reports and risk decisions are co-produced (Lövbrand, 2011; Kuhlicke and Demeritt, 2014). Coproduction occurs through the negotiation of uncertainty and authority in attempts to make evidence-based decisions, and it occurs as scientists and policymakers engage in boundary work… The liminal nature of risk assessment - not only between scientists and policymakers, but often on the edge of scientific philosophical boundaries - necessitates a broader discussion of meaning and uncertainty in understanding the co-production of science and social order (Donovan and Oppenheimer, 2015, p.155).

The extract relates co-production to the changing dynamics of authority and uncertainty in the decision-making process. When explaining how boundaries between science and society can be renegotiated, Donovan and Oppenheimer (2015) draw attention to the liminal aspects of hazard management. For example, liminality exists in the form of documents, scientific reports and artefacts; the mobility and engagement of these communicative objects facilitates co-production. This narrative of boundary relations is also reflective of Latour's approach to ANT, but Donovan and Oppenheimer focus on the process of negotiation rather than connectivity.

As boundaries fragment and methods of communication become increasingly diverse, explorations of hazard networks need to account for the co-evolution of individuals and institutions (Rip, 2002; Graffy and Booth, 2008; Wyborn, 2015). For example, an improved ability to negotiate and neutralise knowledge controversies often stems from greater democracy in the decision-making process:

> Computer simulation modelling can be employed to further a civic rationale in public engagement, so as to produce a more democratic science (Landström *et al.*, 2011, p.1630).

Landström *et al.* (2011) refer to a simultaneous transformation of science and the public. However, success and sustainability are dependent on devices and models that enable individual citizens and scientific institutions to co-evolve. Both the co-production of knowledge and the co-evolution of stakeholder communities have been reflected in an increasing body of academic literature that studies the use of social media in hazard networks (Chatfield *et al.*, 2013; Stone *et al.*, 2014; Mee and Duncan, 2015). For example, platforms such as Facebook and Twitter have been significant to co-producing knowledge of various natural hazards; these include Typhoon Haiyan in the Philippines (Cool *et al.*, 2015), the Christchurch earthquake in New Zealand (Yin *et al.*, 2012), and the Tōhoku earthquake and tsunami in Japan (Cho *et al.*, 2013).

Social media illustrates how devices and software packages can be used to democratise communication and improve the resolution of knowledge controversies:

> Co-production of knowledge over time can also build trusting relationships and resilience (Stone *et al.* 2014). We propose the use of a smartphone application (app), myVolcano, to promote citizen science, combined with real-time analysis of social media… In combination, these will capture new data in real time, enable dialogue and provide redundancy (Mee and Duncan, 2015, p.3).

By drawing specifically on the transformation of citizens into "active subjects" (Jasanoff, 2003, p.241), Mee and Duncan (2015) explain how co-production encourages a bottom-up approach to hazard communication. Social media and smartphone applications allow stakeholder communities to co-construct and negotiate "hybrid" knowledge (Wisner *et al.*, 2012, p.772). Hybridity emerges from dialogue that technical systems encourage to be transparent and participatory; this enables the complexity of hazard networks to be overcome, and resolves controversies by improving stakeholder cohesion. Therefore, explaining co-production in the context of how natural hazards are managed provides evidence of the relativist turn (Rayner, 2012; Birkholz *et al.*, 2014).

However, whilst Donovan and Oppenheimer (2015) have referred to co-production in the context of volcanic hazards, it's theorisation of how volcanoes can be managed remains understudied. For instance, interdisciplinary research councils, partnerships and committees have collectively transformed the structure of volcanic hazard networks and can be interpreted as evolutionary attempts to minimise local and cultural controversies. The construction of these innovative bodies and stakeholder alliances has encouraged both the co-production and co-evolution of knowledge; this has renegotiated the adaptability and engagement of various scientific and socio-political communities. Co-production is of relevance to this PhD research as Iceland's approach to volcanic hazard management is both transformative and participatory.

2.5: Hazard management, Actor-Network Theory and co-production

This concluding section of the review provides a summary of the interdisciplinary links between hazard management and approaches to constructivism. Boundary-work, knowledge exchange and relationality can each be observed to theorise networked infrastructures such as Iceland. Firstly, this review has referred to how ontological boundaries can be progressively weakened in networks that are designed to manage volcanic hazards. By assessing the relevance of "boundary spanners" (Owen *et al.*, 2013, p.9) and information artefacts, this chapter has explained how constructivism can theorise the complexity and adaptability of hazard communication. Boundaries are generally defined by uncertainty and durability (Stalder, 1997) in constructivist approaches; for example, Latour's interpretation of actor-networks undermines boundaries by focussing on the connections of individual actors. Similarly, co-production marginalises boundary spaces by explaining how science, society and technology can synchronously construct knowledge and information. The empirics refer to multiple examples of boundary spanning technologies, and use interdisciplinary narratives to analyse the boundary relations within Iceland's network.

Secondly, partial knowledge is intrinsic to postmodern interpretations of hazard management, and explains why a mixed methods approach has been used in this study of Iceland (see pp.64-66). Partiality can be theorised by both actor-networks and co-production; for example, ANT considers knowledge to be partial until actuarial connections develop a black-box (Latour, 1987; 1993). Meanwhile, co-production describes how partial knowledge exists when social, scientific or technical controversies are unresolved. The empirics examine the ways in which the connections and adaptations of Iceland's network ensure knowledge can evolve from partial strands of quantitative data, to graphics and descriptions that can resonate with stakeholders from socio-political backgrounds.

Finally, this review has drawn on relationality to assimilate hazard management with understandings of actor-networks and co-production. For instance, ANT analyses the relational engagements between human and non-human actors, and implies that "nothing is ever sewn up" (Law, 1992, p.386). Therefore, actor-networks are able to theorise the dynamic stakeholder relations within networked infrastructures such as Iceland. On the other hand, co-production resonates with relationality by referring to how knowledge can be generated through collaboration between scientific, technical and socio-political communities. Both ANT and co-production associate relational engagements with the connectivity and construction of technology. The empirics outline how devices and systems are used to manage volcanic hazards in Iceland, and then assess their impact on stakeholder participation and the relational metaphysics of the network. From a theoretical perspective, this study is authentic as researchers have rarely combined aspects of both ANT and co-production, and have tended to view these approaches in isolation. This thesis analyses associations between the physical and social sciences, and regularly converses between conceptual theory and practice.

2.6: Outlining the subsidiary research questions

The following subsidiary questions resonate with the interdisciplinary narrative of this review and are intended to provide a reflective analysis of Iceland's network:

> 1) How have negotiations of power dynamics and technical actors impacted upon trust, collaborative practices, and flows of information in Iceland's volcanic hazard network?
>
> 2) What impact has stakeholders becoming sensitised to technology had upon the scale at which volcanic hazard networks have the capacity to adapt?

3) To what extent can Actor-Network Theory and co-production be used to interpret interactions between individual stakeholders and institutional entities?

Each question is designed to instigate subjective discussions of the common ground between the social, scientific and technical elements of volcanic hazard networks. Therefore, the questions are purposely holistic and exploratory, and can relate to the evolutionary processes of Iceland's approach to hazard management.

Chapter Three: A methodology for studying Iceland's volcanic hazard network from an interdisciplinary perspective

The preceding chapter explained the interdisciplinary premise of this PhD research, and highlighted the need for Iceland's network to be studied using a mixed methods approach. As the research relates to constructivist concepts such as Actor-Network Theory [ANT] (Latour, 1987; Law, 1992; Callon, 1999) and co-production (Whatmore, 2009; Landström *et al.*, 2011), qualitative analysis is required to interpret Iceland's geophysical environment. This approach allows the humanistic and socio-political characteristics of the network to be described through emotive arguments and opinions. The first section of this chapter refers to the philosophical context in which the methodology has been devised. Each of the three data collection methods, as well as the ethical considerations, are then outlined before the approach taken to conducting qualitative data analysis is explained (Attride-Stirling, 2001).

3.1: Methodological context

Nightingale (2003) and Fielding (2012) both imply that a mixed methods approach allows for additional flexibility in the collection and analysis of research findings. From this perspective, the semi-structured interviewing of stakeholders, participant observations of hazard management practices, and archival research of policymaking and social media use, are viewed as suitable methods for conducting fieldwork that is applicable to the research objectives (see p.20). These objectives were based on several assumptions; firstly, that an exploration of Iceland's network will exhibit a level of cohesiveness that brings together individual actors, technologies and institutional entities. Secondly, that opinionated evidence and first-hand experience of the network can be gained from engaging with scientists, policymakers and members of the public. It can be argued that this thesis takes for granted, and effectively black-boxes (Latour, 1987), the role, uptake and use of technology within Iceland's network. Whilst these assumptions can open the research up to potential flaws, the mixed methods approach is best equipped to minimise setbacks and gather qualitative evidence.

3.1.1: Philosophical perspectives

This PhD research is positioned from the philosophical perspective of grounded theory (Rowlands, 2005; McGhee *et al.*, 2007; Wyatt, 2013); for example, it starts with a research question and uses data analysis to build theoretical interpretations of a complex hazard network (Iceland). A grounded approach allows sociological concepts and trends to be identified based on the research question and objectives. The holistic and interdisciplinary scope of the research also uses constructivist approaches to analyse stakeholder interactions within Iceland's networked infrastructure. However, whilst the research can reflect elements of interpretive social science (Schwartz-Shea, 2014), the grounded approach is maintained as the data presented is ultimately tailored to the research question.

Each of the individual methods (semi-structured interviewing, participant observations and archival research) provide a means of gaining valid information that explains the sociology of Iceland's network. Collectively, these methods allow for a robust and triangulated exploration of Iceland's approach to volcanic hazards (Nightingale, 2003). The research findings refer to partial or situated knowledge (Hesse-Biber, 2012), but primarily convey an interdisciplinary narrative:

> Linking methods provides opportunities to examine the partiality of knowledge produced in different theoretical and methodological contexts (Nightingale, 2003, p.79).
>
> "Mixing methods" allows for the notion that such knowledges are partial and that different vantage points - for example interview participants' perspectives versus researchers' results from observation - will produce different views of particular processes and events (Nightingale, 2003, p.80).

A complete ethnographic reflection of Iceland's network is almost impossible to achieve as a result of its complexity and evolution. Furthermore, this study collects data from numerous institutions in Iceland, the UK and Europe. Due to the nature and breadth of the research, an ethnographic approach was not suitable as no single community or institution could have been studied in considerable depth (Hammersley and Atkinson, 1995; Scott-Jones and Watt, 2010).

Therefore, the research was orientated towards analysing the connectivity of stakeholders, rather than describing the internal dynamics of a specific community or institution. The fieldwork benefitted from being multi-sited, and not having to integrate wholly with one site; the value of the research stemmed from its ability to explore and analyse many sites with reasonable depth (Marcus, 2009). In addition, the limited timeframe and affordability of this study are also indicative of why an ethnographic exploration of the network was not feasible or appropriate in the context of the research. This explains why assumptions needed to be made prior to the fieldwork taking place, and why qualitative methods were used to describe and analyse decision-making processes (Nightingale, 2003).

A mixed methods approach enabled the holism of Iceland's network to be studied, primarily because it extended the scope and diversity of participants. The intention to study a plethora of stakeholder communities also explains the rationale for choosing semi-structured interviews, participant observations and archival research as suitable methods. Firstly, semi-structured interviews were opted for on the basis that the format would allow the research findings to reflect personalised experiences of the network:

> (Semi-structured interviewing) enables interviewees to provide responses in their own terms and in the way that they think and use language. It proves to be especially valuable if the researchers are to understand the way the interviewees perceive the social world under study (Qu and Dumay, 2011, p.246).

Here, Qu and Dumay illustrate how the semi-structured approach allows an individual's perception and mobility to be explored (Matthews and Rose, 2014). Furthermore, the semi-structured format also provides the flexibility to snowball participants (Seidman, 2013); interviewees could be asked whether they knew of other actors who could participate in the study.

When considering the interdisciplinary focus of the research, semi-structured interviews appear to be the most appropriate option for studying the positionality of stakeholders. However, quantitative measures could also have been used during the fieldwork, notably questionnaires or surveys that provide free response sections. A quantitative approach may have eased the process of data analysis (see pp.89-90), primarily by enabling it to be less time-consuming (Gill *et al.,* 2008; Ott and Longnecker, 2015). In addition, questionnaires and surveys are likely to have allowed for contributions from a larger number of stakeholders, with the potential to identify general trends in hazard awareness and the use of technologies (Bird, 2009).

However, quantitative procedures are less likely to reflect individual roles and contributions (McIntosh and Morse, 2015; Mann, 2016); semi-structured interviews can explore the specific interactions, perceptions and attitudes of each interviewee. For example, lines of questioning are not pre-determined, and responses can be probed once an answer has been given; in contrast, questionnaires and surveys do not facilitate ongoing discussion. Furthermore, the "informal feel" created by the semi-structured format allows emotion and opinion to be seamlessly integrated and openly expressed in the interview process (Adams and Cox, 2008, p.22). Therefore, a quantitative approach is less compatible with the research question and objectives; the value of the fieldwork stems from the richness of the empirical data. Other advantages of qualitative methods include the interviewee having the ability to control the flow of semi-structured interviews, and influencing the questions that are asked.

Participant observation is also a valid method for this research as it facilitates close contact with a range of stakeholders in institutional environments, allowing cultures and actions to be explored (Khagram *et al.*, 2010; Fazey *et al.*, 2014). However, the problems associated with "going native" (Gold, 1958, p.221) were also considered prior to the fieldwork; the observations risked becoming too involved with the institutions, and potentially clouding the research perspective (O'Reilly, 2009). Whilst the observations required empathy, steps were taken to lessen the risk posed. For example, numerous stakeholder communities were observed in a short space of time across Iceland; this prevented the research from becoming aligned to a single institution. In addition, observations were completed in one visit, and many were focussed specifically on an exercise or task; this minimised the risk of the research being skewed by a prolonged period of engagement. Therefore, the mixed methods approach and the design of the fieldwork meant that observations did not impact on the objectivity of the research.

Whilst not culturally focussed in the same manner as anthropological studies of hazard networks (Oliver-Smith, 1996), this research uses participant observations to analyse knowledge exchange, particularly within institutional settings. The shadowing of stakeholders has been central to this approach:

> Shadowing research does not rely on an individual's account of their role in an organization, but views it directly… shadowing can produce the sort of first-hand, detailed data that gives the organizational researcher access to both the trivial or mundane and the difficult to articulate… shadowing examines those individuals in a holistic way that solicits not just their opinions or behaviour, but

> both of these concurrently. Thus, actions are contextualized…. and every opinion is related to the situation which produced it (McDonald, 2005, p.457).

Shadowing allows real-time interactions to be identified and analysed (McDonald, 2005; Czarniawska-Joerges, 2007), and for uses of technology to be observed at first-hand. However, shadowing also risked participants acting abnormally once they were being observed and left the study vulnerable to researcher bias (Kawulich, 2012); both issues were taken into consideration when the findings were being analysed.

The evidence gathered from both interviews and observations has generally been compatible with the interdisciplinary narrative of the research, but the management of the data has required "qualitative content analysis" (Elo *et al.*, 2014, p.1). This has led to the findings being colour-coded (Attride-Stirling, 2001), and the extensive use of both Microsoft Word and NVivo. NVivo is a software package that is purposely designed to analyse large amounts of qualitative data; its development and application have been explained by Bazeley and Jackson (2013). As the study generates a considerable volume of information, NVivo has been used to organise the findings and establish connections between the various interview transcripts and observation reports. Therefore, NVivo has been integral to data management, and has enabled interpretive evidence to be sourced efficiently.

Aspects of power, trust, technology and communication were repeatedly discussed during both the fieldwork and archival studies; these broad themes can also be associated with the sociological frameworks that underpin the research. The findings were thematically analysed and colour-coded according to these four categories; this process enabled the data to be refined (Cresswell, 2013; Kitchin and Tate, 1999), and provided evidence of the grounded philosophy of the research (Timmermans and Tavory, 2012; Charmaz, 2014). Once the data had been categorised, an inductive approach ensured the coding remained open and the data was not rigidly bound by the category to which it was assigned (Elo *et al.*, 2014). However, the evidence is presented in an interdisciplinary context within this thesis, and the speculative nature of many findings contributed to an exhaustive data selection process (see pp.89-90).

3.1.2: Methods adopted by similar studies of volcanic hazards

Mixed methods research appears to be gathering pace within geography, and particularly in studies of contemporary hazard management (Barclay *et al.*, 2008; Bird *et al.*, 2009; Fearnley 2013; Donovan and Oppenheimer, 2014b; 2015). Chapter Two refers to natural hazards being explored and analysed from interdisciplinary perspectives, and this trend has highlighted the relevance and application of mixed methods. For example, Donovan and Oppenheimer's (2014b) study of Montserratian volcanoes analysed the interface between science and policy. The research gathered qualitative evidence through a mixture of semi-structured interviews and participant observations. The coding system used to organise and manage the findings mirrors the approach to qualitative data analysis outlined in this methodology (see pp.89-90). Prior to the work of Donovan and Oppenheimer, Haynes *et al.* (2007) had also used the Montserratian context to apply mixed methods to risk research:

> This 'mixed' methodology approach allows us to more fully identify the complexity of the issues that relate to risk perception and map comprehension and permits more confident conclusions [Horlick-Jones *et al.* 2003] (Haynes *et al.,* 2007, p.128).

Here, Haynes *et al.* (2007) refer directly to the merits of mixed methods, and explain the impact of the approach on how risk can be perceived, mapped and analysed; the methodology consisted of interviews and the statistical analysis of questionnaires. Therefore, multiple studies have applied a mixed methods approach to the complex and less economically developed context of Montserrat.

Furthermore, mixed methods have been used in an Icelandic context by Bird *et al.* (2009), and in a North American context by Fearnley (2013). In a study focussing on volcano alert levels, Fearnley (2013) used archival information and semi-structured interviews to conduct research at volcanic observatories in North America. Meanwhile, Bird *et al.* (2009) illustrated the relevance of mixed methods to understanding public perceptions. The research used questionnaires and face-to-face interviews to extract quantitative evidence of how risk is envisioned in the region of Þórsmörk, Southern Iceland. Collectively, these examples of approaches to mixed methods provide evidence of its increasing presence in studies of hazard management, and its positive impact on the interpretive capacity of researchers.

3.2: Research timeframe and location

This next section will outline the timeframe and locations used to conduct this PhD research, with fieldwork carried out in both Iceland and the UK. Due to the varied geographical locations, the research took place during separate fieldwork periods:

1. **March-April 2014:** A five-week fieldwork period spent in Iceland, during which 36 semi-structured interviews (see Table 3.2, pp.75-76) and 5 participant observations were conducted (see Table 3.5, pp.82-83). 9 monitoring or response agencies were contacted and researched, along with community-based stakeholders in Vík (Vík í Mýrdal) and Höfn (Höfn í Hornafirði).
2. **August and October 2014:** Two separate pieces of fieldwork, each with a duration of 5 days, were conducted in the UK. The August fieldwork took place at the Civil Aviation Authority (CAA) and the Cabinet Office in London. The October fieldwork was based at the London Volcanic Ash Advisory Centre (London VAAC) in Exeter and Diamond Aviation in Bournemouth. 10 semi-structured interviews (see Table 3.3, p.76-77) and 3 participant observations were carried out (see Table 3.6, p.83).

In addition, 18 Skype interviews were conducted intermittently between April and December 2014 (see Table 3.4, pp.77-78). Stakeholders that were unreachable in person, primarily due to time, geographical or financial constraints, were contacted in this manner.

3.2.1: Fieldwork conducted in Iceland (4th March 2014 - 8th April 2014)

The fieldwork was mainly conducted at institutional headquarters in or around the capital, Reykjavík (see Figure 3.2, p.71). However, community-based research also took place in Vík (Lat 6°.25'N, Long 19°1'W) and Höfn (Lat 64°15'N, Long 15°13'W).

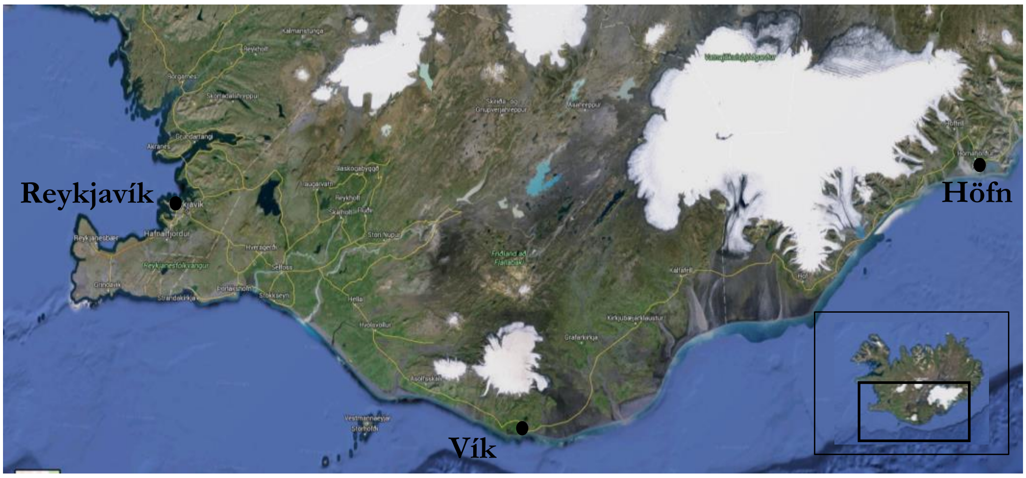

Figure 3.1: *The location of the three research sites in Southern Iceland (Source: Google Maps. Date accessed: June 2016).*

Initial visits were made to four prominent Icelandic institutions at the beginning of the fieldwork, namely the national aviation service provider (Isavia), the Department of Civil Protection (CP), the University of Iceland (UoI) and the Icelandic Met Office.

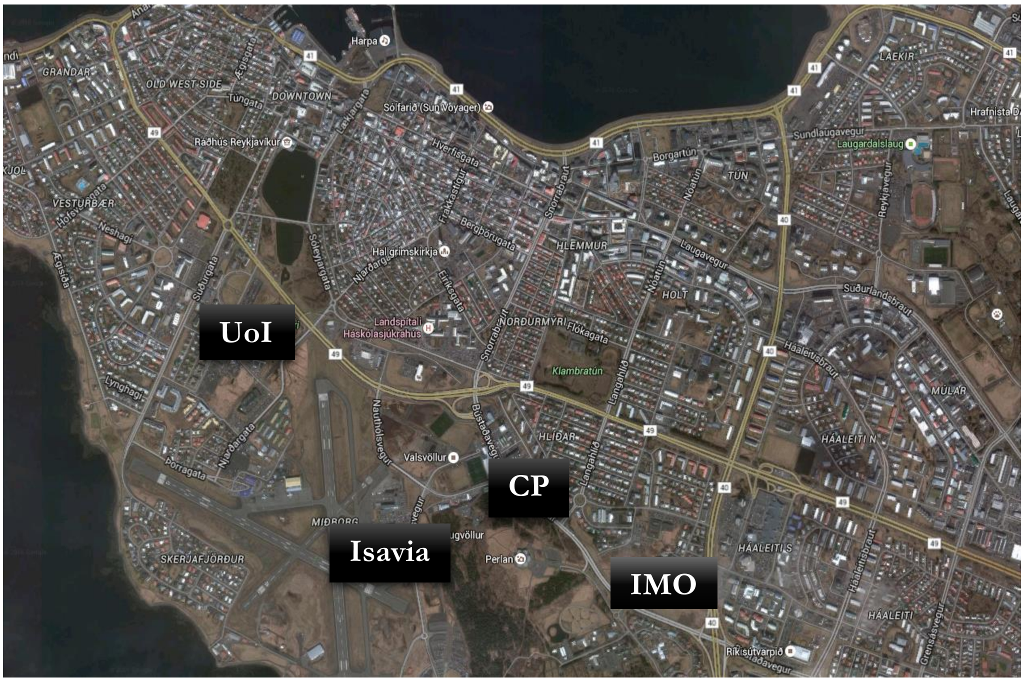

Figure 3.2: *Locations of the monitoring and response institutions in Reykjavík, where preliminary visits were made (Source: Google Maps. Date accessed: June 2016).*

During these preliminary visits, discussions were held in relation to what interviews could be arranged, and what observations were feasible when considering the duration, finance and objectives of the research. Each visit was pre-arranged by email communication prior to the fieldwork commencing, and made a significant impact on how the research progressed. For example, the visits not only allowed for a 'meet and greet' with leading representatives, but also enabled potential interviewees to be identified and contacted at the earliest opportunity. Therefore, the planning of the research was improved, and a fieldwork schedule was constructed.

Interviews and participant observations followed and were carried out on a regular basis with an extensive range of stakeholders from scientific, social and political backgrounds. Many of the participant observations were conducted relatively early during the fieldwork, and most of them provided networking opportunities that led to an increased number of interviews taking place in the latter weeks. Similarly, interviews conducted with the UoI led to contact being made with representatives of FutureVolc, an EU-funded project that is designed to encourage collaboration in the monitoring of volcanic hazards in Europe (see pp.103-106). As the fieldwork progressed, it adopted the snowballing method to broaden the range of interviewees (Seidman, 2013; Davies and Hughes, 2014; Lucas, 2014).

Snowballing is defined as when "samplers recruit and interview some volunteers, afterward asking for referrals to other potential respondents" (Lucas, 2014, p.394). By widening the scope of the research, the snowball technique made a significant contribution to the data collected. However, the reliance on the snowballing method can be challenged as it left the research vulnerable to sampling bias; respondents may have been inclined to mention colleagues who have similar views and outlooks to their own. Therefore, the range, representation and authenticity of the interview sample can be questioned. However, these concerns were recognised prior to the fieldwork, and measures were taken to mitigate against them. For example, the initial sample consisted of interviewees from civil protection services, scientific institutions, academic research communities and the aviation industry; this measure ensured there were a diverse range of participants from the outset.

Whilst much of the research took place in Reykjavík, the fourth week of the fieldwork was spent engaging with the communities of Vík and Höfn (see Table 3.1, p.73), in the south and east of Iceland respectively. Four days were spent in Höfn (23rd - 26th March), with a further three days in Vík (27th - 29th

March); this time allowed for semi-structured interviews to be conducted in both communities, and also at nearby farms. Institutions such as the UoI were returned to during the final week of the fieldwork, and follow-up interviews were conducted. These were also semi-structured and were designed to expand on the data that had been collected previously.

Table 3.1: Fieldwork timetable for Iceland (March - April 2014)

Week One: 4th - 9th March	• Initial meetings with four key institutions that had been contacted prior to the fieldwork (the IMO, the CP, the UoI and Isavia). • Several interviews and observations were arranged.
Week Two: 10th - 16th March	• A tour of the IMO, meeting the Natural Hazards representatives. Semi-structured interviews were conducted. • The VolcIce exercise was observed at the IMO and Isavia. • Follow-up interviews were conducted at Isavia.
Week Three: 17th - 23rd March	• Observations of IMO forecasting, including a tutorial of the software programs that are used to gather, program and share data and information. • Interviews were conducted with members of the FutureVolc project at the UoI.
Week Four: 23rd - 29th March	• Interviews were conducted with farmers, community leaders and members of the public in and around Höfn and Skaftafell National Park, as well as members of the Icelandic Red Cross in Vík and Þórsmörk Nature Reserve.
Week Five: 30th March - 8th April	• A tour of the media facilities at the CP, semi-structured interviews were also conducted. • Follow-up interviews carried out at the UoI in Reykjavík. • Preliminary arrangements made for UK-based fieldwork, following contact with the London VAAC and the British Geological Survey.

3.2.2: Fieldwork conducted in the UK (August and October 2014)

When interviewing or observing Icelandic institutions, notes were taken when participants referred to the collaborative links between Iceland and the UK. The semi-structured format of the interviews enabled these links to be probed, and numerous UK-based contacts were named. Once the fieldwork in Iceland had concluded, emails were sent to these persons or organisations; the research agenda was explained and a potential interview or observation was requested. Following several positive responses, the research was expanded to the UK and the fieldwork was designed to explore the stakeholder cohesion between the two countries. However, unlike the research conducted in Iceland, the UK-based fieldwork was considerably focussed and agency-specific:

> 1) **August 2014:** 3 interviews were conducted at the CAA and Cabinet Office in London, with an emphasis on policymaking and governance.
>
> 2) **October 2014:** 7 interviews were conducted at the London VAAC in Exeter and Diamond Aviation in Bournemouth, along with two participant observations; this research focussed on monitoring practices and responsibilities.

In contrast to the snowballing method, the interviews and observations conducted in the UK were pre-planned and targeted directly at leading institutions. Furthermore, the UK fieldwork was carried out on a much more restricted budget, and was supported by a grant from the Royal Geographical Society.

Nevertheless, the five-day duration of both research periods in the UK (August and October) enabled interviews to be flexibly scheduled with several relevant personnel. However, as the duration was not prolonged, unlike in Iceland, any follow-up interviews were conducted via Skype at a later date. Despite the financial and temporal limitations, the October research did lead to an unanticipated visit to Diamond Aviation at Bournemouth Airport, where an additional interview and observation were carried out. The methods and styles of data collection were largely unchanged between the field sites in Iceland and the UK; this enabled the research to examine the set-up of approaches to volcanic hazard management in both countries. The next section of this methodology refers to the specific process through which various stakeholder communities were interviewed, observed and researched.

3.3: Research methods and materials

3.3.1: Semi-structured interviewing

Interviews were a significant part of the research conducted at each of the study sites in both Iceland (see Table 3.2, pp.75-76) and the UK (see Table 3.3, p.76-77), and generated invaluable qualitative evidence. In addition, semi-structured interviews were also carried out intermittently via Skype with Icelandic, UK and global actors (see Table 3.4, pp.77-78); this demonstrates the scope and expanse of the research. The identity of participant(s) has remained anonymous throughout the fieldwork and transcription process, with contributors generally being referred to in this thesis through the title of the institution they represent (see pp.88-89 for a more extensive outline of the research ethics). An institutional role or position may occasionally be referenced, but only when the participant(s) cannot be traced.

Table 3.2: Interviews conducted in Iceland (March - April 2014)

Organisation and interview location(s)	Number of interviews	Type and role of organisation	Background and range of interviewees
University of Iceland, Reykjavík	6	A leading research institute for volcanic and earth science in Iceland, also a founding member of the FutureVolc community.	Interviewees were largely academics, PhD's and scientists from geophysical, geographical and sustainability backgrounds.
Icelandic Met Office, Reykjavík	7	The meteorological agency responsible for monitoring natural hazards.	Interviewees included specialists in volcanic hazards, seismic development and ash dispersion.
Department of Civil Protection, Reykjavík	4	The service provider for emergency management in Iceland.	Interviewees varied from departmental managers, project managers, PhD's and specialists in hazard response.
Isavia, Reykjavík Airport	4	The service regulator for air navigation in Iceland.	Interviewees were from aviation backgrounds and included project managers, exercise coordinators and air traffic control experts.
Environment Agency of Iceland, Reykjavík	1	An institution promoting public awareness of environmental risks, such as volcanic gas hazards.	The interviewee was a researcher and environmental specialist. Data was provided from an interdisciplinary perspective.

Reykjavík Metropolitan Police, Reykjavík	2	Reykjavík-based police, influential in responding to risks throughout Iceland.	Interviewees included department managers and personnel who were responsible for communicating through social media.
Icelandair, Keflavík Airport	1	The national airline of Iceland with experience of flying during volcanic crises, e.g. Eyjafjallajökull.	A representative was interviewed, offering an insight into how the airline adheres to advice and takes appropriate decisions during times of volcanic activity.
Icelandic Red Cross, Vík	2	A volunteer society assisting in hazard response.	Interviewees were community-based volunteers. The response measures taken during an eruption were outlined.
Icelandic Association for Search and Rescue (ICE-SAR), Reykjavík, Vík and Höfn	3	Search and rescue organisation trained in responding to a range of hazards that occur across Iceland.	Interviewees included personnel that had been involved in preparation and prevention exercises.
Miscellaneous	6	Various community roles/responsibilities.	Community leaders and farmers contributed.

Table 3.3: Interviews conducted in the UK (August and October 2014)

Organisation and interview location(s)	**Number of interviews**	**Type and role of organisation**	**Background and range of interviewees**
London Volcanic Ash Advisory Centre, Met Office, Exeter	7	The forecasting agency responsible for monitoring and modelling plumes of ash from erupting volcanoes.	Interviewees included strategic operations and technical managers, researchers in natural hazards, and the atmospheric dispersion and air quality teams.
Civil Aviation Authority, London	1	The regulatory body and policymaker for aviation in the UK.	A representative of the CAA provided an overview of how UK airspace is governed during a volcanic eruption.

Cabinet Office, London	1	The department of central government responsible for governing risks posed to the UK, including volcanic gas hazards.	An interview was conducted with a project manager who was responsible for the arrangement the Cabinet Office had with managing volcanic gas.
Diamond Aviation, Bournemouth Airport	1	An aviation consultancy and the location of the Meteorological Office Civil Contingencies Aircraft (MOCCA).	A technical specialist took part in an interview that focussed primarily on the use of the UK Met Office's MOCCA aircraft.

Table 3.4: Interviews conducted via Skype (April - December 2014)

Organisation and interview location(s)	Number of interviews	Type and role of organisation	Background and range of interviewees
Department for Transport (DfT), London	1	The government department responsible for transport in the UK.	The interviewee was a key member of the response team, whose objective it is to minimise the impact of volcanic activity upon transportation in the UK.
Nicarnica Aviation AS, Lysaker, Oslo, Norway	1	A private company specialising in the development of sensors that can identify and monitor volcanic ash plumes.	An interview was conducted with a project manager who has had close relations with monitoring institutions in Iceland.
Norwegian Institute for Air Research (NILU), Kjeller, Norway	1	A laboratory and research consultancy that aims to improve awareness of volcanic hazards and the impacts on aviation.	The interviewee was a creator of innovative technology that could be used to identify the presence of volcanic ash.
International Civil Aviation Organization (ICAO)	2	The global regulator and policymaker for aviation, overseeing VAAC's worldwide.	Interviewees included project managers. discussion topics were related to the policymaking process.

UK Universities (Cabot Inst., Bristol; Dept. of Earth Sciences, Cambridge; Sch. of Env Sci, University of East Anglia, Norwich)	7	Academic institutions studying Icelandic volcanism, based in the UK.	Interviewees consisted of research fellows, research associates, professors and PhD's who specialise in Icelandic volcanism and risk.
British Geological Survey (BGS), Nottingham	2	A body conducting geoscientific research in the UK. BGS also produce data that contributes to the monitoring of volcanoes in Iceland.	Interviewees included a technician and a researcher. Interviews were intended to highlight the links between the BGS and Icelandic organisations.
Rolls Royce, Derby	1	A manufacturer of engine components used on civilian aircraft.	An interview took place with a project engineer. Questions focussed on the interaction between ICAO, Rolls Royce and airlines.
EasyJet, Luton	1	An airline based in the UK. EasyJet have played a key role in trialling technology that has been designed to mitigate risks posed by volcanic activity.	A representative of the airline was contacted in relation to EasyJet's trialling of devices such as the Airborne Volcanic Object Imaging Detector (AVOID).
Follow-up Interviews	2	Follow-up interviews were conducted with both the Icelandic Met Office and the Civil Protection following the eruption of Bárðarbunga (2014-2015).	A follow-up interview was conducted with one representative from both institutions. Interviews were tailored to their respective monitoring and response practices.

The wide range of participating stakeholders illustrates the complexity of the research. In addition, it provides evidence of how the targeting of participants became distanced from the original focus on academics and scientists. By the second week of the fieldwork (see Table 3.1, p.73), the range of interviewees had begun to transcend the institutional boundaries of the IMO, the UoI, Isavia and the CP. Personnel from these institutions were initially chosen because of their alignment with the network's exchange of knowledge and information. The pool of interviewees gradually expanded as the research developed; for example, interviewing representatives of the CP led to contact being made with ICE-SAR, the Reykjavík Metropolitan Police and the Icelandic Red Cross. Whilst the approaches made to the recommended contacts were not always successful, in most cases an interview was arranged in due course.

Both networking and the exploitation of stakeholder connections were vital to broadening the research findings and gaining access to the various segments of Iceland's hazard network. Semi-structured interviewing made valuable use of the institutional overlaps and close-knit culture within Icelandic society; however, if this study were to be replicated in volcanic environments that are more politically or demographically challenging (Indonesia and Central/South America for example), considerable difficulties may be experienced. Nevertheless, the semi-structured format and snowballing of interviews was integral to the research extending beyond institutional headquarters in Reykjavík. Lines of questioning were modified accordingly to suit the diverse backgrounds of stakeholders, many of whom were not from scientific institutions.

However, regardless of data being gathered from a holistic array of stakeholder entities, the vast majority of interviews took place in either academic or workplace environments; these included the IMO and the UoI. On the rare occasion that an interview was conducted in a public or domestic location, the setting was noted so that any potential impact on the information shared could be acknowledged (Herzog, 2005). The equipment used during interviews consisted of a Dictaphone, provided free of charge by Aberystwyth University, and a field diary for recording notes. This PhD research was principally funded by the 'Doctoral Career Development Scholarship' from Aberystwyth University, and the 'Geographical Club Award' from the Royal Geographical Society. The funding meant that many interviewees were met in person; the face-to-face contact was significant as it enhanced data collection by establishing a good rapport (Brinkmann, 2014). Interviews conducted at the IMO, and in the community of Vík, varied from twenty minutes to two hours in duration; the lengthier interviews reflect the willingness of many participants to engage in the research.

Whilst the semi-structured format enabled lines of questioning to be individually tailored to the interviewee, a flexible and amendable schedule was drafted and trialled before the fieldwork commenced (see Appendix 1.2, pp.259-261). For example, questions were divided into three relatively distinct sections, titled A, B and C. In section A, questions were asked on the specific role and expertise of the individual, with the intention to explore their background and positionality within Iceland's network. This first section often expanded on the archival research that had been beforehand. Section B included open-ended questions, designed to probe and penetrate the interviewees' interactions. These questions were the most varied between each interview; for example, some focussed on mitigation partnerships or the use of monitoring devices, whilst others addressed inter-agency communication, social media use, or past experiences of volcanic activity. Section B allowed many interdisciplinary characteristics of the network to be identified and examined. Finally, section C focussed on the future evolution of Iceland's network, with questions relating to how its adaptability and resilience were perceived by various stakeholders. The interview schedule facilitated interdisciplinary discussion (Galletta, 2013; Matthews and Ross, 2010) and enabled penetrative arguments to reflect the key collaborative relationships, power dynamics and channels of communication within Iceland's network.

However, several challenges were experienced when arranging and conducting interviews. Firstly, the fieldwork carried out in Iceland did not take place in crisis settings and the only notable signs of activity were speculative rumours of a potential event at the stratovolcano, Hekla. If the fieldwork had taken place during August 2014, at the time when Bárðarbunga erupted, then the information gathered may have varied considerably. Furthermore, the UK-based research was conducted at a time when the eruption of Bárðarbunga was ongoing; therefore, inconsistencies can be identified in the context of the fieldwork. Despite there being few identifiable differences in the tone and narrative of the interviews, the situational variance posed an unexpected challenge. On the other hand, the timing and sequence of the Bárðarbunga eruption can also be interpreted as beneficial to the research; for example, if an eruption had occurred in Iceland whilst the research there was being conducted, the ability to collect data may have been significantly reduced. Furthermore, follow-up interviews were conducted with both the IMO and the CP following the peak of the Bárðarbunga eruption; these enabled situational differences to be partially bridged.

Secondly, exploring Iceland's network from a sociological perspective inevitably led to several misunderstandings of phrases and the research agenda. However, no significant problems were experienced as the interdisciplinary lens of interpretation was not dismissive of the natural sciences. Therefore, the narrative had sufficient scope to recognise and adhere to scientific processes and understandings. A further challenge stemmed from interviews covering topics that could be considered sensitive or judgemental. Whilst each interview had been designed to convey strong and emotive opinions, caution was required when lines of questioning touched on the socio-political implications of the Eyjafjallajökull eruption. In addition, topics such as the intrusion of the media and the evolution of intergovernmental relationships were often only discussed once they had been referred to by the interviewee. The preliminary trialling of interviews, conducted prior to the fieldwork, identified the discussion subjects that needed to be approached discretely.

A further challenge stemmed from the position of the researcher evolving between the separate fieldwork periods; for example, the interviews conducted in the UK had been influenced by the data collected in Iceland. Whilst unavoidable, the researcher's perception of the network had inevitably changed, impacting on the questions asked and the information sought. Several other issues were also experienced during the fieldwork; these included the need to avoid rhetorical questions, and the rejection of interview requests. From the large number of contacts that were approached (a total of 79), six potential interviewees refused to participate, a further seven did not respond to the request, and three cancelled because the time and/or location were unsuitable.

3.3.2: Participant observations

Participant observations took place at selected sites in both Iceland (see Table 3.5, pp.82-83) and the UK (see Table 3.6, p.83); some were focused on observing a specific agency, tool or stakeholder, whilst others observed monitoring exercises that spanned multiple institutions. Like semi-structured interviews, participant observations were intended to provide a qualitative account of Iceland's approach to hazard management, as well as first-hand experience of the network.

Table 3.5: Participant observations conducted in Iceland (March - April 2014)

Observation	**Participants**	**Type of observation**	**Duration**
VolcIce (Volcanic ash exercise in Iceland) Conducted: 11th March 2014	**IMO:** Technical staff, forecasting team and volcanic hazards co-ordinator. **Isavia:** Project manager and exercise leader. **London VAAC:** VolcIce exercise representative (audio call only).	The observation covered the exercise debrief, inter-agency communications, use of technology and in-house discussions. The location changed between the IMO and Isavia, but remained in Reykjavík.	The exercise was observed in its entirety, over a 5-hour period from 08.00 until 13.00 (approx.). The debrief was observed from 15.00 until 16.00 (approx.).
Seismic monitoring equipment and software demonstration Conducted: 18th March 2014	**IMO:** Technical staff and forecasting team.	A demonstration of how specific technical instruments and software programs are used to construct and communicate hazard information. Actions were fully explained and on-the-spot questions were asked.	Approximately two hours were spent observing the equipment.

Media suite and facilities (tour and discussion) Conducted: 31st March 2014	**CP:** Individual staff members experienced in communicating with the media.	A tour was given of the in-house facilities provided for domestic and international press conferences. A discussion between participants was observed and highlighted how the CP communicate with media outlets.	The tour and discussion lasted for approximately one hour (combined).
Isavia control room tour and demonstration Conducted: 21st March 2014	**Isavia:** Project managers and air traffic operations staff.	Isavia provided a tour of the control room and demonstrated how it functions during a volcanic crisis.	The tour and demonstration took two hours to complete (approx.).
University of Iceland group discussion Conducted: 1st April 2014	**UoI:** Research staff, academics and members of the FutureVolc project. Participants were from the Institute of Earth Sciences at the UoI.	A discussion meeting was observed without any intervention from the researcher. Topics included the FutureVolc project.	The discussion lasted for approximately one and a half hours.

Table 3.6: Participant observations conducted in the UK (October 2014)

Observation	Participants	Type of observation	Duration
VolcIce: Volcanic ash exercise (guide and tutorial) Conducted: 2nd October 2014	**London VAAC:** Both the strategic operations staff and forecasting team were involved.	The guide included a demonstration of the specific actions taken by the London VAAC at various points within the VolcIce exercise. Reference was made to the exercise that had previously been observed in Iceland.	The exercise was not studied in real-time but the demonstration took place over a period of approximately two hours.

MOCCA aircraft tour Conducted: 3rd October 2014	**London VAAC:** Technical staff responsible for the MOCCA aircraft.	The MOCCA aircraft was introduced, and the on-board equipment and monitoring facilities were explained. On-the-spot questions were asked.	The tour of MOCCA lasted approximately two hours during a visit to Bournemouth Airport.
UK Met Office forecasting room (tour and demonstration) Conducted: 4th October 2014	**UK Met Office:** Contributors included project managers and forecasters.	The use of technology and the process of communication were both demonstrated during a tour of the forecasting facilities at the UK Met Office.	Approximately one hour was spent completing the tour and demonstration.

Both scientific and aviation communities were observed during the research, with a specific focus on their means of communicating and use of sophisticated technology. By observing the actions of both individuals and stakeholder groupings, it became apparent how data is transferred and where communication channels are most valued. Some of the observations were unplanned and opportunistic, and were conducted as the research developed; examples include the tour of the media suite at the CP and the demonstration of seismic monitoring equipment at the IMO. However, the observation of the VolcIce exercise had been pre-arranged following communication with both the IMO and Isavia. Each observation involved shadowing stakeholders; this allowed on-the-spot questions to be asked and demonstrated Iceland's network in action (McDonald, 2005). By frequently asking on-the-spot questions, the research could penetrate the thoughts and explanations of the observed participant.

Shadowing reinforced the interconnected vision of the network as observations often allowed for a broad and holistic process of communication to be explored in real-time. Therefore, it became possible to identify where knowledge or information were actively co-produced, power was distributed, and the network was configured (McDonald, 2005). All observations were location specific and most were carried out within agency headquarters; the only exception was the observation of the MOCCA aircraft, which took place off-site at Bournemouth Airport. The agency setting added to the authenticity of the observations, primarily because it enabled stakeholder communication to be studied in a dynamic space that is operational during periods of volcanic activity. An informative field diary was used in each observation to record notes, diagrams and key quotations (see Appendix 3.1, p.266).

The qualitative nature of the field diary incorporated time-specific detail and description; therefore, it became a powerful attribute that had the capacity to record and explain any discrepancies. Furthermore, many observed actions could not be orally recorded and video was not an option due to the need to maintain anonymity. As a result, the field diary provided a means of recording individual communications and uses of technology; entries were initially short-hand in form due to time constraints, but were expanded upon when time allowed. Following each observation, the data in the field diary was coded accordingly and links to the interdisciplinary premise of the research were established. The observations varied considerably in duration, and this demonstrated the flexibility of the methodological set-up (see Table 3.5 [pp.82-83] and Table 3.6 [p.83]).

During the observations, technical tools and software's were not used at first-hand by the researcher; the exposure to them resulted from demonstrations of how they would be used, in crisis situations, by the actors responsible. The format of observations also had few commonalities; for example, some actively explored the VolcIce exercise step-by-step, whilst others required the researcher to be a silent observer. Furthermore, there were considerable disparities in the number of participants; for instance, some observations were specific to a department within an agency, and involved only five or six staff members. In contrast, other observations spanned collaborative engagements and addressed numerous actors from both scientific and non-scientific backgrounds.

However, whilst participant observations were largely successful, problems and constraints were experienced. For example, the observation of the VolcIce exercise was particularly problematic as it was carried out at an international scale across multiple institutions. The original intention was to conduct the observation at the IMO and Isavia in March 2014, and at the London VAAC in October 2014. However, due to a combination of the Bárðarbunga eruption (in August 2014) and a change in the responsibilities of the agencies involved, the October exercise could not go ahead as planned.

Nevertheless, the London VAAC were cooperative and used a demonstration of the exercise to illustrate the actions that would otherwise have been taken. Furthermore, this problem with the research is reflective of the tenuous, complex and unpredictable nature of volcanic hazard management. The problems experienced were unavoidable as the feasibility of the fieldwork meant the London VAAC could not be visited prior to the Bárðarbunga eruption. In addition, policy changes were enrolled whilst the fieldwork was ongoing, and this questioned the long-term relevance of exercises such as VolcIce (see pp.114-117). These structural changes to Iceland's network were beyond the control of this study and reflected the evolving dynamics of hazard networks.

3.3.3: Archival research

Both semi-structured interviews and participant observations were influenced by archival research. For example, when preparing for the fieldwork, or addressing any ambiguities that were accrued over the course of it, many policy documents, social media platforms and literary materials were frequently referred to and consulted.

Table 3.7: Archival research completed as part of the fieldwork

Topic	Source	Contribution to fieldwork	Time conducted
VolcIce exercise	**Internet-based:** Exercise reports were accessed and archived from links on the London VAAC website (see References, p.239).	These reports provided an insight into the outcomes of previous exercises, as well as structural changes and the use of its outputs.	**January - March 2014:** Prior to the fieldwork in Iceland.
Department of Civil Protection resources	**Literary-based:** Access was gained to CP resources that illustrated the mapping of risks.	Cartographic materials highlighted the municipal division of risk management in Iceland.	**March - April 2014:** During the fieldwork conducted in Iceland.

Decision-making within the aviation industry	**Internet-based:** The evolution of the decision-making protocol was researched. Policy documents were accessed to identify trends following Eyjafjallajökull.	Archiving policy alterations allowed the empirics to address the dynamism of both governance and decision-making within the aviation industry.	**April - August 2014:** Between the Iceland and UK-based fieldwork.
AVOID technology	**Internet-based:** Documentation of the testing process was studied (see appendix 3.2, p.268). Websites included EasyJet and NILU.	This research expanded on the understanding of AVOID, as discussed during interviews in Iceland.	**May - June 2014:** Following the fieldwork in Iceland.
UK intervention during the Eyjafjallajökull eruption (2010)	**Internet-based:** Minutes of Scientific Advisory Group for Emergencies (SAGE) meetings, and Cabinet Office Briefing Room (COBR) reports, were studied (see appendices 4.1 [pp.269-270] and 4.2 [pp.271-272]).	The minutes enlightened the researcher on the close links between Iceland and the UK, following the 2010 eruption of Eyjafjallajökull.	**August - October 2014:** Between the Iceland and UK-based fieldwork.
Social Media use during the Bárðarbunga eruption (2014-2015)	**Internet-based:** Social media sites were monitored daily for a duration of three months. Communications (messages, graphics) on Facebook and Twitter were stored (see Appendix 3.2, p.267).	Archiving social media interactions allowed the research to analyse the real-time use of such platforms in crisis situations. Pages studied included the IMO and the CP.	**August - October 2014:** During the Bárðarbunga eruption, and prior to the fieldwork conducted in the UK

Prior to the fieldwork being conducted in Iceland, much of the archival research centred on the discovery of background information. The actions of leading institutions such as the IMO and the London VAAC were researched to gain an understanding of the general structure of Iceland's network. However, as the fieldwork evolved, and the study adapted to events such as the Bárðarbunga eruption, the archival research became less pre-empted and more reactionary. Policy and material extracts were stored in a Word document and colour-coded in accordance with the thematic analysis (see pp.89-90). The information gathered was largely subjective and the most relevant segments were used to either influence the empirics, or to present evidence in the form of direct quotations. Much of the archival research was conducted in an office environment in the UK, or within institutional settings whilst on location in Iceland.

As many policy documents, exercise reports and social media resources have an openly accessible presence on-line, much of the information could be gathered without restrictions; the potential problems associated with archiving information have therefore been reduced. In addition, the digital presence of many documents and materials improved the efficiency of the research; for instance, resources could be accessed without needing to travel in person. However, much of the information collected towards the beginning of the research has inevitably become less accurate, and has since been updated. Nevertheless, the archival research that has been carried out has made a valuable contribution to the interpretive capacity of the research findings, and has facilitated a subjective analysis of Iceland's complex network.

3.4: Research ethics

When conducting both semi-structured interviews and participant observations, measures were taken to ensure that ethics and integrity were maintained at all times. For confidentiality and anonymity purposes, the names and identities of those participating were omitted from recordings and transcripts. Instead, reference has only been made to the agency or institution to which they are associated. These measures were intended to maximise clarity and trust between the researcher and the participant; interviewees are likely to be have been more inclined to share information that may not otherwise be divulged if they were identifiable (DiCiccio-Bloom and Crabtree, 2006). Assurances were offered through an informed consent document (see Appendix 2.1, pp.262-263) and an information sheet that clearly outlined the aims and objectives of the research agenda (see Appendix 2.2, pp.264-265). Each interviewee was required to sign the documents before the interview or observation could proceed. In addition, participants were given multiple opportunities to ask questions and raise any concerns they may have had. When presenting the data in this thesis, in the form of interview extracts and direct quotations, the institutional position or role of the respondent may also be referenced, but only when their anonymity can be maintained.

Participants also had the choice of whether a Dictaphone was used to record interview discussions. If there were objections to the Dictaphone, then notes were taken in a qualitative field diary instead. Following each interview or observation, participants were able to access a completed transcript and had the option of removing information that they felt should not have been included. These measures were necessary as observations sometimes recognised human error, and interviews often became personalised or focussed on a specific event or responsibility. When Skype was used to conduct an interview, the informed consent document was signed electronically or posted, and a Dictaphone continued to be used with the interviewee's permission (Sullivan, 2012).

However, ethical issues were experienced as some stakeholders were incorporated into the research whilst an observation was ongoing. For example, the forecasting team at the IMO interacted with the observed participants during the VolcIce exercise, and additional contributors joined a discussion meeting that was convened at the UoI. On both occasions, participants were observed whose engagement had not previously been anticipated, and who had not been briefed beforehand. This problem was unavoidable as the need to preserve the authenticity of the observations meant that they could not be interrupted or ended prematurely. Instead, each participant was retrospectively informed of what had taken place, and only once they had given their consent, could the observation be referred to in this thesis. Although some participants sought reassurance, there were no objections and the potential impact on the research was reduced.

3.5: Qualitative data analysis

The practice of transcribing the semi-structured interviews, and analysing the information documented in the field diary, was initiated shortly after the fieldwork in Iceland and the UK had concluded. Each interview was transcribed in full and then stored electronically in a Microsoft Word document. The transcription process extended until January 2015 due to the large quantity of information gathered. A thematic analysis (Attride-Stirling, 2001) was then carried out with the aid of an NVivo software package (Bazeley and Jackson, 2013); this led to the evidence being colour coded when it related to communication, technology, power or trust (see Appendix 1.1, pp.255-258). The analysis also identified the use of scientific or technical language, and multiple references to specific research projects and initiatives; these have since been explained in Chapter Four (see p.91).

The vast quantity of data collected has meant a level of choice regarding the use of evidence in this thesis. When analysing the research findings, some quotations were deemed to be powerfully expressive and of greater value to the empirics. Participants often referred directly to interactions between leading institutions and stakeholder communities, and mentioned specific technologies when providing examples of how Iceland's network continues to evolve. These findings are of considerable value to the research and are strategically positioned in this thesis. Furthermore, there has been a need to include quotations from across a wide range of stakeholder communities, both scientific and non-scientific. This ensures the findings are reflective of the network's holism and prevents speculative arguments from being dominated by evidence from a one-sided pool of participants. Therefore, the inclusion of selected quotations is determined by the quality of the content and the variation in the background of participants.

However, quotations are not simply outlined or alluded to briefly; due to the interdisciplinary focus of the research, this thesis intersperses quotes with extensive discussion that resonates with social theory. The subjective analysis of Iceland's network allows theory and practice to interact in a critical and speculative manner. Each of the approaches covered in this methodology were implemented effectively (semi-structured interviewing, participant observations and archival research), and have provided interpretations of the network that are of value to an interdisciplinary research agenda. Despite some notable constraints, the mixed methods approach has been compatible with the situational context of this PhD research.

Chapter Four: A contextual overview of Iceland's hazard network

This chapter provides a bridge between the methodological base of the research and the empirical evidence derived from the fieldwork. By exploring the projects, technologies and organisations that have been set-up between recent eruptive episodes, the context of the study is outlined. The eruptions of Eyjafjallajökull (2010), Grímsvötn (2011) and Bárðarbunga (2014-2015) have each provided opportunities to exhibit communication practices within Iceland's network. The first section of this chapter draws on the specificities of Icelandic volcanism, and uses them to explain how Iceland's approach to hazard management tailors itself to this study. An outline of the network's development follows and reference is made to how it has transformed since the eruption of Eyjafjallajökull in 2010. Recent eruptions in Iceland have had profound impacts on the UK; this has led to a robust strengthening of relations between the two countries. Much of the data presented in this chapter has emerged from archival research conducted following the fieldwork in Iceland (see Table 3.7, pp.86-87).

4.1: Icelandic volcanism: Unearthing the need for a complex hazard network

Iceland is located part-way between the continents of Europe and North America (64.9631° N, 19.0208° W), along the highly active Mid-Atlantic Ridge. This has resulted in the country experiencing significant levels of intense volcanic activity:

> Iceland is a high volcanic-risk area at an international level because its 30+ active volcanic systems generate relatively frequent and powerful eruptions (Sigmundsson *et al.*, 2013a, p.1).

The density of volcanic landforms within Iceland is extraordinarily high for a relatively small but geologically turbulent island; for example, unpredictable volcanic eruptions occur at regular intervals of approximately four or five years. The environment is also defined by multi-hazard events of both geological (volcanoes, earthquakes, jökulhlaups) and climatic (avalanche, flood, violent storms) origin (Bell and Glade, 2012). A sophisticated and flexible managerial set-up is therefore required to respond to the changing dynamics and situations (Donovan and Oppenheimer, 2015; Loughlin *et al.*, 2015).

4.1.1: The geology of Icelandic volcanism

Iceland's array of seismic hazards infinitely stems from the country's location on an active hotspot, along the divergent boundary that constitutes the Mid-Atlantic Ridge. With the North American and Eurasian plates moving apart at an average rate of approximately 2-5 centimetres per annum (United States Geological Survey - Understanding Plate Motions, 2016), the fissures beneath the earth's surface have manifested rift zones within which a vast majority of Iceland's volcanic landforms are found. Figure 4.1 (p.92) and Figure 4.2 (p.93) highlight the location of Iceland's volcanic systems in relation to the complex geological setting:

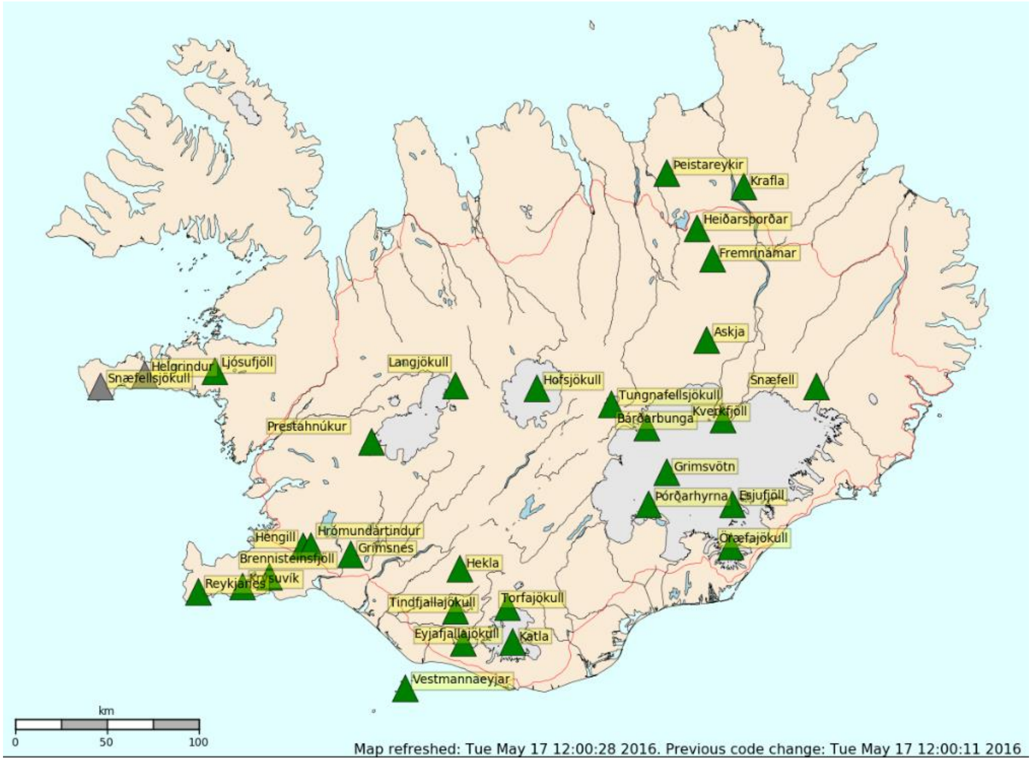

Figure 4.1: *The geographic spread and density of Iceland's volcanic systems, around which a complex hazard network is designed (Source: Icelandic Met Office - Earthquakes and Volcanism page. Date accessed: May 2016).*

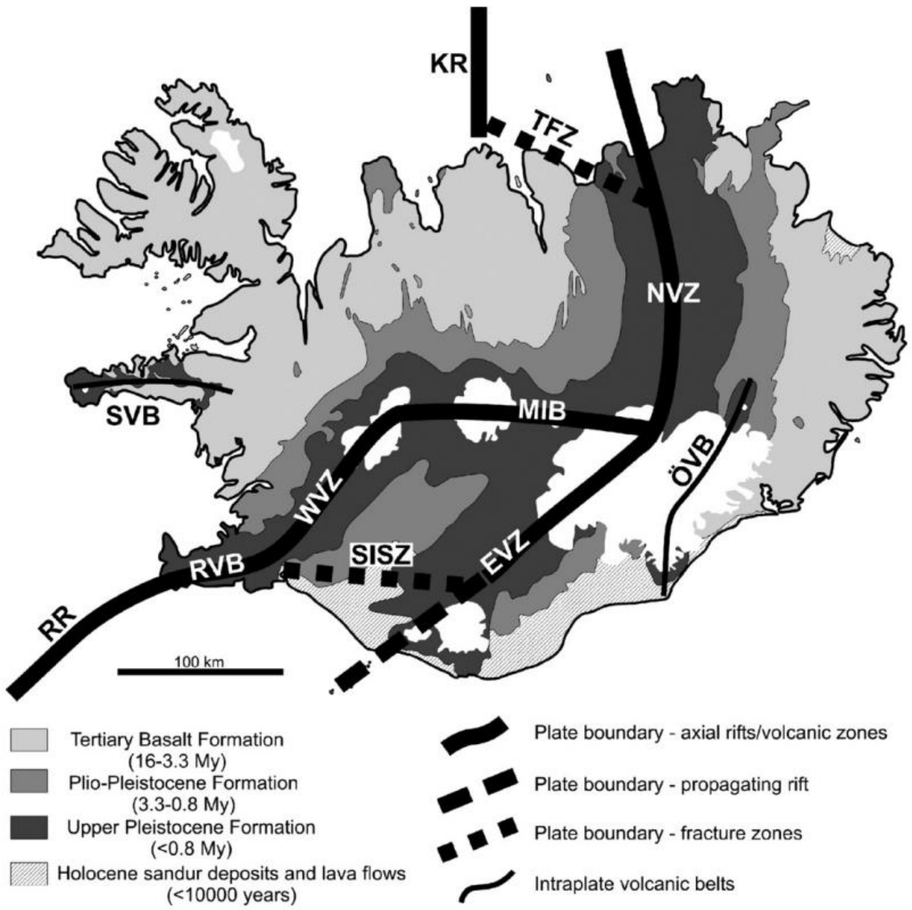

Figure 4.2: *A diagram of Iceland's geology, highlighting the location of the plate boundary and the volcanic zones (Source: Thordarson and Larsen, 2007, p.121).*

Therefore, Icelandic volcanoes are closely aligned with the plate boundary, but volcanism in Iceland should not be considered uniform. For example, disparities exist between the types of volcanic landforms and eruptions that occur. Landforms include stratovolcanoes, calderas and fissures such as Eldgjá, whereas eruptions can be either effusive (Laki, 1783-1784) or explosive (Eyjafjallajökull, 2010). As a result, the hazards stemming from Iceland's volcanic events can be contrasting; primary hazards include lava flows, pyroclastic flows, ash fall and gas pollution, whilst secondary hazards include jökulhlaups and debris flows. With each hazard varying in temporality, characteristics and impact (Thordarson and Larsen, 2007), the mitigation of risk is challenging and stringent mechanisms are required to monitor and respond to ongoing activity.

4.1.2: Anthropogenic vulnerabilities associated with Iceland's volcanoes

The 2010 eruption of Eyjafjallajökull instigated international publicity and notoriety towards Icelandic volcanoes (Budd *et al.*, 2011). However, the catastrophic impacts of volcanic activity have been felt historically, notably during and following the effusive fissure eruption of Lakagígar (Laki, 1783 - 1784). The eruption claimed the lives of approximately one quarter of Iceland's population, largely because of crop failure and the consequential famine across Europe. This case demonstrated not only the severity of the risks posed by volcanoes in Iceland, but also the vulnerability of humanity (Witham *et al.*, 2015). Grattan *et al.* (2003) established that increased mortality rates in England, and across Europe, had coincided with the eruption of Laki:

> July 1783 - June 1784 is recognized as containing a one-star mortality crisis, indicating an annual mortality rate 10 - 20% above the 51- year moving mean; which qualitatively describes the state of the nation's health in the period as 'unhealthy'. In fact, the national death rate for 1783-1784 has been calculated to have been 16.7% above the projected trend for this period (Grattan *et al.*, 2003, p.405).

The risk of volcanic gas and haze continues to be a potential future threat to European countries; these hazards are very different compared to those caused by short duration or explosive eruptions such as Eyjafjallajökull.

However, in more contemporary times, the impacts of explosive eruptions have been magnified by the vulnerability of Europe's dense aviation hub and transatlantic flightpaths. These key transport links are prone to ash-induced disruption stemming from Icelandic volcanism. Therefore, the pivotal location of Iceland between two economically developed continents (Europe and North America) is symbolic of the many unique characteristics and challenges of this volcanic environment (see pp.92-93). Iceland's sparse but highly educated population of approximately 330,000 people (Statistics Iceland, 2016), also highlights the need for a specialised approach to hazard management. Whilst much of the population is demographically centred on the capital city, Reykjavík, at a relatively safe distance from many of Iceland's volcanoes, the country has an array of natural and social particularities that add to the resilience of the network. Iceland's seismic and socio-economic credentials collectively make the island nation a complex, resilient and intriguing volcanic environment to study.

4.2: From Eyjafjallajökull to Bárðarbunga: Developing Iceland's hazard network

Iceland's specific characteristics and attributes, both geological and social, illustrate the need for a resilient and adaptable approach to managing volcanic hazards. This section of the chapter describes the changes that have been made to the network following a series of large-scale eruptions since 2010. Recent eruptive episodes have tested the dynamism of the network and have reconfigured the connections that exist between individual stakeholders and institutional entities. Both the domestic and international set-ups are evolutionary, but also contrasting; this reflects the network's diversity.

The Department of Civil Protection (CP) and the Icelandic Met Office (IMO) occupy leading roles at a domestic level in Iceland, but are reliant on a plethora of institutions for support and expertise. The actions of the CP are bound by the Civil Protection Act:

> To prepare, organise and implement measures aimed at preventing and, to the extent possible, limiting physical injury or damage to the health of the public and damage to the environment and property (Department of Civil Protection - Civil Protection Act, 2008, article 1).

Therefore, the CP are primarily responsible for coordinating actions at the national scale; response measures require extensive planning and are divided into three phases (uncertainty, alert and emergency). The structure of the CP has various levels of engagement, and strategies for responding to an event can be regionalised to municipal authorities (see Figure 4.3, p.96). However, responsibilities are ultimately devolved to the "National Commissioner of the Icelandic Police" (Elíasson, 2014, p.104), with command centres taking a leading role during times of emergency, and administering actions that are intended to alleviate risk. Several institutions actively work alongside the CP on a regular basis; these include the Environment Agency of Iceland, the Icelandic Police, and the Icelandic Association for Search and Rescue (ICE-SAR).

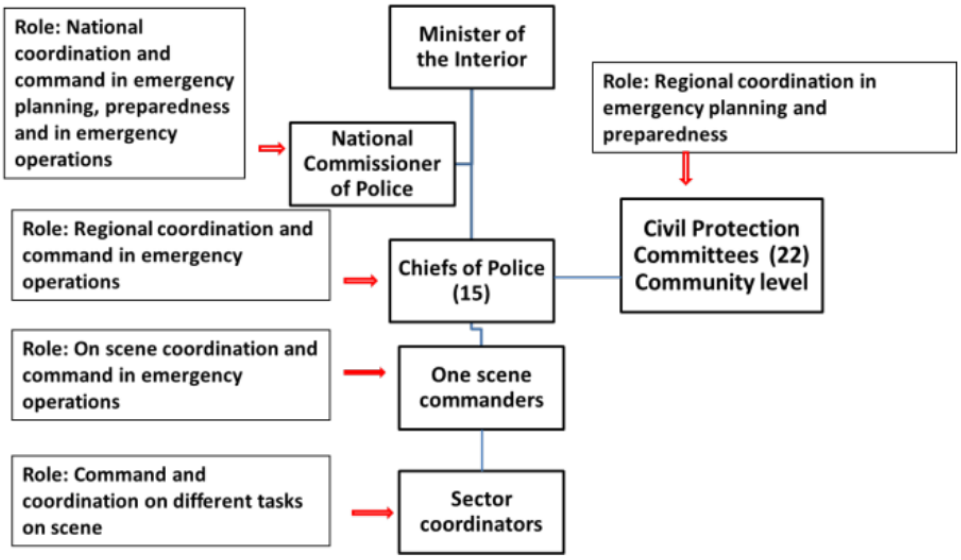

Figure 4.3: *The systematic structure of the civil protection service in Iceland (Source: Elíasson, 2014, p.104).*

Meanwhile, the IMO are responsible for "monitoring natural hazards in Iceland and conducting research in related fields" (Icelandic Met Office - Mission, 2016). The IMO's domestic partners include the University of Iceland (UoI) and Isavia, Iceland's aviation service provider. Both the CP and the IMO work across numerous natural hazards and have extensive affiliations with academic research. However, neither can be viewed in isolation as they are both required to communicate with a wide range of stakeholders, and are wholly reliant on technical devices and software packages. Ideologically, the IMO and the CP focus on different stages of the hazard management process (monitoring and response respectively), but their actions inevitably overlap and the level of engagement between them is considerable.

4.2.1: Instigating change: The eruption of Eyjafjallajökull (20th March - 23rd June 2010)

The first of Iceland's large-scale volcanic events, since 2010, was the now notorious eruption of Eyjafjallajökull; the impacts were widespread as dense volcanic ash was emitted and posed a threat to aviation. Fears of the ash eroding the engines of civilian aircraft, and leading to engine failure as a result of abrasion and overheating, prompted disruption to the aviation industry across Europe. Whilst other risks included potential damage to an aircraft's fuselage and interaction with contaminated air, the vulnerability of engines are viewed as a critical risk (Miller and Casadevall, 2000, in Alexander, 2013a). Incidents such as British Airways Flight 009 (Tootell, 1985; Johnson and Casadevall, 1994; Witham *et al.,* 2012), when a passenger aircraft experienced engine failure following contact with an ash cloud from Mount Galunggung in Indonesia, had raised awareness of the dangers associated with volcanic ash. As a result, the aviation industry reacted to the Eyjafjallajökull eruption in a cautionary manner.

However, the physical impacts of Eyjafjallajökull cannot be understated; for example, the phreatomagmatic eruption measured four on the Volcanic Explosivity Index [VEI] (Szakács and Seghedi, 2013). The volatile interaction of water and magma produced concentrations of ash that led to the shutdown of the aviation network across Europe. In addition, Eyjafjallajökull illustrated how the prevailing wind direction and meteorological forecast has the capacity to re-energise the spread of highly viscous volcanic material (ash, dust and pyroclastic deposits). For example, the wind direction extended the distribution of ash across the Western and Central European landmass (Petersen *et al.*, 2012; Ripepe *et al.*, 2013), expanding the geography of the airspace affected:

> The combination of a prolonged and sustained eruption of fine ash and persistent northwesterly winds transporting the ash towards southeast, resulted in dispersal of ash over a large part of Europe (Gudmundsson *et al.*, 2012, p.1).

Whilst the eruption affected rural Icelandic communities such as Fljótshlíð, and led to numerous evacuations, the expanse of the ash plume (see Figure 4.4, p.98) and the concentration of very fine ash particles meant that the greatest impacts were felt at an international scale. Levels of uncertainty cannot therefore be entirely related to the aviation industry's lack of preparedness, but can also be explained by seismic and locational factors.

Figure 4.4: *A satellite photograph of the ash plume emanating from Eyjafjallajökull in 2010, headed in a south-easterly direction and being transported towards mainland Europe and the UK (Source: British Geological Survey [BGS] - Volcanoes: Icelandic ash research page. Date accessed: May 2016).*

Nevertheless, whilst the Eyjafjallajökull eruption was ongoing, monitoring techniques were available to record ash dispersal in real-time. The lack of communication between the aviation industry and scientists undoubtedly prolonged the crisis. The five-day closure of European airspace (15^{th}-20^{th} April 2010), and the cancellation of 95,000 flights by 21^{st} April 2010 (eventually reaching over 100,000), were arguably as much an outcome of the aviation industry's mismanagement as they were the result of seismic and meteorological processes (Sammonds *et al.*, 2010; Wilson *et al.*, 2014). Closer discussion has since been instigated between scientific institutions and the governing bodies of the aviation industry. Whilst the eruption was ongoing, amendments were made to the protocol for closing airspace; this enabled airspace across Central Europe to be reopened, but also reflected the chaotic and reactionary response to the event:

> Under pressure from airlines, the UK Civil Aviation Authority (CAA) established ad hoc thresholds for safe ash concentrations that allowed the resumption of commercial flights (Sammonds *et al.*, 2010, p.3).

The mobilisation of the threshold reflects the improvisation of the aviation industry's approach to handling the crisis; it also exposed the knowledge gap between policymakers and scientists.

Alexander (2013a) is amongst the many researchers who have been critical of the aviation industry, and implied that the strategy for managing the crisis was based on a "passive 'wait and see' approach" (Alexander, 2013a, p.14). Attention has also been drawn to the political and social conflicts that emanated across Europe because of the airspace closure:

> Eurocontrol, the European Organization for the Safety of Air Navigation… did not move towards a harmonized approach until impelled to do so by the European Commission at a meeting held on 19 April, well into the crisis (Brannigan 2010, in Alexander, 2013a, p.14).

Here, Brannigan refers to the slow and inadequate response of policymakers and strategists, reflected in the lack of coordinated action until the full scale of the crisis had become clear.

However, the notoriety of the event has undoubtedly led to increased investment in monitoring technologies, and has improved levels of engagement between the aviation industry and the scientific community. These measures have helped to elucidate the concentrations of volcanic ash that are considered dangerous to aircraft. Therefore, the 2010 eruption of Eyjafjallajökull can be interpreted as a watershed moment in managing Icelandic volcanism:

> The event was a moment of truth… it dramatically illustrated that Europe's airspace control and coordination system was divided and dysfunctional (Alemanno, 2010, in Parker, 2015, p.102).

Alemanno recognised how the event represented the failings of the industry, and implied that Eyjafjallajökull would directly impact on responses to future volcanic events (Donovan and Oppenheimer, 2012).

4.2.2: Post-Eyjafjallajökull: The eruption of Grímsvötn (22nd May - 25th May 2011)

The 2011 eruption of Grímsvötn had similar characteristics to Eyjafjallajökull, which occurred a little over a year earlier. However, as Grímsvötn was a Plinian eruption (Marzano *et al.*, 2013), the vast quantities of ash emitted were coarse rather than fine. Therefore, the spatial distribution of the particles was much more constrained and the airborne duration was considerably shorter; this limited the potential contamination of airspace. Nevertheless, the eruption measured VEI 4 (Gudmundsson *et al.,* 2014), and had a significant impact on the communities living under the shadow of the ash cloud. Whilst Grímsvötn caused relatively little disruption to international air travel, compared to 2010, there remained extreme tension within the aviation community at a time when the industry was recovering from the economic damage caused by the Eyjafjallajökull eruption. In addition, the location of Grímsvötn, beneath the Vatnajökull glacier, meant there was the potential for a phreatomagmatic eruption that could produce basaltic materials on a level equivalent to Eyjafjallajökull (Gudmundsson, 2012). Consequently, fears were heightened in the aviation industry across Europe, and the need for continued interaction with scientists became clear.

Northerly winds were the protagonist for the 15-20 km high plume and 50-100 km wide umbrella cloud that developed as a result of Grímsvötn; the cloud extended from the south of Iceland to Scandinavia and Northern Europe. However, unlike the eruption of Eyjafjallajökull, only low concentrations of ash were transported (Gudmundsson, 2012). Therefore, the risk posed to civilian aircraft in Central and Western Europe remained extremely low. In addition, the response of the aviation industry was rigorous rather than precautionary, and acknowledged the thresholds for safe concentrations of ash. Despite 900 flights being cancelled across Europe during the Grímsvötn eruption (Parker, 2015), the assessment of the response strategy was considerably less critical than it had been in 2010; for example, it was defined by coherence rather than contradiction.

At a domestic level, the ash stemming from Grímsvötn impacted on surrounding regions, causing poor visibility, road closures, health concerns and damage to rural and agricultural communities (e.g. Kirkjubæjarklaustur) across Southern Iceland (Eiser *et al.*, 2015). However, despite the widespread impacts felt within Iceland, the actions taken by the aviation community remained the focus of international media coverage (Budd *et al.*, 2011). The relatively short temporal margin between the eruptions of Eyjafjallajökull (2010) and Grímsvötn (2011) allowed for rapid and drastic changes in the network to be recognised. For example, Parker (2015) identifies several measures that contributed to the aviation industry's improved management and communication of the event:

> In December 2010, ICAO finalized the revision of its 'volcanic ash contingency plan' for Europe, including standardized guidelines for alerting aircraft when eruptions occur, which procedures should be followed, and for the possible closure of airspace. This guidance material capitalizes on the crisis learning that took place in the Eyjafjallajökull case from 17th to 18th Apr (Parker, 2015, p.102).

Parker refers to the impact of agreements between scientists and decision-makers; the precautionary approach was not ignored, but the amended guidelines had the clarity and flexibility required to avoid a prolonged shutdown of European airspace. Furthermore, prior to the Grímsvötn eruption beginning, the aviation community had been continually active in engaging with scientists and had refined the protocol for responding to volcanic hazards (Donovan and Oppenheimer, 2012). This progressive movement was indicative of a change in the culture of the International Civil Aviation Organization (ICAO), the industry's governing body.

However, whilst advances were made between the Eyjafjallajökull and Grímsvötn eruptions, lingering tensions between scientists and airlines highlighted the need for further improvements to communication and knowledge exchange. For example, Ryanair objected to the closure of Scottish airspace and disputed scientific claims (Donovan and Oppenheimer, 2012). Nevertheless, Parker (2015) suggests that preparatory measures were significantly improved, and refers to the influence and scope of training exercises:

> An ICAO volcanic ash simulation exercise took place to test the effectiveness of changes and improvements to the ICAO volcanic ash contingency plan, ash guidance, and procedures… involved 77 airlines, 14 air navigation service providers, 10 national regulatory authorities, VAAC London, as well as the European Commission, EASA (European Aviation Safety Agency), and Eurocontrol… the European Crisis Visualisation Interactive Tool for Air Traffic Flow and Capacity Management - an interactive tool to support decision making of civil aviation authorities, air navigation service providers, and airline operators - was tested (Parker, 2015, p.103).

The exercise Parker refers to was conducted during the intermediate period between the two eruptions, and illustrated the collaborative efforts of scientists and the aviation industry. Parker (2015, p.103) labelled the exercise a "dress rehearsal" and directly related it to the successful management of the Grímsvötn eruption. Grímsvötn occurred at a time when the aviation community were responding to international scrutiny and undergoing a phase of rapid structural change, influenced by the uptake of new technology (Johnson and Jeunemaitre, 2011). Parker refers to both a holistic range of participants and the use of innovative tools, highlighting the steps taken to avoid another chaotic response to a potentially disruptive volcanic event.

The drastic changes made to the approach of the aviation industry cannot be compared to how volcanic hazard management has been transformed at a local and national level in Iceland. For instance, Icelandic's had not generally been exposed to the frenzied overseas reaction to the 2010 eruption (Harris *et al.*, 2012), and the wave of hysteria that swept through European and North American media outlets. Therefore, Icelandic institutions were not under pressure to alter their approach; for geophysical reasons, the impacts at ground level were more severe during the Grímsvötn eruption, but there were few notable differences in the CP's response to the hazard. This is not a criticism of the Icelandic authorities, as on both occasions (2010 and 2011), the management of the hazard was defined by coherence rather than anxiety.

4.2.3: Between Grímsvötn and Bárðarbunga (29th August - 27th February 2015): Explaining FutureVolc and the Emergency Response Coordination Centre

Following the tumultuous events of the Eyjafjallajökull and Grímsvötn eruptions, several European-wide projects were initiated to reduce uncertainty and encourage closer engagement between stakeholders (Dumont *et al.,* 2014; Puglisi *et al.,* 2014). With over three years of relative quiescence separating the Grímsvötn and Bárðarbunga eruptions, many proposals to improve investment, communication and dialogue, had come to fruition. The eruption of Bárðarbunga lasted for a duration of almost six months (approximately twice the length of Eyjafjallajökull in 2010); the separation of the plates was marked by an increasingly frequent swarm of earthquakes prior to the main eruption (Riel *et al.*, 2015). Bárðarbunga's location (see Figure 4.1, p.92) beneath the Vatnajökull glacier (Gramling, 2014) prompted fears of a large-scale phreatomagmatic eruption, with the potential to disrupt international air travel. However, following a 1.5km fissure eruption within the Holuhraun lava field (Dumont *et al.*, 2015; Jónasdóttir *et al.*, 2015; Schmidt *et al.*, 2015), aviation warnings were downgraded as the development of an ash cloud became less likely. Instead, effusive basaltic magma formed an extensive lava flow and led to increased levels of gas pollution. In response, daily notifications were issued by the CP and the IMO to affected regions in Iceland, as well as to Scandinavian countries (Björk *et al.*, 2015). The remote location of the volcano minimised the impact on rural communities and limited disruption to restrictions on accessibility.

FutureVolc is an example of a project that was devised following the eruptions of Eyjafjallajökull (2010) and Grímsvötn (2011). With the funding of an EU grant, FutureVolc contributed significantly to the monitoring of the 2014-2015 eruption at Bárðarbunga. The project was funded to strengthen the monitoring of volcanic hazards in Europe, with stakeholders from both scientific and socio-political communities supporting a continental approach. FutureVolc comprised of 26 partners from 10 European countries (FutureVolc Project - main page, 2016), and incorporated Volcanic Ash Advisory Centre's (VAAC's), meteorological offices and civil protection services; starting in 2012, the project was active for a duration of three and a half years.

The main aim of the FutureVolc community was to provide a single repository for gathering and distributing hazard information; this would allow stakeholders to acquire relevant data in an efficient manner. The project also intended to centralise monitoring practices, combine knowledge and expertise, and reinforce stakeholder engagements with technical instruments. Sigmundsson *et al.* clearly outline the main aims of the project:

> (i) Establish an innovative volcano monitoring system and strategy
> (ii) Develop new methods for near real-time integration of multi-parametric datasets
> (iii) Apply a seamless transdisciplinary approach to further scientific understanding of magmatic processes
> (iv) To improve delivery, quality and timeliness of transdisciplinary information from monitoring scientists to civil protection
> (Sigmundsson *et al.*, 2015, id.11846).

The scope of end-users to whom the project is intended to reach is notably expansive. Each of the aims work towards the integration of data, expertise and technical infrastructures within complex networks such as Iceland.

A key attribute of FutureVolc is the concept of a supersite, namely an area with numerous large-scale volcanic hazards, where data and monitoring observations can be integrated. By accrediting an area 'supersite' status, the project seeks to improve the management and sharing of information (Sigmundsson *et al.*, 2013a):

> The supersite concept implies integration of space and ground based observations for improved monitoring and evaluation of volcanic hazards, and open data policy (FutureVolc Project - Supersites, 2016).

The supersite is designed to centralise the study area, and confine relevant datasets and communication channels. Contextually, the laboratory landscape of Iceland provides an ideal setting for this element of the project to be recognised:

> Iceland is selected as a laboratory supersite area for demonstration because of (i) the relatively high rate of large eruptions with potential for long ranging effects, and (ii) Iceland's capability to produce the near full spectrum of volcano processes at its many different volcano types (Jordan *et al.*, 2013, p.287).

Here, the high density and varied array of volcanic hazards in Iceland are interpreted as environmental qualities that can define what a 'supersite' represents.

FutureVolc had been fully enrolled by the time the eruption of Bárðarbunga began in 2014; therefore, its contribution to the management of the hazard can be assessed. The project impacted on the technical infrastructure of Iceland's network, and this has since been documented:

> During and after the Bárðarbunga unrest, 16 new GPS sites were installed. These sites played a major role in constraining the deformation field of the dyke intrusion and the subsidence of the Bárðarbunga caldera, thus enabling the modelling of the magma migration and volume change (FutureVolc Project - Exploiting the outcome of FutureVolc report, 2016).

The report draws attention to the flexibility of the project and its relevance to the positioning of technical instruments (Sigmundsson *et al.,* 2016). Furthermore, references to the installation of new equipment reflect the investment in the "major field campaign" which "took place both on ground and from aircraft" during the eruption of Bárðarbunga (FutureVolc Project - Exploiting the outcome of FutureVolc report, 2016). The collaborative efforts of the FutureVolc community were outlined at length in the report, in addition to the project's impact on the efficiency of data management, and the improved ability to share hazard information.

As Bárðarbunga allowed FutureVolc to be analysed in the context of an active crisis situation, the influence of the project on specific response practices can be explored. For instance, communication proved to be far more efficient at a domestic level than it was during the eruptions of Eyjafjallajökull and Grímsvötn; whilst this could have been caused by a number of factors, the 'Exploiting the outcome of FutureVolc' report made a direct link to the project:

> Following the Holuhraun eruption (Bárðarbunga), a questionnaire was distributed to the recipients of the Scientific Advisory Board Factsheet. The Factsheet was sent to 774 email addresses (397 in Icelandic and 377 in English). The survey reveals that the total circulation of the Factsheet was about 8000 recipients. Over 90% of responders believe communication and flow of information was either better or much better during Bárðarbunga in 2015 than in Eyjafjallajökull in 2010 and Grímsvötn in 2011 (FutureVolc Project - Exploiting the outcome of FutureVolc report, 2016).

The FutureVolc community had influenced the introduction of the factsheet (see appendices 6.1 [pp.277-278] and 6.2 [p.279]), which the report relates to the improved communication of risk. Therefore, by constructing informative materials, FutureVolc were instrumental to the exchange and distribution of hazard information at a time of uncertainty.

The "Catalogue of Icelandic Volcanoes" provides a further example of FutureVolc's ability to transform communication practices (Ilyinskaya, *et al.*, 2015, p.12391); as a data repository, it can be accessed online and is open to the public. By containing and representing vast quantities of information, the catalogue enables stakeholders from non-scientific communities to explore Iceland's volcanic systems (see Figure 4.5, p.106). For example, datasets can be customised by a wide range of end-users, and communicated in real-time when conveying knowledge of ongoing activity. Therefore, the catalogue is a reflection of the scope and outreach of the FutureVolc project. However, unlike the factsheet, the catalogue was incomplete at the time of the Bárðarbunga eruption, so it was not a prominent tool in the management of the hazard. Nevertheless, Bárðarbunga "provided a real-world test for FutureVolc, from which further developments were identified" (FutureVolc Project - Exploiting the outcome of FutureVolc report, 2016); the project remained a work in progress at the time, but the event enabled its various outputs and initiatives to be assessed based on their relevance, value and performance.

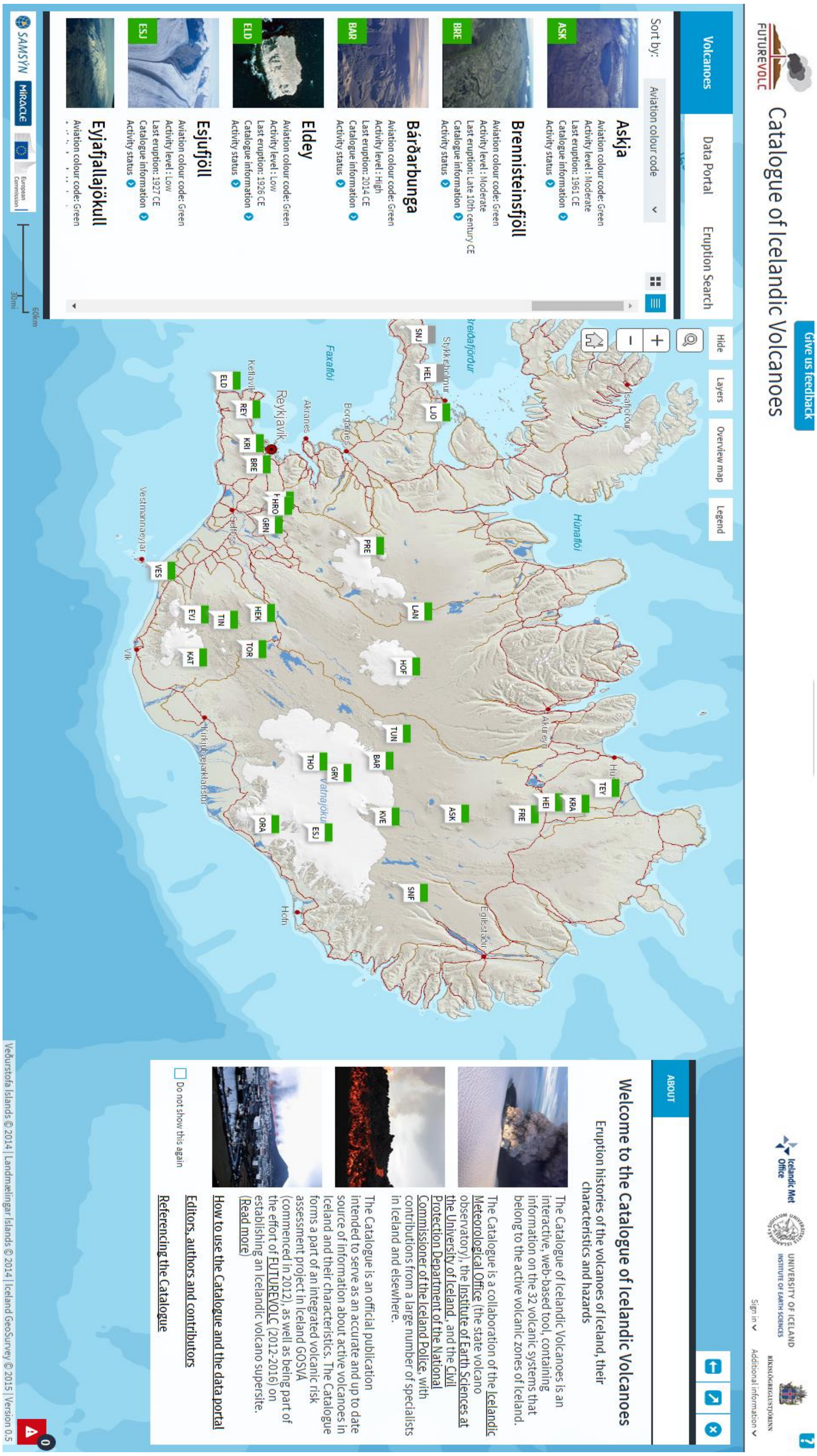

Figure 4.5: *The Catalogue of Icelandic Volcanoes, a customisable, informative and user-friendly output of the FutureVolc project (Source: FutureVolc Project - Catalogue of Icelandic Volcanoes. Date accessed: May 2016).*

In addition to FutureVolc, Bárðarbunga also coincided with the development of the Airborne Volcanic Object Imaging Detector (AVOID). Whilst the implementation of new technology is a rigorous and stringent process in the aviation industry, the London VAAC and Isavia adopted precautionary attitudes towards Bárðarbunga (which had no disruptive impact on aviation). Devices such as AVOID would have provided additional reassurance to the aviation industry, and minimised uncertainty. As alluded to earlier in this chapter, volcanic eruptions pose a significant threat to the safety of aviation, with the engine failures of British Airways flight 9 (Tootell, 1985; Johnson and Casadevall, 1994) and KLM flight 867 (Przedpelski and Casadevall, 1994; Casadevall, 1994), providing timely reminders of the danger that volcanic ash poses to civilian aircraft:

> Volcanic ash in the upper troposphere, where jet aircraft fly, can cause jet engine failure (loss of power), damage to turbine blades and pitot static tubes, with the possibility of the loss of the aircraft and lives (Prata and Tupper, 2009, p.239).

Here, Prata and Tupper stress the vulnerability of aircraft to the impacts of volcanic activity; this explains why mandatory action was taken to ground aircraft across Europe during the eruption of Eyjafjallajökull. Aviation provides an intriguing stakeholder dynamic as it highlights how engineers, policymakers and the service sector are invariably linked to volcanic hazard management. The onus may appear to be on the manufacturing of aircraft engines and their resilience to ash, but the aviation industry has found that it needs to approach volcanic hazards from a holistic perspective.

The disruption caused by Eyjafjallajökull has undoubtedly influenced the innovation of devices such as AVOID. Leading specialists in aviation research, such as Dr Fred Prata (the inventor of the device), have sought to establish mechanisms for identifying dangerous concentrations of volcanic ash from on-board civilian aircraft. The AVOID device provides a means of monitoring ash 100 kilometres away in a precise and efficient manner (Prata *et al.*, 2012); Adam Durant, from the Norwegian Institute for Air Research (NILU), compared the technology "to a weather radar for ash" (Durant, 2012). The device allows an aircraft to track the movement of volcanic ash and to react instantaneously to the real-time data it receives whilst airborne. Therefore, the aircraft is prevented from making contact with ash as pilots can be informed, in real-time, of where it is safe to fly. In addition, airspace can be opened and closed intermittently according to where ash is recorded; this reduces the potential for widespread disruption.

As AVOID is mobile and flexible, it could be used on a wide range of aircraft; its extensive and thorough testing has been vital to its implementation (see Figure 4.6, p.108), and has strengthened the relationship between NILU, Airbus and EasyJet:

> EasyJet estimates that 100 aircraft (20 of which would be EasyJet's) across Europe fitted with AVOID equipment, would provide comprehensive coverage of the continent enabling airlines to supply monitoring information to the authorities to support the new processes and procedures that were introduced after the eruption of Eyjafjallajökull in 2010 (Nyeggen, 2016).

The role of EasyJet illustrates a robust level of engagement between the aviation industry and science. Influenced by projects such as FutureVolc (Prata *et al.*, 2013), this collaborative approach has been integral to the largely successful and highly ambitious trialling of the AVOID technology.

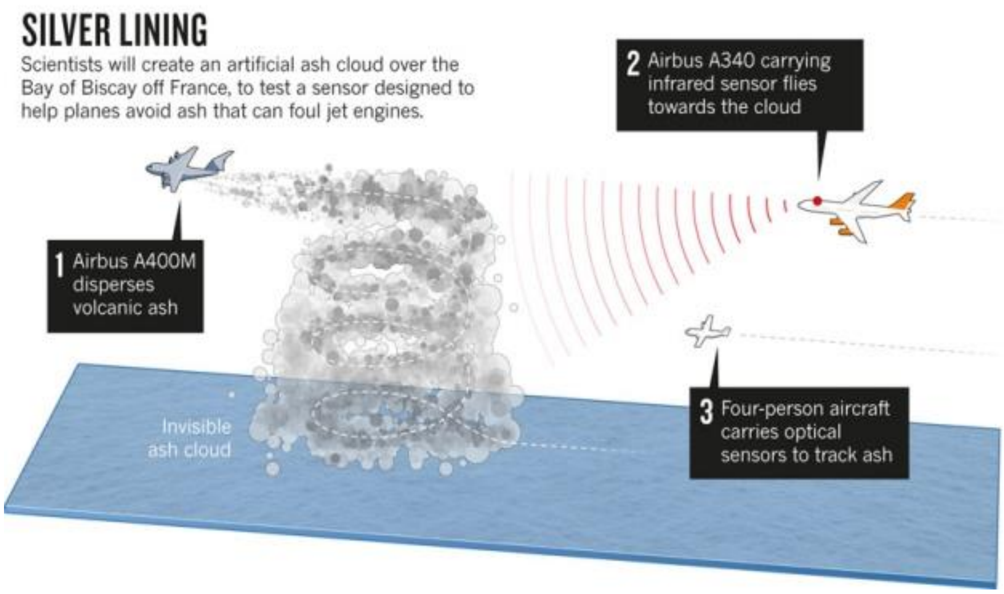

Figure 4.6: *A diagram outlining how the AVOID device has been trialled. The aircraft, equipment and resources used have required collaboration between industry and science (Source: Witze, 2013, p.423).*

Testing has taken place on multiple occasions and in different geographical regions; it has used civilian aircraft, provided by EasyJet, to identify ash at 38,000 feet. Therefore, trials have proven to be highly representative of a real-life situation in which the technology would be deployed. Furthermore, the accuracy of ash plume detection has meant few problems have been identified with the equipment; this has strengthened the case for implementing the device.

However, before AVOID is used on civilian aircraft, it is required to pass through a rigorous assessment process. This is overseen by ICAO, and leads to devices and systems being ranked according to Technology Readiness Levels (TRL's):

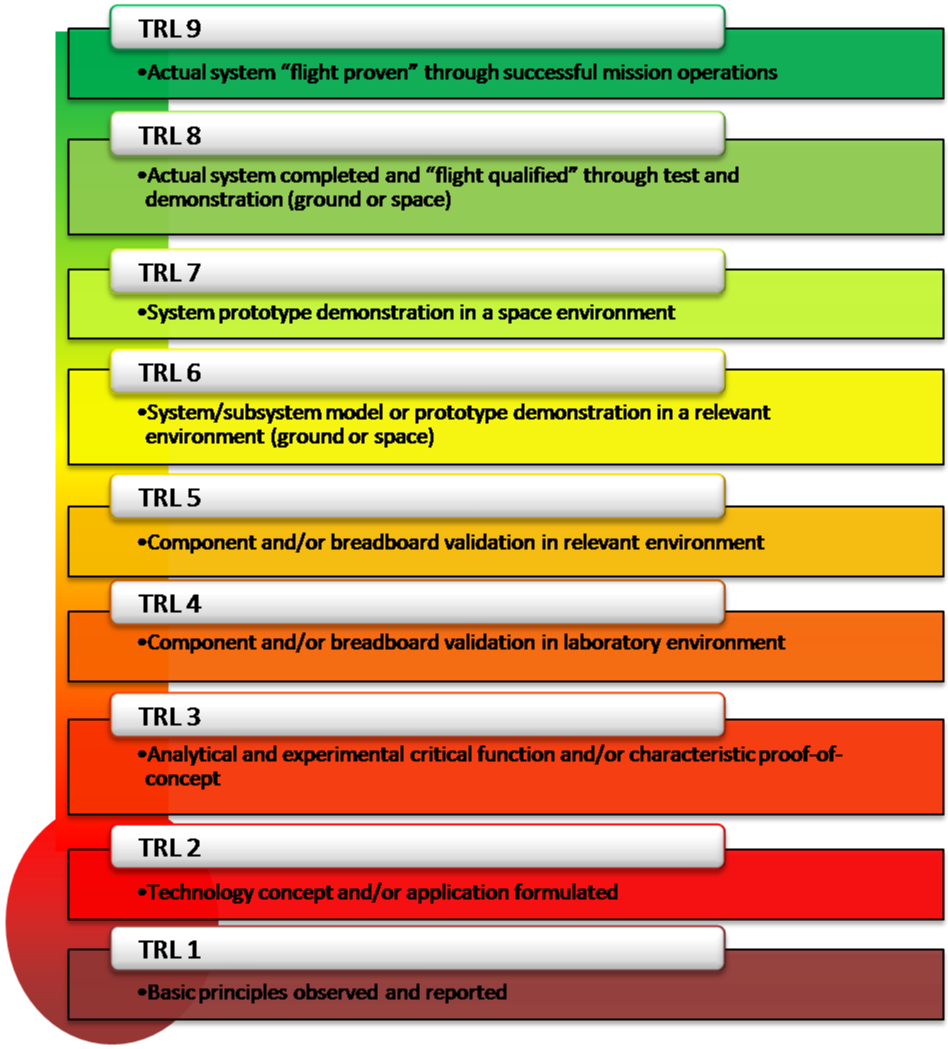

Figure 4.7: *Technology Readiness Level definitions (Source: National Aeronautics and Space Administration. Date accessed: August 2016).*

A TRL number is obtained once the description in the diagram has been achieved. For example, successfully achieving TRL 4 (lab

> environment) does not move the technology to TRL 5. TRL 5 is achieved once there is component/breadboard validation in a relevant environment. The technology remains TRL 4 until the relevant environmental validation is complete (*National Aeronautics and Space Administration [NASA], 2016).*

Aviation primarily uses the NASA definitions for TRL's; devices such as AVOID are required to demonstrate their suitability for use on aircraft at each individual level (see Figure 4.7, p.109). TRL 1 and TRL 2 relate to the transition of science into the research and development of a technology. Studies seek to identify the attributes and characteristics needed for a device or system to function appropriately. TRL 3 and TRL 4 then account for the invention and feasibility of the device; these levels seek to validate its position and performance in a laboratory setting. TRL 5, TRL 6 and TRL 7 follow by assessing the performance of a prototype in a realistic and "relevant environment" (NASA, 2016), initially at ground level and then in space (see Figure 4.7, p.109). These stages are integral to the future development of the technology as they allow specific characteristics to be assessed. Finally, TRL 8 and TRL 9 account for the final stages of the development and integration process, covering the launch and operationalisation of the device or system.

TRL's in the aviation industry are not intended to prevent or restrict the implementation of devices such as AVOID, but are designed to be a "primary mechanism for judging the state of development of technologies" (Newton *et al.*, 2007, p.20). At the time of writing, AVOID had reached the final stages of the process; its implementation was widely expected to quell the heightened sense of anxiety in the aviation community. For example, the device lends itself to the policy reforms and changes that have been made to the process of closing airspace. In line with other global regions, Europe has made the transition to enabling airlines to be responsible for whether their aircraft fly during periods of volcanic activity. These changes to the decision-making process, passed down by ICAO, are intended to reduce conflicts and "enhance organizational capacity for effective improvisation (Lutz and Lindell 2009; Moynihan 2009; 'T Hart 2013)" (Parker, 2015, p.102). Therefore, the additional freedoms granted to individual airlines removes them from the stringent governance of the aviation authorities, and generally devolves responsibility. This decentralisation of decision-making within the aviation industry is likely to have been influenced by the Eyjafjallajökull eruption.

Eyjafjallajökull, Grímsvötn and Bárðarbunga have each impacted on projects or technologies that now feature prominently in Iceland's approach to managing volcanic hazards. Whilst not specifically tailored to Iceland, the EU's Emergency Response Coordination Centre (ERCC) played a key role in responding to the eruption of Bárðarbunga (2014-2015). The ERCC was set-up by the European Commission's Civil Protection Mechanism in 2013, primarily to promote cooperation in responses to hazards across Europe. Countries and organisations can share expertise and resources by communicating through the flexible hub the centre provides:

> It (the ERCC) contains round-the-clock staff, high-tech information and communication systems, and three operational centres to coordinate the EU's role in up to three simultaneous events (Rhinard, 2015; in Bossong and Hegemann, 2015, p.263).

Here, Rhinard refers to the qualities that allow the ERCC to provide specialised assistance to its members and states, strengthening their resilience. Eyjafjallajökull may have had an impact on the creation and structure of the centre, but any links are speculative and ambiguous as the ERCC is equipped to respond to a plethora of natural and manmade hazards (seismic activity, flood events, wildfires, etc.).

Bárðarbunga (2014-2015) remains one of the largest natural hazards that the centre has dealt with, and although the risk to life was relatively low, the reaction of the ERCC demonstrated the flexibility of hazard management in Europe. During the eruption, the centre's "Common Emergency Communication and Information System" was used to distribute advice and guidance (Bossong and Hegemann, 2015, p.259); this highlighted the relevance of the ERCC to Icelandic volcanism. Furthermore, when responding to Bárðarbunga, the centre worked alongside the FutureVolc project to produce maps, flash reports and satellite images. These collaborative efforts informed the public of the area's most at risk of being flooded because of the eruption. However, a FutureVolc deliverable found a rather mixed response when assessing the impact of the ERCC on the Icelandic public. For example, the report established that only 2% of respondents learned about the eruption through the ERCC (p.11), with many having the opinion that the centre's outputs and information could have appeared more "authoritative" (FutureVolc Project - Deliverable 3.4, 2016, p.17). On the other hand, there was a positive reaction to the communication between the ERCC and the CP; it was widely perceived to have contributed to a more coherent approach to volcanic hazard management.

4.3: The dynamics of Iceland - UK relations

The volcanic events in Iceland between 2010 and 2014 have further expanded relations between UK and Icelandic institutions, and have illustrated how the network infrastructure that binds the two countries plays a significant role in risk reduction. First and foremost, the network is designed to facilitate the sharing of hazard information, both for domestic and international purposes. Iceland and the UK constitute an intensely communicative entity, within a much larger European and global community of research, collaboration and governance. For example, leading institutions such as the IMO are dependent on a working relationship with the London VAAC, and vice versa. Secondly, the network is underpinned by a multitude of formal and informal research partnerships; many of these exist between academic and scientific agencies in both countries. For instance, the BGS and the UoI have a long-standing partnership that has transcended each of the three large-scale eruptions addressed in this thesis. Thirdly, the network has played an increasingly significant role in authorising and enforcing policies; for example, the involvement of the Cabinet Office and the Department for Transport (DfT) illustrates the active role now played by the UK government. This final section of the chapter examines the projects, exercises and collaborations that consolidate the ties between Iceland and the UK.

4.3.1: Explaining the UK's intervention

As demonstrated during Eyjafjallajökull, the UK is particularly vulnerable to volcanic activity in Iceland, and potentially at risk of both transport disruption and gas pollution (Reuter, 2015). Iceland and the UK are therefore inseparably linked when managing volcanic hazards; the Volcanic ash exercise in Iceland (VolcIce) is indicative of this relationship as it strengthens inter-agency links between the London VAAC, the IMO and Isavia. Furthermore, ICAO legislature dictates that the London VAAC (based in Exeter) are accountable for notifications of ash in the airspace covering Iceland and Northern Europe.

Figure 4.8: *The areas of responsibility for each VAAC, administered by ICAO (Source: International Civil Aviation Organization - Handbook on the International Airways Volcano Watch, p.2-12. Date accessed: May 2016).*

During the creation of the nine VAAC's in the 1990s, Iceland was placed in the London VAAC's area of responsibility; as a result, the models, observations and forecasts that the London VAAC use have significant value in the decision-making process. The eruptions of Eyjafjallajökull and Grímsvötn have demonstrated the London VAAC's prominent role (Parker, 2015) and strategic position within Iceland's network. However, the London VAAC is not isolated and shares a close working relationship with the Toulouse VAAC, illustrated through the channels of communication existing between them.

Although the UK has no active volcanoes, the socio-economic problems that were caused by Icelandic volcanism in 2010 has led to both explosive and effusive eruptions being recognised on the National Risk Register (Cabinet Office - National Risk Register of Civil Emergencies, 2015). The vulnerability of the UK means that a political, social and economic incentive is now provided for UK-based institutions to play a significant role in managing volcanic hazards. For instance, the Met Office (UK) and the BGS have both contributed to the formation of collaborative groups such as the Natural Hazards Partnership [NHP] (British Geological Survey - Natural Hazards Partnership, 2016). In addition, the Cabinet Office and the DfT are responsible for actively intervening in the management of gas and ash-based hazards respectively. Finally, UK-based academics have continued to play an active role in studying and monitoring volcanic environments in Iceland. This has been reflected in the evolving relationship between the BGS and the IMO:

> BGS has worked in collaboration with the Iceland Met Office to install new seismic stations in the vicinity of Eyjafjallajökull and Katla. These stations are providing real-time data to enable detailed monitoring of any future eruptions (Baptie, 2015).

Collaborative affiliations between Iceland and the UK have had a profound impact on the technical infrastructure of the network, and have improved monitoring practices in regions that are sensitive to either volcanic or multi-hazard events. Therefore, the series of relationships that have developed between the two countries have been paramount to risk reduction in Iceland, the UK and Europe.

4.3.2: The VolcIce Exercise

The VolcIce exercise was set-up in 2008 and preceded the eruptive episodes covered in this thesis. VolcIce simulates volcanic activity in Iceland and models a situation whereby airspace is contaminated with ash. A response is then required from each of the participating institutions:

> (VolcIce) Involves mainly IMO, Isavia and London VAAC where the responses to the initial phase of an eruption are tested and the operational personnel are trained in the use of the contingency plans at each institute (Þorkelsson *et al.*, 2012, p.115).

The exercise ensures that various stakeholder communities are "practised at their response to an eruption and that the communication chain is working effectively" (Met Office [UK] - London VAAC main page, 2016); organisational responsibility is a key element of the exercise. As VolcIce is conducted on a monthly or quarterly basis, it provides "a good opportunity to test the flow of information" between each of the participating institutions (World Meteorological Organization - WMO VAAC 'Best Practice' Workshop Report, 2015, p.23). Although the format and structure of the exercise has been amended on numerous occasions because of policy alterations, VolcIce was conducted prior to the Eyjafjallajökull eruption (Þorkelsson *et al.*, 2012).

The frequency of the exercise maintains and strengthens the robust relationship between the institutions involved. This explains why blame for the lack of clear communication during the eruption of Eyjafjallajökull was attributed to the aviation industry, rather than to the London VAAC, the IMO and Isavia. In contrast to ICAO and many of the aviation authorities, the VolcIce participants had well-prepared contingency plans; these enabled the VolcIce community to respond to Eyjafjallajökull in a near faultless manner. The exercise protocol was also activated during the eruption of Grímsvötn (2011), and again reflected the communicative efficiency of the participating institutions. For instance, the monitoring process was initiated by the IMO contacting both the London VAAC and Isavia to inform them of an eruption beginning. Updates on the airborne conditions were then exchanged on a regular basis in the form of Significant Meteorological Information (SIGMET).

A SIGMET is a packaged form of communication, commonly used and globally recognised within the aviation industry. The outline of a SIGMET does not change and allows information to be shared in a standardised format (see Figure 4.9, p.115); notifications are applicable to all situations, regardless of the individual, institution or means through which they are communicated. The construction and exchange of SIGMET's is a circulatory process within the VolcIce exercise and ensures "good communications between IMO forecasters and Isavia ATC (Air Traffic Control)" (Þorkelsson *et al.*, 2012, p.115). When used to monitor volcanic activity, SIGMET's originate from the IMO and are issued intermittently at intervals of three or six hours.

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Figure 4.9: *A template for a standard SIGMET, used extensively in the VolcIce exercise (Source: Isavia - VolcIce Exercise. Date accessed: May 2016).*

Another key feature of the VolcIce exercise is the use of the Numerical Atmospheric-dispersion Modelling Environment (NAME). The NAME software was used during both the Eyjafjallajökull and Grímsvötn eruptions (Millington *et al.*, 2012), and is integral to the success of monitoring exercises in Iceland. Despite being designed for nuclear and chemical dust, NAME can forecast the movement of volcanic ash beyond the region in which an eruption has taken place (Jones *et al.*, 2007). The London VAAC claim that the software has "enabled the more flexible use of airspace" (Met Office [UK] - Ash Dispersion Leaflet, 2016), and refer to its impact on managerial and decision-making practices. In addition, NAME has strengthened institutional relationships (see Figure 4.10, p.116); for example, the software is used by the London VAAC but is reliant on data and information that is sourced by the IMO. The visual outputs produced by the software are then shared with Isavia and other aviation authorities. As a verifiable forecasting tool, NAME allows both Icelandic and UK-based institutions to accurately predict what regions are likely to be affected by dangerous concentrations of ash. From a UK perspective, the DfT and the CAA also recognise the impact of NAME, highlighting its broader relevance beyond the VolcIce exercise.

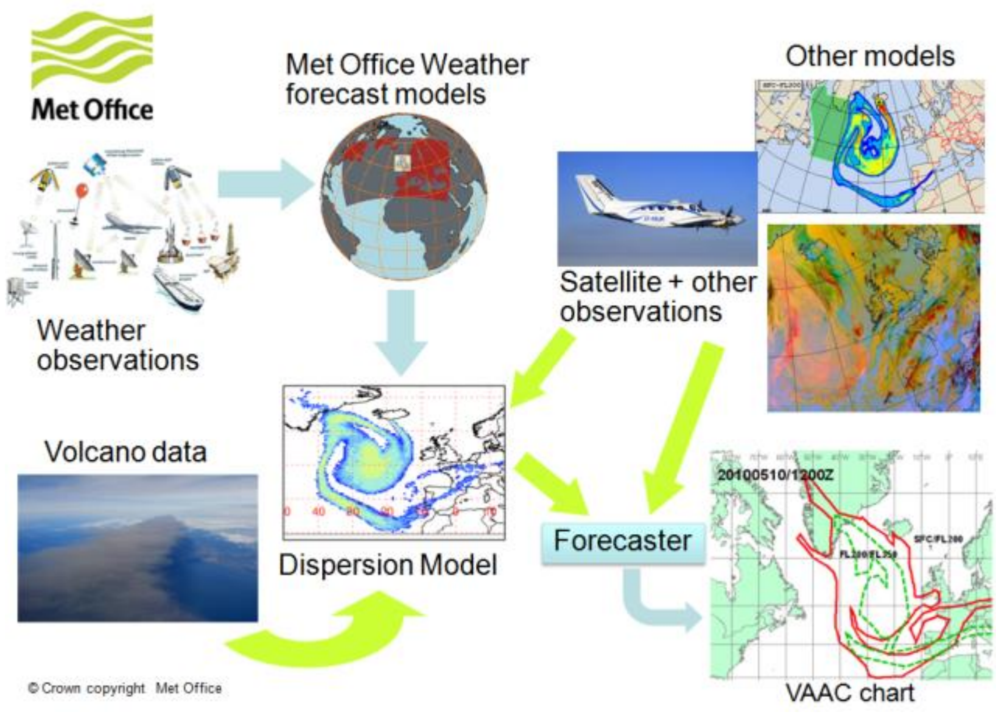

Figure 4.10: *The position of the NAME "Dispersion Model" in the monitoring network (Source: Met Office [UK] - London VAAC main page. Date accessed: May 2016).*

However, whilst SIGMET's and NAME are effective attributes of VolcIce, the idealistic setting of the exercise is much more controlled than a real volcanic eruption. Therefore, the arrangements require flexibility as the spread of end-users that are requesting access to information is likely to be more ambiguous in a crisis situation. For example, the communication process was transformed during the Eyjafjallajökull eruption (2010), and expanded far beyond the confines of the VolcIce community:

> At the end of the first week of the summit eruption changes were made to the collaborative working procedures between the IMO and London VAAC in order to improve the information flow. The creation of the VAR (Volcanic Ash Report, sent from on-board aircraft) was an important step forward, in addition to a direct link which was established between the scientists at IMO and the Atmospheric Dispersion Group at the UK Met Office (Þorkelsson *et al.*, 2012, pp.119-120).

Here, Þorkelsson *et al.* illustrate how an active crisis can redefine the monitoring and communication process that is central to VolcIce. Nevertheless, in the case of Eyjafjallajökull, the IMO highlighted the sophistication of the set-up by using NAME to produce and update "a table of forecasted ash contamination at several airports based on the information from the UK Met Office" (Þorkelsson *et al.*, 2012, p.115). Crises therefore demand dynamism and adaptability in the relationships that exist between each of the participating institutions.

The structure of VolcIce ensures that inter-agency relationships can be continually assessed and amended; for example, the exercise produces a report that outlines a series of aims, objectives and recommendations (see Appendix 5.1, pp.273-275). These are agreed on during the debriefs that take place both within and between the IMO, the London VAAC and Isavia. Recommendations can relate to how SIGMET notifications are distributed, the specific coding of exercise messages, or the monitoring of phone calls that are made to aviation authorities or airlines. VolcIce also provides several additional outputs, including Volcanic Ash Graphics (see Figure 5.4 [p.149] and Figure 5.5 [p.150]); these are produced by the NAME software.

4.3.3: Beyond VolcIce: A complex affiliation

Whilst the relationship between Iceland and the UK can be defined by the VolcIce exercise, an increasing number of software programs, research groups and stakeholder partnerships are intended to strengthen the collaborative engagement between the two countries. For example, the Scientific Advisory Group for Emergencies (SAGE) and the NHP both illustrate how deeply integrated the UK and Iceland are when managing volcanic hazards. SAGE and the NHP have individual roles to play in translating the data provided by the NAME system; these groups are relevant to a wide range of stakeholders including airlines, management strategists and policymakers. Both groups, as well as the VolcIce exercise, are also underpinned by a "memorandum of understanding" (Dash *et al.*, 2013, p.57) between Icelandic and UK-based institutions. This agreement is intended to provide greater clarity, cooperation and stability in the decision-making process.

SAGE is a group that provides the scientific and technical expertise required to guide decision-making during the UK government's Cabinet Office Briefing Room (COBR) meetings (see Appendix 4.1, pp.269-270). The group covers a wide range of hazards and ensures the UK government are equipped with the information needed to make appropriate decisions in crisis situations (Scientific Advisory Group for Emergencies - main page, 2016). In the context of volcanic activity, SAGE became relevant when meetings were held during the 2010 eruption of Eyjafjallajökull. The group initially discussed the potential dangers of allowing civilian aircraft to fly through contaminated airspace, with evidence provided by the BGS, the Natural Environment Research Council (NERC), the Met Office (UK) and the DfT. However, it was not until the third meeting (19th May 2010) that personnel from Icelandic institutions, namely the IMO and the UoI, directly contributed (see Appendix 4.2, pp.271-272). By this stage, discussions were focussed on the technology being used to assess the ash plume. Although SAGE was not activated during the eruptions of Grímsvötn (2011) and Bárðarbunga (2014-2015), Icelandic volcanoes remain a considerable risk to the UK, and a potential hazard for SAGE to address.

The NHP has also strengthened interactions between Iceland and the UK; the group has enabled stakeholders from across an array of UK institutions to bring together knowledge and expertise. Better coordination is a key aim of the partnership, and explains some of its unique features; these include the "daily hazard summary assessment service" and the "hazard impact model" (Natural Environment Research Council - Activities: Natural Hazards page, 2016). The daily summary is intended to inform and update members of an active crisis, providing them with a reliable service that can improve their preparedness, resilience and exchange of knowledge. Meanwhile, the hazard impact model resembles aspects of the FutureVolc project; for example, it aims to "combine data and expertise from partners to identify the impact on populations, areas and assets from a range of natural hazards" (British Geological Survey - Natural Hazards Partnership, 2016). Both the NHP and the FutureVolc project focus on the integration of efforts to monitor and mitigate risk. The scope of these partnerships has undoubtedly encouraged greater interactions between institutions in Iceland, the UK and Europe.

4.4: Concluding remarks

This chapter provides a descriptive and analytical account of Iceland's hazard network, and explores the impact of large-scale volcanic eruptions between 2010 and 2014. Underpinning the exercises, projects and transitions covered in this chapter, are the evolving power dynamics between actors and institutions, the collaboration and trust of stakeholder communities, and the multi-scale platform on which many initiatives are designed. Iceland's network infrastructure has been transformed to develop a flexible approach to decision-making and knowledge exchange. Contextually, this PhD research accounts for Iceland's unique characteristics; these include its rich cultural values, its political stability with Europe and North America, and the positive relationship between Icelandic society and scientific knowledge. The following empirics use sociology to explain the adaptation, resilience and holism of Iceland's approach to volcanic hazard management; communication channels are analysed at length to assess the connectivity of individual stakeholders and institutional entities.

Chapter Five: Exploring power dynamics and technical actors: Illustrating collaboration and trust in Iceland's hazard network

Collaboration and trust are integral features of Iceland's network and are important considerations when analysing the development of communication channels. This chapter carries out an in-depth exploration of how a network's relational and technical infrastructure can renegotiate power dynamics. Stakeholder connections impact on the decision-making process and influence Iceland's efforts to mitigate risks stemming from volcanic activity (Donovan and Oppenheimer, 2012; Eiser *et al.*, 2015). As networks become increasingly complex, the use of technology can be studied to explain how human and non-human actors engage in a manner that is flexible and holistic (Moynihan, 2009). Therefore, elements of Actor-Network Theory [ANT] (Latour, 1993; 2005) and co-production (Jasanoff, 2004; Bijker *et al.*, 2012) can be associated with dynamic approaches to hazard management.

The first section of this chapter uses multiple case study examples to explain how power can be renegotiated within Iceland's network. In the subject area of hazard management, power is conceptually defined by decision-making, policymaking and the responsibility to take effective action (Pearce, 2003). The chapter then focuses on Iceland's innovative use of technology, influenced by interconnections between social, scientific and technical actors. The Airborne Volcanic Object Identifier and Detector (AVOID), and the Numerical Atmospheric-dispersion Modelling Environment (NAME), provide two examples of the technological strides made within Iceland's network to combat ash-related threats to the aviation industry. These devices and software packages have the capacity to facilitate information flows and transform how knowledge is communicated. By explaining the impact of power and technology on the collaboration and trust of stakeholders, this PhD research analyses the construction of an adaptable and resilient approach to volcanic hazard management. Despite being context-dependant and temporally binding, this study accounts for the evolution of knowledge exchange (Haynes *et al.*, 2008; Donovan *et al.*, 2012; Eiser *et al.*, 2015).

Whereas Latour used the interconnections of individual actors to discuss power (1993; 2005), this study approaches power dynamics from a transitional perspective and refers to the expanse and authority of institutional entities. However, this chapter also analyses the relational characteristics of individual actors to explain how decision-making powers are becoming increasingly decentralised from leading institutions. Therefore, this research can resonate with aspects of how Latour interpreted power in his description of ANT. Furthermore, this chapter assigns power to technical devices and systems, as well as to informative materials and communication instruments. However, whilst this research accepts that power can be attributed to both human and non-human actors, it does not discredit or remove sociality in the same manner as Latour (see p.45 and p.47).

Allen (2003) analysed Latour's approach to power and explained the impacts of mediation and translation:

> (Latour) speaks of a 'translation' model of power where everyone shapes the overall process according to their own interests and preferences as the 'order' is passed down the line (Allen, 2003, Part ll: 6).

Despite being rather critical of some aspects of Latour's work, Allen (2003) refers to the influence that technical objects can have on the formation, process and mobility of actuarial connections. Therefore, this chapter can relate to Allen's analysis as it draws on digital and virtual technologies to explain how hazard knowledge can be translated by multiple stakeholder communities. Finally, this study has resonance with constructivist approaches to power as it accounts for how flows and channels have been developed to circulate information through Iceland's networked infrastructure. This narrative reflects Castells' (2007) reference to power in his literature on the network society. For example, Castells associated power dynamics with mobile flows of resources such as information, knowledge and ideas. Therefore, from a thematic perspective, this chapter reflects multiple interpretations of power by explaining how power relations can continually evolve in response to technologies, policymaking and stakeholder connections.

5.1: Renegotiating power relations: The evolution of actor communication

In the context of Iceland's approach to volcanic hazard management, power relations are ambiguous and difficult to define, primarily because the networked infrastructure is not fixed and is continually changing. Power often stems from the evolution and repositioning of human and non-human actors, a fluid process that highlights "stakeholder influences" (Rowley, 1997, p.887). As a dynamic and multi-hazard environment, Iceland's network requires actuarial mobility for risk to be adequately controlled (Slovic, 1999). Therefore, the sharing of information, the capacity to communicate, and the decentralisation of decision-making are influenced by the adaptation of power relations. This first section explores the distribution of power and examines the development of trust, as well as the construction of collaborative affiliations, between stakeholder communities (Pelling, 2003).

5.1.1: Leveraging power: The transient presence of coordinators

By exploring Iceland's network, this study found that the power of actors is often determined by their transience and connectivity. For example, coordinators and decision-makers tend to occupy a strategic position either within or between leading institutions. Power can be assigned to technical actors on the basis of their ability to deliver information to a broad range of end-users. As Iceland is a multi-hazard environment, threatened by both seismic and climatic hazards (Bell and Glade, 2012), the actions of coordinators are integral to conveying information and responding simultaneously to several hazardous events. By conducting observations, this study of Iceland has analysed the role of coordinators in leading institutions such as the Icelandic Met Office (IMO) and the Department of Civil Protection (CP). Several coordinators are responsible for the IMO's monitoring of the various natural hazards that Iceland endures; these coordinator's leverage decision-making power across the network. Furthermore, their privileges bridge stakeholder communities, enabling them to access and influence multiple channels of communication. Therefore, the actions of coordinators are crucial to determining the adaptability of the network.

However, the study established that coordinators do not tend to subsume power from other actors. Instead, they consult with multiple stakeholder communities by developing and utilising robust channels of communication. Therefore, their ability to influence decision-making is not hindered, but their scope of engagement is much more holistic; this was highlighted in an interview with a Volcanic Hazards Coordinator at the IMO:

> Once I receive information I consult with the people in the monitoring room, who will already be observing, and we will go through the contingency plans, along with the forecasters on duty, the seismologist on duty, and the people on the night shift, and then we communicate our findings to the CP or to Isavia (the Icelandic Aviation Service) or elsewhere (IMO, March 2014).

Here, the coordinator provides evidence of their decision-making and synthesising powers; the extract also refers to their individual ability to facilitate or strengthen collaboration beyond the IMO. By referring to the range of supporting actors within the institution, the interviewee illustrates how the coordinator can empower numerous stakeholder communities.

An observation of the debrief that followed the VolcIce exercise highlighted the points of engagement within the network. The research found that exchanges of information do not erode the coordinators power, but mediate their knowledge of the hazard. This process of mediation acknowledges the holism of Iceland's network, and allows decision-making to be influenced by multiple stakeholder communities. A similar analysis can be used to define the positionality of coordinators and project managers within the CP; powerful actors need to engage with stakeholders from both scientific and socio-political backgrounds. Therefore, they are required to use "multiple interaction styles" (Mynatt *et al.*, 1997, p.13) to communicate effectively. This technique is relevant to Iceland as the network environment is complex and institutionally dense.

Furthermore, this PhD research also found examples of coordinators exhibiting an "agency" (Latour, 1999a) that symbolises and defines power. For instance, coordinators possess a level of sociality (Latour, 1996a) that provides them with a standing in the network from which they can maintain an identity. This improves their ability to construct and communicate information, and allows them to acquire the trust of supporting actors. However, power is not uniform between coordinators as roles vary depending on the institution to which they are most closely associated. For example, coordinators tend to be project managers when affiliated with industry-specific organisations such as Isavia. In contrast, the role of a coordinator at the IMO relates to how a particular type of hazard is monitored and prepared for.

Whilst coordinators have access to a plethora of communication channels, this study has found that protocol plays a role in determining the power dynamics of Iceland's network. For example, coordinators at both the IMO and the CP follow an arrangement agreed upon between multiple institutions; this was discussed during an interview with a director at the IMO:

> We are few, we know each other, we know the key persons here at the IMO, and also those at the CP, it is not a formal system but we know who to contact when we need to respond to an event (IMO, March 2014).

The interviewee refers to the largely informal set-up within Iceland's approach to managing volcanic hazards. This is both a strength and a weakness; for example, it reflects the level of familiarity, trust and synergy between the various coordinators, but leaves the system vulnerable when leading personnel change and the collaborative set-up is disrupted. Policy frameworks and protocol are required to maintain resilience, and to provide additional supports to the current relationships between institutions such as the IMO and the CP; the administrative system cannot rely on informal contact alone. Therefore, a formal approach is needed to preserve cohesion and ensure the arrangement has sufficient adaptability to react to staff changes. In addition, formal guidelines also enable Iceland's relatively small population of scientists and planners to work elsewhere.

Nevertheless, the relationship between the IMO and the CP does not suggest an unhealthy imbalance or secession of power in Iceland's network. This PhD research has identified leading personnel and explored the communication channels that evoke close collaboration. Findings suggest that power disparities are lessened by the relationality of the network; for example, coordinators have a degree of power because of their intrinsic connections to supporting actors (seismologists, forecasters, technicians, etc.). Supporting actors are often empowered by their shared responsibility to communicate; this was discussed during an interview with a project manager at Isavia:

> I was very content with our people (at Isavia) because they were actually focussed, they knew how to run the operations, with the telephones they weren't looking to spot something else, all they were focussed on was these telephone calls which they had to make … the people in the air traffic control centre, those people who were working there, were preparing the first signal to send out to aircraft, and these individual efforts help us with making the correct decision and what the next action should be (Isavia, March 2014).

By outlining the responsibilities of supporting actors, the interviewee refers to the value of their role in the VolcIce exercise. The extract does not refer directly to power relations, but provides evidence of how individual actors work as part of a collaborative team.

5.1.2: Collaboration and power: The formation and evolution of the VolcIce ash monitoring exercise

When engaging with coordinators, this study found that their power stems from the trust invested in them, from both their institutional colleagues and the wider network. For instance, by observing the VolcIce exercise, the research could study the dialogue and communication between the IMO, Isavia and the London Volcanic Ash Advisory Centre (VAAC) [see pp.114-117]. As an "international multi-organisation volcanic ash exercise" (Met Office [UK] - London VAAC main page, 2016), VolcIce is purposely designed to encourage collaboration in a controlled and modelled setting. This has enabled the research to examine how coordinators maintain trust and strengthen their connections with numerous stakeholder communities.

The format of VolcIce assigns responsibility to each of the participating institutions; an interview conducted at the IMO referred to the rationale behind the design of the exercise and explained how it facilitates institutional collaboration:

> We (the IMO) understood that we had to strengthen communication, having been under the London Volcano Ash Advisory Centre territory so to speak, so we began to organise these exercises (VolcIce) and knew we had to build up this very good relationship we have today (IMO, March 2014).

The interviewee refers to "London Volcanic Ash Advisory Centre territory" when explaining why monitoring powers are granted to the IMO and the London VAAC. In addition, the extract implies that the VolcIce exercise has been organised and developed in-house, reflecting how powers have been decentralised from the International Civil Aviation Organization (ICAO). However, whilst the participating institutions how been influential in determining the structure of VolcIce, collaboration and the distribution of power are ultimately determined by ICAO's policymaking and the territorial allocation of airspace (see Figure 4.8, p.113).

Despite the territorial assignment of VAAC's being constructed by ICAO, the boundaries between them should not be considered arbitrary; for instance, this research has found that individual actors from within the London VAAC have formed strong alliances with personnel from both the Toulouse VAAC and the Montréal VAAC. However, regardless of these overlaps, ICAO are the global regulatory body for aviation, and their governance of space is undoubtedly a factor when explaining the collaborative engagements between the IMO, the London VAAC and Isavia:

> ICAO plays a leading role as the primary issuer of legislation and guidelines, and as the designer of the system for dealing with erupting volcanoes (Christensen *et al.*, 2013, p.71).

The extract refers to ICAO having the institutional authority to connect and bind the actors that participate in exercises such as VolcIce. This narrative questions the extent to which the exercise is indicative of a clustered stakeholder community that can self-sufficiently evolve.

Nevertheless, first-hand observations of VolcIce have allowed this research to deconstruct and analyse the specific interactions between actors. For example, the research established that many connections have been incrementally constructed and temporally strengthened by an actor's repeated involvement in the exercise. Interviews conducted with both coordinators and supporting actors have referred to improvements in stakeholder familiarity; this was highlighted by an interviewee at the IMO:

> We (the IMO) get updates and messages sent to us by emails, during monitoring exercises, but also routinely when there are any signs of activity, we have meetings with the IMO and the VAAC (London).

> Then of course we have telephone calls or communications through persons to persons, that's how we share information and keep each other updated, but certainly VolcIce has encouraged us to communicate regularly (IMO, March 2014).

Here, the interviewee directly links the VolcIce exercise to the construction of communication channels, both formal and informal; by repeatedly conducting the exercise, synergy and trust can be produced and maintained.

VolcIce has increased the frequency of stakeholder interactions through the standard use of telephones and emails, but has also widened channels of communication by facilitating information artefacts that have the capacity to share hazard knowledge. Examples include advisory notifications containing Significant Meteorological Information (SIGMET's); an interview conducted with a project manager at Isavia referred to the process through which SIGMET's are communicated:

> The first SIGMET is supposed to go out from the Met Office (IMO) and we say to the meteorologist "don't forget to give us the wind", then we tell the air traffic controllers to look for the wind so that they know where it (the volcanic ash) is going; then we come to the second SIGMET, the interim SIGMET (Isavia, March 2014).

When explaining how SIGMET's are constructed, the interviewee refers to meteorologists at the IMO. At both a domestic and international level, the IMO have a legal remit that grants them the power to construct and share hazard information in monitoring exercises such as VolcIce. Therefore, by exploring the communication of SIGMET's, this study has been able to trace the flow of knowledge within the exercise.

As SIGMET's communicate information in a standard format, they can improve trust and knowledge exchange by ensuring that data can be accessed by participants from both scientific and socio-political backgrounds (Fearnley *et al.*, 2012; Nayembil *et al.*, 2016). The project manager at Isavia also explained the importance of collaboration; for example, the meteorologist at the IMO is reminded to include data related to wind (see Figure 4.9, p.115). Therefore, whilst the artefact is constructed by the IMO, Isavia can influence the information that is included; this helps to maintain a balance of power between the institutions. However, despite SIGMET's being digitally formatted and communicated, many interviewees did not refer to the role that technology plays in their construction and dissemination. Nevertheless, SIGMET's widen communication channels as the standard format allows them to be deciphered by numerous stakeholder communities; this increases the diffusion of power within the network. These interpretations support the view of Þorkelsson *et al.* (2012), who state that SIGMET notifications provide "a timely flow of information to stakeholders" (Þorkelsson *et al.*, 2012, p.114); the frequency and transparency of SIGMET's allows trust to be maintained, both within the exercise and the aviation industry.

However, an interview carried out with a forecaster at the IMO highlighted how SIGMET's can represent the institution's power to initiate communication in both crisis and exercise settings:

> Everything starts when the IMO calls Isavia and also the London VAAC, this first action triggers the contingency plans at Isavia, and also at London VAAC, and then yes the people here (the IMO) will continue with their actions and send out a SIGMET (IMO, March 2014).
>
> When we are running these exercises, the expectation of the work is with the Met Office (IMO) and their observers, we choose the site and the height of the ash plume (IMO, March 2014).

Here, the IMO appear to have a considerable degree of power and are interpreted as protagonists of collaboration. This interpretation of institutional responsibility represents what Latour termed "a social structure standing above the level of interactions" (Latour, 1996c, p.228). Information artefacts such as SIGMET's allow the IMO to instigate the actions that are taken by both Isavia and the London VAAC. The IMO collectively stands above the VolcIce interactions as they determine the parameters within which the exercise is conducted.

Despite the IMO having the responsibility to decide the setting for VolcIce, the research also found evidence of how their power dynamics cannot be viewed in isolation. For example, when observing the debrief that followed the exercise, it became apparent that institutional actions and responsibilities were underpinned by a "Memorandum of Understanding" (IMO, March 2014), which each of the participating institutions had previously agreed upon. Therefore, the IMO do not have the power to initiate communication at their own freewill, but do so based on multilateral agreements. As an active partner within the exercise, the IMO do not subsume or acquisition power from institutions such as the London VAAC, and are committed to providing information. This illustrates the need for collaborative engagements and institutional powers to be viewed holistically when considered in the context of monitoring exercises such as VolcIce.

The research has viewed the VolcIce exercise as a microcosmic vision of Iceland's network; the actors within it are empowered by the synergy generated from their interconnections and an intrinsic level of trust. This study found that the exercise can be interpreted as a collaborative core within a complex and institutionally dense network; findings suggest that VolcIce has continually evolved in response to policymaking and volcanic events such as the eruption of Eyjafjallajökull. Furthermore, flexible channels of communication are able to prevent power disparities by ensuring that robust connections between the IMO, the London VAAC and Isavia can be maintained. The exercise is jointly conducted by three institutions, but has the capacity to extend to the broader aviation community in times of crisis; the structure of the exercise is not idealised (see pp.114-117) and can be negotiated by airlines, aviation authorities and the governing body, ICAO.

5.1.3: Repositioning and renegotiating power: Engagement, participation and social media

The lack of stability and permanence within Iceland's hazard network appears to explain the ease with which actors are repositioned and power is renegotiated. For example, VolcIce has in-built connections to the aviation community, but also has sufficient leverage for change. This study has established that communication channels are increasingly leading to a bottom-up approach to managing volcanic hazards in Iceland. For example, citizens and communities alike are gaining the power and responsibility to communicate information that relates to volcanic activity. The power dynamics of leading institutions such as the IMO have not become obsolete, but have been transformed by channels of communication that extend their outreach to non-scientific stakeholder communities.

This study of Iceland's proactive approach to volcanic hazard management has illustrated how power relations can be contradictory within complex networked infrastructures. For example, several interviewees implied that participation in the VolcIce exercise was largely confined to the IMO, the London VAAC and Isavia:

> We only want those (in the exercise) that have been involved in the planning from the beginning, those that are going to actually conduct the exercise, attend the debrief and contact you directly (Isavia, March 2014).

The extract indicates that the scope of the exercise is much narrower than had otherwise been described, with institutional power being centralised. This perception of VolcIce contrasts with the community-based approaches to mitigation that were referred to in numerous interviews. For instance, discussions at the CP outlined a much less authoritative approach to hazard management in Southern Iceland. Power can therefore exist in multiple forms within such a holistic network; as a result, the communication processes have varying impacts on trust and collaboration.

However, the rather critical view of VolcIce, expressed by Isavia, is based on the modelled setting of the mock exercise that was observed within the fieldwork. During a volcanic crisis, a greater number of communication channels are likely to be utilised, expanding the connections with the aviation industry and the media. Furthermore, during the VolcIce debrief, the Isavia representative provided a contrasting vision of the exercise's scope and connectivity:

> We (Isavia) are supposed to call Stavanger, we are supposed to call Prestwick, we are supposed to call Edmonton …. Montréal …. And then local airlines, it's a number when you total it all together (Isavia, March 2014).

By referring to the various communication channels, the extract reflects Iceland's capacity to evolve during crisis situations. Therefore, this research has established that the network can be adjusted to meet the demands of a dynamic array of stakeholders. Analysts have often derided the positionality of the lay public in networks that are tailored to hazard management, but in the case of Iceland, a proactive approach ensures the balance of power with leading institutions can be negotiated.

Iceland's network appears to have sufficient flexibility to perform and adapt to change, largely because of the willingness amongst socio-political stakeholders to engage constructively with both science and technology. For example, the fieldwork led to interviews being conducted with farmers and community leaders in the region surrounding Vík in Southern Iceland. Interviewees repeatedly referred to their regular participation in monitoring exercises, and their use of technology to communicate hazard information:

> We certainly play a more active role than we have done in the past, preparing for the hazard is a community effort, but it is important we talk with the IMO in Reykjavík, that is very important to us (Farmer, near Vík, March 2014).

The extract refers to the distribution of power, to communities, from a hierarchical and institutional elite. In addition, the farmer recognises the importance of having a positive relationship with the IMO; this view was also supported by interviewees in Höfn. Therefore, the study provides evidence of the will of Icelandic society to connect with scientific institutions, widening the distribution of communication channels within the network.

By studying the attitudes of communities such as Vík, this research has been able to identify how social media has renegotiated power and encouraged a participatory approach to volcanic hazard management (Sennert *et al.*, 2015). Platforms such as Facebook and Twitter have empowered community-based actors by enabling them to impact on knowledge exchange (Gultom, 2016); these privileges and responsibilities were previously accrued and acquisitioned by leading institutions such as the IMO and the CP. As powers are increasingly decentralised, the cultures and configurations of these institutional entities are transformed. Furthermore, social media provides greater transparency between stakeholder communities:

> What we (CP) have done is we have built open communications; we've done this because it's always important to adhere to your responsibility (CP, March 2014).

Here, the interviewee refers to how participatory methods of communication have expanded the outreach of institutions to the lay public; therefore, the CP's "social contract" (Gibbons, 1999, C81) has been widened. This research also found that new cyberspaces such as internet forums and newsletters have transformed both trust and collaboration. Since the eruptions of Eyjafjallajökull in 2010 and Grímsvötn in 2011, these channels of communication have had a profound impact on renegotiations of power.

The involvement of the public is significant as it readdresses the 'science' of hazard management. Interviews conducted in both Vík and Höfn highlighted a tendency for Icelandic communities to have a deeply rooted belief in science, and to not view scientific actors as privileged or authoritative figures. Therefore, social attitudes appear to ease and naturalise the process of establishing collaboration, reducing knowledge gaps between science and society. This transition of power between stakeholder communities has had a considerable impact on institutional trust:

> The agency's scoring on trust with the general public has improved since the use of Twitter and Facebook, and now we are one of the most trusted agencies in Iceland (CP, April 2014).

The quotation implies a clear correlation between increased levels of trust and the use of social media. Trust can be defined by the increased strength of relations between scientists and stakeholders from social, economic and political backgrounds.

In the context of this research, trust is measured by asking interviewees questions related to their interpersonal relationships. Although perceptions of trust vary, the semi-structured interview format allows individuals to express their commitment to prominent stakeholders and institutional entities. This enables the research to gauge an understanding of the social capital within Iceland's network, and to extrapolate evidence of trust (Glaeser *et al.*, 2000). The frequency and consistency of communications can also present themselves as measures of trust between leading institutions and community-based stakeholders. In addition, the actions and behaviours of participants in monitoring exercises such as VolcIce are indicative of inter-agency trust, and the willingness of stakeholders to engage constructively with hazard knowledge from multiple sources.

Many non-scientific actors have previously been distanced from how hazard information is constructed; social media improves levels of trust by reducing these disparities:

> Social media has created connections between people and organisations, allowing people to ping each other, talk to the head scientist for example and ask them questions, it doesn't matter whether they are out in the field or in Reykjavík (IMO, March 2015).

The extract implies that a balancing of power dynamics stems from stronger levels of stakeholder connectivity. When explaining the impact of social media, the interviewee refers to the irrelevance of time and space; for example, communication is almost instantaneous and geographical boundaries are removed between the individual contributor and the scientist. However, whilst the use of social media has been valuable to Iceland and is compatible with its close-knit yet diverse stakeholder community, both the CP and the IMO have questioned whether participatory technologies can renegotiate power to the same extent in other multi-hazard environments.

By observing the use of social media, this study has been able to provide substantial evidence of Iceland's advocacy of citizen science (see pp.34-36). Through smartphone applications and other user-orientated platforms, such as MyVolcano and Geosocial, citizen science has become embedded into Icelandic society. For example, the IMO and the University of Iceland (UoI) have both used methods of citizen science to gather hazard information from the public; this has required the institutions to progressively work in collaboration with farming communities and small settlements across Southern Iceland. From the perspective of citizen science, actions taken to renegotiate power can be interpreted as largely social constructs. Interviews carried out near to Þórsmörk have highlighted how the Icelandic public are largely attuned to science and display an awareness of the impacts of volcanic activity on their lives and their culture. In addition, interviews conducted with scientific actors in Reykjavík have also illustrated an awareness of how deeply engrained an "open system" is within Icelandic society (UoI, 2014).

Citizen science has strengthened Iceland's bottom-up approach to hazard management, but is not solely responsible for a decentralisation of power from institutions such as the IMO and the UoI. For example, an interview conducted with an academic at the UoI referred to the longevity of the bottom-up approach, but made no reference to social media:

> We have an open system, we have, over many years, built open access to everything and they (community-based stakeholders) know that, they know that we are not basing this (hazard advice) on some secretive information, we have grounded trust, and I think that is very important, this open decision and open policy is the right way to go for us and for them (UoI, April 2014).

The interviewee implies that open engagement predates social media and can be construed as a characteristic of Iceland's homogenous culture. The interviewee also views trust and collaboration as "grounded" features, rather than the outcomes of newly constructed channels of communication. Furthermore, interviews carried out at the CP attributed the successful use of social media to participatory and "tech-savvy" attitudes (UoI, April 2014), rather than to the innovative engagement of digital platforms.

However, social media communication has become an integral part of the psyche of many at-risk communities in Iceland (Borup *et al.*, 2006). This became apparent during an interview conducted with the CP:

> We are seeing over 200,000 Facebook accounts in Iceland at this point (March 2014), I think it just has to do with the ease of communication, we have needed to react to that (CP, March 2014).

Here, the interviewee refers to the widespread visibility and extensive use of Facebook; the extent to which the platform permeates society means it cannot be overlooked by leading institutions such as the CP and the IMO. On the other hand, renegotiating power is often a fragmentary process and cannot be allied solely to the end-users' preference for accessing information. Open engagement with the public now appears intrinsic to the CP and has been promoted throughout the institution:

> Since 2010 we have had an open desk, so we try to put everything out there, we need to be trusted and this has made what we are doing more transparent, and has broken down barriers, not just to people here in Iceland, but elsewhere also (CP, April 2014).

By referring to "an open desk", the interviewee reflects how the institutional culture of the CP has evolved and now relates to the deconstruction of boundaries. The will to remove "barriers" stems from previous incidents of public scepticism and increased scrutiny following the highly publicised eruption of Grímsvötn in 2011.

Social, economic and political stakeholder communities have progressively moved to a position of power from the margins and peripheries of the Icelandic network. An interview conducted with the CP illustrated this trend:

> Before the eruption began (Grímsvötn, 2011), we had at least one full blown, full scale evacuation exercise, but since then we have

> continued to involve the farmers in the area, so we know that everybody has something prepared for an event, and that they are in a better position to oversee an evacuation if we are unable to reach the area (CP, March 2014).

The interviewee explains the greater inclusion of community-based actors and refers to the improved resilience and adaptability of the region. Power appears to have been spread and redefined in a manner that has granted social actors a more significant voice. Responsibility has also been outsourced as farmers are tasked with overseeing an evacuation; this presents evidence of increased trust and collaboration, and lessens the disparities in power between leading institutions and members of the public.

Both the IMO and the CP have established collaborative partnerships that enable citizens to provide vital hazard information. For example, during the Bárðarbunga eruption (2014-2015), a prominent member of the IMO demonstrated how social media was being used to facilitate knowledge exchange:

> The IMO are encouraging the public to present information on air quality, using social media (Facebook), and this is currently happening on a daily basis (IMO, September 2014).

Here, public engagement allows air quality data to flow in multiple directions between the IMO and the communities affected. Therefore, social media has strengthened mutual trust and exhibited citizen science during a crisis situation (see Figure 5.1 [p.135] and Figure 5.2 [p.136]).

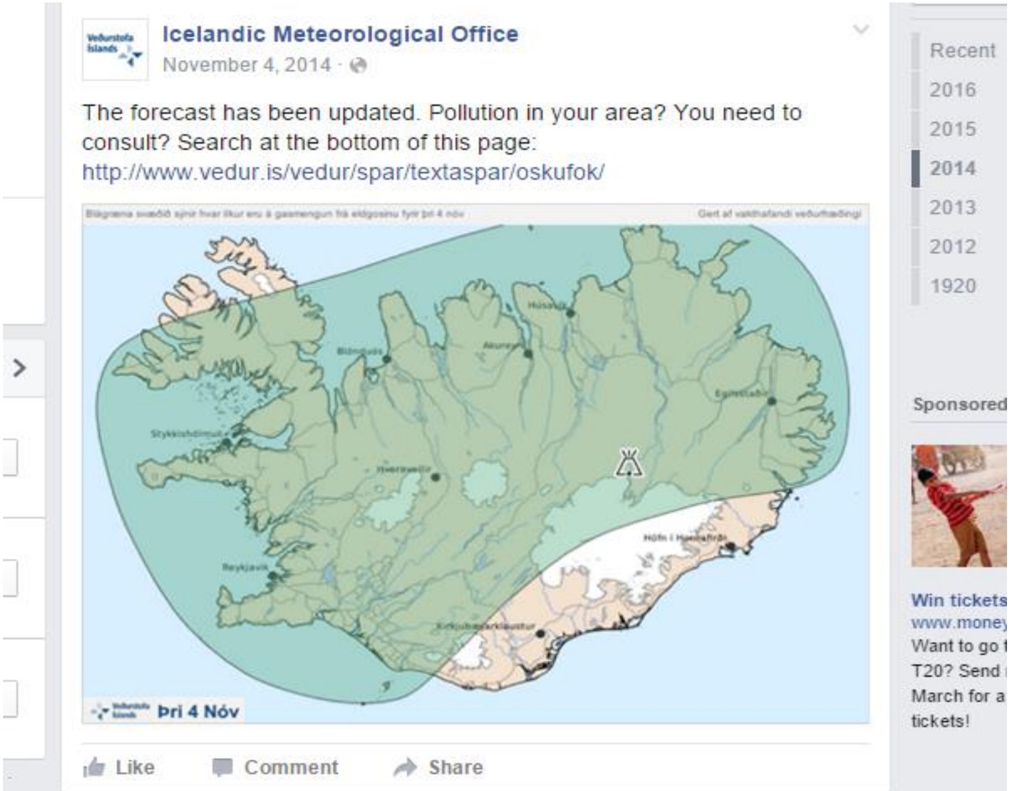

Figure 5.1: *An example of how Facebook was used to collect and share information during Bárðarbunga (Source: Icelandic Met Office - Facebook page. Date accessed: January 2016).*

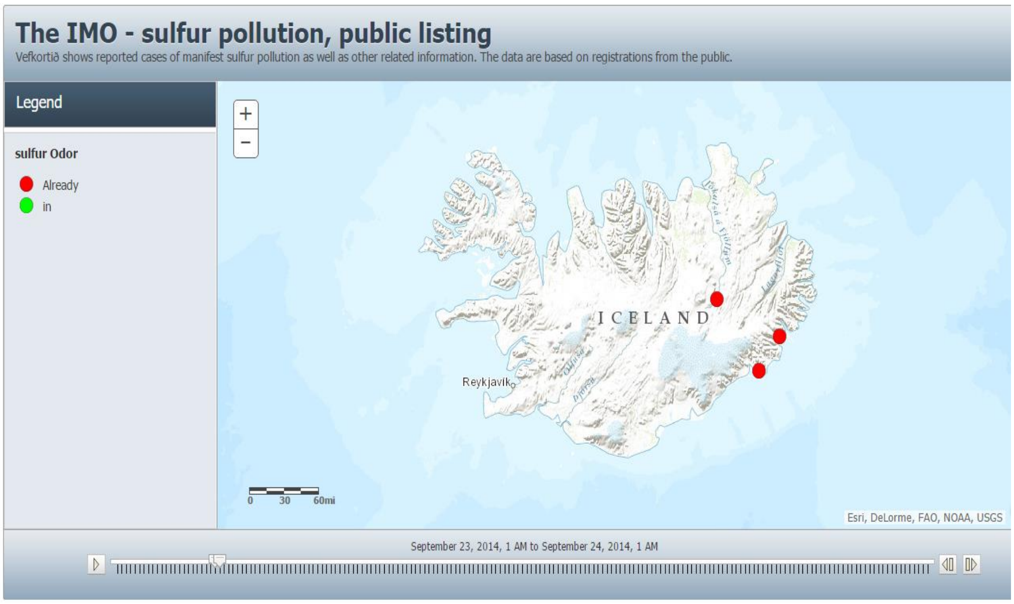

Figure 5.2: *A time-adjustable graphic illustrating sulfur pollution during Bárðarbunga. The data was collected through social media platforms, and is displayed on the IMO webpage (Source: Icelandic Met Office - Holuhraun [Sulfur Pollution Maps]. Date accessed: January 2016).*

The actions and transformations of both the IMO and the CP have illustrated how trust is not one-dimensional, and needs to be earned by the wider society as well as by leading scientists and hazard coordinators. A bottom-up approach to managing volcanic hazards preserves the legislative power of Icelandic institutions, whilst also reinforcing their interactions with socio-political communities (Bird, 2009; Bird *et al.*, 2011; Donovan and Oppenheimer, 2014b). Therefore, the openness of Iceland's network has strengthened the continuity and resilience of collaborative engagements (Scolobig *et al.*, 2015). However, whilst this research has identified several links between reduced power disparities and improved levels of trust and collaboration, the process of renegotiating power cannot be standardised as it is contextually dependant and reliant on the evolution and flexibility of Iceland's hazard network.

5.1.4: The source of power and responsibility: Decision-making and evolution

This study has found that assignments of power and responsibility are only relevant in the short-term and are vulnerable to change. The fieldwork established that whilst coordinators are likely to have a greater level of stability than supporting actors, their cohesion can be eroded and their positionality within the network can become increasingly unclear. For example, the VolcIce exercise may appear to exhibit stability, but both the exercise and its participants were subjected to regulatory changes during the eight months between the original fieldwork and the follow-up research. The positionality and power of coordinators were progressively weakened by changes in the personnel taking part, as well as by the policymaking of ICAO. Therefore, the research findings have viewed Iceland's network in a state of constant flux, highlighting the need for its various stakeholder communities to illustrate adaptability.

In the context of VolcIce, airlines have gained greater decision-making responsibilities over the course of the study (see p.110), and this has impacted on the collective power of the actors who participate in the exercise. An interview carried out with Isavia referred to how VolcIce has sufficient leverage to reform and evolve over time:

> This (VolcIce exercise) is the one that was endorsed September 2010, but we will most likely endorse another one this year when we get a new plan, the international "rules" that govern these exercises (and real events) are for ICAO to decide, so as a result, we are transferring

> responsibility to the airlines and the exercise needs to be up-to-date (Isavia, March 2014).

The interviewee anticipated change as participants were required to comply with policy amendments that were in the process of being authorised by the governing body, ICAO. As responsibilities were transferred to airlines, the decision-making powers of those involved in the exercise were weakened. For example, key personnel were required to make the transition from decision-makers to informants:

> We (Isavia) will not be closing airspaces like we do now, we will be informing, the SIGMET will be sent and they (the airlines) will make decisions (Isavia, March 2014).

As the VolcIce community evolves, new collaborations can be formed with airlines as a result of power being redistributed. The changing composition of the exercise reflects the fluidity of Iceland's networked infrastructure, and illustrates the ambiguity of power dynamics.

However, ICAO should not be viewed as dominating and hierarchical; findings indicate that policy amendments are reliant on the trust and support of airlines. Nevertheless, this research has found that ICAO has sufficient power to evoke change as proposals have been met with widespread compliance. The increased power and responsibility of airlines has not affected the entire structure of the VolcIce exercise, but has demanded adaptability from the leading actors within it. Therefore, institutional power has been decentralised throughout Iceland's network; the acquisition of decision-making power by airlines can be compared to the impact social media has had on the power dynamics of community-based actors. Both transitions have led to responsibilities becoming increasingly fragmented from institutions such as the IMO, the CP and Isavia.

Archival research of the Bárðarbunga eruption (2014-2015) illustrated how connections had formed between the CP and the communities closest to the event. For example, social media activity within Iceland was far greater during Bárðarbunga than it had been for the eruptions of Eyjafjallajökull and Grímsvötn.

Figure 5.3: *The CP's use of Twitter during the Bárðarbunga eruption. Advice was issued and hazard information was requested (Source: Department of Civil Protection - Twitter page. Date accessed: December 2015).*

Platforms such as Facebook and Twitter had begun to present themselves as channels through which to exchange knowledge and circulate hazard information throughout the network (see Figure 5.3, p.138). This has enabled institutions such as the CP and the IMO to outsource power to multiple stakeholder communities and to expand collaborative practices.

Therefore, the adaptation of aviation policy and the expansion of social media have sporadically increased the number of points within Iceland's network at which actors connect and share information. Whilst these transformations highlight the flexibility of Iceland's approach to hazard management, they also refer to an increasingly democratic method of decision-making. However, social media is still in its infancy, so the long-term impacts on the monitoring of volcanic hazards remain largely speculative. Nevertheless, these findings profile the need for complex infrastructures to have the capacity to adapt, and social media has provided a mechanism that can improve stakeholder communication and strengthen levels of trust.

The social and aviation trajectories of Iceland's network demonstrate how it is not only the leading institutions who are "flicking the switch" (CP, March

2014); this has influenced the development of black-boxed knowledge (Latour, 1999a) as facts are no longer sourced or communicated solely by institutional entities. However, the CP and the IMO have both played an active role in nurturing the changes that are referred to in this research:

> Being cooperative, and then being trusted, is the backbone of our decision making; the persons we have to work with have changed, but we have had to be loyal to make sure we are trusted and listened to (CP, March 2014).

The interviewee recognises the importance of loyalty when engaging in a network that is continually evolving; the extract is also indicative of the CP's adaptability, culture and attitudes. By analysing the dynamism of Iceland's approach, this study has found that institutional trust remains "critical" (McAllister and Taylor, 2015, p.89) to the establishment and renegotiation of power.

Whilst this thesis explains how power can be ambiguous and difficult to define, it plays a key role in analysing and navigating complex networks such as Iceland (Oliver-Smith, 1996; Paton, 2006). Through the scope of the research question, the fluidity of power dynamics gives credence to Iceland's holistic approach to hazard management. Furthermore, power relations also explain how volcanic activity is increasingly "co-managed" (Dorcey and McDaniel's, 1999, in Pearce, 2003, p.212), and why multi-hazard environments require trust and collaboration between actors. By analysing power from an interdisciplinary and post-structural perspective, this study has assessed "stakeholder influences" (Rowley, 1997, p.887) and the mobility of decision-making practices. The decentralisation of power has been a recurrent theme and highlights the movement of stakeholder communities from either central or peripheral positions within the network.

5.2: Valuing technical actors: From innovation to evolution

Transitions in power have often been underpinned by improvements in stakeholder engagement; technical actors have been influential in the expansion of communication channels and are integral to the hazard network in Iceland (Donovan *et al.*, 2012). Technology exists in the form of devices and software packages, and can range from mundane computational artefacts to sophisticated satellites. The innovation of digital and virtual technologies has re-energised both trust and collaboration, primarily because they can provide contact areas between society and science. Devices and systems increasingly have value, purpose and policy relevance within hazard management; this section of the chapter addresses the research question by assessing how technical actors are able to bridge multiple stakeholder communities. The mobility and positionality of each individual device can be viewed as part of a process, extending from their innovation to the point at which they either adapt or become disconnected from Iceland's network.

5.2.1: Reforming space and time: The innovation of the screen-world

Iceland provides a model environment in which technical devices can optimally serve the complex and evolving demands of various stakeholder communities. This research has found that technology is increasingly renegotiating the concept of time and space within Iceland's networked infrastructure. For example, social media, mobile applications and real-time information are altering the spatial geography of volcanic hazard management in Iceland. Furthermore, innovative devices have led to the expansion of the screen-world by constructing digital and cybernetic spaces of engagement (Turkle, 2011). Collectively, these tools and software packages have transformed the process of exchanging knowledge:

> In Cyberspace, we can talk, exchange ideas, and assume personae of our own creation, we have the opportunity to build new kinds of communities, virtual communities (Turkle, 2011, p.9).

This study has found that Turkle's interpretation of the screen-world can be applied to Iceland's network; for example, digital spaces between actors and institutions have ensured instantaneous communication and interoperable exchanges of hazard information. Therefore, with improvements to stakeholder connectivity, technical actors have attempted to eradicate the challenges posed by time and space.

The observation of VolcIce highlighted how the screen-world can be used to communicate information artefacts; these include SIGMET notifications between the IMO and the London VAAC. In addition, when interviewing prominent members of the IMO and the UoI, numerous references were made to the value of screen-based devices and software packages:

> Technology has been very important in increasing communication between scientists, it is very helpful, you can sit somewhere as an expert in remote sensing, and if you see something, an event, and have established a contact, you can use technology to share information. Your contact can see what you are seeing regardless of where they are located, your expertise is therefore being shared through the web or on a screen (IMO, March 2014).

Here, a scientist from the IMO explains the impact of the screen-world on communication between scientific institutions, and highlights how time and space can be renegotiated. Therefore, geographical distances have become less significant in the context of how volcanic hazards are monitored; this makes it easier for collaboration and trust to be established within networked infrastructures.

However, screen-based technologies can inhibit valuable face-to-face contact in an environment such as Reykjavík, where the headquarters of scientific institutions, monitoring agencies and response organisations are in close proximity. Therefore, whilst technology has transformed the spatial and temporal dynamics of the network, virtual communication has arguably restricted team building and limited stakeholder familiarity. Digital spaces of engagement are valuable when communicating hazard information between Iceland and the UK, but can be much less beneficial to network cohesion at a domestic level within Iceland. Furthermore, there is a need to consider the multiplicity of many devices and systems; for example, screen-based platforms such as social media improve the frequency of mainstream communication (Yates and Paquette, 2011; Yin *et al.,* 2012), but their value can be questioned as they rarely serve a specific purpose within the network.

5.2.2: Context and standardisation: The use and symbiosis of technical actors

This research has also found that the innovation of the screen-world has promoted standardised methods of communication; these have influenced levels of trust as divisions between stakeholder communities have been further eradicated. Whilst Iceland is a contextually unique environment (see pp.91-94), technologies have the potential to reduce complexity and standardise representations of risk (Fearnley *et al.*, 2012). Felpeto *et al.* (2007) relate standard practices to the autonomy of technological systems:

> The development of automatic systems… lead to the standardization of protocols for hazard assessment and risk management, facilitating the tasks of scientists and technicians in charge of such responsibility and the exchange of information between the different working groups (Felpeto *et al.*, 2007, p.115).

By explaining how standardisation affects knowledge exchange, Felpeto *et al.* (2007) refer to the positive impacts on the management of volcanic hazards. The extract also implies that the actions and responsibilities of multiple stakeholder communities are intrinsically linked to the mobile attributes of technical devices.

Standardisation can also be considered during the convoluted process of constructing and designing innovative technologies:

> When we begin to consider creating new technologies, we need to be aware of the likelihood that we can use them to get information and data in a format that is standardised, but also interchangeable between organisations (IMO, March 2014).

The IMO explain how attributes that facilitate standardisation emerge from collaborative discussions during the research stage of technical innovation. Therefore, the integration of standard practices into Iceland's network can be analysed from a constructivist perspective. For example, if technology is co-produced by the IMO and their partners, then the value of standardised information is also determined by this confluence of knowledge. Both the IMO and the CP refer to stakeholder discussions when explaining the value of standardisation:

> We have had to set standards for giving it (the hazard information) to communities; we have looked at the formats (XML, PDF, etc.) and have identified what is most suitable; it was important that we addressed these issues, however small, before going into the field (CP, March 2014).

Here, the interviewee illustrates how standard practices appear to be controlled by the decision-making of leading institutions. Whilst technology exhibits autonomous capabilities, these are ultimately determined during stakeholder discussions of how a device or software package is intended to be developed.

5.2.3: Exploring technological innovation: The emergence of the Airborne Volcanic Object Imaging Detector

Many interviewees were eager to discuss the impact technology has on trust and collaboration, but tended to refer to the innovation of a system, rather than its use in crisis situations. Both Isavia and the Norwegian Institute for Air Research (NILU) explained the potential impact of the AVOID equipment (see pp.107-109) by referring to the collaborative engagements that had underpinned its testing. Interviewees outlined how the innovation process led to improved collaboration between science and industry; for example, the UK-based budget airline 'EasyJet' (Learmount, 2013) had played a significant role in trialling the equipment in European airspace. This study found that the airline's contribution had been influenced by the economic damage suffered during the eruption of Eyjafjallajökull, and the potential acquisition of additional decision-making responsibilities (see p.110 and pp.137-138). Therefore, the innovation of AVOID has appeared to account for previous volcanic activity in Iceland as well as policy relevance; this has strengthened collaboration between the intended end-user and the scientists constructing the device.

However, over the course of the fieldwork, the influence of protocol and regulatory measures became apparent. Without returning to ICAO's governance of the aviation industry (see pp.125-126 and p.137), interviews conducted with Nicarnica Aviation, the London VAAC and the Civil Aviation Authority (UK), explained how technology is implemented based on regulatory frameworks. For example, an interviewee from the London VAAC referred to the constraints imposed on the implementation of the AVOID equipment:

> It (AVOID) hasn't been approved yet, it is not approved to be flown on a civilian aircraft, so it has got to go through a whole certification process and be cleared to fly, and then of course they have got to write a plan about how they are going to use it operationally, so there is quite a long way to go, to get it into an operational environment (London VAAC, October 2014).

The extract refers to how the technology has been shaped by the need to comply with a rigorous regulatory framework; acceptance and legitimacy are more significant to innovation than attempts to ensure long-term collaboration between stakeholder communities.

Therefore, the construction of the AVOID technology has been reflective of ICAO's sphere of influence; as a result, this thesis now examines the critical importance of protocol such as Technology Readiness Level (TRL) measurements (see pp.109-110):

> Our objective is developing the technology for AVOID, that's our role, that's Nicarnica Aviation, but we have known that there is a need to be developing it in accordance with and through the technology readiness levels. To be able to put an instrument on an aircraft, it has to meet certain requirements, and in working with airbus, this has been really beneficial, you have to have links with the aviation industry (Nicarnica Aviation, July 2014).

The extract provides further evidence of how systems such as AVOID are designed according to regulation (TRL's); for example, the interviewee refers to the establishment of a middle-ground between the ambitions and intentions of scientists, and the governance of technology in the aviation industry. However, Nicarnica Aviation do not view TRL's as a threat to their operations, but interpret them as obstacles to be overcome; this illustrates how deeply embedded TRL's are in the process of technical innovation.

Furthermore, the interview conducted with Nicarnica Aviation also expressed the need for continued collaboration between science and industry. The perceived success of how the AVOID equipment was tested stems from scientific and industrial actors being involved in the innovation process from the outset. For example, EasyJet and Airbus made a significant contribution, with the role of the latter "providing the planes, as well as the radar and technology" that were used for testing the device (NILU, June 2014). Therefore, the industrial involvement allowed the AVOID technology to meet the criteria for TRL's, primarily because testing could take place in an environment where the system would be used at first-hand (see Figure 4.6, p.108). A collaborative approach to designing and using the technology has, therefore, been evident at each stage of its innovation, and was initiated by its creator, Dr. Fred Prata.

The engagement of airlines and aircraft manufacturers provides evidence of AVOID being a product of a "wide-ranging operation" (EasyJet - Corporate page: AVOID section, 2016). Exchanges of knowledge and expertise have been integral to the construction of the equipment, and illustrate how boundaries between stakeholder communities can be transcended. This research has established that these examples of collaboration between science and industry appear to be having long-term impacts on levels of trust within Iceland's hazard network. For instance, the Eyjafjallajökull eruption (2010) strained the relationship between airlines and monitoring institutions such as the London VAAC. Interviews conducted at NILU have since referred to a strengthening of these ties, primarily as a result of continued collaboration in the development of new technologies. Therefore, the value of the AVOID equipment can be enhanced when considering the positive impact its innovation appears to have had on the sociality of the network.

Furthermore, AVOID has been designed for use in the context of volcanic activity in Iceland, but both NILU and the London VAAC have explained how it could also be adapted for use in other global regions. There are a relatively high number of end-users with whom the device can potentially be associated, so the impact on levels of trust between stakeholders could be more widespread than is reflected in this thesis. Both scientists and the aviation industry appear to have recognised the long-term relevance and flexibility of the device; these are particularly valuable attributes for technology to possess in environments such as Iceland. In a post-Eyjafjallajökull age, technical actors have an aura when they can be tailored to socio-economic responsibilities (Learmount, 2013); this research studied numerous devices and software packages that have impacted on trust and collaboration because of their socio-political relevance.

As Iceland's network is complex and evolving, connections between end-users and innovators are integral to ensuring that devices and systems are resilient. For instance, Nicarnica Aviation have created camera systems such as "NicAir" (Nicarnica Aviation, July 2014), and have consulted extensively with the end-user, namely the IMO:

> The instrument we have, you would take it into the field, and plug it in, and then take measurements. IMO wanted something very much sort of automated, so when we were designing the device to deliver to them, we knew that once it was in the field, it would need to operate by itself and connect to their server (Nicarnica Aviation, March 2014).

Here, the interviewee refers to how the IMO has influenced the construction and autonomy of the NicAir device. The extract also highlights the existence of a collaborative and trustworthy relationship, between Nicarnica Aviation and the IMO, prior to the physical construction of the technology.

Therefore, NicAir has been shaped and designed in a manner that has ensured its compatibility with the culture and actions of its end-user:

> We (Nicarnica) are sort of responsible for the technology, but we have been in discussion with the IMO because they are going to be the ultimate user of the three instruments we are developing; so we have been discussing how they want to use the instruments in a slightly different way to how they have been used in the past… we have designed this instrument (NicAir) with Iceland in mind, any sort of comments or feedback that IMO have are sent back to us (Nicarnica Aviation, June 2014).

By referring to specific discussions and exchanges of knowledge, the interviewee provides evidence of Nicarnica Aviation's constructive know-how connecting with the scientific expertise of the IMO. This has allowed the individual attributes of NicAir to be nurtured through institutional collaboration and trust. However, whilst the extract explains the contextual niche within which the NicAir cameras were assembled, the device has since been used in environments other than Iceland, notably the Canary Islands and the Kamchatka Peninsula (Mackie *et al.,* 2016). Nevertheless, the development of both NicAir and AVOID has illustrated how technology can impact on trust and collaborative engagements in complex hazard networks. As monitoring devices become increasingly mobile and autonomous, they have a greater ability to become self-sufficient once deployed in fields of research.

5.2.4: Valuing information: The Numerical Atmospheric-dispersion Modelling Environment

By interviewing and observing stakeholders at the IMO, the London VAAC and Isavia, this research has been able to study the mobility and independence of monitoring devices and communication platforms. Software programs are often shared between these institutions, with an example being the Numerical Atmospheric-dispersion Modelling Environment (NAME). Unlike the AVOID equipment, the NAME software had already been deployed within Iceland's network when the fieldwork was conducted, and was used extensively during the

VolcIce exercise (Jones *et al.*, 2007). The purpose and functioning of NAME (see p.116) has strengthened trust and maintained collaborative links between the IMO and the London VAAC. Interviewees from both institutions explained how the software had improved their adaptability and resilience in the context of VolcIce.

Software packages such as NAME are integral to this research, primarily because they illustrate how technology can ensure that leading institutions have the capacity to co-evolve (Rip, 2002). Furthermore, first-hand experience of NAME has enabled this study to recognise how technical actors can be purposely designed to react to change. Whilst observing the VolcIce exercise (see Appendix 3.1, p.266), notes recorded in the field diary highlighted the value of the connective bridging point that NAME provides between the IMO and the London VAAC:

> 1) The London VAAC use the NAME modelling software once they have received a warning (within the exercise) from the IMO.
>
> 2) Graphs constructed by NAME are shared with the IMO and Isavia.
>
> 3) The NAME outputs are used by each of the institutions participating in the exercise - to identify the concentration and dispersal of volcanic ash (Research field diary, March 2014).

By constructing graphical outputs, NAME generates information artefacts that are dynamic and can be used by multiple stakeholder communities (see Figure 4.10, p.116). When discussing NAME with the IMO and the London VAAC, it became apparent that the form and representation of the outputs were considered at length during the software's innovation; the Volcanic Ash Graphics are designed to facilitate efficient communication between end-users.

Therefore, NAME has impacted on the scope of knowledge exchange within Iceland's network, primarily by translating hazard data into Volcanic Ash Graphics (see Figure 5.1 [p.135] and Figure 5.2 [p.136]). This research has assessed the software's contribution to the aviation industry, and has found that the mode of representation is navigable by both coordinators and supporting actors. The communication of graphics depicting the dispersion of volcanic ash has transformed decision-making, both within the VolcIce exercise and during ongoing volcanic eruptions. Furthermore, this analysis of the NAME software can reflect key elements of Latour's approach to ANT (1993; 2005); for example, Volcanic Ash Graphics can be viewed as circulatory artefacts that generate and reinforce connections within the network. However, NAME is largely used in modelled situations and can inadvertently lead to stakeholder communities, such as the aviation industry, being over-reliant on the data and graphs it exhibits. In addition, NAME is also constrained by the governance of ICAO; for example, an assigned colour code is not evident on NAME illustrations, as this would contravene ICAO regulations.

Nevertheless, NAME demonstrates how technical actors are able to self-sufficiently translate hazard information. By removing the quantitative purity from datasets, and converting them into graphics, NAME translates knowledge so that it can be exchanged by a wide range of stakeholder communities (Jones *et al.*, 2007, p.580). Furthermore, this study has recognised the dependency of the VolcIce participants on the NAME software; this has drawn attention to the power dynamics between human and technical actors. During a period of volcanic activity, when information needs to be distributed to multiple communities, NAME restricts human intervention to computational demands and demonstrates the autonomy of Iceland's technical infrastructure. The technology is equipped with the in-built capability to act and communicate information; this makes differentiating between human and technical contributions to hazard management, a challenging task.

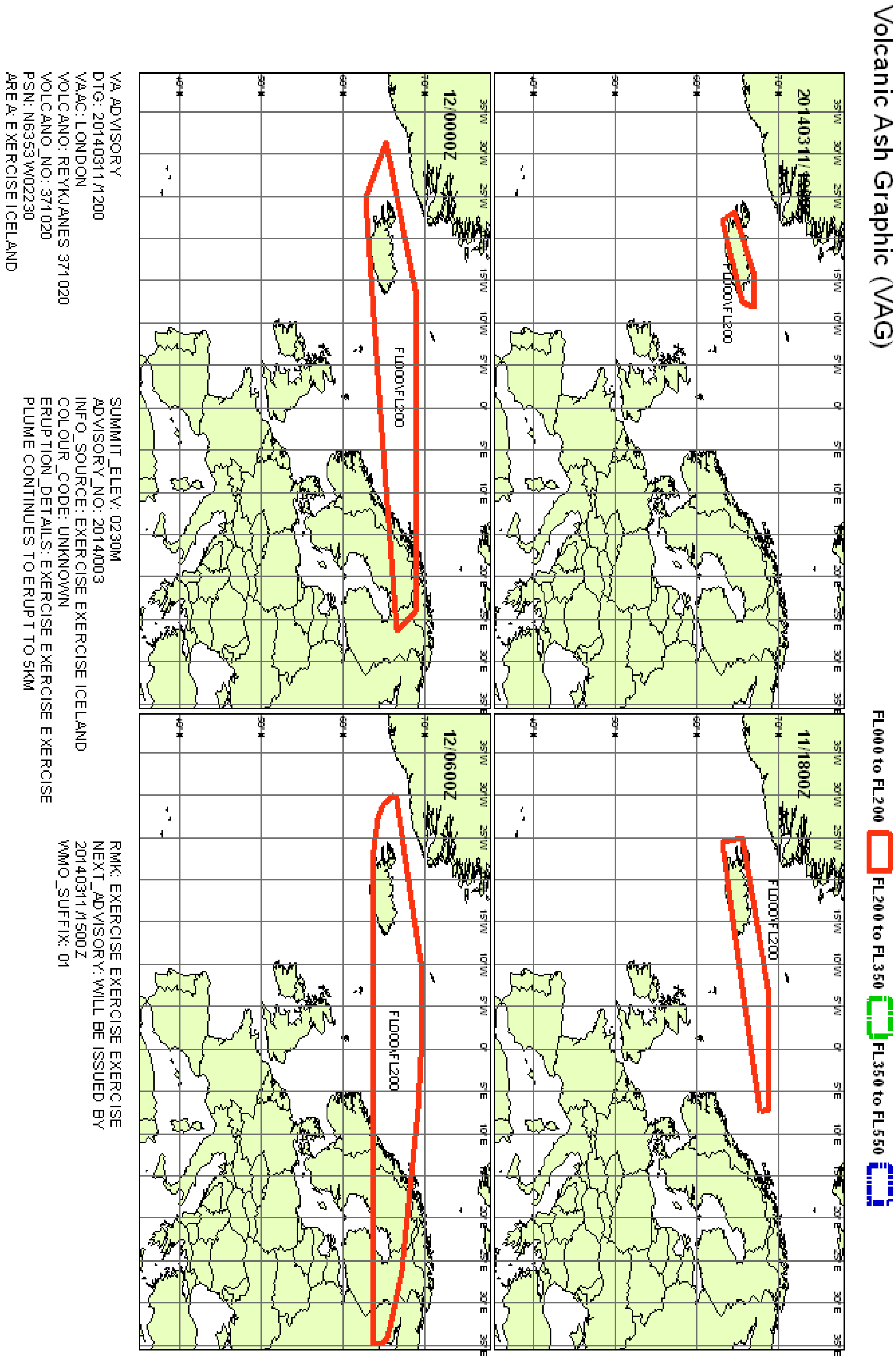

Figure 5.4: *A graph displaying ash dispersal data, produced by the NAME software and communicated as part of the VolcIce exercise (Source: Met Office [UK] - London VAAC: Volcanic Ash Graphics page. Date accessed: January 2015).*

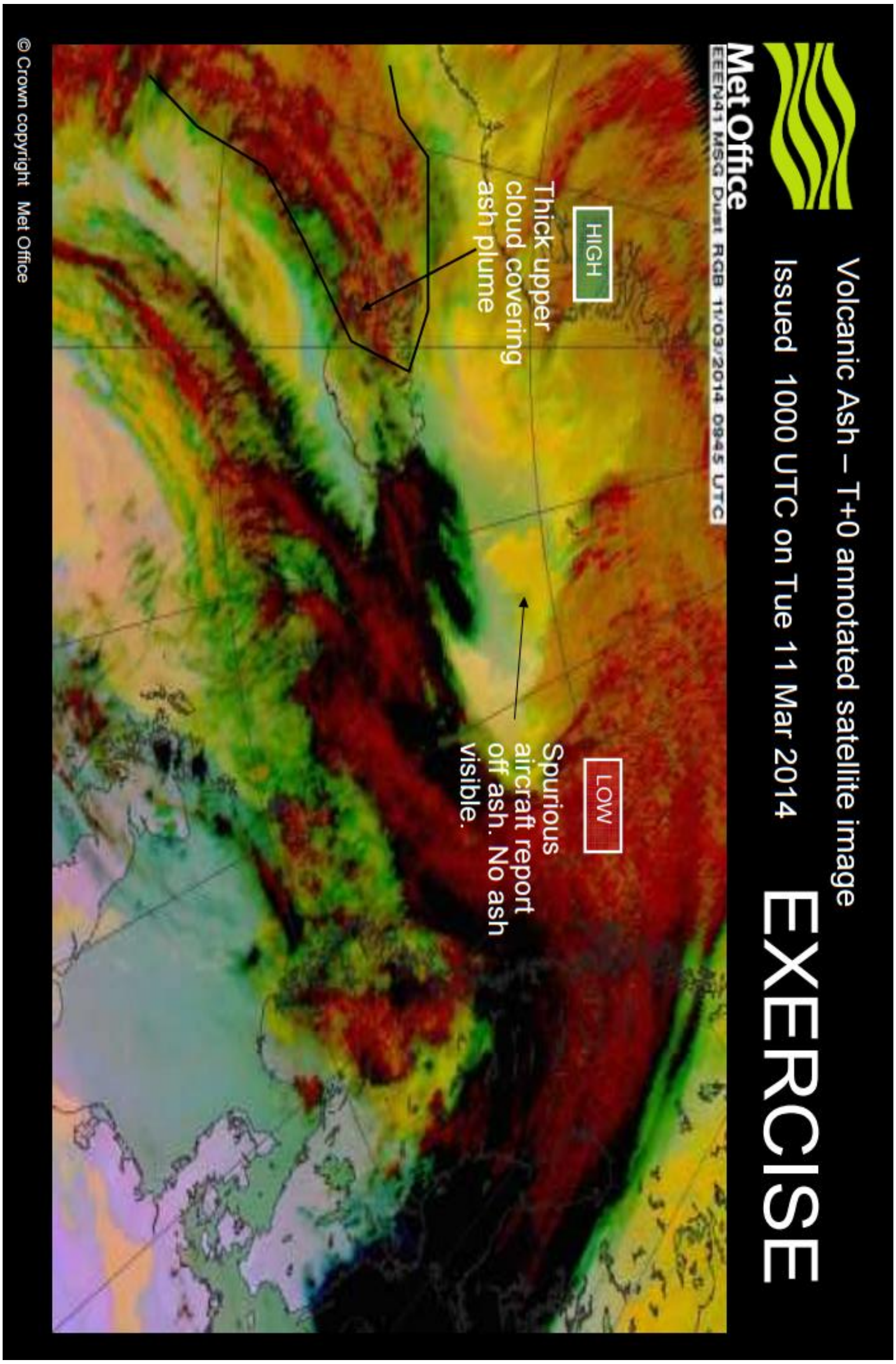

Figure 5.5: *A further output illustrating volcanic ash, using data that has been converted by the NAME software [Nephanalysis] (Source: Met Office [UK] - London VAAC: Volcanic Ash Nephanalysis. Date accessed: August 2016).*

However, whilst this research has been able to establish the power dynamics of the NAME software, the extent to which its contributions to hazard management are self-sufficient remain questionable. For example, an interview conducted with the IMO referred to the actions of forecasters in response to receiving NAME outputs:

> We (the IMO) amend ash cloud forecasts when we receive the information coming from the ash distribution model (NAME); it is the VAAC that share this with us, and we have had to make sure that, through the exercise, we have a good relationship with them (IMO, March 2014).

The interviewee views NAME as the distributor and communicator of hazard information, but its value and significance would be lessened if channels of communication did not already exist between the IMO and the London VAAC. NAME provides an efficient means of utilising these channels, but does not actively form or widen them. In addition, the role and influence of institutional coordinators cannot be discredited as NAME outputs are subject to the IMO's amendments of ash forecasts; therefore, human intervention is required and is not replaced entirely by the technology available.

This study has recognised the need to interpret technical actors from holistic perspectives; whilst transforming information is significant, AVOID and NAME can only impact on collaboration and trust when their end-users are able to engage with the artefacts and outputs they produce. Therefore, analysing the encoding and decoding of outputs is integral to appreciating the value, positionality and autonomy of technical devices and software's (Hall, 2001). An interview with the IMO highlighted how this has been reflected in the context of VolcIce:

> The London VAAC are not likely to be interested in the same data as what we are defining, so in interpreting the data we need to consider what is relevant and concerns our view? The volcanic ash graph is different for each of us, depending on our local view (IMO, March 2014).

By referring to the outputs of NAME, the interviewee illustrates how interpretations can vary once the graphics are distributed to human actors. The outreach of the technology is extensive, and whilst the information is transformed by the software in a largely autonomous manner, its impact on various stakeholder communities can be diverse. If Volcanic Ash Graphics are to influence trust and decision-making, they ultimately require individual negotiation by a plethora of human actors.

5.2.5: Negotiating technical actors: The importance of translation

Prominent stakeholders from both the IMO and the London VAAC have repeatedly referred to the medial process of negotiating technical devices and systems. Kirsch (1995) viewed technology as a producer of space, and it is the exponential growth of the digital space within Iceland's networked infrastructure that human actors have negotiated. Space is produced by the construction and mobilisation of datasets, as well as the multiplicity of cyber-based channels of communication. Real-time data, Geographical Information Systems and "Big Data" (Boyd and Crawford, 2012; Bowker, 2014) have collectively expanded Iceland's network, developing technological spaces that institutions and communities alike have needed to negotiate.

The negotiation process has been aided by projects such as FutureVolc (see pp.103-106 for additional information), a research community that has intended to centralise data streams, construct feedback loops and improve knowledge exchange. Many approaches to negotiating technology have involved the removal of boundaries between quantification and sociology; in a complex network such as Iceland, this has led to the expansion of citizen science (Rotman *et al.*, 2012) and Volunteered Geographic Information (Zook *et al.,* 2010; Elwood *et al.*, 2012; Dransch *et al.,* 2013; Haklay, 2013). Interviews conducted with the CP and the UoI have provided examples of how these methods facilitate negotiation between social, scientific and technical communities:

> If people can take photographs and electronically send us photographs of the areas identified at high risk, then that can help us with the mapping of risk, this is something that has come from advances in technology (UoI, April 2014).

The interviewee refers to the use of mobile technology, and explains the importance of virtual space when sharing and interpreting hazard information. Communities such as Vík are actively engaging with monitoring institutions in

Reykjavík on a regular basis, using either smartphone applications or internet links:

> We use technology to observe threats, and send any information we have to the IMO and to the university in Reykjavík, we do it on the computer database, we follow reports and also message through to Reykjavík using the internet (Vík-based interviewee, April 2014).

Here, the extract provides an example of how digital spaces are being negotiated and utilised to maintain or improve communication. By conducting interviews in Vík, this research has found that trust and resilience have generally been enhanced by an advocacy of citizen science.

Innovative technologies tend to provide the space for stakeholders to negotiate, and this has led to a psychological reduction in distance between science and society. Therefore, a change in stakeholder perception appears to have made it simpler to strengthen trust and collaborative engagements (Pearce, 2003; Cronin *et al.*, 2004b; Paton, 2008); this was referred to during an interview carried out with a researcher from the UoI:

> We have found that technological breakthroughs have helped to close gaps between scientists and the general public; the general public quite often denies access to validity, if you associate communities of end-users to your assessment, and expose them to the technology, then they are more likely to accept the conclusion of that assessment. Technology brings this possibility of interactions, and you increase the likelihood of having the results of a risk assessment accepted by all stakeholders (UoI, April 2014).

The extract directly refers to the link between technology and trust, and explains the impact on Icelandic communities and scientific institutions. As technologies become increasingly participatory, they have a greater ability to empower human actors in the manner expressed by the interviewee. Participatory devices and systems can be continually negotiated, and improve hazard knowledge by ensuring a close relationship between the technical infrastructure and the community affected.

The process of negotiating technology can prevent hazard information from becoming too closely aligned to scientific or social ideals. Instead, it can close the knowledge gap by reflecting multiple stakeholder communities, and encouraging actors from contrasting backgrounds to work progressively alongside each other. However, an interview conducted with the CP questioned the extent to which an effective negotiation process can be attributed to technical actors:

> It has nothing to do with changes in technology, we could have these relations with the communities anytime, the technology only allows us (CP) to do more things, but if you are not prepared mentally to explore new ways then the technology is useless, you need perspective (CP, March 2014).

The extract implies that the Icelandic network strives for maximum trust and collaboration, with or without the use of participatory devices and systems. Whilst the interviewee accepts that technology may enhance interaction, the attitudes and willingness of society are much more significant. The translation of hazard knowledge is strengthened by social actors negotiating with technology, but is ultimately underpinned by their enthusiasm to access and connect with the leading institutions that implement the devices and software packages, namely the IMO or the CP.

Within hazard management, the characteristics and behaviours of human actors need to be considered to a greater extent. Innovative technologies are valued highly in Iceland's network as an engaging stakeholder community is openly exposed to them. Channels of communication present themselves as binding features of the network, but can only be maintained and widened by technology if local communities are prepared to utilise them for sharing and translating hazard knowledge. For example, during the VolcIce exercise, the research established that both trust and collaboration stemmed from the presence of a post-structural space that allowed for frequent consultation. Each of the participating institutions had coordinators and supporting actors who were willing to negotiate with the technology at multiple points in the exercise, both in-house and during the debrief that followed. Therefore, interactions between human and technical actors can explain the mobility of knowledge exchange and the flexibility of monitoring exercises. Technology enables hazard knowledge to be translated (Akrich *et al.*, 2002), but requires an engaging and interconnected stakeholder community.

5.2.6: The reliance of stakeholders on technical actors

The VolcIce exercise and the FutureVolc project have both illustrated the prominent role now played by technical actors in Iceland's network. As the technical infrastructure has expanded, it has become difficult to decipher communication channels that are increasingly mobile and overlapping. This research has found that many human actors are reliant on the technology available to them; this was reflected in an interview conducted with the CP:

> We rely on technology to solve problems, it is a gut feeling, we rely on technology to take care of problems that will arise, whether that be to protect us from the sea, or from the volcanoes (CP, March 2014).

The interviewee expresses the emotive connections between technology and stakeholder communities in Iceland, and illustrates the extent to which human actors are reliant on their technical counterparts for protection. Technology can enhance the adaptive capacity of Iceland's network, but over-relying on it highlights the potential flaws of a techno-centric approach to volcanic hazard management. For example, in the event of a malfunctioning device or software program, the resilience of the network can be undermined. The reliance on technology was felt most strongly when observing the VolcIce exercise; for instance, the recommendations that were documented in the exercise report stemmed directly from the performance and mediation of artefacts such as NAME. Furthermore, during the exercise, representations of ash dispersal were constructed and communicated by both mundane and advanced technologies; this demonstrated, in the relatively confined settings of VolcIce, how technical actors were able to determine the flow and format of hazard information.

Technology appears to have become so deeply integrated within Icelandic society that it can be challenging to distinguish between the human and technical elements of the hazard network. For example, a staff member at the CP explained how participatory forms of technology had impacted on the flexibility and attitudes of human actors:

> People are extremely computerised in this country (Iceland), young and old, and they have smartphone and tablet apps, so in that sense they are well equipped, they check forecasts, not only from the Icelandic Met Office but also from the Norwegian Met Office, and instinctively use the mobile device (CP, March 2014).

The interviewee does not explicitly draw on trust and collaboration, but refers to the intrinsic relationship between community-based stakeholders and mobile devices. This illustrates how technical actors are normalised and viewed as default measures for monitoring volcanic hazards in Iceland. The digital agency exhibited by many devices and systems appears to have enabled human actors to become dependent upon them, particularly during a time of anxiety or crisis. This has been reflected in the development of crowdsourcing (Rossi *et al.*, 2015) and citizen science; these methods of data collection and knowledge exchange provide an insight into how embedded technical actors are in hazard management.

Furthermore, the routine use of Iceland's technical infrastructure appears to have rendered many human actor's unconscious to their reliance upon it. For example, an interview conducted in Vík illustrated how devices and systems have become less visible as they assimilate with day-to-day life in the hazardous regions of Southern Iceland:

> We don't really see technology because it is such a part of our lives, it is all around us, we often do not notice when we are using it directly, whether it be for monitoring the volcano or whatever (Vík, March 2014).

Here, the extract reflects the level of compatibility between technical actors and Icelandic society; the regular use of technology underpins human interaction and influences both trust and collaboration. The research also found that interviewees from the IMO and the CP were keen to refer to the contextual relevance of many innovative devices, as well as the information artefacts they produce.

Therefore, the impact of technology on trust and collaboration is determined by far more than the innovation of a device or software package. When informative outputs are translatable by their intended users, value is attached to how the technical infrastructure is integrated with society and relied upon by stakeholders. During interviews and observations, the IMO and the CP both referred to technology increasing social expectations of what knowledge and information should be communicated. This approach to Iceland's network resonates with the views of Donovan *et al.* (2012):

> The dependence on technology, coupled with its complexity, has produced social gradients of understanding, reliance and knowledge acquisition (Donovan *et al*., 2012, p.680).

Donovan *et al.* imply that social attitudes can be reconstructed and redesigned by community engagement with technical actors; this constructivist approach to explaining a hazard network is contextualised within this PhD research. For example, by exploring Iceland's network, this study has been able to identify how stakeholder communities negotiate technology and translate information artefacts. The research has analysed multiple communication channels and assessed several data translation mechanisms within the network.

5.3: Conclusions

To conclude, technical actors are essential components of Iceland's network, and their fluid flow of information is integral to understanding knowledge exchange. In addition, the study has highlighted how power dynamics are continually evolving, with a trend towards power being distributed from leading institutions to a plethora of stakeholder communities. The widespread use of participatory technologies, and the outreach of projects such as FutureVolc, have collectively transformed collaboration and trust. In response to the research question, Iceland's approach to hazard management accepts that both power and technology evolve in a manner that tends to widen channels of communication and improve the adaptability of the network.

This research has established that stakeholder connectivity is more significant than a balance of power when explaining the dynamism and resilience of hazard management. By analysing the VolcIce exercise and models such as NAME, this chapter has interpreted Iceland's network from a range of interdisciplinary perspectives. The exchange and translation of knowledge are recurring themes, and highlight the relevance of constructivist approaches such as co-production and ANT. However, these findings are specific to Iceland and may not be a fair reflection of how stakeholders communicate in hazardous regions that are less economically developed. Nevertheless, as levels of trust improve and collaborative engagements expand, actors and institutions have a greater capacity to frequently interact across local, national and international scales. Therefore, the study emphasises the need for a relational approach to managing volcanoes in multi-hazard environments such as Iceland.

Chapter Six: Transcending scale: The emergence of a borderless hazard network in Iceland

The evolution of decision-making power and innovative technologies have illustrated how the concept of scale can be redefined within Iceland's hazard network. For example, this research has identified a general strengthening of trust and collaboration, easing the process through which scale boundaries can be transcended. By documenting how amendments have been made to the scale at which monitoring and response practices take place, this study has analysed the convergence of stakeholder communities and the expansive outreach of leading institutions. Therefore, the configuration and composition of Iceland's network can represent a microcosm of a largely borderless social and technical world. This chapter will critically assess the features of the network that support this view; scale boundaries between Icelandic institutions and communities are contestable, and can be explored from a range of interdisciplinary perspectives.

This chapter approaches scale in a way that can relate to broader geographic debates. Geographers have seldom established a collective understanding of what constitutes scale, but have referred to the flexibility and dynamism of scale boundaries (Marston *et al.,* 2005). By analysing the institutionalisation of hazard management, this study resonates with the politics of scale (Cidell, 2006) and explains how local, national and international stakeholders are interconnected by flows of information. A focus on boundary spaces progressively weakens rigid and hierarchical interpretations of scale, and counters the view that clearly defined scales of importance can be attributed to actors and institutions, particularly in the context of hazard networks.

An increasing number of geographers are acknowledging the fluidity and mobility of scales and boundaries (Lemke, 2000; Cash *et al.*, 2006; Hein, 2006). This trend resonates with Iceland as the transition, interaction and changeability of things between local and international scales are documented extensively within this thesis. Therefore, geographical engagements that replace scale with a flat ontology of "complex, emergent spatial relations" (Marston *et al.,* 2005, p.422) can be associated closely with this research. For example, the flat ontology argument appreciates relationality and constructivism; flows and channels allow scale to progressively fragment through the construction of the social world. This narrative relates to the research conducted in Iceland, primarily because it replaces scale boundaries and hierarchies with disordered and unstable interactions. Furthermore, it can also be reflective of ANT (Moore, 2008) and the sociological approaches that underpin this PhD research. For instance, Smith's (2003) explanation of a flat ontology does not differentiate between humans and non-humans.

Wisner and Luce (1993), and Blaikie *et al.* (2005), have both used the lens of social vulnerability to associate scale with volcanic hazards. These works referred to there being a choice of contextual scales at which to manage volcanic activity, whereas this study analyses the connections that exist between local, national and international scales. Furthermore, this thesis analyses how the process of transcending scale impacts on the adaptive capacity of Iceland's approach to volcanic hazard management. Scale directly relates to the research question as boundary-work can theorise communication practices between the human and technical components of Iceland's network. This research argues that an interdisciplinary approach can redefine the relationship between volcanic hazards and scale (Renschler, 2005; Biasse *et al.*, 2014); for example, Actor-Network Theory (ANT) implies that both scale and context are subsumed by interconnectivities between individual actors (Latour, 1999b). Meanwhile, co-production explains how tensions between local and international scales can be overcome by generating knowledge and technology.

When viewing a volcanic hazard in isolation, the volcano represents a fixed geophysical construct, conditioned at a local scale through social attitudes and attachments. However, unlike many climatic or other seismic hazards, volcanoes possess surface permanence within landscapes that are otherwise evolving. In addition, the impacts of volcanic activity are not static and can be localised (lava and pyroclastic flows, e.g. Hekla [2000]), nationalised (gas pollution, e.g. Bárðarbunga [2014-2015]) or internationally significant (ash fall, e.g. Eyjafjallajökull [2010]). Therefore, hazard management practices need to adapt to changing demands, and require the flexibility to extend communication and decision-making across a range of scales. This chapter will draw on the FutureVolc project and the Emergency Response Coordination Centre (ERCC) to analyse how scale is transcended in the context of Icelandic volcanism. The second part of the chapter then assesses how the construction and calibration of data allows information and knowledge to be communicated across boundary spaces.

6.1: Transcending scale: The fragmentation of boundaries

The stability of scale in Iceland's hazard network has become increasingly speculative; since the eruption of Eyjafjallajökull (2010), a fluid transgression of scale has been evident. Boundaries are breached on a regular basis as actors and institutions increasingly interact at multiple scales. This section examines how the relevance of scale has been transformed and focuses on what actions are taken at scale boundaries. In the context of this research, boundaries are interpreted as imagined spatialities or dividing lines between actors positioned locally, domestically and internationally within Iceland's network. Boundary spaces are integral to understanding the transformation of hazard management as communicating across them provides an insight into a network's flexibility (Donovan and Oppenheimer, 2012). As boundaries have been eroded by frequent communication and knowledge exchange, they have become increasingly difficult to define and identify. Boundary crossing has been explained by scholars such as Gieryn (1983), and is used extensively in this chapter to examine how network dynamics improve Iceland's adaptive capacity and resilience.

6.1.1: Positioning hazard response and monitoring beyond Iceland: The European Response Coordination Centre and the FutureVolc project

As channels of communication become more expansive in hazard networks, decision-making is increasingly influenced at a European or global scale. This research found that the creation of EU-governed institutions, such as the ERCC (see pp.110-111), has altered the scale at which monitoring responsibilities and responsive actions are determined. The ERCC provides one example of how the science and socio-politics of Icelandic volcanoes extend far beyond regional and national boundaries:

> A coordination hub facilitating a coherent European response during emergencies helping to cut unnecessary and expensive duplication of efforts (European Commission - ERCC main page, 2016).

By encouraging collaboration between the Civil Protection (CP) and their European partners, the ERCC typifies how scale can be annexed within Iceland's network. For example, knowledge is co-constructed and exchanged at a European level; this improves the resilience and adaptive capacity of the network as actors are less reliant on local and domestic interactions.

The ERCC has improved the co-production and communication of hazard knowledge; this demonstrates not only the holism of Iceland's network, but also the value of supranational intervention. For example, an interview conducted with the CP touched on the largely positive attitude towards an EU-level response to Iceland's volcanic hazards:

> Iceland, it is a country where we have volcanoes that are local hazards, but sometimes we need international help, for example, health, agriculture issues, technology issues, we understand that and react to it (CP, March 2014).

The interviewee does not refer to the impact on the adaptive capacity of the network, but demonstrates how actors are willing to transform the scale of hazard response. Both the IMO and the CP have referred to the practical grounds on which European intervention is authorised and boundaries are transcended (Guston, 2001). For instance, there is a relative scarcity of human actors at a local and domestic scale in Iceland; this explains the will for hazards to be governed from a supranational level, and gives credence to Wisner and Luce's (1993) contextual affiliation with scale.

Actors and leading institutions appear to support the spatial expansion of Iceland's hazard network, and refer to the ease with which scale boundaries can be breached and contested. Several interviewees from both the University of Iceland (UoI) and the CP explained how the monitoring network can be modelled on the concept of a 'supersite' laboratory (see pp.103-104). Whilst this terminology implies that Iceland can be viewed as an enclosed study area (see Figure 6.1, p.162), the scope and design of the FutureVolc project has enabled Icelandic actors to integrate with a European research community. An interview carried out with the British Geological Survey (BGS) expanded on the structural meaning of a supersite:

> The supersite brings together large clusters of people across Europe as a template for future project development, determining what the future directions should be in European geo-infrastructure and geo-research (BGS, March 2015).

The extract refers explicitly to supranational influences; by envisioning the supersite as a "template", context and individuality are removed, and engagement and "coordination" are prioritised (Cocco, 2014). In addition, the interviewee appears to embrace the European perspective, using it to explain the relevance of supersites to the future monitoring of volcanic hazards in Iceland.

However, a supersite is not only confined to a local, domestic or international scale; instead, it utilises boundary-less attributes such as "open data policies" (CP, March 2014) to expand and contract scale intermittently. This explains how supersites can improve the adaptability and resilience of a complex network such as Iceland. As a dynamic and interactive entity, a supersite facilitates coordination and uses the European scale of hazard management to take a bird's-eye view of monitoring practices (see Figure 6.1).

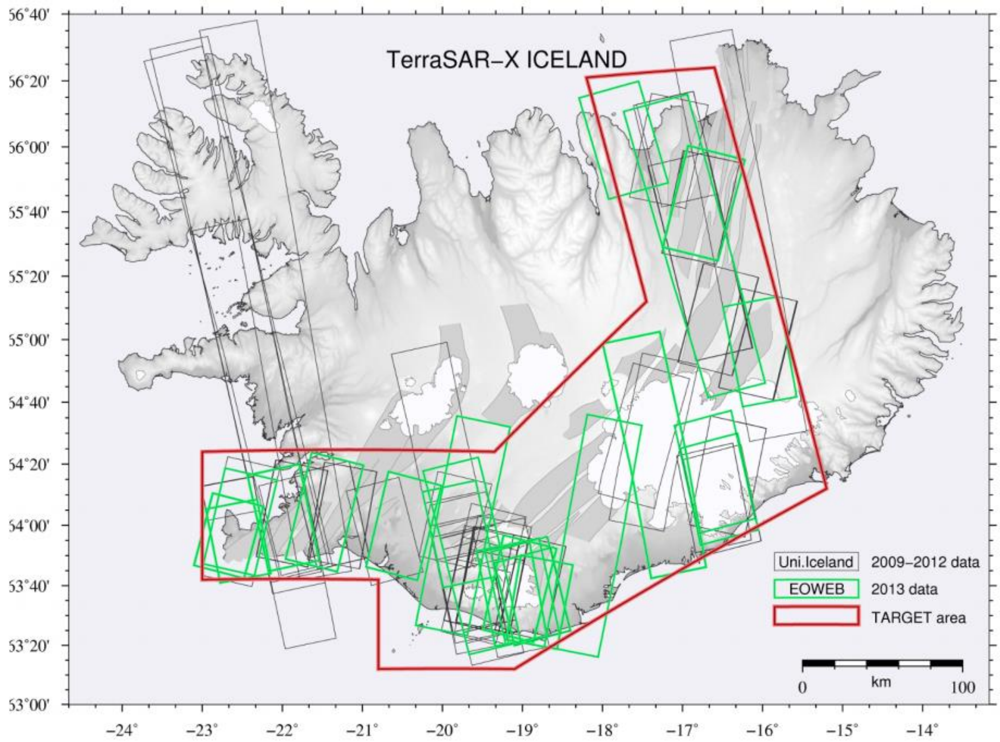

Figure 6.1: *An illustration of the regions covered by Iceland's Supersite, with the area of interest defined by the red polygon. The green rectangles represent the area covered by TerraSAR-X satellites, used to collect hazard data (Source: FutureVolc Project - Supersites, p.18. Date accessed: March 2016).*

On the other hand, interviews conducted with the UoI and the CP stressed the uncertainty of supranational approaches to monitoring volcanic hazards. For example, this research found that the stability and duration of holistic projects such as FutureVolc (see pp.103-106) can be met with scrutiny; a researcher from the UoI questioned the longevity of supersites, one of the project's core concepts.

Therefore, whilst approaches to hazard management can increasingly be positioned beyond Iceland's borders, their sustainability and continuation is questionable. Nevertheless, the supersite concept appears to operationalise Iceland's network (Cocco, 2014; Sigmundsson *et al.*, 2013b), apportioning responsibility and decision-making to an international community of actors and institutions. This interpretation is reflective of an interconnected "European infrastructure" (BGS, July 2014) for hazard management; the continental approach was referred to on numerous occasions during interviews and observations conducted at the CP. However, collecting and monitoring hazard information from a European perspective is not exclusive to Iceland (Rhinard, 2015). For instance, the database of information constructed by the World

Organization of Volcano Observatories (WOVOdat), has also stemmed from a collective effort to standardise data so that it can be effectively communicated beyond local and domestic boundaries (Widiwijayanti *et al.*, 2015). Both FutureVolc and WOVOdat work to transcend and fragment scale, as well as to co-produce and co-manage hazard knowledge.

6.1.2: Contesting boundary spaces: The role of information hubs and partnerships

This research also analysed the contextual and technical forces that have driven prominent actors beyond the domestic scale of hazard communication. Fluid nodal points, information hubs and institutional partnerships permeate Iceland's network; these have collectively weakened boundaries by transforming knowledge exchange. Interviewees in both Iceland and the wider European community referred to how boundary spaces have become increasingly challenging to maintain, primarily because new alliances have progressively undermined their resilience. This research has recognised the positive impacts that many of these transformations have had on the network's adaptability.

The ERCC and the FutureVolc project have both exploited boundaries by facilitating international consultation and assistance. Following interviews with stakeholders in Iceland, the UK and Europe, this study has found that Iceland's network does not possess a deterministic or rigid structure, but contains boundary spaces that are continually renegotiated by the actions of coordinators and leading institutions. From a sociological perspective, the flexibility of boundaries enable knowledge to be co-produced, and construct a resilient and adaptable approach to hazard management. This interpretation is supported by the protocol of the ERCC:

> We can send a request into the hub managed by the ERCC, and the hub can send that request to all the member states. The states would then respond directly, through an internet database, and an email would follow, which everybody would see and recognise that the UK has promised to help Iceland with this, for example; this allows us to work together to form a response (CP, April 2014).

Here, the ERCC are viewed as a cross-scale entity that allows responses to be co-managed, providing a robust exchange of information and assistance. By constituting a hub-like repository, the ERCC allows the responsive actions of the CP and their European counterparts to coalesce.

Information sharing and co-management are priorities of the ERCC (CP, March 2014), and demonstrate the convergence and connectivity of Iceland's network. By positioning the ERCC within the boundary space between the domestic and supranational level of interaction, this research can explain how the problems alluded to by Cash *et al.* are prevented:

> Knowledge is often held, stored, and perceived differently at different levels, resulting from differences across levels about what is perceived as salient, credible, and legitimate knowledge (Cash *et al.*, 2006, p.8).

As the ERCC coordinates responsive actions, knowledge disparities are lessened between local and continental actors. During the fieldwork, prominent members of the CP were keen to accredit the ERCC with a reduced knowledge gap between actors from social and scientific backgrounds. The ERCC converges, but does not replace, existing approaches to hazard response; therefore, by analysing "boundary organizations" (Cash *et al.*, 2006, p.8), this study has assessed multiple responses to volcanic activity can co-exist and be simultaneously commandeered.

The structure of European-wide institutions can appear authoritarian, but interviewees were generally eager to draw on how management practices are assimilated between actors at the local and continental scale (Webersik *et al.*, 2015). Therefore, boundary spaces are flexible and this was also highlighted during an interview conducted at the CP:

> If something happened in Iceland, the format and content of our request for assistance would be determined in-house by us (CP). It is only when the ERCC receive the request, that they can reformat it and send it out to everybody in their report of what's going on, at which stage the information compiling the report will have been included by us and amended by the ERCC (CP, March 2014).

Here, the interviewee describes an exchange of information between national and international stakeholders, referring directly to the importance of communication channels. The "request for assistance" can be interpreted as an intermediary artefact that co-evolves as it is communicated from the CP to the ERCC. By acting as a "point of contact" (CP, March 2014), the ERCC do not co-produce the request as they do not influence its content until they receive it. The CP repeatedly acknowledged the privilege of having a collaborative relationship with a European hub, and explained how it is widely perceived to have a positive impact on the adaptive capacity and resilience of the network.

Therefore, boundary spaces are relevant to this research as they theorise how the ERCC and FutureVolc facilitate the processes that Cash *et al.* claimed were integral to cross-scale exchanges of knowledge:

> (1) Accountability to both sides of the boundary; (2) the use of "boundary objects" such as maps, reports, and forecasts that are co-produced by actors on different sides of the boundary; (3) participation across the boundary; (4) convening; (5) translation; (6) coordination and complementary expertise; and (7) mediation (Cash *et al.*, 2006, p.8).

By explaining how Iceland's network has evolved to accommodate these processes, this study can establish how hazard management is co-produced by national and international stakeholders. Furthermore, research projects such as 'Cosmic' (Cosmic Project, 2015) and 'POP-ALERT' (POP-ALERT Project, 2015) also illustrate how boundary spaces are continuing to reduce the prominence of scale. Both projects were designed in accordance with the European Commission's '7th Framework Programme' for hazard research; as a result, they work to continue improving interactions between stakeholder communities at multiple scales.

6.1.3: Communicating at the boundary: Distributing knowledge and reducing complexity

With boundary spaces continuing to develop within Iceland's network, this research has been able to explore how channels of communication impact on the transcendence of scale (Gieryn, 1983; Seo and Creed, 2002; Hage *et al.*, 2010). As scale provides a categorised means of analysing the dynamics of the network, it can relate to the research question by explaining the extension and evolution of communication practices. By observing the Volcanic ash exercise in Iceland (VolcIce), this study found that regular communication contributes to the expansion of boundary spaces between institutions based in Iceland and the UK. Frequent communication garners familiarity and erodes the boundary between the national scope of the Icelandic Met Office (IMO), and the international expanse of the London Volcanic Ash Advisory Centre (VAAC).

An interview conducted with the IMO implied that the repetitive undertaking of VolcIce had weakened boundaries between the participating institutions. The exercise was interpreted as a European alliance of actors with shared interests:

> We have been doing these exercises (VolcIce) for many years and we have encouraged new groups to join us, expanding the exercise and working with it in different ways. It is very much a European exercise, even though only us three participate directly (the IMO, Isavia [Icelandic Aviation Service] and the London VAAC). We need to know where everyone else is and what they need to do so that we can prepare and react (IMO, March 2014).

However, attaching scale to VolcIce is contentious as the exercise focusses primarily on its participants (the IMO, the London VAAC and Isavia), but can also interact with external actors in the aviation industry during volcanic crises. Nevertheless, this study observed VolcIce from an Icelandic and UK perspective, and found that it illustrated a range of "boundary objects (e.g., concepts, problem definitions, models, standards), boundary workers (e.g., scientific advisers, experts) and boundary institutions" (Hage *et al.*, 2010, p.257).

Significant Meteorological Information (SIGMET's), and the Numerical Atmospheric-dispersion Modelling Environment (NAME), can both be construed as boundary objects that consolidate ties between the IMO and the London VAAC. By deconstructing the network and analysing how SIGMET's and NAME communicate location data, this study has been able to identify boundary characteristics. From a sociological perspective, SIGMET's and NAME resolve knowledge controversies by enabling volcanic ash to be communicated across scale boundaries. Therefore, the role of both objects can resonate with the modelling of flood risk in literature that explains co-production (Landström *et al.*, 2011; Lane *et al.*, 2011).

Furthermore, this study has demonstrated how the expansion of boundary spaces has led to a hierarchical flattening of scale within Iceland's hazard network (Collinge, 2006; Moore, 2008). Participatory technologies and international affiliations have encouraged greater cross-scale communication; this appears to have transformed institutional cultures. For example, both the IMO and the CP have become internationally focussed following the eruption of Eyjafjallajökull (2010), but have also retained the ability to communicate in-house or at a local scale in regions such as Þórsmörk. An interviewee from the CP referred to the institution's ability to effectively communicate knowledge and information across multiple scales:

> The Civil Protection has grown, we speak with task forces and committees from all over Europe, some less formal than others, and we use the information and advice we gain from those meetings to produce documents or something like that, often as a joint publication with them. But we also use the forums that we attend to go into affected areas here in Iceland and talk to locals, showing them our outputs, and feeding back to them by offering them advice, we have all this information now and these opportunities to work with other people who we are sometimes not that familiar with, but it is better to share your knowledge and learn from others also (CP, March 2014).

This extract demonstrates how Icelandic institutions are perceived to have become increasingly reflexive, with communications transcending both local and international stakeholder communities. Therefore, by analysing institutions from a sociological perspective, the holism and adaptability of Iceland's network can be appreciated.

The research findings represent a destabilisation of scale; this is relevant to the research question as it directly associates communication methods with the evolution of actors. However, an interview carried out at the IMO implied that boundaries and structure have not become obsolete:

> We communicate new-found knowledge or new-found information about the Icelandic volcanoes in a European hub (the ERCC), it's not just OK we are going to tell you once something's happened, it has to be more systematic, who has what information at which time? The hub allows us to communicate with others whether they are local or from the UK or wherever through modules, predesigned packages for help, and that is what's legal for them to use, we all need to understand what information is going to be sent, and who it is going to be sent to (IMO, March 2014).

The interviewee refers to commands and modulated criteria when explaining communication between the IMO and European institutions. Iceland's network does not represent a post-structural entity, but transcends scale by communicating in a "systematic" way that "packages" hazard information. By referring to legal remits, the interviewee explains how boundaries remain relevant as communication is not completely free-flowing.

Therefore, the study has also found evidence to suggest that cross-scale communications are purposely constructed; for example, interviews conducted with members of the FutureVolc project have referred to "licenses" and "registrations" (CP, March 2014) when explaining communication practices. These legislative artefacts represent the structural elements of an otherwise malleable boundary between national and international levels of hazard management. FutureVolc highlights how boundaries are weakened, but an interview conducted at the UoI illustrated how the process of engagement across them is pre-determined and controlled by stakeholder discussion:

> Discussions within FutureVolc determine the standard and packaging of the data, and its presentation in the databank that each member uses; you have to have a uniform goal for the data so everyone knows what they are getting (UoI, April 2014).

Whilst scale boundaries are breached, communication practices are purposely constructed by the actors and institutions involved. Similarly, boundary objects such as SIGMET's and NAME are powerful acquisitions of Iceland's network, but their functionality and degradation of boundaries are determined by the "Memorandum of Understanding" (IMO, March 2014) that underpins the VolcIce exercise.

Nevertheless, boundary objects have the capacity to impact on scale, and many can adapt to policy changes. In the case of the VolcIce exercise, boundary objects are crucial to preserving the communication of knowledge and information between Iceland and the UK. However, their resilience and ability to withstand change are likely to have been influenced by effective stakeholder discussions across multiple scales:

> As part of a scientific committee, which includes our colleagues in Iceland, we (London VAAC) are supposed to meet two times a year, I think, and put forward our views on what we would like to improve. So, the agreements we have are evolving, they are different between each year and each meeting (London VAAC, October 2014).

The interviewee describes the evolution of cross-scale dialogue and discussion, and refers to the involvement of the London VAAC in biannual meetings. In addition to VolcIce, entities such as the ERCC and the FutureVolc project are also able to construct discussion spaces whilst developing boundary objects.

Members of FutureVolc have referred to boundary crossing in the context of wider publics, often touching on the importance of stakeholder connectivity and knowledge management. For instance, an interviewee from the IMO explained how all stakeholder groups can transcend scale boundaries, regardless of their size or background:

> We (the IMO) build on our role of representing the views of the local community, and together with our own view, we take their input and work with others in FutureVolc; this is where I would like to return to this idea of a network, as it is not just a data collection - transformation - distribution process, as there are wider publics that, however small, have some say in what happens… it is important that we ensure each contribution filters through to the FutureVolc community (IMO, April 2014).

Here, the extract describes how knowledge is co-produced and exchanged; the interviewee implies that effective communication channels can filter knowledge through the network. This extract reflects aspects of Latour's approach to ANT by focussing on the importance of connectivity, and drawing attention to the multiplicity of boundary crossing. Weaker boundaries can improve the resilience of Iceland's network by enhancing its ability to withstand "node failures" (Barabási, 2009, p.413). For example, the cross-scale interactions within the VolcIce exercise and the FutureVolc project have illustrated how stakeholder relationality can be improved by forming a single and customisable source of information.

6.1.4: Technical actors and scale: Improving adaptability by deconstructing borders

Scale boundaries have become increasingly difficult to identify, with technology playing a significant role in providing a randomised web of interaction amongst stakeholders. By exploring Iceland's technical infrastructure, this research has recognised what Lemke (2000, p.275) termed "semiotic artifacts". Rawolle (2015) explains their role and position in the context of actor-networks, and refers to how they facilitate cross-scale interactions:

> Actor-Network Theory adds the rather crucial observation that networks are in general non-local, and that (semiotic) artifacts are often the 'boundary objects' that mediate non-local, scale-breaking interconnections (Rawolle *et al.*, 2015, p.45).

Technical actors have been influential in weakening scale boundaries and enabling greater "non-local" interactions; this is evident in the use of hazard notification systems to channel commands between the CP and the ERCC. During the fieldwork, interviewees also referred to social media's "push notification" feature (UoI, April 2014), and "colour-coded alert notification" graphics (IMO, March 2014); these technological outputs have improved the exchange of hazard knowledge by deconstructing geographical, educational and social boundaries. Notifications provide an example of how fluid methods of communication are continuing to destabilise scale throughout Iceland's networked infrastructure.

As Iceland's approach to managing volcanic hazards has become increasingly digitised, the length of communication channels has been significantly reduced. New methods of sourcing, representing and sharing hazard information have enabled communication practices to circulate the network, removing knowledge and data from the confines of the scale at which it is constructed (Murdoch, 2005; Bosco, 2014). The supersite concept also provides a further illustration of how technical actors can influence perceptions of scale; for instance, interviewees referred to "new opportunities for engagement" following the initiation of the FutureVolc project (BGS, June 2014). These interpretations of the network resonate with Leitner and Miller's view that "technologies of power" are closely related to the "social construction of scale" (Leitner and Miller, 2007, p.120).

Interpreting Iceland's network from a sociological perspective is relevant as it explains how stakeholder communities have adapted in a techno-centric manner, primarily to prevent the problems identified by Cash *et al.* (2003) in their analysis of cross-level interaction:

> The production of scientific and technical information that lacks salience, credibility, or legitimacy in the eyes of critical players at different levels (Cash *et al.*, 2003, in Cash *et al.*, 2006, p.8).

A circulation of appropriate knowledge and information facilitates a democratic approach to mitigating and managing volcanic hazards. This study has found that technical innovation and foresight have ensured the harmonious relationships between different actors and institutions are not affected or marginalised by the regularity of cross-scale interactions.

Therefore, technology has transformed the adaptability and holism of Iceland's network, and has enabled an expansive European community to become an integral part of monitoring and responding to volcanic activity:

> There's a collaborative ability to do science, and send and receive hazard information across Europe very easily. We have established a very good network here, and our ability to do things together, and to work as a community, not just with the IMO or the UK, has certainly been enabled by technology, and it will be exciting how this continues (UoI, March 2014).

Here, the interviewee directly relates technology to an evolution of scale; by removing borders between local, domestic and international stakeholder communities, technical actors have enabled the network to become largely scale-free (Hein *et al.*, 2006; Caldarelli, 2007). Devices, systems and software packages have collectively eased the process of transcending multiple scales, explaining why local communities in Iceland generally recognise a European contribution to the management of volcanic hazards (Puglisi *et al.*, 2014).

This research has explored the connections between Icelandic society, innovative technology and the integration of a European stakeholder community. The study has established that proactive social engagements are of considerable value to transcending scale (Christiansen *et al.*, 1999; Risse, 2004); this explains why many technical devices and software packages have been designed at European or global scales, but have successfully conflated with communities in Southern Iceland:

> I am sure the ministers here have to say there is a strong domestic and international accord when asked about their capabilities to monitor and respond to activity. Our approach involves many groups of people working together, both in the communities here in Iceland, but also with our partners in Europe… it's very good for the science and for us (the IMO) to be able to use and share different types of devices that are global. If I just give you an example, the strainmeters we are using are the same type of strainmeters that are installed on Mt Etna (IMO, March 2014).

The extract refers to the institutional flexibility of the IMO, and outlines how interconnections have been strengthened between the local context and Europe's monitoring of volcanic hazards. By referring to "different types of devices", the interviewee highlights the multiplicity of technical actors and explains how they are able to be deployed in numerous seismic environments.

Furthermore, interviewees in Höfn and Vík have repeatedly described how technical devices, enrolled across Europe, work "in tandem" (Vík resident, March 2014) with Icelandic society; this illustrates how boundaries can be deconstructed between local and European stakeholders. Both WOVOdat and supersites have been designed to use technology that is purposefully equipped to transcend scale. When discussing these databases, the CP and the UoI referred to how devices and systems can be freely transferred from one hazardous region to another. These include social media platforms and objects such as strainmeters; both can be deployed globally and have the mobility required to expand or contract boundary spaces. Therefore, the adaptability and coherence of Iceland's network can be explained from both social and technical perspectives.

6.2: Managing and calibrating data: The evolution of hazard information

The previous section of this chapter demonstrated how communication practices, technical actors and information hubs have collectively transformed scale. Whilst at times theoretical, a general move towards a supranational approach to volcanic hazard management has been explained, and the dynamics of boundary spaces have been analysed at length. However, each of the projects and technologies that encourage cross-scale interactions have transformed the construction and communication of data variables. Therefore, managing and handling data are also significant when explaining the relevance of scale and boundaries.

6.2.1: Communicating open data: An assessment of the impact on scale

This study found that the ERCC and the FutureVolc project are designed to communicate data openly:

> All of the data gathered in the project (FutureVolc) will be made available through an open-access policy (Jordan *et al.*, 2013, p.287).

FutureVolc uses openness and transparency to empower actors and mobilise data; this strengthens communication nodes in networks such as Iceland. The project is predicated on improving the size and scope of data repositories, enabling them to become infinitely larger as a greater number of stakeholders can add and consume information:

> If 20 countries need access to the data, people (actors) that are in these 20 countries all have access to the databank; they can get all the data they require and develop their opinion of what is going on (UoI, March 2014).

By referring to the vast and expansive databanks that FutureVolc provides, the interviewee illustrates how abstract scale has become. In addition, the extract also questions the relevance of context, primarily because the databank allows information and knowledge to be interpreted openly by stakeholders across Europe.

Archival research and penetrative interviewing has led to this study establishing that openness and transparency are the driving forces behind improving the adaptability of Iceland's approach to hazard management. Scale becomes less distinct as open data policies have the capacity to deconstruct local, national and international boundaries. Whilst open data is not inscribed into legislation, it has become an integral aspect of the Civil Service ethos. For example, Icelandic communities expect to have open access to transparent data, so this method of communication is assisted by the actions and intentions of the CP and their partners. In contrast, interviews conducted with institutions based in the UK illustrate a greater level of resistance towards openly communicating hazard information. This is particularly true for stakeholders affiliated with the aviation industry, where legal remits can limit the distribution and transparency of data.

The value of open data in Iceland is increased as hazard information is likely to be deciphered and understood correctly by stakeholders from socio-political backgrounds. For example, interviews conducted with farmers and community leaders explained how the public tend to be attuned to a diverse variety of data types. Furthermore, the FutureVolc project intended to use and combine a myriad of data formats to facilitate and encourage consultation. This point was relayed during an interview carried out at the UoI:

> FutureVolc is a big project that seems to have created this database with historical data and raw data and all types of real time data from the volcanoes (UoI, March 2014).

Combining datasets has been integral to the success of the project, and further demonstrates a lack of commitment to scale. From a sociological perspective, an amalgamation of data resonates with co-production as it contributes to the prevention of knowledge controversies (Whatmore, 2009; Lane *et al.*, 2011). Furthermore, the database constructed by the FutureVolc community can arguably represent a digital nodal point within Iceland's network (Sigmundsson *et al.*, 2013b; Dumont *et al.*, 2014). For example, the combination of data allows connective pathways to overlap as actors from contrasting backgrounds seek to produce or access the vast quantity of information. This interpretation of data handling conceptualises how clarity and knowledge can be navigated through networks that are complex and evolving.

6.2.2: Representing hazard information: Scale and the mapping of risk

The ability for stakeholders to openly source information has transformed how data variables are calibrated (Sangianantoni and Puglisi, 2014) and hazards are represented. Technical infrastructures are increasingly leading to a confluence of data channels within hazard networks; WOVOdat (Widiwijayanti *et al.*, 2015) and Vhub (Palma *et al.*, 2014) aggregate data so that it can transcend spatial and demographic scales. An interview conducted with a Vhub user referred to the discussions that have influenced how these platforms function:

> We, together, define what it is we want to put into the databank (Vhub) - what do people want to have in the databank? How can this be represented? Who do we need the data to be interpreted by? (UoI, April 2014).

The extract highlights the active role of various individuals and institutions; the design and functioning of Vhub can relate to co-production as it enables multiple stakeholders to voice their opinions and impact on the capabilities of the platform.

However, this study also observed scale conflict, primarily in relation to how risk is represented at a domestic and international scale. For example, during the debrief that followed the VolcIce exercise, data discrepancies became clear and illustrated the scalar divide between the IMO and the London VAAC (see Figure 5.2, p.277). The debrief raised the issue of mapping risk and found that the internationally recognised Mercator projection was incompatible with Iceland:

> In the polar area we cannot use Mercator, because Mercator - you stretch out the pole to be as long as the equator (Isavia, March 2014).

Therefore, scale is still relevant to Iceland's approach to hazard management as it impacts on how risk is represented. Data can extend beyond scale boundaries and be used by the both the IMO and the London VAAC, but representing the data can expose divisions that question the relationship between scale dynamics and the adaptability of the network.

Furthermore, the debrief also highlighted divisions between the national and international responsibilities of the IMO and the London VAAC respectively. For example, discussion was instigated when the IMO raised the issue of the London VAAC being unable to measure and represent re-suspended ash from Icelandic volcanoes:

> London VAAC don't measure or communicate re-suspended ash concentrations over Iceland very well, in fact we don't do them at all (London VAAC, March 2014).

The extract refers to scale limitations, and implies that the London VAAC do not always have the ability to transcend boundary spaces, despite being tasked with monitoring and forecasting volcanic ash at a supranational scale. However, the VolcIce debrief provides a cross-scale platform where these constraints can be addressed and flaws can be negotiated. This research also established that the discussion space within the debrief allows exercise reports to be co-produced by the coordinators of the IMO, Isavia and the London VAAC.

However, interviewees beyond the VolcIce community have also referred to the need for scale boundaries when discussing how data is represented:

> If you use a community approach for all European countries then sometimes it barely makes sense, but for Iceland, the administrative boundaries cover large areas where you have nobody, so how you represent data should take into consideration these potential issues (UoI, March 2014).

Here, a researcher from the UoI refers to the relevance of boundaries when representing data in a unique and multi-hazard environment such as Iceland. The extract indicates that international or global representations of risk are unreliable and lack the ability to relate to the demographics of an affected region. Various interviewees from both the IMO and the CP have highlighted how scales of representation should be spatially and temporally focussed rather than extended.

Therefore, the evolving relationship between scale and data is widely disputed amongst stakeholder communities in Iceland. Contradictions illustrate the need for greater flexibility in how data and risk are conveyed and represented to various end-users. For example, an interview conducted with the IMO referred to the value of a medial and dynamic approach:

> When you make a map you display information to assert an extent. In dynamic representations, you can check and uncheck many layers, so you have much more freedom and can aggregate information; but you need to decide at which scale you think about the resolution, this is something that is often very underestimated, the impact of scale in mapping. You need to assume that generally the population pays more attention to something at the national level than at a European level, but we return to the same question, at which scale do you deliver the results? (IMO, March 2014).

The interviewee explains the need for risk to be mapped in a way that is adaptable, but does not dismiss or eradicate the concept of scale. Instead, the extract explains how disparities between the local, domestic and international scale can be lessened when both data and methods of representation are mobile and evolving (Kruke and Morsut, 2015). The adaptive capacity of a complex network can be annexed depending on how data is calibrated and representations of risk are constructed.

6.2.3: The value of calibrating data: From adaptation to interpretation

Technical devices and systems can mediate scale boundaries by calibrating data; interviews conducted with both the CP and the IMO referred to the need for adjustable representations of risk, primarily because hazard information relates to actors positioned at multiple scales. Furthermore, the research assessed how the network's adaptation and resilience have been revolutionised by data repositories that are customisable. The UoI and the CP both explained how these repositories are constructed by sourcing data from a plethora of stakeholder communities:

> Whenever someone goes out and does a risk analysis, it is likely that people will not be wanting just a report, but they will want your underlying data, and for you to share it in a repository that is going to be accessible to anybody. So, if you want to start mashing up your data with somebody else's data, you can get something out of it, new knowledge of the risk that is posed, or the hazard in question (CP, March 2014).
>
> I can go and take data from ten different research studies and I can start mashing that together or finding things out, I may find something brand new and much more interesting than any one of those ten can find by themselves, or anybody could have found by just looking at the results. Technology is vital in allowing us to do this, and it is most effective when we mash data and then study and interpret it as a group (UoI, March 2014).

Both extracts refer to the "mashing" of data; the use of technology is integral to this process as it enables repositories to be accessible and customisable. The management of data within hazard networks is increasingly leading to the establishment of "mashups" and "dashboards" (Liu and Palen, 2010); these innovative mechanisms for handling data have enlarged scale boundaries by improving the network's capacity to tailor information to the end-user. An interviewee from the IMO referred to existing mashups such as the "Geospatial Disaster Management Mashup Service Study" (Ranghieri and Ishiwatari, 2014), and explained how the GeoWeb (Haklay *et al.*, 2008; Roche *et al.*, 2013) has provided equal access to information and resources.

Therefore, mashups can contribute to the co-production of knowledge within hazard networks; for example, by seamlessly integrating data and then situating it according to the end-user, the repository has a greater ability to resolve knowledge controversies (Whatmore, 2009; Lane *et al.,* 2011). The scale of data management has become increasingly protracted as local and regional actors have the flexibility to access a repository of mashed-up data that has been sourced from an international community of stakeholders. Repositories are designed in a way that enables datasets to be mobilised across geographic scales for both analytical and actionable purposes. Calibration is an essential part of this process and was referred to during an interview at the IMO:

> Are we willing and are we capable of delivering results to the level of a village, to the level of a building, or the level of an agglomeration? Of course, but sometimes it's a matter of using data more effectively, how far can we go in the analysis? And also the datasets, how can we alter, or rather calibrate, the data variables so that they can allow for finer analysis at a local, regional or national level? (IMO, April 2014).

The interviewee directly refers to the impact that calibration has had on scale and the adjustability of data. By occupying digital spaces within Iceland's network, repositories allow data to be redefined by numerous actors, gradually eroding its purity. This interpretation of data management resonates with constructivism as it reflects key aspects of Latour's approach to ANT.

Calibration is becoming increasingly relevant to volcanic hazard management due to the expansion of Big Data and Volunteered Geographic Information (Zook *et al.*, 2010). For example, the process of calibrating data was central to the principles and objectives of the FutureVolc project:

> Converge and harmonize observation methods and tools, to promote the use of standards and references, inter-calibration and data assimilation (FutureVolc Project - Data Policy page, 2015).

Interviews conducted with FutureVolc members have referred to how calibration has influenced the models and datasets that have been constructed by the FutureVolc community. As a result, calibration has transformed the "interpretative flexibility" (Latour *et al.*, 1992, pp.44-45) of forecasters and seismologists at institutions such as the IMO.

However, when applying calibration to the performance of FutureVolc, the role technology and translation play cannot be overlooked:

> In FutureVolc we combine the different techniques, monitoring what is in the ground, what goes on inside the ground and what goes on in the air, and we rely both on ground based techniques and satellites to do this. We are also focussing on how we then use that data effectively, how we exploit the databanks to successfully integrate the information we have, and how we then present the information to non-scientific stakeholders (UoI, April 2014).

By referring to "techniques and satellites", the interviewee demonstrates the reliance of the FutureVolc community on technical actors. Furthermore, the extract also alludes to the process of translating data so that it can be shared effectively with non-scientific stakeholder communities. Unlike the scale conflicts that were identified during the debrief of the VolcIce exercise (see p.175), the FutureVolc project has illustrated how calibrating data prevents information from being confined by time and space.

By exploring Iceland's network, this research has established that the quantity of data, and number of communication channels, have progressively increased because of new technology and projects such as FutureVolc (Sigmundsson *et al.*, 2013b). Paradoxically, calibration has led to a decrease in the positions from which data is sourced as nodal points have been strengthened by cross-scale models and repositories. For example, the calibration of ash dispersal data has operationalised NAME within the network (Jones *et al.*, 2007); the set-up of the model was explained during an interview carried out at the London VAAC:

> We can combine the data into one model (NAME), and a related goal is to disseminate this information effectively to the IMO and others in Iceland, to local aviation, international, and elsewhere, and what we do is merge information from different techniques in a timely manner, coming up with a general model that brings the information forward, so this is a very important step (London VAAC, April 2014).

Here, the interviewee refers to how the NAME software distributes information to actors through a multitude of communication channels. Whilst data variables are reduced to a single model, the distribution of hazard knowledge remains complex and transcends scale.

The eruption of Bárðarbunga (2014-2015) also highlighted how innovative software packages calibrate hazard data and impact on the scale at which information is managed. For example, the gas dispersion model was used extensively by the IMO during the eruption (see Figure 6.2, p.180), and calibrated data that had been gathered at national and international scales. The model stored data in one digital space, but distributed real-time hazard information to stakeholders using adjustable graphics. Calibration provided the flexibility required for both local and European stakeholders to interact with the model; for example, its adaptability meant that scale and representations of risk could spatially expand or contract depending on the interests, location and demands of the end-user.

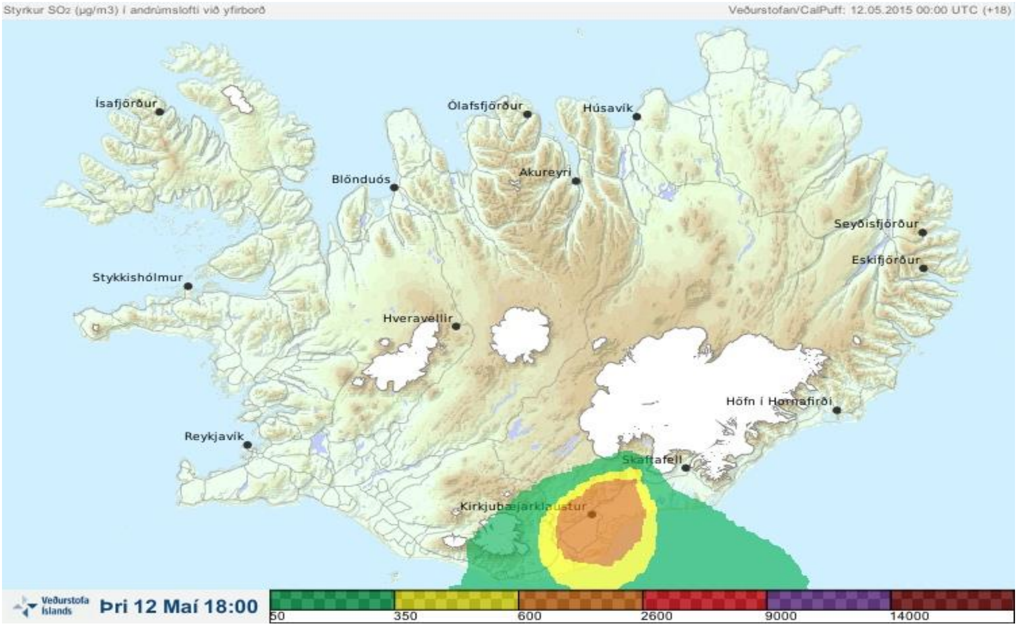

Figure 6.2: *A real-time graphic generated by the gas dispersion model during the Bárðarbunga eruption (2014-2015). Calibrated data is used to visualise the movement of gas and to communicate information effectively with the public (Source: Icelandic Met Office - Holuhraun [Gas Model page]. Date accessed: March 2015).*

Therefore, in the context of Bárðarbunga, the capability to adjust information is a valuable attribute for Iceland's hazard network to have in times of uncertainty.

As stakeholders become accustomed to using data that can represent and simulate risk in real-time, the scale and adaptive capacity of Iceland's network evolves. This research has demonstrated how scale is widely perceived to have become less relevant, and has explained how the mobilisation of data variables has led to spatial and temporal boundaries appearing less restrictive. By analysing technology such as NAME and the gas dispersion model, this study has explored "spaces of negotiation" (Murdoch, 1998, p.364) between human and technical actors. These spaces handle and redefine data in a way that widens communication channels and improves the "interpretative flexibility" of leading institutions (Latour *et al.*, 1992, pp.44-45).

6.3: Concluding remarks

As a rapidly evolving and complex entity, Iceland's hazard network appears to contradict scale. For instance, the FutureVolc project and the VolcIce exercise have both weakened scale by expanding boundary spaces (Gieryn, 1983).

Furthermore, when analysing the construction of data repositories and models such as NAME, this study has illustrated how Iceland's approach enables knowledge to be co-produced, and transcends scale to resolve controversies (Whatmore, 2009; Lane *et al.,* 2011). Therefore, this chapter implies that scale boundaries are more erodible in the management of volcanic hazards than has been purported by academics such as Blaikie and Wisner.

The eruption of Eyjafjallajökull (2010) illustrated how the impacts of Icelandic volcanoes can naturally transcend geographical boundaries, with potential disruption to local, national and international stakeholder communities. Mitigation requires cross-scale interactions, which in the context of Iceland, have been facilitated by open and transparent means of communication. By interviewing and observing multiple stakeholder communities, the research has studied the connections and processes that have led to the "co-management" (Dorcey and McDaniel's, 1999, in Pearce, 2003, p.212) of volcanic hazards in Iceland. Co-management resonates with constructivism, and can be defined by the allegiance of many stakeholders to European research projects.

This chapter addresses the research question as it explains how cross-scale communication improves the adaptability and resilience of Iceland's network. Despite projects such as FutureVolc being limited in duration, their dynamic characteristics appear to have a long-term impact on the interactions of stakeholder communities. Data and information are increasingly being communicated through a circulatory process that recognises the holism of Iceland's network. Nevertheless, there is a need to further explore group dynamics, and assess the extent to which actions are taken or constructed by either individual actors or institutional entities.

Chapter Seven: Defining actors and stakeholder communities in Iceland's hazard network

The preceding chapters have analysed power relations and scale dynamics, and have drawn on the evolution and complexity of Iceland's approach to volcanic hazard management. From the fieldwork conducted in both Iceland and the UK, it transpired that the network is composed of a myriad of interacting stakeholder communities. This chapter examines the extent to which these communities are influenced by the synergy and relationality of institutional entities, or the flexibility and evolution of individual actors. Constructivist approaches such as Actor-Network Theory (ANT) and co-production are referred to when analysing the positionality of actors within the network. ANT is ideologically inclined to explain Iceland's network from an individualistic perspective, primarily because it focuses on connectivity rather than sociality (Latour, 1993; 2005; Callon, 1999). In contrast, co-production is more accommodating of collective entities and can be used to explain the clustering of actors into institutions.

This chapter takes a more holistic and distanced view of Iceland's network, primarily to recognise the positionality and dynamics of different stakeholder communities. The interdisciplinary narrative identifies and critically analyses the overlaps between hazard management and sociology (Glickman and Gough, 2013). Firstly, this chapter discusses the extent to which individual actors can be grouped and institutionalised according to their scientific or socio-political allegiances. Secondly, the chapter questions whether institutional entities can collectively shape and cultivate change in how volcanic hazards are approached. This study of Iceland's network has explored how actors are either moulded into, or detached from, leading institutions such as the Icelandic Met Office (IMO) and the London Volcanic Ash Advisory Centre (VAAC). Analysing the positionality and mobility of both individuals and institutions can further explain the spread of expertise and the evolution of communication channels within the network.

7.1: Deconstructing institutional entities: The contentious role of individual actors

Whilst a number of actors in Iceland's network can be observed through the actions of the institution to which they are aligned, others display an ability to act heterogeneously as individuals. An actor's positionality is important in the context of this research as it can explain mediation, communication practices and institutional flexibility. This section examines how it has become increasingly difficult to define an actor's mobility and independence within a networked infrastructure such as Iceland. For example, community leaders and policymakers have highlighted how flexibility and interconnections have blurred the division between autonomy and dependency.

7.1.1: Institutional flexibility: The impact on the positioning of actors

When distinguishing between institutions and actors, this research has often needed to detach the latter from the former. By exploring Iceland's approach to volcanic hazard management, it has become apparent that monitoring institutions can promote or constrain the self-determination of actors. Social constructivists are inclined to argue that individual actors can be restricted by the institutionalisation of networks such as Iceland:

> For Berger and Luckmann, such control is intrinsic to institutions… institutions achieve a reality that 'confronts the individual as an external and coercive fact' (Berger and Luckmann, 1966, 76, in Bevir and Rhodes, 2015, p.101).
>
> That they do so, and thereby achieve such an effect, is principally through the assignment of roles to actors and the codification (both formally and informally) of such roles through the establishment and reproduction of a series of rules and associated expectations (Hay, 2016, p.3).
>
> Constructivism is certainly no exception in having a deeply socialised conception of the actor (Hay, 2016, p.6).

These quotations imply that institutional frameworks have the capacity to control or constrain the heterogeneity of actors, undermining their individuality. However, the research findings presented thus far have generally disputed these claims, and have demonstrated the evolution, independence and mobility of stakeholders in Iceland's network.

This study has found examples of actor's independently deviating from the ideological premise of institutions such as the IMO. For example, the University of Iceland (UoI) and the IMO are both orientated towards pre-emptive research, whilst the Department of Civil Protection (CP) tends to have a reactive approach to managing volcanic hazards. Regardless of the different attitudes and ideologies, an interview conducted with the CP illustrated how actors have the capacity to migrate between these institutions:

> Our role here at the Civil Protection is to get information and apply it, we are in the business of taking the new-found scientific information from others (the IMO, the UoI, etc.), and then using it to work for the public. But in FutureVolc, we are forming a route for the information to flow freely. It is by working alongside each other that we can have a lexicon of our volcanoes, this has meant we are doing work that we are not familiar with (CP, March 2014).

Here, the interviewee perceives the FutureVolc project to be a vacuum through which multiple institutional entities interact; it can be deduced from the extract that individual actors have gained a greater ability to work between pre-emption and reaction. The increased exposure to the information and working practices of the IMO and the UoI implies that individuals from the CP have been mobilised to fill knowledge gaps; this contradicts the narrative of Hay (2016). Furthermore, by emphasising institutional differences, the interviewee refers to individuals moving from binary or default positions.

By deconstructing Iceland's network, this PhD research has highlighted how projects such as FutureVolc generate informative artefacts that ensure actors can transcend institutional entities. This narrative resonates with Latour's approach to ANT (Latour, 1993; 2005), primarily because it associates technical artefacts with the agency and connections of individual actors. However, Latour's understanding disputed institutionalisation, and Murdoch highlighted how explanations of individual agency can vary:

> The agency of humans and nonhumans can be continually transformed one into the other (Murdoch, 1997, p.746).
>
> Pickering believes intentionality to be a stable and real distinction between human and nonhuman entities: although he is keen to stress that agency and action are emergent effects, dependent on networks of intimate human-nonhuman interactions and relations, he sees intentionality as a mobilising force (Murdoch, 1997, p.746).

Murdoch (1997) presents two contrasting interpretations of human agency; in the first extract, agency is interchangeable between human and non-human actors, in-line with the narratives of Latour (1993; 2005) and Callon (1999). However, in the second extract, Murdoch refers to the human-centred approach of Pickering (1993), who recognises the role of intentionality and focuses on the impact of artefacts to a lesser extent.

This research has found that both of Murdoch's interpretations are applicable to Iceland's network, and can be used to explain the mobilisation and evolution of individual actors. For example, an interviewee from the UoI claimed:

> The primary goal of academic institutions like ours (the UoI) is to produce interesting research; conventionally, our goal has been to work with the data that we collect and to ensure that it complements our longer-term ambitions. However, FutureVolc has allowed us to extend our research to a wider community, giving us a greater ability to independently share our data with the end-users ourselves (UoI, March 2014).

The extract initially draws attention to the institutions ideology, and the constraints that are imposed on the freedoms of individual actors. However, the interviewee also refers to how the FutureVolc project has provided actors with the agency required to remain in the collective set-up of the UoI, whilst also having the self-determination to strategically extend the scope of their research. By alluding to actors autonomously forming associations with end-users, the interviewee presents a post-structural interpretation of Iceland's scientific and academic research community. Furthermore, this narrative demonstrates how the intentions of actors can be individually realigned, reflecting the views of Pickering (1993).

By studying the autonomy of stakeholders, this research has recognised that the politics of Iceland's network are continually evolving. However, writing in an economic context, Boettke and Coyne (2009) caution against deconstructing institutions to the level of individual actors:

> Institutions direct individual behavior for better or worse. We cannot fully understand economic outcomes without considering the institutional context within which that outcome emerged (Boettke and Coyne, 2009, p.150).

This extract acknowledges the conditioned environment that institutions create and sustain, and implies that actors can be mobilised by institutional flexibility rather than individual choices and intentions (Lee and Hassard, 1999; Elder-Vass, 2008). In the context of Iceland's approach to hazard management, this study found that the Volcanic ash exercise in Iceland (VolcIce) provides evidence of how stakeholders can migrate to spaces in-between institutions. By observing the exercise at first-hand, this research could grasp an understanding of the positional flexibility of VolcIce coordinators.

Since the eruption of Eyjafjallajökull (2010), prominent members of the IMO and the London VAAC have repeatedly demonstrated a greater level of institutional flexibility, and have transitioned to connective spaces between scientific institutions and the aviation industry (Kruke and Morsut, 2015). This narrative is compatible with the views of Gunderson (1999):

> One way in which institutional flexibility appears is when an unforeseen policy crisis allows for restructuring of power relationships among stakeholders (Gunderson, 1999, p.7).

Despite Gunderson's approach being tailored to ecology and resilience, it is applicable to the trends identified in Iceland since Eyjafjallajökull, and can be used to explain the transformation of the relationship between aviation and science. This interpretation can also be applied to the development of the FutureVolc project, primarily because membership facilitates the evolution of research communities.

The study has highlighted how VolcIce and FutureVolc have both annexed actors from leading institutions. For example, an interviewee from the British Geological Survey (BGS) described FutureVolc as the bringing together of "large clusters of people" (BGS, October 2014). However, by referring to "clusters", membership is related to institutions and research communities rather than individual actors. The representation of institutions within the project enables FutureVolc to resonate with co-production rather than ANT, largely because individuals are acting in an institutional capacity to resolve knowledge gaps, and not in response to their personal choices and connections. Nevertheless, whilst this research can explain institutional flexibility through the construction and design of projects such as FutureVolc, Iceland's network is complex and evolving, and the heterogeneity of actors cannot be discounted.

7.1.2: The persistence of heterogeneity

This next section focuses on an individual actors' expertise and authority (Misztal, 2013); when exploring Iceland's network, the research identified several influential mediators that displayed a level of autonomy, intentionality and independence. Elder-Vass (2008) draws upon Latour's rejection of sociality to explain the theoretical differences between mediators and intermediaries:

> Instead of a sociology of the social, Latour proposes a 'sociology of associations' (Latour 2005: 9)… any collective influence is always passed through chains of *mediators*, who actively shape and translate that influence in ways that correspond to their own projects and purposes, as oppose to *intermediaries*, who transmit tokens of authority unchanged [Latour 2005: 39] (Elder-Vass, 2008, p.465).

Mediators have the leverage required to reconstruct and redefine collective influences; they are not entirely disconnected from actuarial clusters but are able to maintain a degree of individuality and self-determination. In the context of Iceland's network, observations of both the IMO and the CP demonstrated how coordinators and project leaders gather information from supporting intermediaries. This communication process enables coordinators to redefine the network by translating information and redistributing it to multiple stakeholder communities.

Coordinators from the IMO, the London VAAC and Isavia were each observed during VolcIce; this study established that their roles within the exercise can be assimilated to Elder-Vass' interpretation of mediators:

> 08:30: IMO co-ordinator endorses communication with the London VAAC and Isavia after being informed of volcanic activity.
>
> 14.30: Exercise co-ordinators simultaneously chair meeting with institutional colleagues, during which information is shared by the co-ordinator; the exercise is discussed as a team, and the institutions collectively devise feedback for the coordinator to discuss in the debrief (Research field diary, VolcIce exercise, March 2014).

The field diary highlights the elevated status and decision-making capabilities of each coordinator. However, the extracts also allude to the multitude of interconnections a coordinator has with a 'team' of supporting actors (Moor, 2012); these associations reflect the holism of institutional entities and are integral to the success of the exercise. By interpreting the set-up from a sociological perspective, this research theorises Iceland's networked infrastructure and identifies the stakeholder interactions that ensure it remains adaptable and resilient. Furthermore, if coordinators and project leaders can be viewed as mediators, then this study can explain how the network can be further adjusted to improve knowledge exchange and the efficiency of communication.

However, the collective influence of an institution cannot be overlooked in Iceland's network. For example, an interviewee implied that the internal structure of the IMO actively promotes the grouping of actors:

> Here at the IMO there are five coordinators for natural hazards, they are for the volcanic hazards, the seismic hazards, the hydrological hazards, the hydrological/meteorological hazards, and for the avalanche hazards, so there are these five main fields. The coordinator will influence what we do (IMO, March 2014).

Here, actors are categorised according to the hazard for which they are responsible; this undermines their heterogeneity as positions are determined by the approach, vision and ethos of the IMO. Furthermore, this set-up does not address the key transverse actions that occur between individual actors in different assigned categories. Unlike previous approaches to ANT (Latour, 1993; 2005; Callon and Law, 1995), this research has not denied the existence of institutions, but has studied an actor's individual capacity to deviate from them. By exploring Iceland's network from a holistic perspective, this study has established that institutional frameworks cannot be refuted or deconstructed in the way implied by Latour. The autonomy of actors is contentious and challenging to assess (Knoblauch, 2013); for instance, coordinators and project managers are less constrained by institutional attitudes, but cannot be detached from their intrinsic connections with intermediaries.

7.1.3: Institutions and individual actors: The rejection of ideology

When defining institutions, theorists such as Stalder have drawn on the importance of associations, and have interpreted actions as outcomes of collective movements. The FutureVolc project and the Emergency Response

Coordination Centre (ERCC) provide examples of how collective movements merge specialist expertise from a wide range of individuals within Iceland's network. This study has analysed multiple levels of stakeholder interaction, and has found that institutions such as the IMO do not ideologically hold together a dense network of actors, but instead position actuarial representatives across several inter-organisational frameworks. As a result, distinguishing between institutional entities and individual actors has become increasingly arduous.

Interviewees at the IMO often referred to institutional responsibilities, and outlined the process through which these are devolved to individual actors such as coordinators and forecasters. For example, both the IMO and the London VAAC have a legal remit and policy framework; this determines what responsibilities are assigned to leading actors. However, this study discovered that many actors occupy several roles, enabling them to work both within and between institutions:

> Actors may play multiple roles. The roles they elect to play may be in tension with or even in contradiction with the expectations or demands of other actors or the constraints of institutions. Individual human actors are members of organisations, research groups, disciplinary communities and policy networks which, as collectives, can all have agency and which may play different and contradictory roles from those played by the individual human actors who make them up.
>
> Considering actors as playing roles in processes (policy processes, innovation processes), rather than seeing them as simply fulfilling a specific function in a pseudo-mechanical "system", acknowledges the reality that "actors" are defined by their agency (Flanagan *et al.*, 2011, p.706).

Flanagan *et al.* reflect on the multiplicity of roles in complex networks, and explain the relevance of agency. The extract relates to Iceland's network as the agency attached to transient actors influences their contribution to mitigation efforts, decision-making and response mechanisms. By analysing the positional flexibility of actors, this study has found that many of their actions are co-produced by their affiliations with several institutions. These interpretations reject the view that actors can be confined by the ideological conventions of institutional entities.

The agency and roles of actors are relevant to the research question as they explain the evolution and flexibility of many stakeholder communities.

Findings suggest that actions and capabilities are not determined by the heterogeneity of an actor, or by the collective influences of the institutions to which they are affiliated. For example, interviewees often referred to both their institutional allegiances and their individual interactions:

> Every individual within the network has very defined responsibilities, so all of us are aware of our line of work, but I would say that we now can adapt to policy changes better. We do find that we can readily disconnect ourselves from the IMO if we need to; I think this is true for those that frequently work in the field or have close links with the University (IMO, March 2014).

Here, a forecaster from the IMO illustrates the varied commitments of an actor within Iceland's network, and highlights the ease with they can adapt to changing roles and responsibilities. Furthermore, the interviewee directly refers to connectivity, and implies that institutional connections are intermittent and circumstantial; this narrative resonates with elements of Latour and Callon's understandings of ANT.

By interacting with numerous stakeholder communities, this research highlighted how actors can occupy a position in-between institutions. In environments such as Iceland, where actors often need to respond to multi-hazard events, this observation explains their capacity to connect with both domestic and international communities. Therefore, individual actors can be viewed as part of a holistic process, questioning their ability to remain rigidly committed to institutional ideologies. However, writing in the context of firms and markets, Grossetti refers to the differences between the adaptation of actors, and the renegotiation of institutions:

> No matter what the space considered, the mobility of individuals is not the same as that of the firms to which they belong. It is necessary to take into account at least these two levels of action and to understand how they interact (Grossetti, 2004, p.613).

The extract acknowledges the need to avoid envisaging institutions as "dummy entities with no real impact on their members" (Grossetti, 2004, p.613). For instance, the IMO and the London VAAC are likely to be much more resistant to change than the actors within them (coordinators, forecasters and technicians for example), so their transformation in response to projects such as FutureVolc should not be presumed.

However, during the eruption of Eyjafjallajökull (2010), the aviation industry experienced an "institutional crisis" (Jessop, 2001, p.1215) that reformed their engagement with entities such as the IMO. This study has found that the transformation of the industry, following the event, has required individualists and holists to work together. For example, as individual actors have mobilised, institutions have become increasingly open and interconnected. The preceding chapters have also reflected this sustained movement, and have identified closer affiliations between scientific institutions and those prominent in the policymaking process (such as the International Civil Aviation Organization [ICAO]).

7.2: Institutions, actors and expertise: Cultivating change within stakeholder communities

Over the course of this research, network evolution has been a recurring theme, and has influenced discussion related to power, technology, trust and scale. However, the various stakeholder communities within Iceland's network have made it almost impossible to establish, without contradiction and ambiguity, how expertise has been renegotiated. Stakeholder expertise can be evaluated from both technical and collaborative perspectives, and this study has attempted to explain how it is shared and translated between actors and institutions.

7.2.1: The relevance of intermediaries in conveying expertise

The research has focussed on the medial role that actors play between multiple institutions, and has found evidence to suggest that many retain a level of autonomy despite being a member of entities such as the London VAAC:

> There's lots of people in universities working on monitoring tools and technology, and generating knowledge, but in most cases, it is down to us as individuals what we do with our findings and developments; of course, we have to act in the interests of the VAAC, but we also need to make sure that we maximise the potential of what we create, so for instance, I also work closely with the IMO (London VAAC, October 2014).

Here, the interviewee displays an awareness of their obligation to work towards the London VAAC's collective interests and objectives, but also reflect on the degree of independence they have when conducting research and handling information. Therefore, the extract indicates that institutions allow expertise to be conditioned and shared by individual researchers. ANT and co-production interpret expertise differently, but neither explanation has recognised both the individuality of actors and the collectivism of institutions. For instance, approaches to ANT have generally associated expertise with an actor's ability to translate knowledge and information, usually through a circulation of artefacts and technologies (Kaghan and Bowker, 2001). Therefore, the role and collective influence of institutional entities are not explained.

This study of Iceland's network has assessed the positionality of intermediary actors; these include forecasters at the IMO and technicians at the London VAAC. The research found that many intermediaries were exposed to numerous technologies, and had their specialist expertise shaped by either current or previous exchanges of knowledge. Therefore, findings suggest that expertise is cultivated over time by the range of institutions to whom an intermediary is connected. Whilst actors can collectively represent institutions such as the London VAAC or the IMO, they have individually progressed to their current position in the network. Interviews were conducted with various "cultural intermediaries" (Maguire and Matthews, 2010, p.412), and have provided evidence of how expertise can be mobilised between institutions (Van Leeuwen, 1996; Dwiartama and Rosin, 2014):

> We actually are working with a guy from the Finnish Meteorological Institute (FMI), who helps us with the LIDAR (Light Detection and Ranging) data issue, he assists us in the LIDAR measurement, and this is really good because we allow his expertise to come into the IMO. Otherwise, it is sometimes difficult here when you don't have people in-house (IMO, March 2014).

The extract refers to the openness of Iceland's approach to hazard management, and provides an example of how it enables expertise to flow freely and be transferred between geographical regions. Furthermore, the interviewee seldom refers to the institute that the technician represents (the FMI), focussing instead on their individual engagement with the IMO. A holistic view of Iceland's network needs to be taken so that the impact of such transitions and mobilities in expertise can be analysed.

However, this narrative of intermediaries and expertise does not resonate with Latour's approach to ANT. For example, Latour claims that it is not possible "to follow how an element goes from being individual - a - to collective - b - and back" (Latour, 1996b, p.371). As the connections of each individual actor contribute to the establishment of black-boxed knowledge (Latour, 1993; 2005), their engagement and expertise is circulatory and cannot be transferred in multiple directions between two institutional entities. On the other hand, approaches to co-production can account for the mobilisation and transfer of expertise in Iceland's network; co-production enables the networked infrastructure to be explained from a holistic perspective. An analysis of expertise is of value to this research as it underpins how Iceland's approach to volcanic hazards has been transformed, particularly since the eruption of Eyjafjallajökull. This is true for the changing dynamics of the aviation industry, and the interactions between scientific institutions and communities such as Vík.

Co-production explains that whilst expertise stems from the connections and experiences of individual actors, it gradually becomes institutionalised by various collective influences:

> One emerging science policy frame, called co-production, questions institutionalized notions of expertise from the outset and hard demarcations between nature and society (Jasanoff, 2004). The frame of co-production aims to open-up how authoritative technical knowledge is produced in society and gets stabilized and institutionalized over time, so that it becomes a 'given' or 'taken for granted truth (Corburn, 2007, p.152).

Corburn does not dismiss the evolution of expertise, but takes an opposing view to Latour; this interpretation can explain how expert knowledge is produced and shared in Iceland's network in a way that is compatible with the unique challenges and characteristics of a multi-hazard environment. By observing institutions such as the IMO and the CP, this study has established that both intermediary actors and technologies play a vital role in how expertise can be institutionalised.

7.2.2: Sharing, transferring and coalescing expertise: The role of institutions

As Iceland's network continues to evolve, this study has established that actors are generally becoming less grounded and increasingly mobile. Stone (2002) used the dynamics of expertise to explain how institutions remain relevant:

> As global and regional networks proliferate, one important aspect of their operations has been the exchange of knowledge, information and expertise (Stone, 2002, p.1).
>
> The network may become institutionalized with the creation of formal arrangements such as advisory committees, consultation procedures and recognition by state and multilateral agencies in the implementation of policies (Stone, 2002, p.4).

The extracts recognise the interchangeability of expertise, and refer to how the infrastructure of networks such as Iceland can be transformed. For example, the creation and development of interdisciplinary advisories, committees and research programmes have become integral to Iceland's approach to managing volcanic hazards, but have also reworked how expertise and information are exchanged (Sigmundsson *et al.*, 2013a; Kruke and Morsut, 2015).

During an interview conducted with a researcher at the BGS, a discussion of expertise led to questions being asked in relation to the EU's 'Exchange of Experts in Civil Protection Programme' (European Commission - Exchange of Experts page, 2016):

> We recently took part in the 'EU Exchange of Experts Programme', which involved us flying to Iceland to meet others involved in emergency management, including some who we had not really had that much contact with previously. We established our links and now we keep in contact with them, for ongoing risks, but also for the wider monitoring of potential hazards, so yes there is now a good degree of crossover, everyone is uncultured, they can be considered transferable experts (BGS, June 2014).

Here, the interviewee demonstrates how EU initiatives have extended the influence and engagement of the BGS. The extract uses a collective tone throughout, with language such as "our" and "we"; this illustrates how actors participate in the programme in an institutional capacity. Furthermore, by referring to the generation of institutional "crossover", the researcher indicates how expertise can coalesce and hazard knowledge can be co-produced.

Therefore, it is unclear whether actuarial engagements with interdisciplinary research platforms are led by the objectives of institutions, or the intentionality of individuals. This study has found that even when a specific actor engages with a diverse community, they do not become completely detached from their homogenous institution. For example, the IMO and the London VAAC are established entities, and if an actor within them integrates with FutureVolc or the 'Strengthening Resilience in Volcanic Areas' project (STREVA), then the detachment is only temporary. The finite durations of both FutureVolc and STREVA do not allow actors to become wholly independent (Guffanti and Tupper, 2014).

On the other hand, interviews conducted with members of the 'Volcanic Ash Observations Review Group' (VAORG), and the UK-based 'Scientific Advisory Group for Emergencies' (SAGE), have suggested that individual actors can be mobilised from a wide range of institutions:

> If there is a crisis which involves a scientific element, the government say 'go to some nominated experts in this field, pull them together and they can be our advisors in this crisis', so VAORG is a group of academics from various research institutes, and they advise the COBR (Cabinet Office Briefing Rooms) on volcanic ash observation work, it gives us here at the Met Office a bit more of a spread in expertise (London VAAC, October 2014).

The extract indicates that actors are integrated into VAORG based on their specific research background and perceived expertise. Furthermore, the interviewee implies that consultation extends to the individual and not to the collective influences of their institution. However, human actors cannot be viewed as free-flowing variables, primarily because their membership of institutions is likely to have orchestrated their research agenda and contribution to VAORG.

Nevertheless, when conducting interviews with individual members of the STREVA project (Strengthening Resilience in Volcanic Areas - main page, 2016), it became apparent that many contributions were interpreted in a largely heterogenous manner:

> Some of us within STREVA have operations with individuals from the United States Geological Survey (USGS), for example, and we had a small volcano workshop that rated the volcano seismology last year. I don't have any kind of formal links to the USGS, but it is up to us to maintain good working relationships with the individuals in

> STREVA, both whilst the programme is ongoing and after it has concluded (STREVA, January 2015).

Here, the STREVA member implies that individuals choose the connections they establish within the project. The extract also indicates that actors have the capacity to circumvent the institutional entity to which they originally belonged, and to make independent decisions regarding their relationship with other stakeholder communities. Therefore, the expertise exchanged within STREVA appears to result from self-determination and intentionality; from a sociological perspective, this narrative can reflect Pickering's (1997) interpretation of actor-networks (see pp.184-185).

7.3: Concluding comments

To conclude, this chapter has analysed the mobility of individual actors and the flexibility of institutional entities. Iceland's complex and evolving network illustrates how actors are neither controlled by institutions, or detached from their collective influences. Stone (2002) draws on advocacy to explain the impact networked infrastructures have on the holism and fluidity of actuarial relations:

> A network amplifies and disseminates ideas, research and information to an extent that could not be achieved by individuals or institutions alone. Moreover, a network mutually confers legitimacy and pools authority and respectability in a positive-sum manner. In other words, a network can often be greater than its constituent parts (Stone, 2002, p.3).

This study has demonstrated how Stone's narrative is compatible with Iceland's approach to volcanic hazard management. By deconstructing institutions, this research has explored the mechanisms that allow the IMO, the London VAAC, the CP and various other entities to be adaptable and resilient.

Iceland represents a networked infrastructure rather than a system, primarily because knowledge exchange is facilitated by interconnections between actors, flexible entities and technological objects. The research has established that many human and non-human actors can be positioned 'in-between' institutions; these transitions stem from robust stakeholder connections and the mobilisation of expertise. However, whilst actors can function as hybrids in both institutional and network environments, links to ANT remain tenuous as the research findings are less representative of Latour (1993; 2005) and Callon's (1999) ideological approaches. This chapter is relevant to the research question because the points raised can improve understandings of how communication channels can be mediated and utilised in Iceland's network. Actors and institutions have a dynamic relationship, which the interdisciplinary scope of this research explores to illustrate both heterogeneity and institutional flexibility.

Chapter Eight: Research conclusions and recommendations

The first part of this concluding chapter responds to the main and subsidiary research questions, before the outcomes of the research are explained at length. These can be tailored to various disciplines, research communities, monitoring institutions and the aviation industry. The second part then focuses on the shortcomings of the study, before a series of recommendations are outlined; these relate to future trends in academic research, as well as to policy frameworks. This study attempts to explain stakeholder connections and knowledge exchange using an interdisciplinary narrative. The research draws on aspects of social constructivism to analyse how the dynamics of Iceland's hazard network have impacted on the adaptation and resilience of stakeholder communities. Focussing on collaborative engagements, scales of interaction and the evolution of institutional entities, the research findings reflect the complexity of Iceland's approach to volcanic hazard management. Post-Eyjafjallajökull, this research has increased relevance as it explains how communication breakdowns can be prevented, and close contact can be progressively maintained between scientists, the aviation industry, and communities in Southern Iceland.

8.1: Responding to the subsidiary research questions

By using a mixed methods approach, this study has been able to access a wide range of stakeholder communities, both in Iceland and the UK. For instance, the semi-structured interview format could be adapted to the aviation industry, civil protection services or communities such as Vík. On the other hand, participant observations enabled scientists to be studied in laboratory or institutional environments. Therefore, the subsidiary questions can be addressed from a holistic perspective.

1) **How have negotiations of power dynamics and technical actors impacted upon trust, collaborative practices, and flows of information in Iceland's volcanic hazard network?**

Technology has revolutionised Iceland's management of volcanic hazards, and **Chapter Five** refers to the impact on consultation between scientific and non-scientific communities. Firstly, the research observed a general strengthening of trust as technology has tended to spread decision-making powers to multiple stakeholder communities within the network. For instance, technical innovation and policy reform have contributed to the increased involvement of airlines, and their improved interactions with scientists. Secondly, by analysing the impact of smartphone applications and social media, this research has referred to the expansion of information flows between the Department of Civil Protection (CP), the Icelandic Met Office (IMO) and vulnerable communities across Southern Iceland. These findings suggest that collaborative engagements have stemmed from the increased transparency of communication between scientists, policymakers and the public. By addressing this subsidiary question, the research has been able to effectively illustrate how Icelandic volcanoes are becoming increasingly co-managed (Armitage *et al.*, 2009).

2) **What impact has stakeholders becoming sensitised to technology had upon the scale at which volcanic hazard networks have the capacity to adapt?**

The development of Iceland's network has generally encouraged interaction between local, national and international stakeholders. **Chapter Six** explains how research partnerships have provided technologies that allow Icelandic institutions to form and maintain connections with their European counterparts. Therefore, in addressing the question, technology has impacted on the network's responsiveness to change, primarily by allowing both local and international stakeholders to influence policymaking. For example, the construction and use of real-time communication platforms has enabled stakeholders to interact across multiple scales; this was illustrated during the eruption of Bárðarbunga (2014-2015), when local communities were frequently using social media to communicate with monitoring institutions in both Iceland and the UK. As stakeholders become intrinsically connected to technical devices and systems, their ability to communicate beyond Iceland has been significantly improved; this appears to have had a largely beneficial impact on the adaptability and resilience of the network.

3) **To what extent can Actor-Network Theory and co-production be used to interpret interactions between individual stakeholders and institutional entities?**

By analysing Iceland's approach to hazard management from a sociological perspective, this study has found that elements of both Actor-Network Theory (ANT) and co-production can be used to explain the set-up. Iceland's network is dynamic and institutionally dense, and **Chapter Seven** critically assesses the relationship between individual stakeholders and institutional entities. The development of task forces such as the Scientific Advisory Group for Emergencies, and the Natural Hazards Partnership, illustrate how stakeholders act as neither individuals or as members of a single institution. Instead, their ability to acquire, translate and communicate knowledge is determined by their interactions within the network. This interpretation resonates with both ANT and co-production, highlighting the need for a holistic approach to hazard networks. For instance, in the context of Iceland, prominent individuals within the aviation industry have demonstrated the flexibility to connect with stakeholders beyond the institution to which they are affiliated.

8.2: Responding to the research question and outcomes

This next section begins by addressing the research question and drawing on the empirical findings:

How may developing communications between human and non-human 'actors' be explored to theorise and manage a volcanic hazard network in Iceland?

Each of the empirical chapters highlight how hazard communication is continually evolving within Iceland's network. Therefore, communication practices can be explored by recognising the techniques that enable the network to be adaptable and resilient. Firstly, since the eruption of Eyjafjallajökull (2010), communication methods have been defined by agreements between scientific institutions and the aviation industry. Compromises have led to frequent interactions, improved levels of trust and the development of a proactive approach to sharing hazard information. Therefore, effective exchanges of knowledge have been constructed between scientists and prominent members of the aviation community; this has been reflected in volcanic ash exercises.

Communication practices can also be explored by focussing on the development and impact of technology. For example, during the eruption of Bárðarbunga (2014-2015), the use of social media demonstrated how stakeholder interaction had been transformed. Technology has allowed communication to become increasingly diverse, and has facilitated closer engagements between scientists and local communities. In the context of Iceland, the public has generally been empowered by methods of crowdsourcing and citizen science; this has enabled communities to actively participate in hazard management, and to maintain contact with both scientists and the civil protection services. Therefore, interactions between human and technical actors have increased in both frequency and value, with many instigating policy reform.

Finally, social constructivism can be used to theorise the existence and dynamics of communication channels within Iceland's network. The innovation and use of technical devices has been required to facilitate stakeholder interactions that have the capacity to fill any continuing knowledge gaps. Therefore, methods of communication are constructed by multiple communities, and are dependent on connectivity between human and non-human actors. A holistic approach to Iceland's management of volcanoes can acknowledge both the scientific and socio-political factors that underpin how hazard information is shared. This research has found that stakeholder agreements, technical innovation and social constructivism each have value when interpreting the complex and continual development of communication.

8.2.1: Establishing the research outcomes

The scope of this research means that the following outcomes can be influential to scientific institutions in Iceland and the UK, the aviation industry, and local communities across Southern Iceland. Furthermore, this study is likely to be of relevance to academics from numerous disciplines, and potentially significant to stakeholders involved in the management of volcanic hazards in other global regions.

1) Iceland's adaptability and resilience

This research provides an example of how hazard management can be studied from a range of interdisciplinary perspectives, many of which remain unexplored. By focussing on the adaptability and resilience of Iceland's approach to volcanic activity, the findings documented in this thesis have the capacity to impact on a wide range of academic disciplines. The research has analysed numerous stakeholder communities from both scientific and non-scientific backgrounds; this has led to several collaborative engagements being outlined between multiple actors and institutional entities. Therefore, the study is well positioned to analyse the expansion of a field of research that has traditionally been dominated by the physical sciences. Volcanic hazards can increasingly be co-managed by both scientific and socio-political communities, and this highlights the significant role that social scientists can now play in the design and influence of complex hazard networks that have the capacity to evolve.

The eruptions of Eyjafjallajökull (2010), Grímsvötn (2011) and Bárðarbunga (2014-2015) have each elicited a need to recognise the value of co-management in networks such as Iceland (Armitage *et al.*, 2009). This study has illustrated how the adaptability and resilience of multiple stakeholder communities are integral to this process. Therefore, the research conducted in Iceland can potentially influence future approaches to Disaster Risk Reduction. For example, the study has explained the relevance of stakeholder co-ordination, knowledge exchange and institutional partnerships. As a result, the findings can be valuable to policymakers and strategists, as well as a host of academic research communities. In addition, the study has also highlighted the relevance and merits of a mixed methods approach to hazard research; this has enabled the adaptation of the network to be acknowledged and critically explored. Therefore, the success of this study can potentially impact on the methods that are used to study the future evolution and development of volcanic hazard management, with less of a focus on quantitative measures such as probabilistic modelling, and a greater emphasis on social media analysis.

2) The role of virtual and participatory technologies

A further outcome of this research has been the increased focus on the role that technology plays in the management of volcanic hazards in Iceland. The findings explain the use of participatory technologies such as social media and Geographical Information Systems (Renschler, 2005; Scaini *et al.*, 2014). These devices and software packages are creating the digital and virtual space required for stakeholders to interact and share hazard information in real-time. This analysis of Iceland's network can potentially be valuable to the aviation community and the institutions that were directly involved in responding to the Eyjafjallajökull eruption. For example, this study has assessed how real-time communication could have significantly reduced the impacts on aviation in Europe, whilst also ensuring a robust relationship between the industry and scientific institutions such as the IMO.

In addition, the findings are also relevant to the innovators who are responsible for the research and development of technology in hazard networks. The study has the potential to influence and encourage future collaborative engagements between scientists and technicians, primarily because it directly relates to the design and construction of specific devices and software programs. Furthermore, the focus on platforms such as Facebook and Twitter enables this research to be valuable to the media, both within Iceland and internationally. Despite the rather critical assessment of some media outlets in response to Eyjafjallajökull, the study explains the need for hazard information to be translated by various end-users. Social media analysis has illustrated how participatory technologies can facilitate stakeholder interaction during an ongoing volcanic crisis. These findings and research methods can potentially be valuable to the future management of volcanic hazards in less economically developed regions, where the use of social media platforms and other participatory devices are likely to expand.

3) The transformation of the scientific community

By analysing Iceland's network from a sociological perspective, this research has provided new means of understanding scientific communities. For instance, many of the findings are defined by the interactions that exist between scientists and policymakers. In the context of Iceland, scientists now appear to be interconnected with the aviation industry, a progressive movement that has been ongoing since the eruptions of Eyjafjallajökull (2010) and Grímsvötn (2011). Explaining the development of this collaborative relationship illustrates the policy relevance of the study, primarily to the aviation community in Europe. For example, it highlights the importance of continued interaction with scientists, and the need to maintain valuable connections between institutions in Iceland and the UK.

Furthermore, scientific institutions have frequent and robust links to Icelandic communities such as Vík; these appear to have stemmed from collective efforts to promote citizen science, and illustrate the value of the research to community leaders, farmers and the public in Iceland. The interdisciplinary analysis presented in this thesis can potentially be significant to future trends and attitudes in regions where scientists are less accessible or trusted by local communities; examples include Soufriere Hills in Montserrat (Haynes *et al.*, 2008), and Mt Merapi in Indonesia (Mei *et al.*, 2013). Therefore, the study has focussed on how the dynamic between science, society and technology continues to evolve, and has evaluated their co-existence within Iceland's approach to volcanic hazard management. Communication and knowledge exchange have both played a significant role in constructing a diverse network that is sustainable, adaptable and resilient.

8.3: Research limitations

This PhD research has largely been successful, but there are limitations regarding its contextual focus on Iceland, and the speculative nature of the evidence presented in this thesis. Firstly, whilst foreseen as a potential problem before the research was conducted (see pp.20-21), the findings only represent Iceland's approach to managing volcanic activity. Chapter Four refers to several unique characteristics of Iceland's environment and society (see pp.91-94); these include its high density of volcanic systems, and the small but interconnected population. Collectively, these factors explain why Iceland provides an atypical example of volcanic hazard management. Furthermore, the lack of demographic or socio-political challenges means that Iceland contrasts with hazard networks in less economically developed regions. Despite the findings having the potential to influence Disaster Risk Reduction in future, this criticism could have been negated if the research was conducted in multiple hazardous environments. However, temporal and financial constraints meant the study could not be extended, and Iceland provided a suitable location. Nevertheless, if the research were to be repeated, it could be expanded to numerous volcanic regions, both within and beyond Europe; this would improve the representation of the findings.

Secondly, this thesis has analysed a considerable number of informed arguments from various stakeholder communities; however, much of the discussion has lacked conviction. The research has identified adaptations and trends within Iceland's management of volcanic hazards, but if it were to be repeated, then it could be less holistic and focussed instead on a clearly defined section of the network. For example, by restricting the scope of the research to the connective links between the aviation industry and scientific institutions, a small number of stakeholders could be studied in greater depth; this may provide more definitive conclusions. Furthermore, Iceland's network is complex and continually evolving; therefore, it cannot be explored in one study.

Thirdly, the longevity of the findings can be questioned as many features of Iceland's approach to hazard management are short-term measures; these include the design and duration of the FutureVolc project. However, this is a criticism that could be offset by conducting follow-up or comparative research, either at a later date or once the network has experienced a large-scale volcanic event such as Eyjafjallajökull (2010). Finally, sections of this thesis have focussed on the theoretical aspects of an interdisciplinary approach to Iceland's volcanic hazard network; as a result, the practicality of managing volcanic activity has been overlooked. Despite Chapter Four referring to the geology and tectonics of Icelandic volcanism (see pp.91-93), these were rarely probed during the fieldwork and do not feature in the empirics.

8.4: Recommendations

Based on the research conducted, the following recommendations can be made for how volcanic hazard networks should be designed and developed, both within and beyond Iceland:

> 1) Facilitate knowledge exchange at an inter-organisational level, encouraging co-production and the resolution of knowledge controversies between stakeholder communities.
>
> 2) Maximise the use of social media and crowdsourcing, and provide transparent methods of communication. Where possible, allow participatory technologies to provide frequent two-way communication between end-users and leading institutions.
>
> 3) Establish, at the earliest opportunity, a robust collaborative relationship between science and industry (aviation) when innovating, planning, constructing or trialling new technology.
>
> 4) Continue to devolve decision-making responsibilities, from leading institutions to community-based stakeholders; this can maintain or improve trust by empowering individual actors.
>
> 5) Encourage collaborative working groups, effective partnerships and task forces, ensuring they are designed to mediate or translate scientific, social or industrial expertise.

These recommendations can influence or elicit action from many contrasting stakeholder communities, both scientific and socio-political. The complexity of Iceland's networked infrastructure is defined by its institutional density, knowledge exchange and incorporation of participatory technologies. As volcanic hazard networks continue to develop post-Eyjafjallajökull, there is a need to maximise their adaptive capacity and resilience; technical actor's and stakeholder connectivity are integral to this process.

References

Adams, A. & Cox, A.L. (2008). *Questionnaires, in-depth interviews and focus groups*. In: Cairns, P. & Cox, A.L. (Eds.). (2008). Research Methods for Human Computer Interaction, First Edition, Cambridge University Press: Cambridge, pp.17-34.

Adger, N., Paavola, J., Huq, S. & Mace M.J. (Eds.). (2006). *Fairness in Adaptation to Climate Change*, Second Edition, Cambridge, MA: MIT Press. In: Barry, A., (2012). Political situations: Knowledge controversies in transnational governance, *Critical Policy Studies*, 6(3), pp.324-336.

Akrich, M., Callon, M., Latour, B. & Monaghan, A. (2002). The key to success in innovation part I: The art of interessement, *International Journal of Innovation Management*, 6(02), pp.187-206.

Alam, N., Ali, Z., Haq, M. & Ghouri, B.M. (2015). Flood Hazard Zonation and Damage Assessment Using Geospatial Techniques, *Global Journal of Multidisciplinary Studies*, 4(6), pp.38-51.

Albertsen, N. & Diken, B. (2004). Artworks' Networks Field, System or Mediators?, *Theory, Culture & Society*, 21(3), pp.35-58.

Alemanno, A. (2010). The European regulatory response to the volcanic ash crisis: Between fragmentation and integration, *European Journal of Risk Regulation*, 1, pp.101-106. In: Parker, C.F. (2015). Complex negative events and the diffusion of crisis: Lessons from the 2010 and 2011 Icelandic volcanic ash cloud events. *Geografiska Annaler: Series A*, *Physical Geography*, 97(1), pp.97-108.

Alemanno, A. (Ed.). (2011). *Governing disasters: The challenges of emergency risk regulation*, Edward Elgar Publishing: Cheltenham.

Alexander, D.E. (2010). The L'Aquila Earthquake of 6 April 2009 and Italian Government Policy on Disaster Response, *Journal of Natural Resources Policy Research,* 2:4, pp.325-342.

Alexander, D.E. (2013a). Volcanic ash in the atmosphere and risks for civil aviation: a study in European crisis management, *International Journal of Disaster Risk Science*, 4(1), pp.9-19.

Alexander, D.E. (2013b). *Paradoxes and Perceptions: Four Essays on Disaster*, University College London: Institute for Risk and Disaster Reduction.

Alexander, D.E. (2014). Communicating earthquake risk to the public: The trial of the "L'Aquila Seven", *Natural Hazards*, 72(2), pp.1159-1173.

Allen, J. (2003). *Lost Geographies of Power*. Illustrated Edition, Wiley & Sons.

Andonova, L., Betsill M. & Bulkeley H. (2009). Transnational Climate Governance, *Global Environmental Politics*, 9 (2), 52-73. In: Barry, A. (2012). Political situations: Knowledge controversies in transnational governance, *Critical Policy Studies*, 6(3), pp.324-336.

Aradau, C. (2010). Security that matters: Critical infrastructure and objects of protection, *Security Dialogue*, 41(5), pp.491-514.

Aradau, C. & Van Munster, R. (2007). Governing terrorism through risk: Taking precautions, (un)knowing the future, *European Journal of International Relations*, 13(1), pp.89-115.

Armitage, D.R., Plummer, R., Berkes, F., Arthur, R.I., Charles, A.T., Davidson-Hunt, I.J., Diduck, A.P., Doubleday, N.C., Johnson, D.S., Marschke, M. & McConney, P. (2009). Adaptive co-management for social-ecological complexity, *Frontiers in Ecology and the Environment*, 7(2), pp.95-102.

Ashman, K. & Barringer, P. (Eds.). (2005). *After the science wars: Science and the study of science*, Routledge: London.

Aspinall, W.P. (2006). *Structured elicitation of expert judgement for probabilistic hazard and risk assessment in volcanic eruptions*. In: Mader, S., Connor, C., & Connor, L., (Eds.). (2006). *Statistics in Volcanology*, First Edition, Geological Society: London, pp.15-30.

Aspinall, W.P. (2010). A route to more tractable expert advice, *Nature*, 463, pp.294-295.

Aspinall, W.P., Loughlin, S.C., Michael, F.V., Miller, A.D., Norton, G.E., Rowley, K.C., Sparks, R.S.J., & Young, S.R. (2002). *The Montserrat Volcano Observatory: Its evolution, organization, role and activities*, Geological Society: London, Memoirs, 21(1), pp.71-91. In: Donovan, A. & Oppenheimer, C. (2014b). Science, policy and place in volcanic disasters: Insights from Montserrat, *Environmental Science and Policy*, 39, pp.150-161.

Attride-Stirling, J. (2001). Thematic networks: An analytic tool for qualitative research, *Qualitative Research,* 1(3), pp.385-405.

Avgerou, C., Ciborra, C. & Land, F. (2004). *The social study of ICT: Innovation, actors and contexts*, Oxford University Press: Oxford.

Ayer, A.J. (1966). *Logical positivism (The library of philosophical movements)*, Free Press.

Banks, D. (2011). *A Brief Summary of Actor-Network Theory,* Cyborgology: The Society Pages. [On-line]. Available at: www.thesocietypages.org/cyborgology/2011/12/02/a-brief-summary-of-actor-network-theory/&gt (Date last accessed: June 2016).

Bankston III, C.L., Barnshaw, J., Bevc, C., Capowich, G.E., Clarke, L., Das, S.K., Donato, K.M., Dynes, R.R., Eargle, L.A., Elliott, J.R. & Esmail, A.M. (2010). *The sociology of Katrina: Perspectives on a modern catastrophe*, Kindle Edition, Rowman & Littlefield Publishers: Lanham, Maryland.

Baptie, B. (2015). *British Geological Survey - Iceland Volcanoes.* [On-line]. Available at: www.bgs.ac.uk/research/volcanoes/iceland (Date last accessed: May 2016).

Barabási, A.L. (2009). Scale-free networks: A decade and beyond, *Science*, 325(5939), pp.412-413.

Barclay J, Haynes K, Mitchell T, Solana C, Teeuw R, Darnell A, Crosweller H. S, Cole P, Pyle D. M, Lowe C, Fearnley C, & Kelman I. (2008). *Framing* *volcanic risk communication within disaster risk reduction: Finding ways for the social and physical sciences to work together*, Geological Society: London, 305(1), pp.163-177.

Bardini, T. (1997). Bridging the gulfs: From hypertext to cyberspace [1]. *Journal of Computer-Mediated Communication,* ACSUSC, 3(2). [On-line]. Available at: www.ascusc.org/jcmc/vol3/issue2/bardini.html (Date last accessed: March 2016).

Barron, C., Bruce, N. & Nunan, D. (2014). *Knowledge and Discourse: Towards an Ecology of Language*, Kindle Edition, Routledge: London.

Barry, A. (2012). Political situations: Knowledge controversies in transnational governance, *Critical Policy Studies*, 6(3), pp.324-336.

Bazeley, P. & Jackson, K. (Eds.). (2013). *Qualitative data analysis with NVivo*, Second Edition, SAGE Publications Limited.

Beck, U. (2000). 'Risk Society Revisited: Theory, Politics and Research Programmes'. In: Adam, B., Beck, U. & Van Loon, J. (Eds.). (2007). The Risk Society and Beyond: Critical Issues for Social Theory, Sage: London, pp.211-229. In: Aradau, C. & Van Munster, R. (2007). Governing terrorism through risk: Taking precautions, (un)knowing the future, *European Journal of International Relations*, 13(1), pp.89-115.

Beck, U. (2014). The Risk Society. In: Etkin, D. (2015). *Disaster Theory: An Interdisciplinary Approach to Concepts and Causes,* First Edition, Butterworth-Heinemann: UK.

Bee, E., Bell, P., Diaz-Doce, D., Flower, S., Mee, K., Reay, S., Richardson, S. & Shelley, W. (2014). Can the citizen help the scientist to help the citizen? How information obtained from social media and smartphones can help scientists understand more about natural hazards, *GSA Annual Meeting in Vancouver, British Columbia, October 2014*, pp.192-198.

Beech, D. (2015). Redesigning hazard communication through technology: Collaboration, co-Production and coherence, *Belgeo. Revue Belge de Géographie*, 1, pp.1-18.

Bell, R. & Glade, T. (2012). Multi-hazard analysis in natural risk assessments. In: Mambretti, S. (Ed.). (2012). *Landslides, Safety and security engineering series,* WIT Press: Southampton, pp.1-10.

Berger, P.L. & Luckmann, T. (1966). *The social construction of reality, A Treatise in the Sociology of Knowledge.* In: Bevir, M. & Rhodes, R.A.W. (Eds.). (2015). Routledge Handbook of Interpretive Political Science, Routledge Handbooks: London.

Bergmann, G. (1978). *The metaphysics of logical positivism*, Revised Edition, Praeger.

Bevir, M. & Rhodes, R.A.W. (Eds.). (2015). *Routledge Handbook of Interpretive Political Science*, Routledge Handbooks: London.

Biasse, S., Scaini, C., Bonadonna, C., Folch, A., Smith, K. & Höskuldsson, A. (2014). A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes: Part 1: Hazard assessment, *Natural Hazards & Earth System Sciences*, 14(8), pp.2265-2287.

Bijker, W.E. (1990). Social construction of technology. In Olsen, J.K.B., Pedersen, S.A. & Hendricks, V.F. (2009) *A Companion to the Philosophy of Technology (Blackwell Companions to Philosophy),* First Edition, John Wiley & Sons, pp.88-94.

Bijker, W.E. (2010). How is technology made? That is the question!, *Cambridge Journal of Economics*, 34(1), pp.63-76.

Bijker, W.E., Hughes, T.P., Pinch, T. & Douglas, D.G. (2012). *The social construction of technological systems: New directions in the sociology and history of technology*, Anniversary Edition, MIT press: MA.

Bilham, R. (2010). Lessons from the Haiti earthquake, *Nature*, 463(7283), pp.878-879.

Bingham, N. (1996). Object-ions: from technological determinism towards geographies of relations, *Environment and Planning D: Society and Space,* 14(6), pp.635-657.

Bingham, N. (1999). Unthinkable complexity? Cyberspace otherwise. In: Crang, M., Crang, P. & May, J. (Eds.). (1999). *Virtual geographies. Bodies, space and relations*, Routledge: London, pp.244-260.

Bingham, N. & Thrift, N. (2000). Some new instructions for travellers: The geography of Bruno Latour and Michel Serres. In: Crang, M. & Thrift, N.J. (Eds.). (2000). *Thinking space,* Reprint, Psychology Press, 13, pp.281-301.

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 & Earth System Sciences*, 9(4), pp.1307-1325.

Bird, D.K., Gísladóttir, G. & Dominey-Howes, D. (2009). Resident perception of volcanic hazards and evacuation procedures, *Natural Hazards & Earth System Sciences,* 9(1), pp.251-266.

Bird, D.K., Gísladóttir, 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), pp.1209-1227.

Birkholz, S., Muro, M., Jeffrey, P. & Smith, H.M. (2014). Rethinking the relationship between flood risk perception and flood management, *Science of the Total Environment*, 478, pp.12-20.

Blaikie, P., Cannon, T., Davis, I. & Wisner, B. (2005). A*t risk: Natural hazards, people's vulnerability and disasters*, Kindle Edition, Routledge: London.

Bloor, D. (1983). *Wittgenstein: A social theory of knowledge,* Columbia University Press: NY.

Bloor, D. (1984*).* The strengths of the Strong Programme. In: Brown, J.R. (Ed.). (1984). *Scientific rationality: The sociological turn (The Western Ontario Series in Philosophy of Science)*, 1984 Edition, Springer: Netherlands, pp.75-94.

Bloor, D. (2004). Sociology of scientific knowledge. In: Moser, P.K. (Ed.). (2005). *Handbook of Epistemology (Oxford Handbooks in Philosophy)*, New Edition, Oxford University Press, pp.919-962.

Boettke, P.J. & Coyne, C.J. (2009). *Context matters: Institutions and entrepreneurship (Foundations and Trends in Entrepreneurship)*, First Edition, Now Publishers: Netherlands, pp.136-196.

Boghossian, P. (2001). What is social construction?, *Times Literary Supplement*, 23 February 2001, pp.6-8.

Bolic, T. & Sivcev, Z. (2012). *Air Traffic Management in Volcanic Ash Events in Europe: A Year After Eyjafjallajökull Eruption*, Transportation Research Board 91st Annual Meeting, No. 12-3009.

Bonadonna, C. (2014). *Volcanic ash and civil aviation: A new perspective*, EuroGeoSurveys Workshop, pp.1-24.

Borup, M., Brown, N., Konrad, K. & Van Lente, H. (2006). The sociology of expectations in science and technology, *Technology Analysis & Strategic Management*, 18(3-4), pp.285-298.

Bosco, F.J. (2015). "Actor-Network Theory, Networks, and Relational Geographies". In: Valentine, G. & Aitken, S. (Eds.). (2015). *Approaches to Human Geography: Philosophies, Theories, People and Practices*, Second Edition, Sage: London, p.150.

Bossong, R. & Hegemann, H. (Eds.). (2015). European Civil Security Governance: Diversity and Cooperation in Crisis and Disaster Management. In: Croft, S. (Ed.). (2015). *New Security Challenges*, First Edition, Palgrave Macmillan: Basingstoke.

Bourova, E., Maldonado, E., Leroy, J.B., Alouani, R., Eckert, N., Bonnefoy-Demongeot, M. & Deschatres, M. (2016). A new web-based system to improve the monitoring of snow avalanche hazard in France, *Natural Hazards & Earth System Sciences*, 16(5), pp.1205-1216.

Bowker, G.C. (2014). Big Data, Big Questions: The Theory/Data Thing, *International Journal of Communication*, 8, pp.1795-1799.

Boyd, D. & Crawford, K. (2012). Critical questions for big data: Provocations for a cultural, technological, and scholarly phenomenon, *Information, Communication & Society*, 15(5), pp.662-679.

Brannigan, V.M. (2010). Alice's Adventures in Volcano Land: The Use and Abuse of Expert Knowledge in Safety Regulation, *European Journal of Risk Regulation*, 1(2), pp.107-113. In: Alexander, D.E. (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), pp.9-19.

Brinkmann, S. (2014). Unstructured and Semi-Structured. In: Leavy, P. (Ed.). (2014). *The Oxford Handbook of Qualitative Research*, First Edition, Oxford University Press: Oxford, pp.277-299.

British Geological Survey - Citizen science: Geosocial. (2016). [On-line]. Available at: www.bgs.ac.uk/citizenScience/home.html (Date last accessed: September 2016).

British Geological Survey - Natural Hazards Partnership. (2016). [On-line]. Available at: www.bgs.ac.uk/research/earthHazards/naturalHazardsPartnership/ (Date last accessed: May 2016).

British Geological Survey - Volcanoes: Icelandic ash research page. (2016). [On-line]. Available at: www.bgs.ac.uk/research/volcanoes/icelandic_ash/ (Date last accessed: May 2016).

Brown, N. & Rappert, B. (2000). *Contested futures: A sociology of prospective techno-science*, Ashgate Pub Limited: Aldershot.

Bryant, L., Srnicek, N. & Harman, G. (Eds.). (2011). *The speculative turn: Continental materialism and realism,* Melbourne: re. press.

Budd, L., Griggs, S., Howarth, D. & Ison, S. (2011). A fiasco of volcanic proportions? Eyjafjallajökull and the closure of European airspace, *Mobilities*, 6(1), pp.31-40.

Bulkeley, H. & Newell, P. (2010). *Governing Climate Change*, Routledge: London. In: Barry, A. (2012). Political situations: Knowledge controversies in transnational governance, *Critical Policy Studies*, 6(3), pp.324-336.

Burgess, J., Stirling, A., Clark, J., Davies, G., Eames, M., Staley, K. & Williamson, S. (2007). Deliberative mapping: a novel analytic-deliberative methodology to support contested science-policy decisions, *Public Understanding of Science*, 16(3), pp.299-322.

Burr, V. (2015). *Social constructionism*. Third Edition, Routledge: London.

Bursik, M., Calder, E., Gallo, S. & Jones, M. (2014). *CDI-Type II Proposal: VHub: Collaborative Research: Cyberinfrastructure for Volcano Eruption and Hazards Modelling and Simulation*. [On-line]. Available at:

www.agingportfolio.org/projects/project/NSF-0940831 (Date last accessed: September 2016).

Cabinet Office - National Risk Register of Civil Emergencies 2015. (2016). [On-line]. Available at: www.gov.uk/government/uploads/system/uploads/attachment_data/file/419549/20150331_2015-NRR-WA_Final.pdf (Date last accessed: May 2016).

Cadag, J.R.D. & Gaillard, J.C. (2013). Integrating people's capacities in disaster risk reduction through participatory mapping. In: López-Carresi, A., Fordham, M., Wisner, B., Kelman, I. & Gaillard, J.C. (Eds.). (2013). *Disaster management: International lessons in risk reduction, response and recovery*, Routledge: London.

Caldarelli, G. (2007). *Scale-free networks: Complex Webs in Nature and Technology (Oxford Finance Series)*, Oxford University Press: Oxford.

Callon, M. (1984). Some elements of a sociology of translation: Domestication of the scallops and the fishermen of St Brieuc Bay, *The Sociological Review*, 32(S1), pp.196-233.

Callon, M. (1999). Actor-network theory - The market test, *The Sociological Review*, 47(S1), pp.181-195.

Callon, M. & Blackwell, O. (2007). Actor-Network Theory. In: Asdal, K., Brenna, B. & Moser, I. (Eds.). (2007). *Technoscience: The Politics of Interventions*, Akademika Publishing, pp.273-286.

Callon, M. & Law, J. (1995). Agency and the hybrid collectif, *The South Atlantic Quarterly*, 94(2), pp.481-507.

Cardona, O.D. (2004). The need for rethinking the concepts of vulnerability and risk from a holistic perspective: A necessary review and criticism for effective risk management. In: Bankoff, G., Frerks, G., Hilhorst, D. (Eds.). (2004). *Mapping Vulnerability: Disasters, Development and People*, Earthscan: London, pp.37-51.

Carreño, M.L., Cardona, O.D. & Barbat, A.H. (2012). New methodology for urban seismic risk assessment from a holistic perspective, *Bulletin of Earthquake Engineering*, 10(2), pp.547-565.

Casadevall, T.J. (1994). The 1989-1990 eruption of Redoubt Volcano, Alaska: impacts on aircraft operations, *Journal of Volcanology and Geothermal Research*, 62(1), pp.301-316.

Cash, D.W., Adger, W.N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L. & Young, O. (2006). Scale and cross-scale dynamics: governance and information in a multilevel world, *Ecology & Society*, 11(2), p.8.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J. & Mitchell, R.B. (2003). Knowledge systems for sustainable development, *Proceedings of the National Academy of Sciences of the United States of America* 100(14), pp.8086-8091.

Castells, M. (2007). Communication, power and counter-power in the network society, *International journal of communication*, 1(1), pp.238-266.

Cavallo, A. & Ireland, V. (2012). SoS in disasters: why following the manual can be a mistake, *IEEE 7th International Conference on System of Systems Engineering (SoSE),* Genova, Italy.

Cavallo, A. & Ireland, V. (2014). Preparing for complex interdependent risks: a system of systems approach to building disaster resilience, *Global Assessment Report on Disaster Risk Reduction 2015*, pp.1-25.

Chatfield, A.T., Scholl, H.J.J. & Brajawidagda, U. (2013). Tsunami early warnings via Twitter in government: Net-savvy citizens' co-production of time-critical public information services, *Government Information Quarterly*, 30(4), pp.377-386.

Charmaz, K. (2014). *Constructing grounded theory,* Second Edition, Sage Publications Limited.

Chen, R., Sharman, R., Chakravarti, N., Rao, H. R., & Upadhyaya, S. J. (2008). Emergency response information system interoperability: development of chemical incident response data model, Journal of the Association for Information Systems, 9(3), pp.1-54. In: Bharosa, N., Lee, J. & Janssen, M. (2010). Challenges and obstacles in sharing and coordinating information during multi-agency disaster response: Propositions from field exercises, *Information Systems Frontiers*, 12(1), pp.49-65.

Chipangura, P., Van Niekerk, D. & Van Der Waldt, G. (2016). An exploration of objectivism and social constructivism within the context of disaster risk, *Disaster Prevention and Management,* 25(2), pp.261-274.

Cho, S.E., Jung, K. & Park, H.W. (2013). Social media use during Japan's 2011 earthquake: how Twitter transforms the locus of crisis communication, *Media International Australia*, 149(1), pp.28-40.

Christensen, T., Johannessen, M. & Lægreid, P. (2013). A system under stress: The Icelandic volcano ash crisis, *Journal of Contingencies and Crisis Management*, 21(2), pp.71-81.

Christiansen, T., Jorgensen, K.E. & Wiener, A. (1999). The social construction of Europe, *Journal of European Public Policy*, 6(4), pp.528-544.

Cidell, J. (2006). The place of individuals in the politics of scale, *Area,* 38(2), pp.196-203.

Cilliers, P. & Spurrett, D. (1999). Complexity and post-modernism: Understanding complex systems, *South African Journal of Philosophy,* 18(2), pp.258-274.

Cirella, A., Piatanesi, A., Cocco, M., Tinti, E., Scognamiglio, L., Michelini, A., Lomax, A. & Boschi, E. (2009). Rupture history of the 2009 L'Aquila (Italy) earthquake from non- linear joint inversion of strong motion and GPS data, *Geophysical Research Letters,* 36(L19304).

Cocco, M. (2014). *The European Supersites coordination: joining efforts for a federated data infrastructure,* EGU General Assembly Conference Abstracts, 16, p.15447.

Cole, S. (1992). *Making science: Between nature and society*, Harvard University Press: MA.

Collier, S.J. (2009). Topologies of power Foucault's analysis of political government beyond 'governmentality', *Theory, Culture & Society,* 26(6), pp.78-108.

Collinge, C. (2006). Flat ontology and the deconstruction of scale: A response to Marston, Jones and Woodward, *Transactions of the Institute of British Geographers*, 31(2), pp.244-251.

Cool, C.T., Claravall, M.C., Hall, J.L., Taketani, K., Zepeda, J.P., Gehner, M. & Lawe-Davies, O. (2015). Social media as a risk communication tool following Typhoon Haiyan. *Western Pacific Surveillance and Response Journal*, 6(1), pp.86-90.

Corburn, J. (2007). Community knowledge in environmental health science: co-producing policy expertise, *Environmental Science & Policy*, 10(2), pp.150-161.

Cornelissen, J.P., Durand, R., Fiss, P.C., Lammers, J.C. & Vaara, E. (2015). Putting communication front and center in institutional theory and analysis, *Academy of Management Review*, 40(1), pp.10-27.

Corpataux, J. & Crevoisier, O. (2016). Lost in space: A critical approach of ANT and the social studies of finance, *Progress in Human Geography*, 40(5), pp.610-628.

Cosmic Project. (2015). [On-line]. Available at: www.cosmic-project.eu (Date last accessed: October 2015).

Cresswell, J.W. (2013). *Qualitative inquiry and research design: Choosing among five approaches*, Third Revised Edition, Sage Publications.

Cresswell, K.M., Worth, A. & Sheikh, A. (2010). Actor-Network Theory and its role in understanding the implementation of information technology developments in healthcare, *BMC Medical Informatics and Decision Making*, 10(1), p.1.

Cronin, S.J, Petterson, M.G, Taylor, P.W. & Biliki R. (2004a). Maximising multi-stakeholder participation in government and community volcanic hazard management programs: A case study from Savo, Solomon Islands, *Natural Hazards*, 33(1), pp.105-136.

Cronin, S.J., Gaylord, D.R., Charley, D., Alloway, B.V., Wallez, S. & Esau, J.W. (2004b). Participatory methods of incorporating scientific with traditional knowledge for volcanic hazard management on Ambae Island, Vanuatu, *Bulletin of Volcanology,* 66(7), pp.652-668.

Cupples, J. & Glynn, K. (2014). The mediation and remediation of disaster: Hurricanes Katrina and Felix in/and the new media environment, *Antipode*, 46(2), pp.359-381.

Cutter, S.L. & Zoback, M.L. (2013). Improving the Nation's Resilience to Disasters, Eos, *Transactions American Geophysical Union*, 94(9), pp.89-89.

Cvetkovich, G. & Lofstedt, R.E. (2013). *Social trust and the management of risk,* Routledge: London.

Czarniawska-Joerges, B. (2007). *Shadowing: And other techniques for doing fieldwork in modern societies,* Copenhagen Business School Press: Copenhagen.

Dash, S.R., Mishra, U.S. & Mishra, P. (2013). Emerging issues and opportunities in disaster response supply chain management, *International Journal of Supply Chain Management*, 2(1), pp.55-61.

Davies, M.B. & Hughes, N. (2014). *Doing a successful research project: Using qualitative or quantitative methods*, Second Edition, Palgrave Macmillan: Basingstoke.

De Marchi, B. (2015). Risk Governance and the Integration of Different Types of Knowledge. In: Fra.Paleo, U. (Ed.). (2015). *Risk Governance: The Articulation of Hazard, Politics and Ecology,* 2015 Edition, Springer: Netherlands, pp.149-165.

Del Casino Jr, V.J. (2015). Social geographies II: Robots, *Progress in Human Geography*, 1, pp.1-10.

DeLanda, M. (2006). *A new philosophy of society: Assemblage theory and social complexity,* Annotated Edition, Continuum: NY.

Demeritt, D. (1998). Science, social constructivism and nature. In: Castree, N. & Braun, B. (Eds.). (1998). *Remaking reality: Nature at the millennium*, Routledge: London, pp.173-193.

Department of Civil Protection - Twitter Page. (2015). [On-line]. Available at: www.twitter.com/almannavarnir?lang=en-gb/ (Date last accessed: December 2015).

Department of Civil Protection - Civil Protection Act. (2016). No. 82, Section 1, Article 1, 12 June 2008. [On-line]. Available at: www.eng.innanrikisraduneyti.is/laws-and-regulations/english/civil-protection/ (Date last accessed: May 2016).

Derrida, J. (1976). *Of Grammatology (1967)*, Translated by Gayatri Chakravorty Spivak, Johns Hopkins University Press: Baltimore, pp.247-272.

Derrida, J. & Caputo, J.D. (1997). *Deconstruction in a nutshell: A conversation with Jacques Derrida*, Fordham University Press: NY.

DiCicco-Bloom, B. & Crabtree, B.F. (2006). The qualitative research interview, *Medical Education,* 40(4), pp.314-321.

Dolwick, J.S. (2009). 'The social' and beyond: Introducing actor-network theory, *Journal of Maritime Archaeology,* 4(1), pp.21-49.

Donovan, A. (2012). Earthquakes and volcanoes: Risk from geophysical hazards. In Roeser., S, Hillerbrand., R, Sandin., P, & Peterson., M. (Eds.). (2012). *Handbook of Risk Theory: Epistemology, Decision Theory, Ethics, and Social Implications of Risk*, 2012 Edition, Springer: Netherlands, pp.341-371.

Donovan, A.R. & Oppenheimer, C. (2012). The aviation sagas: Geographies of volcanic risk, *The Geographical Journal,* 178(2), pp.98-103.

Donovan, A. & Oppenheimer, C. (2014a). Managing the uncertain earth: geophysical hazards in the risk society, *The Geographical Journal*, 180(1), pp.89-95.

Donovan, A. & Oppenheimer, C. (2014b). Science, policy and place in volcanic disasters: Insights from Montserrat, *Environmental Science & Policy*, 39, pp.150-161.

Donovan, A., Oppenheimer, C. & Bravo, M. (2012). Science at the policy interface: Volcano-monitoring technologies and volcanic hazard management, *Bulletin of Volcanology*, 74(5), pp.1005-1022.

Donovan, A.R. & Oppenheimer, C. (2015). Modelling risk and risking models: The diffusive boundary between science and policy in volcanic risk management, *Geoforum*, 58, pp.153-165.

Donovan, K. (2010). Doing social volcanology: Exploring volcanic culture in Indonesia, *Area,* 42(1), pp.117-126.

Dorcey, A.H.J. & McDaniels, T. (1999). Great expectation, mixed results: trends in citizen involvement in Canadian environmental governance. [On-line]. Available at: www.interchg.ubc.ca/dorcey/trends (Date last accessed: August 2016). In: Pearce, L. (2003). Disaster management and community planning, and public participation: How to achieve sustainable hazard mitigation, *Natural hazards*, 28(2-3), pp.211-228.

Doyle, E.E., Paton, D. & Johnston, D.M. (2015). Enhancing scientific response in a crisis: Evidence-based approaches from emergency management in New Zealand, *Journal of Applied Volcanology*, 4(1), pp.1-26.

Drake, P. (2016). *Indonesia and the Politics of Disaster: Power and Representation in Indonesia's Mud Volcano*, Routledge: London.

Dransch, D., Poser, K., Fohringer, J. & Lucas, C. (2013). Volunteered Geographic Information for Disaster Management. In: Silva. C.N. (2013). *Citizen E-Participation in Urban Governance: Crowdsourcing and Collaborative Creativity*, First Edition, IGI Global: Hershey, PA.

Dumont, S., Parks, M., Sigmundsson, F., Vogfjörð, K., Einarsdóttir, H.M., Tumi Gudmundsson, M., Kristinsson, I., Loughlin, S., Ilyinskaya, E., Hooper, A. & Kylling, A. (2014). European collaboration for improved monitoring of Icelandic volcanoes: Status of the FutureVolc project after the initial 18 months, *EGU 2014 General Assembly Conference Abstracts,* 16, p.12033.

Dumont, S., Parks, M., Sigmundsson, F., Hooper, A., Hreinsdóttir, S., Ófeigsson, B., Spaans, K., Vogfjörd, K., Jónsdóttir, K., Hensch, M. & Gudmundsson, G. (2015). The feeder system for the 2014 fissure eruption at Holuhraun, Bárðarbunga volcanic system, Iceland: Geodetic and seismic constraints on subsurface activity in the area north of the Vatnajökull ice cap, *EGU 2015 General Assembly Conference Abstracts,* 17, p.10601.

Durant, A. (2012). *NILU - AVOID.* [On-line]. Available at: www.nilu.no/Nyhetsarkiv/tabid/74/language/en-US/NewsId/261/AVOID-volcanic-ash-detection-technology-tested-on-Airbus-aircraft.aspx/ (Date last accessed: September 2015).

Dwiartama, A. & Rosin, C. (2014). Exploring agency beyond humans: The compatibility of Actor-Network Theory (ANT) and resilience thinking, *Ecology & Society*, 19(3), p.28.

Earle, T.C. (2010). Trust in Risk Management: A Model-Based Review of Empirical Research*, Risk Analysis,* 30(4), pp.541-574.

EasyJet - Corporate page: AVOID section. (2016). [On-line]. Available at: www.corporate.easyjet.com/corporate-responsibility/avoid-volcanic-ash-detection (Date last accessed: August 2016).

Echeverría, J. (2003). Science, technology, and values: Towards an axiological analysis of techno-scientific activity, *Technology in Society*, 25(2), pp.205-215.

Eiser, J.R., Donovan, A. & Sparks, R.S.J. (2015). Risk perceptions and trust following the 2010 and 2011 Icelandic Volcanic Ash Crises, *Risk Analysis*, 35(2), pp.332-343.

Elder-Vass, D. (2008). Searching for realism, structure and agency in Actor Network Theory, *The British Journal of Sociology*, 59(3), pp.455-473.

Elíasson, J. (2014). Katla volcano in Iceland, potential hazards and risk assessment, *Natural Science*, 6(3), pp.99-107.

Elo, S., Kääriäinen, M., Kanste, O., Pölkki, T., Utriainen, K. & Kyngäs, H. (2014). Qualitative content analysis: A Focus on Trustworthiness, *Sage Open,* 4(1), pp.1-10.

Elwood, S., Goodchild, M.F. & Sui, D.Z. (2012). Researching volunteered geographic information: Spatial data, geographic research, and new social practice, *Annals of the Association of American Geographers*, 102(3), pp.571-590.

Endsley, M.R. & Jones, W. (2013). Situation awareness. In: Lee, J.D. & Kirlik, A. (2013). *The Oxford Handbook of Cognitive Engineering,* Oxford University Press, pp.88-108.

European Commission - ERCC main page. (2016). [On-line]. Available at: www.ec.europa.eu/echo/what/civil-protection/emergency-response-coordination-centre-ercc_en (Date last accessed: March 2016).

European Commission - Exchange of Experts page. (2016). [On-line]. Available at: www.exchangeofexperts.eu/EN/Home/home_node.html (Date last accessed: August 2016).

Farias, I. & Bender, T. (Eds.). (2012). *Urban assemblages: How actor-network theory changes urban studies*, Routledge: London.

Fazey, I., Bunse, L., Msika, J., Pinke, M., Preedy, K., Evely, A.C., Lambert, E., Hastings, E., Morris, S. & Reed, M.S. (2014). Evaluating knowledge exchange in interdisciplinary and multi-stakeholder research, *Global Environmental Change,* 25, pp.204-220.

Fearnley, C.J. (2013). Assigning a volcano alert level: Negotiating uncertainty, risk, and complexity in decision-making processes, *Environment & Planning A*, 45(8), pp.1891-1911.

Fearnley, C.J., McGuire, W.J., Davies, G. & Twigg, J. (2012). Standardisation of the USGS Volcano Alert Level System (VALS): Analysis and ramifications, *Bulletin of Volcanology*, 74(9), pp.2023-2036.

Felpeto, A., Martí, J. & Ortiz, R. (2007). Automatic GIS-based system for volcanic hazard assessment, *Journal of Volcanology and Geothermal Research*, 166(2), pp.106-116.

Fernandez-Steeger, T.M., Hu, H., Li, C. & Azzam, R. (2015). Wireless Sensor Networks and Sensor Fusion for Early Warning in Engineering Geology. In: Lollino, G., Giordan, D., Crosta, G., Corominas, J., Azzam, R., Wasowski, J., & Sciarra, N. (Eds.). (2015). Landslide Processes, *Engineering Geology for Society and Territory,* Springer: Cham, 2, pp.1421-1424.

Fielding, N.G. (2012). Triangulation and mixed methods designs data integration with new research technologies, *Journal of Mixed Methods Research*, 6(2), pp.124-136.

Flanagan, K., Uyarra, E. & Laranja, M. (2011). Reconceptualising the 'policy mix' for innovation, *Research Policy*, 40(5), pp.702-713.

Florêncio, J. (2011). Of Lights, Flesh, Glitter and Soil, p.73. In: Mörtenböck, P. & Mooshammer, H. (Eds.). (2014). *Space (Re)Solutions: Intervention and Research in Visual Culture*, Transcript-Verlag: Bielefeld, Transaction Publishers: New Brunswick & London.

Foucault, M. (1982). The subject and power, *Critical Inquiry,* 8(4), pp.777-795.

Foucault, M. (2007). Questions on geography. In: Crampton, J.W. & Elden, S. (Eds.). (2007). *Space, Knowledge and Power: Foucault and Geography,* Ashgate: Aldershot, pp.173-182.

Fountain, J.E. (2001). *Building the virtual state: Information technology and institutional change*, Illustrated Edition, Brookings Institution Press: WA.

Frodeman, R. (2010). *The Oxford handbook of interdisciplinarity*, First Edition, Oxford University Press: Oxford.

Fuenfschilling, L. & Truffer, B. (2014). The structuration of socio-technical regimes: Conceptual foundations from institutional theory, *Research Policy,* 43(4), pp.772-791.

FutureVolc Project - Catalogue of Icelandic Volcanoes. (2016). [On-line]. Available at: www.futurevolc.hi.is/sites/futurevolc.hi.is/files/Pdf/Deliverables/fv_d4_2_to_submit.pdf (Date last accessed: May 2016).

FutureVolc Project - Data Policy page. (2016). [On-line]. Available at: www.futurevolc.hi.is/data-policy (Date last accessed: May 2016).

FutureVolc Project - Deliverable 3.4. (2016). [On-line]. Available at: www.futurevolc.hi.is/sites/futurevolc.hi.is/files/Pdf/Deliverables/fv_d_3_4_to_submit.pdf (Date last accessed: May 2016).

FutureVolc Project - Exploiting the outcome of FutureVolc report. (2016). Stakeholder workshop, 5th November 2015, Hótel Örk, Hveragerði, South West Iceland, pp.1-32. [On-line]. Available at: www.futurevolc.hi.is/sites/futurevolc.hi.is/files/Pdf/vedurstofan_futurevolc_baeklingur.pdf (Date last accessed: June 2016).

FutureVolc Project - Main page. (2016). [On-line]. Available at: www.futurevolc.hi.is/ (Date last accessed: May 2016).

FutureVolc Project - Supersites. (2016). pp.1-24. [On-line]. Available at: www.futurevolc.hi.is/sites/futurevolc.hi.is/files/Pdf/iceland_ceos_proposal.pdf (Date last accessed: March 2016).

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), pp.315-328.

Galletta, A. (2013). *Mastering the semi-structured interview and beyond: From research design to analysis and publication*, New York University Press: NY.

Garcia, C. & Fearnley, C.J. (2012). Evaluating critical links in early warning systems for natural hazards, *Environmental Hazards,* 11(2), pp.123-137.

Gencturk, M., Kabak, Y., Arisi, R., SPA, L., Di Ciano, M., Innova Puglia, S.P.A., Toscano, L. & Palmitessa, A. (2015). *Profiling Approach for the Interoperability of Command and Control Systems with Sensing Systems in Emergency Management.* [On-line]. Available at: www.ceur-ws.org/Vol-1414/paper6.pdf (Date last accessed: September 2016).

Gibbons, M. (1999). Science's new social contract with society, *Nature*, 402, pp.C81-C84.

Gibson, H., Akhgar, B. & Domdouzis, K. (2015). Using Social Media for Crisis Response: The ATHENA System, *Proceedings of the 2nd European Conference on Social Media 2015 (ECSM 2015),* Porto: Portugal, pp.183-192.

Gieryn, T.F. (1983). Boundary-work and the demarcation of science from non-science: Strains and interests in professional ideologies of scientists, *American Sociological Review*, 48(6), pp.781-795.

Gieryn, T.F. (1999). *Cultural boundaries of science: Credibility on the line,* Second Edition, University of Chicago Press: IL.

Gill, P., Stewart, K., Treasure, E. & Chadwick, B. (2008). Methods of data collection in qualitative research: Interviews and focus groups, *British Dental Journal,* 204(6), pp.291-295.

Glaeser, E.L., Laibson, D.I., Scheinkman, J.A. & Soutter, C.L. (2000). Measuring trust, *The Quarterly Journal of Economics,* 115(3), pp.811-846.

Glickman, T.S. & Gough, M. (2013). *Readings in risk,* Kindle: First Edition, RFF Press: Washington DC.

Gold, R.L. (1958). Roles in sociological field observations, *Social forces*, 36(3), pp.217-223.

Goodman, D. (1999). Agro-food studies in the 'age of ecology': Nature, corporeality, bio-politics, *Sociologia Ruralis*, 39(1), pp.17-38.

Google Maps. (2016). [On-line]. Available at: www.google.co.uk/maps/ (Date last accessed: June 2016).

Graffy, E.A. & Booth, N.L. (2008). Linking environmental risk assessment and communication: An experiment in co-evolving scientific and social knowledge, *International Journal of Global Environmental Issues*, 8(1-2), pp.132-146.

Graham, S. & Marvin, S. (2001). Splintering urbanism: Networked infrastructures, technological mobilities and the urban condition, First Edition, Routledge: London.

Gramling, C. (2014). As volcano rumbles, scientists plan for aviation alerts, *Science*, 345(6200), p.990.

Grattan, J., Durand, M. & Taylor, S. (2003). Illness and elevated human mortality in Europe coincident with the Laki Fissure eruption, *Geological Society: London, Special Publications*, 213(1), pp.401-414.

Greenhough, B. (2006a). Tales of an island‐ laboratory: Defining the field in geography and science studies, *Transactions of the Institute of British Geographers*, 31(2), pp.224-237.

Greenhough, B. (2006b). Decontextualised? Dissociated? Detached? Mapping the networks of bioinformatics exchange, *Environment & Planning A,* 38(3), pp.445-463.

Grossetti, M. (2004). Proximities and embedding effects, *European Planning Studies*, 16(n°), pp.613-616.

Gudmundsson, M.T., Pálsson, F., Thordarson, T., Hoskuldsson, A., Larsen, G., Hognadóttir, T., Oddsson, B., Oladóttir, B.A. & Gudnason, J. (2014). Water/magma mass fractions in phreatomagmatic eruption plumes-constraints from the Grímsvötn 2011 eruption, *AGU 2014 Fall Meeting Abstracts*, 1, p.4718.

Gudmundsson, M.T., Thordarson, T., Höskuldsson, Á., Larsen, G., Björnsson, H., Prata, F.J., Oddsson, B., Magnússon, E., Högnadóttir, T., Petersen, G.N. & Hayward, C.L. (2012). Ash generation and distribution from the April-May 2010 eruption of Eyjafjallajökull, Iceland, *Scientific Reports*, 2(572), pp.1-12.

Guffanti, M. & Tupper, A. (2014). Volcanic Ash Hazards and Aviation Risk. In: Papale, P. & Shroder, J.F. (Eds.). (2014). *Volcanic Hazards, Risks and Disasters*, First Edition, Elsevier: Waltham, MA, pp.87-108.

Guffanti, M., Tupper, A., Mastin, L.G. & Lechner, P. (2012). Volcanic-Ash Hazards to Aviation - Changes and Challenges since the 2010 Eruption of Eyjafjallajökull, Iceland, *AGU 2012 Fall Meeting Abstracts*, 1, p.1627.

Gultom, D.I. (2016). Community-based disaster communication: How does it become trustworthy?, *Disaster Prevention and Management*, 25(4), pp.478-491.

Gunderson, L. (1999). Resilience, flexibility and adaptive management: Antidotes for spurious certitude, *Conservation Ecology*, 3(1), p.7. [Online]. Available at: www.consecol.org/vol3/iss1/art7/ (Date last accessed: August 2016).

Guston, D.H. (2001). Boundary organizations in environmental policy and science: An introduction, *Science, Technology, & Human Values*, 26(4), pp.399-408.

Habers, H. (1995). "Book Review: `We Have Never Been Modern' by Bruno Latour.", *Science, Technology & Human Values*, 20(2), pp.270-275. In: Walsham, G. (1997). Actor-network theory and IS research: Current status and future prospects, *Information systems and Qualitative Research,* Springer: US, pp.466-480.

Hackett, E.J., Amsterdamska, O., Lynch, M. & Wajcman, J. (2008). *The handbook of science and technology studies,* Revised Edition, MIT Press: Cambridge, MA.

Hage, M., Leroy, P. & Petersen, A.C. (2010). Stakeholder participation in environmental knowledge production, *Futures*, 42(3), pp.254-264.

Haklay, M. (2013). Citizen Science and volunteered geographic information: Overview and typology of participation. In: Sui, D., Elwood, S. & Goodchild, M.F. (Eds.). (2013). *Crowdsourcing geographic knowledge: Volunteered Geographic Information in Theory and Practice*, 2013 Edition, Springer: Netherlands, pp.105-122.

Haklay, M., Singleton, A. & Parker, C. (2008). Web mapping 2.0: The neogeography of the GeoWeb, *Geography Compass*, 2(6), pp.2011-2039.

Hall, S. (2001). Encoding/decoding, *Media and Cultural Studies: Keyworks*, pp.166-176.

Hammersley, M. & Atkinson, P. (1995). *Ethnography: Principles in practice*, Second Edition, Routledge: London.

Haraway, D. (1991). *Simians, cyborgs, and women: The reinvention of nature,* Second Edition, London: Free Association Books.

Hård, M. & Jamison, A. (2013). *Hubris and hybrids: A cultural history of technology and science*, New Edited Edition, Routledge: London.

Harris, A.J., Gurioli, L., Hughes, E.E. & Lagreulet, S. (2012). Impact of the Eyjafjallajökull ash cloud: A newspaper perspective, *Journal of Geophysical Research: Solid Earth,* 117(B9), pp.1-35.

Hart, J.K. & Martinez, K. (2006). Environmental Sensor Networks: A revolution in the earth system science?, *Earth-Science Reviews*, 78(3), pp.177-191.

Hay, C. (2016). Good in a crisis: The ontological institutionalism of social constructivism, *New Political Economy*, 21(6), pp.520-535.

Haynes, K., Barclay, J. & Pidgeon, N. (2007). Volcanic hazard communication using maps: An evaluation of their effectiveness, *Bulletin of Volcanology,* 70(2), pp.123-138.

Haynes, K., Barclay, J. & Pidgeon, N. (2008). Whose reality counts? Factors affecting the perception of volcanic risk, *Journal of Volcanology and Geothermal Research*, 172(3), pp.259-272.

Heiðarson, E.P., Jónasson, H.I. & Ingason, H.T. (2014). Geographical Sovereignty in Times of Crisis: The Eyjafjallajökull Eruption and the International Community from a Project Management Perspective, *Procedia-Social and Behavioral Sciences*, 119, pp.902-911.

Hein, D.I.O., Schwind, D.W.I.M. & König, W. (2006). Scale-free networks, *Wirtschaftsinformatik,* 48(4), pp.267-275.

Herfort, B., Eckle, M. & Zipf, A. (2015). Towards assessing the quality of volunteered geographic information from OpenStreetMap for identifying critical infrastructures, *Proceedings of the ISCRAM 2015 Conference,* Agder: Norway, pp.24-27.

Herzog, H. (2005). On home turf: Interview location and its social meaning, *Qualitative Sociology*, 28(1), pp.25-47.

Hesse-Biber, S.N. (2012). Feminist approaches to triangulation: Uncovering subjugated knowledge and fostering social change in mixed methods research, *Journal of Mixed Methods Research,* 6(2), pp.137-146.

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 (NHESS),* 14, pp.1871-1887.

Hillier, J. (2005). Straddling the post-structuralist abyss: Between transcendence and immanence?, *Planning Theory*, 4(3), pp.271-299.

Hinchliffe, S. (1996). Technology, power, and space: The means and ends of geographies of technology, *Environment & Planning D: Society & Space,* 14(6), pp.659-682.

Hoffmann, M.H.G., Schmidt, J.C. & Nersessian, N.J. (2013). Philosophy of and as interdisciplinarity, *Synthese*, 190(11), pp.1-9.

Horlick-Jones, T. & Sime, J. (2004). Living on the border: Knowledge, risk and transdisciplinarity, *Futures*, 6(4), pp.441-456.

Horlick-Jones, T., Sime, J. & Pidgeon, N. (2003). The social dynamics of environmental risk perception: Implications for risk communication research and practice. In: Pidgeon. N., Kasperson, R.E. & Slovic, P. (Eds.). (2003). *The social amplification of risk,* Illustrated Edition, Cambridge University Press: Cambridge, pp 262-285.

Huang, Q. & Cervone, G. (2016). Usage of Social Media and Cloud Computing During Natural Hazards. In: Vance, T.C., Merati, N., Yang, C. & Yuan, M. (Eds.). (2016). *Cloud Computing in Ocean and Atmospheric Sciences*, Academic Press: US, pp.297-324.

Huang, Q. & Xiao, Y. (2015). Geographic situational awareness: Mining tweets for disaster preparedness, emergency response, impact, and recovery, *ISPRS International Journal of Geo-Information,* 4(3), pp.1549-1568.

Icelandic Met Office - Earthquakes and Volcanism page. (2016). [On-line]. Available at: www.vedur.is/earthquakes-and-volcanism/volcanic-eruptions/ (Date last accessed: May 2016).

Icelandic Met Office - Facebook page. (2016). [On-line]. Available at: www.facebook.com/Vedurstofan/ (Date last accessed: January 2016).

Icelandic Met Office - Holuhraun [Bárðarbunga Article]. (2016). [On-line]. Available at: www.vedur.is/earthquakes-and-volcanism/articles/nr/2947/ (Date last accessed: August 2016).

Icelandic Met Office - Holuhraun [Sulfur Pollution Maps]. (2016). [On-line]. Available at: www.vedur.is/earthquakes-and-volcanism/volcanic-eruptions/holuhraun/ (Date last accessed: January 2016).

Icelandic Met Office - Holuhraun [Gas Model page]. (2015). [On-line]. Available at: www.en.vedur.is/weather/forecasts/gas-model (Date last accessed: March 2015).

Icelandic Met Office - Mission. (2016). [On-line]. Available at: www.vedur.is/about-imo/mission/ (Date last accessed: May 2016).

Ilyinskaya, E., Larsen, G., Vogfjörd, K., Tumi Gudmundsson, M., Jonsson, T., Oddsson, B., Reynisson, V., Barsotti, S. & Karlsdóttir, S. (2015). *Catalogue of Icelandic volcanoes*, EGU 2015 General Assembly Conference Abstracts, 17, p.12391.

Instone, L. (2004). Situating nature: On doing cultural geographies of Australian nature, *Australian Geographer*, 35(2), pp.131-140.

International Civil Aviation Organization - Handbook on the International Airways Volcano Watch. (2004). Second Edition, p.2-12. [On-line]. Available at: www.icao.int/publications/Documents/IAVW%20Handbook%20Doc%209766_en.pdf (Date last accessed: May 2016).

Isavia - VolcIce Exercise. (2016). [On-line]. Available at: www.isavia.is/english/c/notam/a-notam-no.-0256-15-bird-volcice-exercise/26506 (Date last accessed: May 2016).

Jasanoff, S. (1990). The Fifth Branch: Science Advisers as Policymakers, Harvard University Press: MA. In: Donovan, A.R. & Oppenheimer, C. (2015). Modelling risk and risking models: The diffusive boundary between science and policy in volcanic risk management, *Geoforum*, 58, pp.153-165.

Jasanoff, S. (1996). Beyond epistemology: Relativism and engagement in the politics of science, *Social Studies of Science,* 26(2), pp.393-418.

Jasanoff, S. (1998). The political science of risk perception, *Reliability Engineering and System Safety*, 59(1), pp.91-99.

Jasanoff, S. (2003). Technologies of humility: Citizen participation in governing science, *Minerva*, 41(3), pp.223-244.

Jasanoff, S. (2004). *States of Knowledge: The Co-Production of Science and the Social Order*, Reprint, Routledge: Abingdon.

Jasanoff, S. (2005). *Designs on Nature: Science and Democracy in Europe and the United States*, First Edition, Princeton University Press: Princeton.

Jasanoff, S. (2010). A field of its own: The emergence of science and technology studies. In: Frodeman, R. (2010). *The Oxford handbook of interdisciplinarity*, First Edition, Oxford University Press: Oxford, pp.191-205.

Jessop, B. (2001). Institutional re(turns) and the strategic-relational approach, *Environment & Planning A,* 33(7), pp.1213-1235.

Johnson, R.W. & Casadevall, T.J. (1994). Aviation safety and volcanic ash clouds in the Indonesia-Australia region, *Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety,* Seattle: WA, US Geological Survey Bulletin, 2047, pp.191-197.

Johnson, C. & Jeunemaitre, A. (2011). Risk and the role of scientific input for contingency planning: A response to the April 2010 Eyjafjallajökull volcano eruption. In: Alemanno, A. (Ed.). (2011). *Governing disasters the challenges of emergency risk regulation*, Edward Elgar: Cheltenham, pp.51-64.

Jónasdóttir, E.B., Petersen, G.N., Björnsson, H., Pfeffer, M.A., Barsotti, S., Jóhannsson, Þ. & Dürig, T. (2015). The 2014 Holuhraun volcanic eruption gas emission: A case study of an extreme SO2 concentration event, *EGU 2015 General Assembly Conference Abstracts,* 17, p.10946.

Jones, A., Thomson, D., Hort, M. & Devenish, B. (2007). The UK Met Office's next-generation atmospheric dispersion model, NAME III, *Air Pollution Modelling and its Application XVII*, Springer-Verlag: US, pp.580-589.

Jordan, C., Sigmundsson, F., Vogfjord, K., Gudmundsson, M.T., Kristinsson, I., Loughlin, S., Ilyinskaya, E., Hooper, A., Kylling, A., Witham, C. & Bean, C. (2013). Futurevolc: A European volcanological supersite observatory in Iceland, a monitoring system and network for the future, *2013 IEEE International Geoscience and Remote Sensing Symposium-IGARSS,* Melbourne: Australia, pp.286-289.

Kaghan, W.N. & Bowker, G.C. (2001). Out of machine age?, Complexity, sociotechnical systems and actor network theory, *Journal of Engineering and Technology Management,* 18(3), pp.253-269.

Kar, B. (2015). Citizen science in risk communication in the era of ICT, *Concurrency and Computation: Practice and Experience*, 28(7), pp.2005-2013.

Kawulich, B. B. (2012). Collecting data through observation. In: Wagner, C., Kawulich, B.B. & Garner, M. (2012). *Doing social research: A global context,* McGraw-Hill Education: Europe, Middle East & Africa, pp.150-160.

Khagram, S., Nicholas, K.A., Bever, D.M., Warren, J., Richards, E.H., Oleson, K., Kitzes, J., Katz, R., Hwang, R., Goldman, R. & Funk, J. (2010). Thinking about knowing: Conceptual foundations for interdisciplinary environmental research, *Environmental Conservation,* 37(4), pp.388-397.

Khorram-Manesh, A., Ashkenazi, M., Djalali, A., Ingrassia, P.L., Friedl, T., Von Armin, G., Lupesco, O., Kaptan, K., Arculeo, C., Hreckovski, B. & Komadina, R. (2015). Education in disaster management and emergencies: Defining a new European course, *Disaster Medicine and Public Health Preparedness,* 9(3), pp.245-255.

Kirsch, S. (1995). The incredible shrinking world? Technology and the production of space, *Environment & Planning D: Society & Space*, 13(5), pp.529-555.

Kitchin, R. & Tate, N. (2013). *Conducting research in human geography: Theory, methodology and practice,* 01 Edition, Routledge.

Klein, H.K. & Kleinman, D.L. (2002). The social construction of technology: Structural considerations, *Science, Technology & Human Values*, 27(1), pp.28-52.

Knoblauch, H. (2013). Communicative constructivism and mediatization, *Communication Theory,* 23(3), pp.297-315.

Knorr-Cetina, K.D. (1983). The ethnographic study of scientific work: Towards a constructivist interpretation of science. In: Knorr-Cetina, K.D. & Mulkay, M. (1983). *Science Observed: Perspectives on the Social Studies of Science,* Sage: London, pp.115-140.

Knorr-Cetina, K.D. (2008). Objectual practice. In: Mazzotti, M. (Ed.). (2016). *Knowledge as social order: Rethinking the sociology of Barry Barnes,* Routledge, pp.184-197.

Kruke, B.I. & Morsut, C. (2015). Resilience in a multilevel crisis governance context: A tale of joint implementation of community, regional, national and EU response capabilities. In: Podofillini, L., Sudret, B., Stojadinovic, B., Zio, E. & Kröger, W. (Eds.). (2015). *Safety and Reliability of Complex Engineered Systems: ESREL 2015,* Pap/Com Edition, CRC Press, pp.187-194.

Kuhlicke, C. & Demeritt, D. (2014). Risk, uncertainty, and the institutional geographies of adaptation to future flooding in England, 5th Biennial ECPR Standing Group for Regulatory Governance Conference, Barcelona: Spain, 17, p.12. In: Donovan, A.R. & Oppenheimer, C. (2015). Modelling risk and risking models: The diffusive boundary between science and policy in volcanic risk management, *Geoforum,* 58, pp.153-165.

Kuhlicke, C., Scolobig, A., Tapsell, S., Steinführer, A. & De Marchi, B. (2011). Contextualizing social vulnerability: Findings from case studies across Europe, *Natural Hazards,* 58(2), pp.789-810.

Lagendijk, A. & Cornford, J. (2000). Regional institutions and knowledge-tracking new forms of regional development policy, *Geoforum,* 31(2), pp.209-218.

Landström, C., Whatmore, S.J., Lane, S.N., Odoni, N.A., Ward, N. & Bradley, S. (2011). Coproducing flood risk knowledge: Redistributing expertise in critical 'participatory modelling', *Environment & Planning A,* 43(7), pp.1617-1633.

Lane, S.N., Odoni, N., Landström, C., Whatmore, S.J., Ward, N. & Bradley, S. (2011). Doing flood risk science differently: An experiment in radical scientific method, *Transactions of the Institute of British Geographers,* 36(1), pp.15-36.

Latour, B. (1983). Give me a laboratory and I will Raise the world. In: Murdoch, J. (1997). Inhuman/nonhuman/human: Actor-network theory and the prospects for a nondualistic and symmetrical perspective on nature and society, *Environment & planning D: Society & Space,* 15(6), pp.731-756.

Latour, B. (1987). *Science in action: How to follow scientists and engineers through society,* Edited Edition, Harvard University Press: Cambridge, MA.

Latour B. (1993). *We have never been modern,* Illustrated Edition (reprint), Harvard University Press: Cambridge, MA.

Latour, B. (1996a). *Aramis, or, The love of technology,* Illustrated Edition, Harvard University Press: Cambridge, MA.

Latour, B. (1996b). On actor-network theory: A few clarifications, *Soziale welt,* Nomos Verlagsgesellschaft mbH, Baden-Baden: Germany, pp.369-381.

Latour, B. (1996c). On interobjectivity, *Mind, Culture, and Activity,* 3(4), pp.228-245.

Latour, B. (1999a). On recalling ANT, *The Sociological Review,* 47(S1), pp.15-25.

Latour, B. (1999b). *Pandora's hope: Essays on the reality of science studies,* Illustrated Edition, Harvard University Press: Cambridge, MA.

Latour, B. (2005). *Reassembling the social: An introduction to actor-network-theory,* Illustrated Edition (reprint), Oxford University Press: Oxford.

Latour, B. & Woolgar, S. (1979). *Laboratory life: The social construction of scientific facts,* Reprint Edition, Princeton University Press: Princeton, NJ.

Latour, B., Mauguin, P. & Teil, G. (1992). A note on socio-technical graphs, *Social Studies of Science,* 22(1), pp.33-57.

Laurier, E. & Philo, C. (1999). X-morphising: Review essay of Bruno Latour's Aramis, or the Love of Technology, *Environment & Planning A,* 31(6), pp.1047-1071.

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), pp.273-287.

Law, J. (1992). Notes on the theory of the actor-network: Ordering, strategy, and heterogeneity, *Systems Practice,* 5(4), pp.379-393.

Law, J. (1999). After ANT: Complexity, Naming and Topology. In: Hassard, J. & Law, J. (Eds.). (1999). *Actor-Network Theory and After (Sociological Review Monographs),* Wiley-Blackwell: Oxford.

Law, J. (2000). Transitivities, Environment & Planning D: Society & Space, 18, pp.133-148. In: McFarlane, C. (2009). *Translocal assemblages: Learning, space and development,* Department of Geography: Science Site, Durham University: Durham, pp.1-25.

Law, J. (2002). Objects and spaces, *Theory, Culture & Society,* 19(5-6), pp.91-105.

Law, J. (2009a). Actor network theory and material semiotics, The New Blackwell Companion to Social Theory, 3, pp.141-158. In: Banks, D. (2011). *A Brief Summary of Actor-Network Theory,* Cyborgology: The Society Pages. [On-line]. Available at: www.thesocietypages.org/cyborgology/2011/12/02/a-brief-summary-of-actor-network-theory/&gt (Date last accessed: June 2016).

Law, J. (2009b). *The Greer-Bush test: On politics in STS*, pp.1-13. [On-line]. Available at: www.heterogeneities.net/publications/Law2009TheGreerBushTest.pdf (Date last accessed: September 2016).

Law, J. & Mol, A. (2001). Situating technoscience: An inquiry into spatialities, *Environment & Planning D: Society & Space,* 19(5), pp.609-621.

Lawhon, M. & Murphy, J.T. (2012). Socio-technical regimes and sustainability transitions: Insights from political ecology, *Progress in Human Geography,* 36(3), pp.354-378.

Learmount, D. (2013). EasyJet to create own ash cloud to validate Avoid kit, *Flight International,* 183(5390), p.18.

Lee, N. & Hassard, J. (1999). Organization unbound: Actor-network theory, research strategy and institutional flexibility, *Organization,* 6(3), pp.391-404.

Leitner, H. & Miller, B. (2007). Scale and the limitations of ontological debate: A commentary on Marston, Jones and Woodward, *Transactions of the Institute of British Geographers,* 32(1), pp.116-125.

Lemke, J.L. (2000). Across the scales of time: Artifacts, activities, and meanings in ecosocial systems, *Mind, Culture, and Activity,* 7(4), pp.273-290.

Leonard, G. & Potter, S. (2015). Developing effective communication tools for volcanic hazards in New Zealand, using social science. In: Loughlin, S.C., Sparks, S., Brown, S.K., Jenkins, S.F. & Vye-Brown, C. (Eds.). (2015). *Global Volcanic Hazards and Risk,* Illustrated Edition, Cambridge University Press: Cambridge, p.305.

Levine, J.M., Thompson, L.L. & Messick, D.M. (1999). *Shared cognition in organizations: The management of knowledge,* First Edition, Psychology Press: New York & Hove.

Liu, S.B. & Palen, L. (2010). The new cartographers: Crisis map mashups and the emergence of neogeographic practice, *Cartography and Geographic Information Science,* 37(1), pp.69-90.

Loughlin, S.C., Vye-Brown, C., Sparks, R.S.J., Brown, S.K., Barclay, J., Calder, E., Cottrell, E., Jolly, G., Komorowski, J.C., Mandeville, C. & Newhall, C. (2015). An introduction to global volcanic hazard and risk. In: Loughlin, S.C., Sparks, S., Brown, S.K., Jenkins, S.F. & Vye-Brown, C. (Eds.). (2015). *Global Volcanic Hazards and Risk,* Illustrated Edition, Cambridge University Press: Cambridge.

Lövbrand, E. (2011). Co-producing European climate science and policy: A cautionary note on the making of useful knowledge, Science and Public Policy, 38(3), pp.225-236. In: Donovan, A.R. and Oppenheimer, C. (2015). Modelling risk and risking models: The diffusive boundary between science and policy in volcanic risk management, *Geoforum,* 58, pp.153-165.

Lowe, A. (2001). Accounting information systems as knowledge-objects: Some effects of objectualization, *Management Accounting Research,* 12(1), pp.75-100.

Lucas, S.R. (2014). Beyond the Existence Proof: Ontological conditions, epistemological implications, and in-depth interview research, *Quality & Quantity,* 48(1), pp.387-408.

Lutz, L.D. & Lindell, M.K. (2009). Incident command system as a response model within emergency operation centers during Hurricane Rita*, Journal of Contingencies and Crisis Management,* 16(3), pp.122-134. In: Parker, C.F. (2015). Complex negative events and the diffusion of crisis: Lessons from the 2010 and 2011 Icelandic volcanic ash cloud events, *Geografiska Annaler: Series A, Physical Geography,* 97(1), pp.97-108.

Lynch, M. (2000). Against reflexivity as an academic virtue and source of privileged knowledge, *Theory, Culture & Society,* 17(3), pp.26-54.

Lynch, M. & Cole, S. (2005). Science and technology studies on trial: Dilemmas of expertise, *Social Studies of Science,* 35(2), pp.269-311.

Mackenzie, D. (2008). Material Markets: How Economic Agents are Constructed, Oxford University Press: Oxford. In: Barry, A. (2012). Political situations: Knowledge controversies in transnational governance, *Critical Policy Studies,* 6(3), pp.324-336.

Mackie, S., Cashman, K., Ricketts, H., Rust, A. & Watson, M. (Eds.). (2016). *Volcanic ash: Hazard observation*, Elsevier Publishing.

Maguire, J.S. & Matthews, J. (2010). Cultural intermediaries and the media, *Sociology Compass,* 4(7), pp.405-416.

Manicas, P.T. & Rosenberg, A. (1985). Naturalism, Epistemological Individualism and 'The Strong Programme' in the Sociology of Knowledge, *Journal for the Theory of Social Behaviour*, 15(1), pp.76-101.

Mann, S. (2016). Research Interviews: Modes and Types. In: Mann, S. (2016). *The Research interview: Reflective practices and reflexivity in research processes,* First Edition, Palgrave Macmillan: Basingstoke, pp.86-113.

Marcus, G. E. (2009). Multi-sited ethnography: Notes and Queries, *Multi-sited ethnography: Theory, praxis, and locality in contemporary research,* Ashgate: Farnham, pp.181-196.

Marston, S.A., Jones, J.P. & Woodward, K. (2005). Human geography without scale, *Transactions of the Institute of British Geographers*, *30*(4), pp.416-432.

Marzano, F.S., Lamantea, M., Montopoli, M., Herzog, M., Graf, H. & Cimini, D. (2013). Microwave remote sensing of the 2011 Plinian eruption of the Grímsvötn Icelandic volcano, *Remote sensing of Environment,* 129, pp.168-184.

Marzocchi, W., Newhall, C. & Woo, G. (2012). The scientific management of volcanic crises, *Journal of Volcanology and Geothermal Research,* 247-248, pp.181-189.

Matthews, B. & Ross, L. (2010). *Research methods: A Practical Guide for the Social Sciences,* 01 Edition, Longman: London.

McAllister, R.R. & Taylor, B.M. (2015). Partnerships for sustainability governance: A synthesis of key themes, *Current Opinion in Environmental Sustainability,* 12, pp.86-90.

McCallum, I., Liu, W., See, L., Mechler, R., Keating, A., Hochrainer-Stigler, S., Mochizuki, J., Fritz, S., Dugar, S., Arestegui, M. & Szoenyi, M. (2016). Technologies to support community flood disaster risk reduction, *International Journal of Disaster Risk Science,* 7(2), pp.198-204.

McEntire, D.A. (2007). *Disciplines, disasters, and emergency management: The convergence and divergence of concepts, issues and trends from the research literature,* Illustrated Edition, Charles C. Thomas Publisher: Springfield, IL.

McFarlane, C. (2009). *Translocal assemblages: Learning, space and development,* Department of Geography, Science Site, Durham University: Durham, pp.1-25.

McGhee, G., Marland, G.R. & Atkinson, J.M. (2007). Grounded theory research: Literature reviewing and reflexivity, *Journal of Advanced Nursing,* 60(3), pp.334-342.

McIntosh, M.J. & Morse, J.M. (2015). Situating and constructing diversity in semi-structured interviews, *Global Qualitative Nursing Research,* 2, pp.1-12.

Mee, K. & Duncan, M.J. (2015). *Increasing resilience to natural hazards through crowd-sourcing in St. Vincent and the Grenadines,* BGS: Nottingham, p.50.

Mei, E.T.W., Lavigne, F., Picquout, A., de Bélizal, E., Brunstein, D., Grancher, D., Sartohadi, J., Cholik, N. & Vidal, C. (2013). Lessons learned from the 2010 evacuations at Merapi volcano, *Journal of Volcanology and Geothermal Research,* 261, pp.348-365.

Mercer, J., Gaillard, J.C., Crowley, K., Shannon, R., Alexander, B., Day, S. & Becker, J. (2012). Culture and disaster risk reduction: Lessons and opportunities, *Environmental Hazards,* 11(2), pp.74-95.

Met Office [UK] - Ash Dispersion Leaflet. (2016). pp.1-2 [On-line]. Available: www.metoffice.gov.uk/media/pdf/5/h/DispersionLeaflet_VolcanicAsh0914.pdf (Date last accessed: May 2016).

Met Office [UK] - London VAAC main page. (2016). [On-line]. Available at: www.metoffice.gov.uk/aviation/vaac/ (Date last accessed: May 2016).

Met Office [UK] - London VAAC: Volcanic Ash Graphics page. (2015). [On-line]. Available at: www.metoffice.gov.uk/aviation/vaac/data/VAG_1394530885.png (Date last accessed: January 2015).

Met Office [UK] - London VAAC: Volcanic Ash Nephanalysis. (2016). [On-line]. Available at: www.metoffice.gov.uk/aviation/vaac/data/VolcanicAsh-Nephanalysis-1396973242issue.pdf (Date last accessed: August 2016).

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., Van Den Bergh, J., Bouwer, L., Bubeck, P., Ciavola, P., Genovese, E., Green, C.H. & Hallegate, S. (2013). Review article: Assessing the costs of natural hazards-state of the art and knowledge gaps, *Natural Hazards and Earth System Sciences,* 13(5), pp.1351-1373.

Miller, T.P. & Casadevall, T.J. (2000). Volcanic Ash Hazards to Aviation. In: Sigurdsson, H. (Ed.). *Encyclopaedia of Volcanoes,* Academic Press: San Diego, CA, pp.915-930.

Millington, S.C., Saunders, R.W., Francis, P.N. & Webster, H.N. (2012). Simulated volcanic ash imagery: A method to compare NAME ash concentration forecasts with SEVIRI imagery for the Eyjafjallajökull eruption in 2010, *Journal of Geophysical Research: Atmospheres,* 117(D20), pp.1-14.

Misztal, B. (2013). *Trust in modern societies: The search for the bases of social order,* Kindle Edition, John Wiley & Sons: NJ.

Moor, L. (2012). Beyond cultural intermediaries? A socio-technical perspective on the market for social interventions, *European Journal of Cultural Studies,* 15(5), pp.563-580.

Moore, A. (2008). Rethinking scale as a geographical category: From analysis to practice, *Progress in Human Geography,* 32(2), pp.203-225.

Moynihan, D.P. (2009). The network governance of crisis response: Case studies of incident command systems, Journal of Public Administration Research and Theory, 19, pp.895-915. In: Parker, C.F. (2015). Complex negative events and the diffusion of crisis: Lessons from the 2010 and 2011 Icelandic volcanic ash cloud events, *Geografiska Annaler: Series A Physical Geography,* 97(1), pp.97-108.

Mukherjee, B., Habib, M. & Dikbiyik, F. (2014). Network adaptability from disaster disruptions and cascading failures, *IEEE Communications Magazine,* 52(5), pp.230-238.

Murdoch, J. (1997). Inhuman/nonhuman/human: Actor-network theory and the prospects for a nondualistic and symmetrical perspective on nature and society, *Environment & planning D: Society & Space,* 15(6), pp.731-756.

Murdoch, J. (1998). The spaces of actor-network theory, *Geoforum,* 29(4), pp.357-374.

Murdoch, J. (2005). *Post-structuralist geography: A guide to relational space,* Sage Publications: UK.

Mynatt, E.D., Adler, A., Ito, M. & O'Day, V.L. (1997). Design for network communities, *Proceedings of the 1997 ACM SIGCHI Conference on Human factors in computing systems,* pp.210-217.

Naranjo, J.L., Sigurdsson, H., Carey, S.N. & Fritz, W. (1986). Eruption of the Nevado Del Ruiz volcano, Colombia, on 13 November 1985: Tephra fall and lahars, *Science,* 233(4767), pp.961-963.

National Aeronautics and Space Administration. (2016). [On-line]. Available: www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1/ (Date last accessed: August 2016).

Natural Environment Research Council - Activities: Natural Hazards page. (2016). [On-line]. Available at: www.nerc.ac.uk/innovation/activities/risk/naturalhazards/ (Date last accessed: May 2016).

Nayembil, M., Loughlin, S. & Duncan, M. (2016). Developing an integrated and interdisciplinary information platform for volcanic hazard and risk data, *RIMMA 2016: RISK Information Management, Risk Models and Applications,* Berlin: Germany, 27-28 June (Unpublished).

Neisser, F.M. (2014). 'Riskscapes' and risk management: Review and synthesis of an actor-network theory approach, *Risk Management,* 16(2), pp.88-120.

Newton, P., Holsclaw, C., Ko, M. & Ralph, M. (2007). *Long Term Technology Goals for CAEP,* Seventh Meeting of CAEP: Montréal [On-line]. Available at: www.icao.int/environmentalprotection/Documents/Publications/LongTermTechnologyGoals.pdf (Date last accessed: September 2016).

Nightingale, A. (2003). A feminist in the forest: Situated knowledges and mixing methods in natural resource management, *ACME: An International E-journal for Critical Geographies,* 2(1), pp.77-90.

Nyeggen, A. (2016). *Science Nordic - AVOID* [On-line]. Available at: www.sciencenordic.com/volcanic-ash-detection-technology-tested-aircraft/ (Date last accessed: May 2016).

Oliver-Smith, A. (1996). Anthropological research on hazards and disasters, *Annual Review of Anthropology*, 25(1), pp.303-328.

Oppenheim, R. (2007). Actor-network theory and anthropology after science, technology, and society, *Anthropological Theory,* 7(4), pp.471-493.

O'Reilly, K. 2009. *Key concepts in ethnography*, SAGE: Key Concepts, SAGE Publications Ltd: London, pp.88-92.

Ott, R.L. & Longnecker, M.T. (2015). *An introduction to statistical methods and data analysis,* Nelson Education.

Owen, C., Bearman, C., Brooks, B., Chapman, J., Paton, D. & Hossain, L. (2013). Developing a research framework for complex multi-team coordination in emergency management, *International Journal of Emergency Management,* 9(1), pp.1-17.

Palliyaguru, R., Amaratunga, D. & Baldry, D. (2014). Constructing a holistic approach to disaster risk reduction: The significance of focusing on vulnerability reduction, *Disasters,* 38(1), pp.45-61.

Palma, J.L., Courtland, L., Charbonnier, S., Tortini, R. & Valentine, G.A. (2014). Vhub: A knowledge management system to facilitate online collaborative volcano modelling and research, *Journal of Applied Volcanology,* 3(1), p.1.

Parker, C.F. (2015). Complex negative events and the diffusion of crisis: Lessons from the 2010 and 2011 Icelandic volcanic ash cloud events, *Geografiska Annaler: Series A Physical Geography,* 97(1), pp.97-108.

Paterson, M. (1996). Global warming and global politics, Illustrated Edition (reprint), Psychology Press: Hove. In: Barry, A. (2012). Political situations: Knowledge controversies in transnational governance, *Critical Policy Studies,* 6(3), pp.324-336.

Paton, D. (2006). Disaster resilience: Building capacity to co-exist with natural hazards and their consequences. In: Paton, D. & Johnston, D.M. (2006). *Disaster resilience: An integrated approach,* Charles C. Thomas Publisher: Springfield, IL, pp.3-10.

Paton, D. (2008). Risk communication and natural hazard mitigation: How trust influences its effectiveness, *International Journal of Global Environmental Issues,* 8(1-2), pp.2-16.

Paton, D. & Johnston, D.M. (2006). *Disaster resilience: An integrated approach,* Charles C. Thomas Publisher: Springfield, IL.

Paton, D., Johnston, D. & Houghton, B.F. (1998). Organisational response to a volcanic eruption, *Disaster Prevention and Management: An International Journal*, 7(1), pp.5-13.

Patton, J.W. (2004). An Introduction to Science and Technology Studies, *Science Studies,* 17(1), pp.66-69.

Patwardhan, A. & Ajit, M. (2007). *Disaster prevention, preparedness and management and linkages with climate change adaptation,* Technology Information, Forecasting and Assessment Council: New Delhi, 10, pp.1-24.

Pearce, L. (2003). Disaster management and community planning, and public participation: How to achieve sustainable hazard mitigation, *Natural hazards,* 28(2-3), pp.211-228.

Peary, B.D., Shaw, R. & Takeuchi, Y. (2012). Utilization of social media in the east Japan earthquake and tsunami and its effectiveness, *Journal of Natural Disaster Science,* 34(1), pp.3-18.

Pelling, M. (2003). *The vulnerability of cities: Natural disasters and social resilience,* Earthscan: London.

Pereira, R.L., Trindade, J., Gonçalves, F., Suresh, L., Barbosa, D. & Vazão, T. (2014). A wireless sensor network for monitoring volcano-seismic signals, *Natural Hazards and Earth System Sciences,* 14(12), pp.3123-3142.

Pérez-González, L. & Susam-Saraeva, Ş. (2012). Non-professionals translating and interpreting: Participatory and engaged perspectives, *The Translator,* 18(2), pp.149-165.

Petersen, G.N., Bjornsson, H. & Arason, P. (2012). The impact of the atmosphere on the Eyjafjallajökull 2010 eruption plume, *Journal of Geophysical Research: Atmospheres,* 117(D20), pp.1-14.

Pickering, A. (1993). The mangle of practice: Agency and emergence in the sociology of science, American Journal of Sociology, 99(3), pp.559-589. In: Murdoch, J. (1997). Inhuman/nonhuman/human: Actor-network theory and the prospects for a nondualistic and symmetrical perspective on nature and society, *Environment & planning D: Society & Space,* 15(6), pp.731-756.

Pierson, T.C., Wood, N.J. & Driedger, C.L. (2014). Reducing risk from lahar hazards: Concepts, case studies, and roles for scientists, *Journal of Applied Volcanology,* 3(16).

Pinch, T. (1996). The social construction of technology: A review. In: Fox, R. (2012). *Technological change: Methods and themes in the history of technology,* e-Book Edition, Routledge: London, pp.17-36.

POP-ALERT Project. (2015). [On-line]. Available at: www.pop-alert.eu (Date last accessed: October 2015).

Þorkelsson, B., Karlsdóttir, S., Gylfason, Á.G., Höskuldsson, Á., Brandsdóttir, B., Ilyinskaya, E., Guðmundsson, M.T. & Högnadóttir, Þ. (2012). The 2010 Eyjafjallajökull eruption, Iceland: Report to ICAO, *International Volcanic Ash Task Force: Fourth Meeting,* Montréal [On-line]. Available at: www.jardvis.hi.is/sites/jardvis.hi.is/files/Pdf_skjol/Eyjafjallajokull_2010/icaoreport_web.pdf (Date last accessed: August 2016).

Potts, L. (2009). Using actor network theory to trace and improve multimodal communication design, *Technical Communication Quarterly,* 18(3), pp.281-301.

Power, R., Robinson, B., Colton, J. & Cameron, M. (2014). Emergency situation awareness: Twitter case studies*, Information Systems for Crisis Response and Management in Mediterranean Countries,* Lecture Notes in Business Information Processing, Springer International Publishing, pp.218-231.

Prata, A.J. & Tupper, A. (2009). Aviation hazards from volcanoes: The state of the science*, Natural Hazards,* 51(2), pp.239-244.

Prata, A.J., Durant, A. & Kylling, A. (2012). The airborne volcanic object imaging detector (AVOID): A new tool for airborne atmospheric remote sensing of clouds, *EGU 2012 General Assembly Conference Abstracts,* 14, p.8977.

Prata, A.J., Zehner, C. & Stebel, K. (2013), Earth observations and volcanic ash, *A report of the ESA/Eumesat Workshop 2013,* Dublin, Ireland, pp.4-7.

Przedpelski, Z.J. & Casadevall, T.J. (1994). Impact of volcanic ash from 15th December 1989: Redoubt volcano eruption on GE CF6-80C2 turbofan engines, *Volcanic ash and aviation safety: Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety*, US Geological Survey Bulletin, 2047, pp.129-135.

Puglisi, G., Vogfjord, K.S., Bachelery, P. & Ferreira, T. (2014). Integration of European Volcano Infrastructures. In: Papale, P & Shoder, J. (Eds.). (2014). *Volcanic Hazards, Risks and Disasters*, Academic Press, pp.419-444.

Pyyhtinen, O. & Tamminen, S. (2011). We have never been only human: Foucault and Latour on the question of the Anthropos, *Anthropological Theory,* 11(2), pp.135-152.

Qu, S.Q. & Dumay, J. (2011). The qualitative research interview, *Qualitative Research in Accounting & Management,* 8(3), pp.238-264.

Racovita, M. (2013). Lost in translation, *EMBO Reports*, 14(8), pp.675-678.

Ranghieri, F. & Ishiwatari, M. (Eds.). (2014). *Learning from megadisasters: Lessons from the Great East Japan Earthquake,* World Bank Publications.

Rawolle, S., Wells, M., Paatsch, L., Tytler, R. & Campbell, C. (2015). *Improving Schools: Productive Tensions between the Local, the Systemic and the Global*, First Edition, Springer: Singapore.

Rayner, S. (2012). Risk and Relativism in Science for Policy. In: Johnson, B.B. & Covello, V.T. (Eds.). (2012). *The Social and Cultural Construction of Risk: Essays on Risk Selection and Perception,* Reprint, Springer: Netherlands, pp.5-23.

Renn, O. (1998). Three decades of risk research: Accomplishments and new challenges, *Journal of Risk Research,* 1(1), pp.49-71.

Renschler, C.S. (2005). Scales and uncertainties in using models and GIS for volcano hazard prediction, *Journal of Volcanology and Geothermal Research,* 139(1), pp.73-87.

Reuter C. (2015). *Emergent collaboration infrastructures: Technology design for inter-organizational crisis management,* Springer Gabler: Siegen, Germany.

Rhinard, M. (2015). Who Cares? The Relevance of EU Crisis Cooperation for EU Scholars. In: Bossong, R. & Hegemann, H. (Eds.). (2015). *European Civil Security Governance: Diversity and Cooperation in Crisis and Disaster Management,* Palgrave Macmillan: Basingstoke, pp.256-277.

Riel, B., Milillo, P., Simons, M., Lundgren, P., Kanamori, H. & Samsonov, S. (2015). The collapse of Bárðarbunga caldera, Iceland, *Geophysical Journal International,* 202(1), pp.446-453.

Rip, A. (2002). Co-Evolution of Science, Technology and Society, *Expert Review for the Bundesministerium Bildung und Forschung's Forderinitiative 'Politik, Wissenschaft und Gesellschaft' (Science Policy Studies),* pp.1-59.

Ripepe, M., Bonadonna, C., Folch, A., Delle Donne, D., Lacanna, G., Marchetti, E. & Höskuldsson, A. (2013). Ash-plume dynamics and eruption source parameters by infrasound and thermal imagery: The 2010 Eyjafjallajökull eruption, *Earth and Planetary Science Letters,* 366, pp.112-121.

Roberts, T. & Parks B. (2007). Climate of Injustice: Global Inequality, North-South Politics and Climate Policy, MIT Press: Cambridge, MA. In: Barry, A. (2012). Political situations: Knowledge controversies in transnational governance, *Critical Policy Studies,* 6(3), pp.324-336.

Rogstadius, J., Vukovic, M., Teixeira, C.A., Kostakos, V., Karapanos, E. & Laredo, J.A. (2013). CrisisTracker: Crowdsourced social media curation for disaster awareness, *IBM Journal of Research and Development,* 57(5), pp.4:1-4:13.

Rossi, C., Stemberger, W., Bielski, C., Zeug, G., Costa, N., Poletto, D., Spaltro, E. & Dominici, F. (2015). Coupling crowdsourcing, earth observations, and E-GNSS in a novel flood emergency service in the cloud, *2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS),* Milan, Italy, pp.2703-2706.

Rotman, D., Preece, J., Hammock, J., Procita, K., Hansen, D., Parr, C., Lewis, D. & Jacobs, D. (2012), Dynamic changes in motivation in collaborative citizen-science projects, *Proceedings of the ACM 2012 Conference on Computer Supported Cooperative Work,* Bellevue: WA, pp.217-226.

Rowlands, B.H. (2005). Grounded in practice: Using interpretive research to build theory, *The Electronic Journal of Business Research Methodology,* 3(1), pp.81-92.

Rowley, T.J. (1997). Moving beyond dyadic ties: A network theory of stakeholder influences, *Academy of Management Review,* 22(4), pp.887-910.

Salter, J. (1997). Risk management in a disaster management context, *Journal of Contingencies and Crisis Management,* 5(1), pp.60-65.

Samarajiva, R. & Waidyanatha, N. (2009). Two complementary mobile technologies for disaster warning, *Digital Policy, Regulation and Governance,* 11(2), pp.58-65.

Sammonds, P., McGuire, B. & Edwards, S. (2010). *Volcanic Hazards from Iceland, Analysis and Implications of the Eyjafjallajökull Eruption,* UCL Institute for Risk and Disaster Reduction: London, pp.1-21.

Sangianantoni, A. & Puglisi, G. (2014). *MED-SUV Data policy,* EGU General Assembly Conference Abstracts, 16, p.6700.

Scaini, C., Felpeto, A., Martí, J. & Carniel, R. (2014). A GIS-based methodology for the estimation of potential volcanic damage and its application to Tenerife Island, Spain, *Journal of Volcanology and Geothermal Research,* 278-279, pp.40-58.

Schillmeier, M. (2015). What ELSA/I makes big and small in Nanotechnology Research, *Absence in Science, Security and Policy,* First Edition, AIAA, pp.55-77.

Schmidt, A., Leadbetter, S., Theys, N., Carboni, E., Witham, C.S., Stevenson, J.A., Birch, C.E., Thordarson, T., Turnock, S., Barsotti, S. & Delaney, L. (2015). Satellite detection, long-range transport, and air quality impacts of volcanic sulfur dioxide from the 2014-2015 flood lava eruption at Bárðarbunga (Iceland), *Journal of Geophysical Research: Atmospheres,* 120(18), pp.9739-9757.

Schneider, S.K. (2005). Administrative breakdowns in the governmental response to Hurricane Katrina, *Public Administration Review,* 65(5), pp.515-516.

Schwartz-Shea, P. (2014). Interpretive Social Science. In: Gibbons, M.T., Coole, D., Ellis, E. & Ferguson, K. (Eds.). (2014). *The Encyclopedia of Political Thought,* Wiley-Blackwell: NJ, pp.1895-1900.

Scientific Advisory Group for Emergencies - main page. (2016). [On-line]. Available at: www.gov.uk/government/groups/scientific-advisory-group-for-emergencies-sage/ (Date last accessed: January 2016).

Scolobig, A., Prior, T., Schröter, D., Jörin, J. & Patt, A. (2015). Towards people-centred approaches for effective disaster risk management: Balancing rhetoric with reality, *International Journal of Disaster Risk Reduction,* 12, pp.202-212.

Scott, W.R. (2005). Institutional theory: Contributing to a theoretical research program. In: Smith, K.G. & Hitt, M.A. (Eds.). (2005). *Great minds in management: The process of theory development,* Reprint, Oxford University Press: Oxford, pp.460-485.

Scott, B.J. & Travers, J. (2009). Volcano monitoring in NZ and links to SW Pacific via the Wellington VAAC, *Natural hazards*, 51(2), pp.263-273.

Scott-Jones, J. & Watt, S. (2010). *Ethnography in Social Science Practice*, Routledge: London.

Seidman, I. (2013). *Interviewing as qualitative research: A guide for researchers in education and the social sciences,* Third Revised Edition, Teachers College Press: NY.

Sennert, S.S., Klemetti, E.W. & Bird, D.K. (2015). Role of Social Media and Networking in Volcanic Crises and Communication. In: Nemeth, K. (Ed.). (2015). *Advances in Volcanology Series,* Springer: Berlin Heidelberg, pp.1-12.

Seo, M.G. & Creed, W.D. (2002). Institutional contradictions, praxis, and institutional change: A dialectical perspective, *Academy of Management Review,* 27(2), pp.222-247.

Serres, M. & Latour, B. (1995). *Conversations on science, culture, and time,* Reprint, University of Michigan Press.

Shapin, S. (1995). Here and everywhere: Sociology of scientific knowledge, *Annual Review of Sociology,* 21, pp.289-321.

Sigmundsson, F., Vogfjörð, K.S., Ófeigsson, B.G., Hreinsdóttir, S., Roberts, M.J., Ripepe, M. & Guðmundsson, M.T. (2013a). *Present day in-situ monitoring networks of volcanic and seismic hazards in Iceland and FutureVolc,* pp.1-14. [On-line]. Available at: www.earthobservations.org/documents/gsnl/proposals/Iceland_Supplement.pdf (Date last accessed: March 2015).

Sigmundsson, F., Vogfjord, K.S., Gudmundsson, M.T., Kristinsson, I., Loughlin, S.C., Ilyinskaya, E., Hooper, A.J., Kylling, A., Witham, C.S., Bean, C.J. & Braiden, A. (2013b). FutureVolc: A European volcanological supersite in Iceland, a monitoring system and network for the future, *AGU 2015 Fall Meeting Abstracts,* 1, p.1615.

Sigmundsson, F., Hooper, A., Hreinsdóttir, S., Vogfjörd, K.S., Ófeigsson, B., Rafn Heimisson, E., Dumont, S., Parks, M., Spaans, K., Guðmundsson, G.B. and Drouin, V., (2015). Contribution of the FutureVolc project to the study of segmented lateral dyke growth in the 2014 rifting event at Bárðarbunga volcanic system, Iceland, *EGU 2015 General Assembly Conference Abstracts,* 17, p.11846.

Sigmundsson, F., Vogfjord, K.S., Gudmundson, M.T., Ofeigsson, B.G., Dumont, S., Parks, M., Jonsdóttir, K., Hooper, A., Hreinsdottir, S., Rafn Heimisson, E. & White, R. (2016). Exploiting the outcome of FutureVolc: The 2014-2015 rifting event, effusive eruption and gradual caldera collapse at Bárðarbunga volcanic system, Iceland, *EGU 2016 General Assembly Conference Abstracts,* 18, p.10436.

Sismondo, S. (2010). *An introduction to science and technology studies,* Second Revised Edition, Chichester: Wiley-Blackwell.

Slovic, P.E. (1999). Trust, emotion, sex, politics, and science: Surveying the risk-assessment battlefield, *Risk Analysis,* 19(4), pp.689-701.

Slovic, P.E. (2000). *The perception of risk*, Reprint, Earthscan: London.

Smith, R. G. (2003). World city topologies, *Progress in Human Geography,* 27(5), pp.561-582.

Snow, C.P. (1959). *Two cultures,* First Edition, University Press.

Sokal, A.D. (Ed.). (2000). *The Sokal hoax: The sham that shook the academy,* University of Nebraska Press (Bison Books): NA.

Soto, D., Renard, F. & Magnon, A. (2014). Evaluating Environmental Risk to Technological Hazards: Using GIS Spatial Decision Making, *International Conference on Computational Science and its Applications,* Guimaraes: Portugal, Lecture Notes in Computer Science, Springer International Publishing, pp.15-25.

Stalder, F. (1997). *Actor-network-theory and communication networks: Toward convergence,* Unpublished Doctorate, University of Toronto: Toronto.

Statistics Iceland. (2016). [On-line]. Available at: www.statice.is/statistics/population/inhabitants/ (Date last accessed: May 2016).

Steelman, T.A. & McCaffrey, S. (2013). Best practices in risk and crisis communication: Implications for natural hazards management, *Natural Hazards,* 65(1), pp.683-705.

Stirling, A. (2006). Analysis, participation and power: Justification and closure in participatory multi-criteria analysis, *Land Use Policy,* 23(1), pp.95-107.

Stone, D. (2002). Introduction: Global knowledge and advocacy networks, *Global Networks,* 2(1), pp.1-12.

Stone, J., Barclay, J., Simmons, P., Cole, P.D., Loughlin, S.C., Ramón, P. & Mothes, P. (2014). Risk reduction through community-based monitoring: The vigías of Tungurahua, Ecuador, *Journal of Applied Volcanology,* 3:11.

Strengthening Resilience in Volcanic Areas - main page. (2016). [On-line]. Available at: www.streva.ac.uk/ (Date last accessed: August 2016).

Sullivan, J.R. (2012). Skype: An appropriate method of data collection for qualitative interviews, *The Hilltop Review,* 6(1), pp.54-60.

Sutton, J., Palen, L. & Shklovski, I. (2008). Backchannels on the front lines: Emergent uses of social media in the 2007 southern California wildfires, *Proceedings of the 5th International ISCRAM Conference,* Washington DC, pp.624-632.

Szakács, A. & Seghedi, I. (2013). The relevance of volcanic hazard in Romania: Is there any?, *Environmental Engineering and Management Journal,* 12(1), pp.125-135.

'T Hart, P. & Sundelius, B. (2013). Crisis management revisited: A new agenda for research, training and capacity building within Europe, *Cooperation & Conflict,* 48(3), pp.444-461. In: Parker, C.F. (2015). Complex negative events and the diffusion of crisis: Lessons from the 2010 and 2011 Icelandic volcanic ash cloud events, *Geografiska Annaler: Series A Physical Geography,* 97(1), pp.97-108.

Tatnall, A. & Davey, B. (2015). The internet of things and beyond: Rise of the non-human actors, *International Journal of Actor-Network Theory and Technological Innovation (IJANTTI),* 7(4), pp.56-67.

Teschke, B. & Heine, C. (Eds.). (2016). The dialectic of globalisation: A critique of Social Constructivism. In: Rupert, M. & Smith, H. (2016). *Historical*

Materialism and Globalisation: Essays on Continuity and Change, Reprint, Routledge: Oxon.

The National Archives - SAGE Volcanic Ash Minutes PDF [5th May 2010]. (2016). [On-line]. Available at: www.bis.gov.uk/assets/goscience/docs/s/10-1372-sage-volcanic-ash-minutes-5-may-2010.pdf (Date last accessed: May 2016).

The National Archives - SAGE Volcanic Ash Minutes PDF [19th May 2010]. (2016). [On-line]. Available at: www.bis.gov.uk/assets/goscience/docs/s/10-1373-sage-volcanic-ash-minutes-19-may-2010.pdf (Date last accessed: May 2016).

Thierry, P., Neri, M., Le Cozannet, G., Jousset, P. & Costa, A. (2015). Preface: Approaches and methods to improve risk management in volcanic areas, *Natural Hazards and Earth System Sciences (NHESS),* 15, pp.197-201.

Thordarson, T. & Larsen, G. (2007). Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history, *Journal of Geodynamics,* 43(1), pp.118-152.

Thrift, N. (1996). *Spatial formations,* Illustrated Edition, Sage.

Thrift, N. (1999). The place of complexity, *Theory, Culture & Society,* 16(3), pp.31-69.

Thrift, N. (2000). Still life in nearly present time: The object of nature, *Body & Society,* 6(3-4), pp.34-57.

Tierney, K. (2012). Disaster governance: Social, political, and economic dimensions, *Annual Review of Environment and Resources,* 37, pp.341-363.

Timmermans, S. & Epstein, S. (2010). A world of standards but not a standard world: toward a sociology of standards and standardization, *Annual Review of Sociology,* 36, pp.69-89.

Timmermans, S. & Tavory, I. (2012). Theory construction in qualitative research: From grounded theory to abductive analysis, *Sociological Theory,* 30(3), pp.167-186.

Tobin, G.A. & Whiteford, L.M. (2002). Community resilience and volcano hazard: The eruption of Tungurahua and evacuation of the faldas in Ecuador, *Disasters,* 26(1), pp.28-48.

Tootell, B. (1985). *All Four Engines Have Failed: The True and Triumphant Story of Flight BA 009 and the 'Jakarta Incident',* Illustrated Edition, Andre Deutsch Publishers.

Turkle, S. (2011). *Life on the Screen: Identity in the Age of the Internet*, Simon & Schuster: NY.

United States Geological Survey - Understanding Plate Motions. (2016). [On-line]. Available at: www.pubs.usgs.gov/gip/dynamic/understanding.html (Date last accessed: May 2016).

Van Der Duim, R., Ren, C. & Jóhannesson, G.T. (2013). Ordering, materiality and multiplicity: Enacting ANT in Tourism, *Tourist Studies,* 0(0), pp.1-18.

Van Krieken, R. (2002). The paradox of the 'two sociologies': Hobbes, Latour and the constitution of modern social theory, *Journal of Sociology,* 38(3), pp.255-273.

Van Leeuwen, T. (1996). The representation of social actors. In: Caldas-Coulthard, C.R. & Coulthard, M. (1996). *Texts and practices: Readings in critical discourse analysis,* Reprint, Taylor & Francis Publishing, 1, pp.32-70.

Van Manen, S., Avard, G. & Martínez-Cruz, M. (2015). Co-ideation of disaster preparedness strategies through a participatory design approach: Challenges and opportunities experienced at Turrialba volcano, Costa Rica, *Design Studies,* 40, pp.218-245.

Vieweg, S.E. (2012). Situational Awareness in Mass Emergency: A Behavioral and Linguistic Analysis of Microblogged Communications. [On-line]. Available at: www.works.bepress.com/vieweg/15/ (Date last accessed: September 2016).

Voight, B. (1990). The 1985 Nevado del Ruiz volcano catastrophe: Anatomy and retrospection, *Journal of Volcanology and Geothermal Research,* 42(1-2), pp.151-188.

Wachinger, G., Renn, O., Begg, C. & Kuhlicke, C. (2013). The Risk Perception Paradox - Implications for Governance and Communication of Natural Hazards, *Risk Analysis,* 33(6), pp.1049-1065.

Wang, W. & Guo, L. (2012). The application of wireless sensor network technology in earthquake disaster, *Industrial Control and Electronics Engineering (ICICEE) 2012 International Conference,* Xi'an: China, pp.52-55.

Webersik, C., Gonzalez, J.J., Dugdale, J., Munkvold, B.E. & Granmo, O.C. (2015). Towards an integrated approach to emergency management: interdisciplinary challenges for research and practice, *Culture Unbound: Journal of Current Cultural Research,* 7(3), pp.524-540.

Weichselgartner, J. & Pigeon, P. (2015). The role of knowledge in disaster risk reduction, *International Journal of Disaster Risk Science,* 6(2), pp.107-116.

Weinberg, S. (1996). *Sokal's hoax: An Exchange,* New York Review of Books: NY, 43(13), pp.11-15.

Werner-Allen, G., Lorincz, K., Welsh, M., Marcillo, O., Johnson, J., Ruiz, M. & Lees, J. (2006). Deploying a Sensor Network on an Active Volcano, *IEEE Internet Computing archive,* 10(2), pp.18-25.

Wesselink, A., Buchanan, K.S., Georgiadou, Y. & Turnhout, E. (2013). Technical knowledge, discursive spaces and politics at the science-policy interface, *Environmental Science & Policy,* 30, pp.1-9.

Whatmore, S. (2002). *Hybrid Geographies: Natures, Cultures, Spaces,* Sage: London.

Whatmore, S.J. (2006). Materialist returns: Practising cultural geography in and for a more-than-human world, *Cultural geographies*, *13*(4), pp.600-609.

Whatmore, S.J. (2009). Mapping knowledge controversies: science, democracy and the redistribution of expertise, *Progress in Human Geography,* 33(5), pp.587-598.

Widiwijayanti, C., Costa, F., Zar Win Nang, T., Tan, K., Newhall, C. & Ratdomopurbo, A. (2015). WOVOdat as a worldwide resource to improve eruption forecasts, *EGU 2015 General Assembly Conference Abstracts,* 17, p.10221.

Wilkinson, I. (2001). Social theories of risk perception: At once indispensable and insufficient, *Current Sociology,* 49(1), pp.1-22.

Williams, T. & Shepherd, D. (2016). Building Resilience or Providing Sustenance: Different Paths of Emergent Ventures in the Aftermath of the Haiti Earthquake, *Academy of Management Journal,* 59(6), pp.2069-2102.

Wilson, G., Wilson, T.M., Deligne, N.I. & Cole, J.W. (2014). Volcanic hazard impacts to critical infrastructure: A review, *Journal of Volcanology and Geothermal Research,* 286(1), pp.148-182.

Wisner, B. & Luce, H.R. (1993). Disaster vulnerability: Scale, power and daily life, *GeoJournal,* 30(2), pp.127-140.

Wisner, B., Gaillard, J.C. & Kelman, I. (Eds.). (2012). *Handbook of hazards and disaster risk reduction and management,* Routledge Handbooks: London.

Witham, C., Webster, H., Hort, M., Jones, A. & Thomson, D. (2012). Modelling concentrations of volcanic ash encountered by aircraft in past eruptions, *Atmospheric Environment,* 48, pp.219-229.

Witham, C., Vieno, M., Schmidt, A., Aspinall, W., Braban, C., Hort, M. & Loughlin, S. (2015). UK hazard assessment for a Laki-type volcanic eruption: modelling results for sulphur dioxide and sulphate aerosol, *EGU 2015 General Assembly Conference Abstracts,* 17, p.14100.

Witze, A. (2013). Volcanic-ash sensor to take flight, *Nature,* 502(7472), pp.422-423.

Woolgar, S. (1981). Critique and criticism: Two readings of ethnomethodology, *Social Studies of Science,* 11(4), pp.504-514.

World Meteorological Organization - WMO VAAC 'Best Practice' Workshop Report. (2015). Westminster, London, UK, 5th-8th May 2015, Final Report, pp.1-30. [On-line]. Available at: www.wmo.int/aemp/sites/default/files/VAAC_BP_Report_FINAL.pdf (Date last accessed: May 2015).

Wright, A. & Ehnert, I. (2010). Making sense of trust across cultural contexts. In: Saunders, M.N.K., Skinner, D., Dietz, G., Gillespie, N. & Lewicki, R.J. (Eds.). (2010). *Organizational trust: A cultural perspective,* First Edition, Cambridge University Press: Cambridge, pp.107-126.

Wyatt, K. (2013). How to "Get" Grounded and Not "Get" Lost: Review of Grounded Theory for Qualitative Research: A Practical Guide, *The Qualitative Report,* 18(16), pp.1-4.

Wyborn, C. (2015). Co-productive governance: A relational framework for adaptive governance, *Global Environmental Change,* 30, pp.56-67.

Yamin, F., Rahman, A. & Huq, S. (2005). Vulnerability, adaptation and climate disasters: A conceptual overview, *IDS bulletin*, 36(4), pp.1-14.

Yates, D. & Paquette, S. (2011). Emergency knowledge management and social media technologies: A case study of the 2010 Haitian earthquake, *International Journal of Information Management,* 31(1), pp.6-13.

Yin, J., Lampert, A., Cameron, M., Robinson, B. & Power, R. (2012). Using social media to enhance emergency situation awareness, *IEEE Intelligent Systems,* 27(6), pp.52-59.

Zook, M., Graham, M., Shelton, T. & Gorman, S. (2010). Volunteered geographic information and crowdsourcing disaster relief: A case study of the Haitian earthquake, *World Medical and Health Policy,* 2(2), pp.7-33.

Appendices

Appendix One: Research materials for methodology

1.1: Interview transcript examples

Key

Technology

Power

Trust

Communication

I(number) - interviewee number, as noted on either the Dictaphone or in the field diary

R: Researcher

Icelandic Met Office

I6: Technology has enormously impacted on our knowledge about how the different types of processes, improving the system. Technology has been very important in general and our understanding, to …. it has been influential in increasing communication between scientists, it is very helpful, you can sit somewhere as an expert in remote sensing using a satellite and if you see something, an event, and have established a contact, of course you have to have that, you can then give information to your colleagues for them to see. The expertise then comes into the institute?

R: And do you feel that is an opinion reflective of the wider institute?

I6: Yes certainly, technology has helped us a lot in dealing with natural hazards, at least in this system, when we started this risk assessment of volcanoes in Iceland, one thing we can say in our arguments when we took them to the ministry was to say that in modern society we are also vulnerable.

R: If we have the technology available, then why do you feel we remain vulnerable?

I6: Exactly, we have improved knowledge and know-how and it has made all communication between different institutes really much better but we are vulnerable if something happens because we rely on the technology.

R: Have your communication practices changed in response to technology?

I6: Yes, I would say so. We could say that now, for instance, we use the web a lot to put out information, we send out these three hourly volcanic ash reports during an event, we have this colour code on the web to not only transfer information but also enhance our dissemination methods to show where we are, we disseminate it to stakeholders, so, so, it has absolutely, for example, in 2010 eruption, I had a call from CAA in England and they wanted the chemical composition of the ash, I could then give them the website vedur.is where we had put out the information, because they are dealing with those things and they were very grateful for the information because they could reuse it to put out information, both national and international people can get information because it is useful for their operation work.

University of Iceland (Institute of Earth Sciences)

R: Have there been any significant changes in the way that volcanic hazards, or natural hazards, are managed in Iceland since 2010/2011?

I4: Definitely, a big increase in, in investment and monitoring equipment that is being used now throughout the volcanic zone but primarily Katla volcano and northwest of Vatnajökull, to take a few examples, seismic stations and broadband seismic stations that are collecting data continuously and transmitting data in real-time back to IMO in Reykjavík, we have invested in all sorts of ash detection hardware, and you have probably heard about this already, including ground based LIDAR for measuring particle composition and ash density LIDARs and that of course reflects foreign investment, there's the global stream network, that's been expanded and processors have been installed to borehole strainmeters near Katla, and that's again with mostly UK and US financial support, so overall there has been a big increase in the amount of data, to the extent that it is becoming quite a challenge to process it all and use it effectively in day to day monitoring and that's maybe the, the sort of a side of the story that you will become overwhelmed with the different types of monitoring data, and it is as much a task to install the equipment and maintain it as it is to process it, to the process the data and the make that data into useable results

R: What level of control or influence do you feel academic research have on the technology that you use?

I4: More, yes, obviously there are some, most of the networks are fully incorporated, those networks where there are four or five stations processing data are telemetered in real-time and warnings can be given out here based on set thresholds, and we play a very important role in that

R: You mentioned increases in investment, following the eruption in 2010, do you think that investment was solely an outcome of the international disruption to communication, trade, transport?

I4: Well we know, from my experience, with the networks we are responsible for, there are state level support from different countries, and government funding that's coming from the BGS, we, we have a contact at the BGS, and the mandate for that came from the Cabinet Office, apparently there was a meeting during, well a series of meetings during and after the 2010 eruptions of Eyjafjallajökull and the decision was made that, well the UK should be seen to be making a, a move in assisting Iceland, in real-time volcanological measurements, you see more pure research interest from scientific groups in UK, US and European universities, particularly wanting to follow the aftermath of the eruption, looking at the recovery, the landscape for instance or wanting to install other monitoring equipment in collaboration with us at the IMO, it's about giving warnings and taking steps to clear airspace which initially has to be done and then from a research aspect we have teams coming here interested in collecting scientific data which has a monitoring purpose as well, potentially the people who are installing the equipment for research purposes don't make any attempt to relay the data in real-time or to make use of it operationally as we would

Department of Civil Protection

I20: the International Civil Aviation Organisation, ICAO, they have been working with the IMO and their response to all kinds of equipment, for example, mobile radars which Sigrun probably told you about, so they would be able to respond to that radar, hang it from the back of a truck and drive to the mountain which is erupting and they could place it under there and the radar could measure with much more precision, much more precisely the quantity of the ash going into the air, so using technology in that sense and perhaps creating and providing a solution

R: Do you feel FutureVolc, as a project, is helping the system to become more efficient, more transparent, and more open to the public?

I20: I can definitely see a trend, for example, in Iceland we see money coming in for the study of volcanoes, and it's for a reason, because before the Icelandic volcanoes were not on the registers of the European nations but now they are and that's for a reason, because they saw the aviation industry, they bore the cost of having a bad system, or not, having precise measurements, or not precise enough, so if you want to increase the uptake for the airlines, so you see a tremendous amount of money is in place there

R: You mentioned earlier about the hub in Europe extending outside, are there any conflicts in the advice given in Europe compared to outside of Europe?

I20: Well, this ECHO organisation, the European Commission Humanitarian Organisation, they organise humanitarian aid given by the European Union and for that they monitor people outside of Europe, in those location, helping and distributing food and aid and whatever and I know the modules we have designed in the system we can use them inside of Europe and we can apply them outside of Europe, for example, in the typhoon in the Philippines, there were people giving aid exactly through these same channels so we were asked by the system to assist, if you could send technical assistance down there, and that would be registered like the European assistance,

R: Do you expect to be participating in further similar projects or initiatives?

I20: it's not a European platform, it was no platform, it was a scientific platform, so it was just the scientists were speaking to each other and they were coming from different parts of the world and from different institutions, some of them were working for the government or local communities or the universities, my next step in my role in FutureVolc is to get some of that information and apply it, we are in the business of taking the scientific information and new-found information and connecting the Civil Protection and the public because it is public money of course for the sake of the public, so we are taking the information coming from making a route for the information to flow freely and to have like a lexicon of our volcanoes

Isavia

I24: Here are explanations of every step, the start of the eruption, the first SIGMET which was sent out 120 nautical miles from the area, the radius, the second action is when you get the interim SIGMET, the cover of the ash, the third action is when we get the first information from the VAAC

R: What is the significance of the information in the notifications?

I24: We are using the VAAC data at different times, 3:00, 6:00, 12:00, 18:00, 0:00, we take new observations and make new forecasts, if we get data at 6:00, then we get an observation at 6:00, we take these two and merge it into one and that is how we control the air traffic within our area, then the people in the air traffic control centre, those people who were working there, were preparing the first signal to send out to aircraft, depending on the polygons in the areas, it is only a snapshot after twelve hours, we send it out four times a day with three intervals, zero to six, six to twelve, twelve to eighteen hours

R: And is that the same policy across Europe

I24: It should be according to the contingency but I won't say so, I think it's different to how the states do it but we stick to the plan because it's equal, here is an explanation of what's happening in the first action, in the ICAO contingency plan they have a preactive phase, proactive phase and a reactive phase in the present one but they have changed the name and in the future they will be pre-eruption phase, eruption phase and ongoing eruption phase, here is the first warning SIGMET, the first SIGMET that is supposed to go out from the Met Office, I say to the air traffic controllers look for the wind, then you know where it is going, then we come to the second, then we get the interim SIGMET, we went through all these steps, the whole thing, it took a lot of time to think through, we only have them in two categories because as you know we have to lose control of closing airspace later this year so we are going to look at this again in May and again in September and probably in December if there is not change but if there is change we don't have to do it

1.2: Interview questions (preliminary guide)

<u>Interview schedule</u>

Ask interviewee if now is a suitable time to conduct the interview, or would it be better for me to I return at a later date? *(If the interview cannot take place at the time, then arrange a more suitable time later during the fieldwork).*

<u>Section A - Introduction</u>

- Thank interviewee for agreeing to meet and for their contribution to the research.
- Give interviewee an estimated length for the interview (1 hour).
- Ask for the interviewee's permission - use of a voice recorder
- Introduce interviewee to "information for participants" sheet and advise future reference to it.

<u>Section B</u>

1) What is your specialist area/s of expertise?
- What is your role within the Met Office *(or organisation/academic institute)*?

2) To what extent has the Met Office influenced existing approaches to hazard management in Iceland?
- In your opinion, what is the role of the Met Office in the hazard management process?

3) How do you, as an individual interpret what is meant by a "hazard management network"?

- How does this interpretation of "hazard management" differ from what you understand by the term "mitigation"?

4) Are you familiar with the VOLCICE and VOLCEX exercises carried out jointly by the Met Office, ISAVIA and the Imo?
- Would you agree that communication between those directly involved is improved significantly as a result of the exercises?
- What is your role within the exercise?

5) What technological tools or other approaches do you use, directly and indirectly, on a regular basis?
- Do you think monitoring technology has shaped, or reshaped, interaction between the Met Office and the Icelandic organisations? If so, how has this happened?

6) In the context of hazard management, how do you define and understand technology, whether material or virtual?
- Has your use of technology, however limited or intrinsic, altered your approach or interpretation altered what is meant by a hazard or risk?

7) To what extent do you think the Met Office utilises social media opportunities to enhance communication with stakeholders in times of volcanic activity?
- How do you envisage social media further altering the means by which hazards are monitored and managed?

<u>Section C</u>

1) Academic and policy documents have indicated that links and partnerships between Icelandic and UK-based organisations are extensive and have rapidly expanded. Could you clarify in greater depth, what these links are?
- What is you, or your organisation's role in maintaining these links or partnerships?
- Did the aviation crises in 2010 and 2011 alter the formation of partnerships and their operations?
- What impact has this had upon policymaking?
- Are your links to Iceland mirrored by your links to other countries, particularly within Europe?
- To what extent do you think communication between Icelandic and UK organisation's has been facilitated by, or accelerated by, the use of technology?
- How do you think communication shall further develop?

2) To what extent can the use of technology within hazard management now play a particular role in terms of sourcing, using and distributing data?
- What specific technological devices, instruments or representations are of particular relevance to this process? How are these used or known by your organisation?
- As you are users or end-users of monitoring technology, do you have any influence on how the technology that you use is constructed and operated?

- Does the use of technology enhance the flexibility of your organisation in responding to hazardous activity?
- Do you think technology has altered power dynamics, not just within hazard management organisations such as your own, but also between them?

3) Do you define the relationship between the UK and Iceland as a mitigation partnership?
- To what extent are you aware of the FutureVolc project?
- What impact do you think projects such as FutureVolc have on technology and partnerships going forward?

4) From previous reading, I have noted how projects such as FutureVolc have enhanced the relationship between the Icelandic Met Office, ISAVIA and the Met Office in the UK
- To what extent do you think a similar interactive partnership has been, or can be generated between the Met Office in the UK and the CAA, as it has between the IMO and ISAVIA?
- Do you share communications with any other aviation authorities to the same extent?
- To what extent did the high profile volcanic eruptions in 2010 and 2011 alter or advance collaboration between the UK and Iceland?
- What relationship do you think the Met Office has with ICAO? How will the current set-up be renegotiated by the upcoming alterations that shall see the airlines gain the power to determine whether or not to fly in times of volcanic activity? How could this alter the power, influence and responsibility of the Met Office?

5) To what extent do you share knowledge and resources with academic institutes, both within the UK and in Iceland? Where do you source the equipment from to monitor volcanic activity?
- To what extent do you think that technology can now be viewed as an essential component of a hazard management system?
- Do you think technology has simplified the management of volcanic hazards, or has it increased its complexity? If yes, in what way?
- To what extent is crowdsourcing and citizen science now an essential aspect of hazard management in Iceland? How has the use of technology complemented or progressed these emerging forms of hazard communication?

<u>Section D</u>

1) Following the high-profile aviation crises of 2010 and 2011, do you think Iceland's links with Europe and North America are essential in the adequate management of volcanic hazards?
- To what extent has this been propagated by the media coverage of past crises?
- How do you envisage Iceland-UK affiliations developing with further investment, use and recognition of technology?
- Do you think the system could be improved in any way?

2) Are you aware of any individuals or organisations, within either Iceland or the UK, who may be interested in my research or who I could contact and arrange an interview with?

- If a further interview needs to be arranged then would you be willing to meet me again?

- Thank you for your time today, your input to my research is of value and I appreciate being given the opportunity to interview you.
- Are there any questions that you would like to ask me, either about my research or about the issues we have discussed today?

Appendix Two: Fieldwork supplements

2.1: Informed consent form (used for Iceland and UK-based fieldwork)

Informed Consent Agreement

Before the interview/observation can begin, please read and consider the following information and then sign to give your consent to being interviewed/observed as part of the research project:

- I fully understand and accept the request to participate in the research project conducted by Daniel Beech from Aberystwyth University. I understand that the project is designed to highlight and analyse the role that technology plays in communicating and disseminating knowledge of volcanic hazards.
- My institution has given Daniel permission to carry out his research with us and any questions I have asked have been answered to a satisfactory standard.

- I understand that my participation within the project is completely voluntary. If I commit to being interviewed then I am free to leave or terminate the interview at any time I wish.
- I understand the potential topics that may arise within the interview/observation and I do not object to being asked about them.
- I am aware that notes may be taken during the interview/observation and that any tape recordings shall be kept private at all times and my name will not be shared with any external parties or in any reports or publications. The original tape and feedback forms will be destroyed within twelve months and stored securely. I understand that any recordings are only be used for transcription by the interviewer/observer. My confidentiality and rights to anonymity within the research will be exercised at all times.
- I give Daniel my permission to use the name of my institution in his thesis and research outputs. I can withdraw this permission at any time I wish.
- I understand that the research has been approved by the Daniel's institution and that if any problems do arise then the institution (Aberystwyth University) can be contacted.

I retain a copy of this consent form and contact Daniel (dib8@aber.ac.uk) if I have any further questions.

Name:

____

Signature:

____

Date:

____

2.2: Information document (used for Iceland and UK-based fieldwork)

PRIFYSGOL ABERYSTWYTH UNIVERSITY

Thank you for your willingness to participate in this research, I am a PhD candidate within the Department of Geography and Earth Sciences at Aberystwyth University in the UK. My PhD is titled **"Managing Volcanic Hazards: An Actor-Network of Technology and Communication"**, and my academic supervisors are **Professor Michael Woods** and **Dr Carina Fearnley** of **Aberystwyth University**. Your contribution to this research would be of great interest and would enable me to further explore how volcanic hazards in Iceland are managed. I have a geographical background and a keen interest in volcanic landscapes and hazards. A CV can be viewed on request. This research has been awarded the 'Geographical Club Award' from the Royal Geography Society, enabling it to be conducted with the use of the grant provided.

About the Research

The aim of this research is to explore how hazard management networks, particularly those overseeing volcanic activity within Iceland, are furthered in their capability to mitigate risk by information technology (Geographical Information Systems, sensory networks, digitised channels of communication, participatory technologies, etc.). The research focuses on the interrelationships that exist between scientific, sociological and technological communities, exploring how the mitigation and preparedness of volcanic hazards can be incorporated into collective, hybrid networks.

My subsidiary research questions are outlined to provide further information about what my research is seeking to explore:

> **1) How have negotiations of power dynamics and technical actors impacted upon trust, collaborative practices, and flows of information in Iceland's volcanic hazard network?**
>
> **2) What impact has stakeholders becoming sensitised to technology had upon the scale at which volcanic hazard networks have the capacity to adapt?**
>
> **3) To what extent can Actor-Network Theory and co-production be used to interpret interactions between individual stakeholders and institutional entities?**

Methodology

This research intends to highlight how technology and communications are a part of monitoring and policymaking practices, and how the collection, communication and dissemination of knowledge relating to volcanic hazards is being enhanced. My intention to interview/observe you is subject to your consent and your name and details will remain anonymous. I would like to use a Dictaphone to record conversations but this is subject to your informed consent and acceptance of confidentiality assurances; the use of a Dictaphone is not essential to this research.

Potential impact

By conducting this research, I hope to further geographical knowledge relating to the structure, coherence and organisation of hazard management networks. This will hopefully contribute to the expansion and broadening of the field of volcanology, further enhancing its interdisciplinary and sociological credentials. The links between Iceland and the UK, particularly following the aviation crises in 2010, are of great interest to me and I hope my research can draw attention to the communication channels between contrasting stakeholder communities. Through my research, I intend to further mobilise hazard management, allowing it to be viewed to a greater extent, as a participatory and democratic process that transcends science, technology and society.

Thank you

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Appendix Three: Participant observation and archival research examples

3.1: Participant observation: Field diary example

Volcanic ash observation (VolcIce): 11/03/2014 - the IMO, ISAVIA and the London VAAC

8AM: IMO send notice to London VAAC. Activity imminent on Reykjanes Peninsula.

8.30AM: IMO send confirmed activity notice to London VAAC and ISAVIA.

SIGMET's issued to the London VAAC from the IMO. Irregularities are present, so a correction message is sent to explain the error.

8.45AM: Radar scanning begins, monitoring of activity is expanded by the IMO.

9.05AM: Volcanic ash chart sent from the London VAAC to the IMO, ash cloud projections are developed by the IMO in due course.

SIGMET 5 issued: IMO amend ash cloud forecast and receive updates from the London VAAC, the ash distribution model is shared.

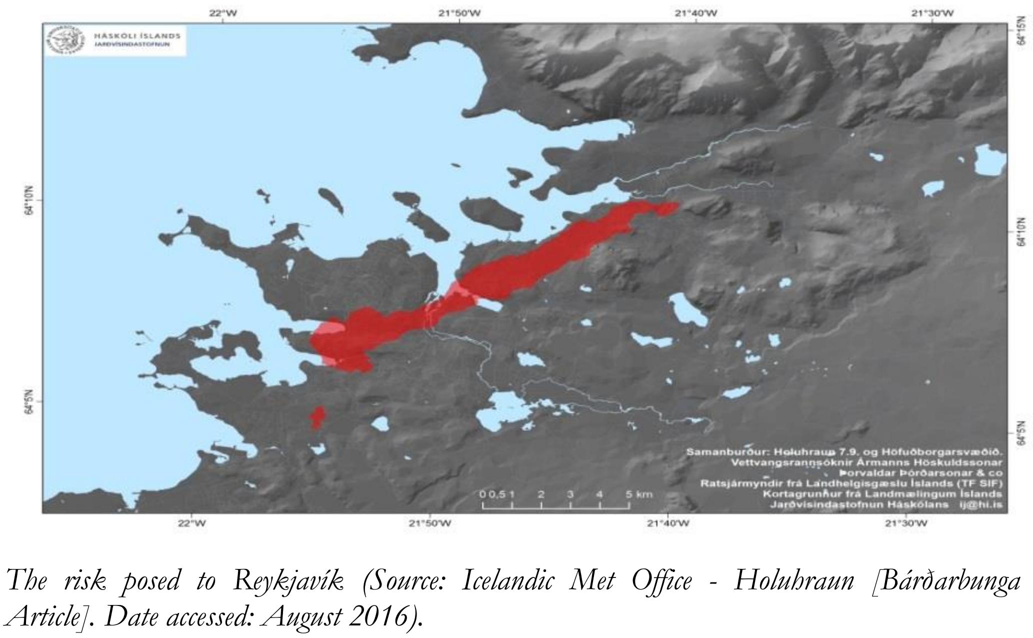
10.15: IMO warn the London VAAC and ISAVIA of misrepresentation in polygons on information reports. The London VAAC and ISAVIA amend reports individually.

The London VAAC reruns the exercise whilst the IMO awaits communication. The Volcanic Ash report is compiled by the IMO and sent to the London VAAC. London VAAC compile the data and report back to both ISAVIA and the IMO, necessary actions are then taken.

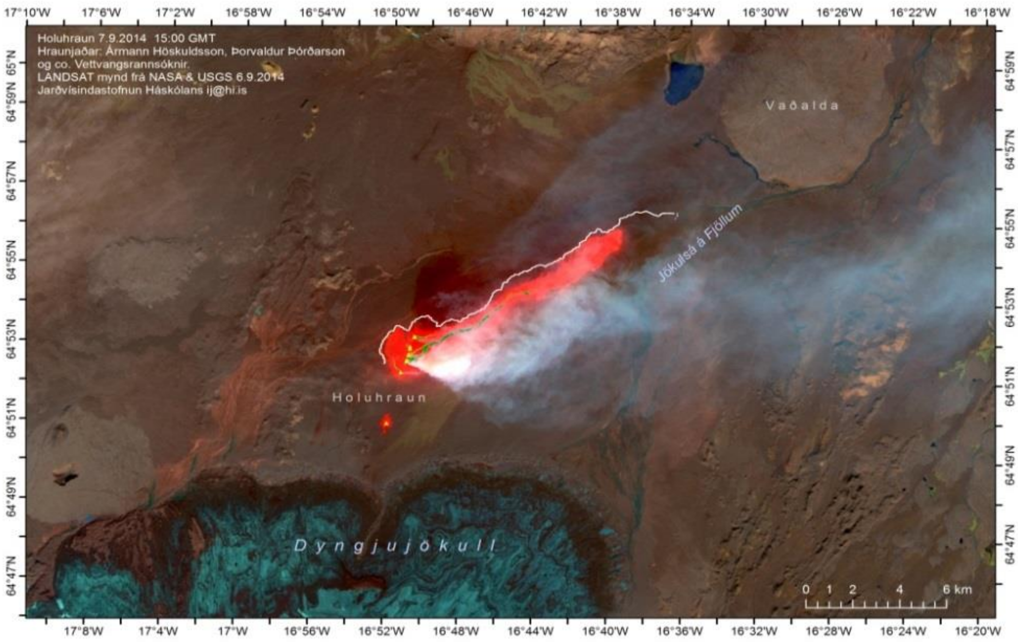
14.00: Institutional debriefs: Debriefs are held within the IMO, ISAVIA and London VAAC. The institute's contribution to the report, is discussed, and feedback is shared.

15.00: Exercise debrief: A debrief takes place between representatives of IMO, ISAVIA and London VAAC, to discuss the success or failure of the exercise.

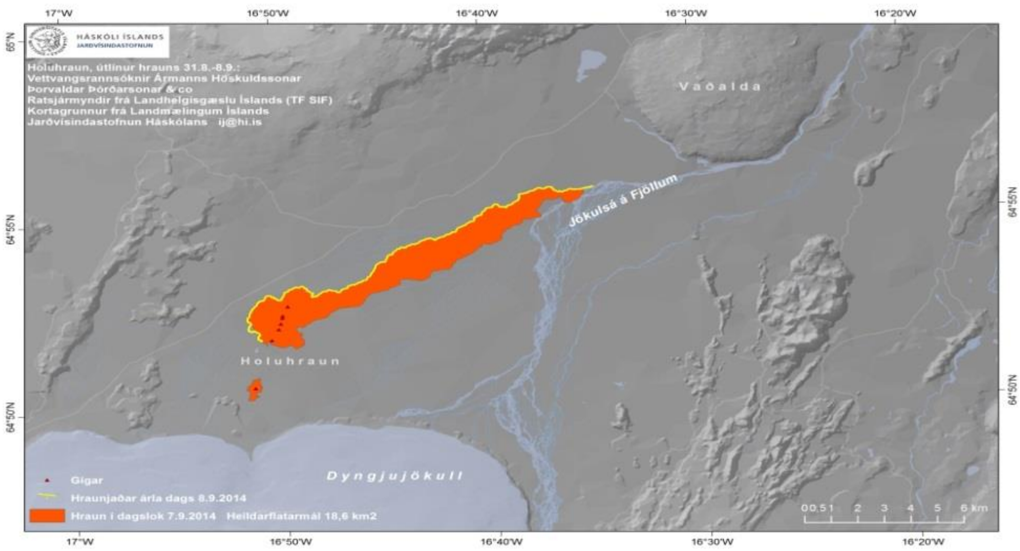
3.2: Archival research: Internet-based resources



The risk posed to Reykjavík (Source: Icelandic Met Office - Holuhraun [Bárðarbunga Article]. Date accessed: August 2016).



Images of the 2014-2015 volcanic eruption at Bárðarbunga, an example of the materials that were distributed on the social media platforms of the IMO, the UoI, and the CP (Source: Icelandic Met Office - Holuhraun [Bárðarbunga Article]. Date accessed: August 2016).



The movement of lava on 7th September 2014 (Source: Icelandic Met Office - Holuhraun [Bárðarbunga Article]. Date accessed: August 2016).

An online video of the AVOID technology test flight; the video is available to view (Source: EasyJet - Corporate page: AVOID section. Date accessed: August 2016).

Appendix Four: Scientific Advisory Group for Emergencies - Minutes

4.1: 5th May 2010: Examples of selected discussion extracts and actions

AGENDA ITEM 1: WELCOME AND REVIEW OF MINUTES

Professor Beddington welcomed the group and thanked them for attending at short notice. Miles Elsden (GO-Science) reviewed the actions.

Action 1 - Confidentiality Agreement and Terms of Reference - This was complete. The secretariat will send copies of the confidentiality agreement back to SAGE members.

ACTION 2: BRITISH GEOLOGICAL SURVEY, with the SAGE SECRETARIAT to finalise letter to Icelandic Authorities requesting certain information. This had been completed, a letter has been sent, and a copy has also been sent to SAGE members.

ACTION 3: DR MATT WATSON to talk to contacts at the Science and Technology Facilities Council about modelling the agglomeration of volcanic ash particles, and to communicate results to SAGE. Dr Watson told the group that work was progressing well in this area, and that colleagues from Oxford University were making measurements on the amount of Black Carbon in the plume. He said that he was looking at a range of funding sources.

ACTION 4: MET OFFICE to form a sub-group to investigate better definitions of particle size distribution and mass at source, and over UK. This had been completed and progress was discussed as part of agenda item 2.

ACTION 5: BRITISH GEOLOGICAL SURVEY and MET OFFICE to work with CIVIL CONTINGENCIES SECRETATIAT and the GOVERNMENT OFFICE FOR SCIENCE to investigate lower probability, higher impact Icelandic volcano risks, as part of the National Risk Assessment process. This has been completed, and progress was discussed as part of agenda item 2.

Action 6: DR WILLY ASPINALL to form a sub-group to investigate the likelihood of a Katla eruption as a result of the current volcanic activity, and likely magnitude of this. A paper would be presented at the next meeting of SAGE. This had been completed and was discussed as part of agenda item 3.

ACTION 7: MET OFFICE, CIVIL CONTINGENCIES SECRETARIAT, GOVERNMENT OFFICE FOR SCIENCE AND THE BRITISH GEOLOGICAL SURVEY, on behalf of SAGE, to develop a range of indicative scenarios considering plausible short- and longer-term impacts. This had been completed and was discussed as part of agenda item 4.

ACTION 8: NATURAL ENVIRONMENT RESEARCH COUNCIL (NERC) and DEPARTMENT FOR TRANSPORT to discuss the timing of the scheduled refurbishment of the NERC research aircraft, and the associated implications on surveillance. This was completed in the discussion during agenda item 5.

ACTION 9: MET OFFICE and the NERC to explore options for developing the UK's monitoring capability for volcanic ash and other airborne particulates, and also ways of widening coverage beyond UK borders. This was completed during the discussions during agenda item 6.

ACTION 10: NATURAL ENVIRONMENT RESEARCH COUNCIL to liaise with Defence Science and Technology Laboratory, through the MINISTRY OF DEFENCE Chief Scientific Adviser's office, to organise the chemical analysis of NERC's airborne particulate samples. This had been completed. This work was being coordinated by the Natural History Museum and Professor Mobbs gave an update as part of agenda item 3.

(Source: The National Archives - SAGE Volcanic Ash Minutes PDF [5th May 2010]. Date accessed: August 2016).

4.2: 19th May 2010: Examples of selected discussion extracts and actions

Item 1 - Welcome and Review of actions

Professor John Beddington welcomed Dr Thor Thordarson, Dr Kristin Vogfjord (Icelandic Meterological Office) and Dr Gudrun Larsen (Institute of Earth Sciences) to the group.

Review of Actions

Actions 1 and 2 were complete. **Actions 3 and 4** were discussed as part of **agenda item 4** and were complete. **Actions 5 and 6** were discussed as part of **agenda item 2** and were complete. **Action 7** was discussed as part of **agenda item 7** and was complete. **Action 8** (the aviation sub-group) had been superseded by other actions (see **agenda item 5**). **Action 9** was on-going and was discussed as part of **agenda item 6**. **Action 11** was on-going.

Item 2 - situation report

British Geological Survey (BGS)

BGS reported that the plume had reduced in height since the weekend (5000m compared to 6000 to 7000m). This along with the decrease in the number of earthquakes indicated a decline in activity. However, the depth of the earthquakes (most originated at 16-18km below the surface) was likely to indicate a continued magma supply. The Institute of Earth Sciences in Iceland continued to collect samples which would allow better definition of the source parameters.

The key points raised in the discussion were:

- The composition and particle size distribution of the ejected material varied daily and there had been significant pulses of sulphur dioxide;
- The particles collected 30km from the source on the 16/17 May were very fine (80% of them were under 90μm) indicating that there could be some interaction between magma and water, and
- There were many other volcanoes in Iceland which presented a risk to the UK.

BGS said that they had procured 6 seismometers from a UK manufacturer. These seismometers would be similar to the backbone formed by the IMO network and would provide real-time information. There were also a number of non-real time measurements undertaken by university groups from around the world. The group agreed that a wider agreement was needed to allow this information to be shared.

ACTION 3.1: BRITISH GEOLOGICAL SURVEY to work with DR GUDRUN LARSEN to produce a short paper which listed which volcanoes in Iceland were a current cause for concern, to clarify the reasons for this and to quantify the risk as far as was currently possible.

Met Office

The Met Office reported that there was currently a southerly (favourable) airflow over the UK. Conditions were expected to change at the weekend with northerly and easterly winds predicted early in the following week. The risk that this would pose to UK airspace was dependent on the size of the plume at that time (SAGE [Scientific Advisory Group for Emergencies] (10) (05) (16).

Professor Adrian Simmons introduced a paper (SAGE (10) (05) (11) which analysed six-hourly data on airflow between Iceland and the UK and the likelihood of shifting weather regimes. He advised against over-interpretation of this analysis but reported that it indicated that climatologically there was a 28% chance of north-westerly (unfavourable) airflows over the UK at any one time. There was estimated to be only a chance of under 2% of being in unfavourable conditions that would last a further 5 days or more. In contrast, there was estimated to be about a 30% chance of being in favourable conditions that would remain so for 5 or more days.

Volcanic Hazards Sub-group update

Dr Willy Aspinall reported that initial analysis showed a weak positive correlation between the preceding gap and the Volcanic Explosively Index (VEI) of eruptions at Katla. Collegues at the Institute of Earth Sciences reported they had noted a similar correlation between the VEI and the length of time following eruptions at Katla. Work was now needed to determine whether failed eruptions should be included in this analysis.

ACTION 3.2: VOLCANIC HAZARDS ASSESSMENT SUB-GROUP to look at data from Iceland to assess correlation between magnitude of eruption and the following repose time.

ACTION 3.3: VOLCANIC HAZARDS ASSESSMENT SUB-GROUP to consider building "failed eruptions" that didn't reach the surface into model looking at possibility of Katla erupting.

<u>CAA</u>

The CAA noted that they had held an industry briefing day on the 13th May and that this had been supported with presentations from SAGE members.

(Source: The National Archives - SAGE Volcanic Ash Minutes PDF [19th May 2010]. Date accessed: August 2016).

Appendix Five: VolcIce exercise materials

5.1: VolcIce report for the observed exercise (March 2014)

EXERCISE VOLCICE 2014/02 CAT-II.

EXERCISE DIRECTIVE.

<u>DATE & DISTAFF</u>

Exercise date: 11 March 2014.

Exercise leader: Egill Thordarson

DISTAFF members:

Anton Muscat, VAAC London.

Sara Barsotty, IMO.

Arni Gudbrandsson, Isavia.

PARTICIPATING ORGANIZATIONS

IMO,
Isavia,
VAAC London.

AIMS AND OBJECTIVES

Exercise the conduct of NAT Doc 006, Part II. December 2010.

EXERCISE DURATION

08:00 to approx. 13:00utc.

EXERCISE VOLCANO

Reykjanes, 1701-02, 63 52.3N 022 30.0W, Iceland SW.

SCENARIO OF VOLCANIC ACTIVITY

08:00 Eruption imminent or already in progress. Estimated plume height 1-5 km.

08:30 Volcano continues to erupt, seismic tremor increasing, plume height observed 5 km.

EXERCISE SCENARIO MESSAGES

To be promulgated by Isavia Monday 10 March 2014.

(Axxxx/13 NOTAMN

Q) BIRD/QWWXX/IV/NBO/W/000/999/6425N01719W

A) BIRD

B) 1403110800 C) 1403111300

D)

E) EXERCISE VOLCICE CAT-II

VOLCANIC ASH DISPERSION EXERCISE TAKES PLACE

11 MARCH FROM 08:00 TO APPROX. 13:00UTC.

PROJECT NAME: EXERCISE VOLCICE

EXERCISE VOLCANO: REYKJANES, 1701-02, 63 52.3N 022 30.0W, ICELAND SW

FREE TEXT OF PROMULGATED EXERCISE MESSAGES STARTS WITH: EXERCISE VOLCICE.

AND ENDS WITH:

EXERCISE EXERCISE EXERCISE

F) SFC G) UNL

08:00 Telcon message from IMO

EXERCISE VOLCICE.

INCREASING SEISMIC ACTIVITY IN REYKJANES PENINSULA HAS BEEN RECORDED THE LAST WEEK. CHANGES IN GEOTHERMAL ACTIVITY ALSO REPORTED. ERUPTION IN REYKJANES IS IMMINENT OR ALREADY IN PROGRESS. ASH PLUME COULD REACH 1-5 KM.

08:30 Telcon message from IMO.

ASH PLUME UP TO 5 KM OBSERVED OVER SUTHERN COAST OF REYKJANES FROM GROUND BASED RADAR IN KEFLAVIK. SEISMIC TREMOR CONTINUES TO INCREASE AND REYKJANES VOLCANO CONTINUES TO ERUPT.

COMMUNICATIONS

Exercise telcons to start with EXERCISE VOLCICE.

Exercise messages to start with EXERCISE VOLCICE and

End with EXERCISE EXERCISE EXERCISE.

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SPECIAL INSTRUCTIONS.

-- END –

5.2: VolcIce exercise debrief transcript example (field diary)

London VAAC: I think that was the thinking behind the USGS' because they sent the email out in September and I think they kind of assumed it would be implemented by the end of the year but some of the some VAACS, mostly Tokyo pushed back and said they wouldn't be able to do it until after the Tokyo meeting

Isavia: Yes because Tokyo are … they have their internal relationship with their volcanoes and they want this to be compatible

London VAAC: Yes

Isavia: And, and there careful, personally I am concerned because they don't want to issue to their customers, the end users, a numbering system that has not been issued by ICAO, not formally released, and I have been pushing on ICAO Paris and on ICAO Montréal

London VAAC: Yes

Isavia: There is another issue that was discussed, that the VAAC London, that you were suggesting that, you used Mercator projection for data, this causes a lot of ambiguity in the high latitudes

London VAAC: So this is the Mercator projection on the LAT/longs

Isavia: Yes, the LAT/longs yes

London VAAC: But I think that's the ICAO recommendation that we use Mercator projections

Isavia: I will have to write you something on this because in the polar area we cannot use Mercator, because Mercator you stretch out the pole to be as long as the equator

IMO: Yes

London VAAC: Yes I know, we see this on our intervention tool, but anything that goes over the poles creates a load of noise and a load of spikes, because it goes over the same point multiple times

Isavia: Yes, indeed, yes

London VAAC: We have transferred this into a, a lambert projection because the aviation world, the airlines and air traffic controls which help to deal with large areas, they are always using, the, lambert in high latitudes, and polar projection in polar latitudes

Isavia: Yes

IMO: What are they using in Anchorage for example?

Isavia: I don't know what they are using, but I have of course, I have been using a Mercator because we are processing at low speed and in relatively small areas each time so it is no problem, but with a large area, the high latitudes, we need to have the lambert projection

IMO: Maybe this problem in Iceland has not been apparent to the VAACS because there is no civil contingency or, and there not covered

Appendix Six: Bárðarbunga

6.1: Update report log example - 29th August 2014

Bárðarbunga update 29082014
2014-08-29 16:20 UTC
Bárðarbunga update

Compiled by
Icelandic Met Office and University of Iceland Þórður Arason (Ed.)

Based on

Seismic, GPS, Hydrology, Radar, Webcam, PIREP, visual observations

Eruption plume

Height (a.s.l.)
No plume was detected by radar (detection limit above 1 km) and webcam indicated low level gases and steam from lava fountains during the night.

Heading
No plume now, but winds were about 10 m/s from SE during the night.

Colour
No plume now.

Tephra fallout
No tephra fall now.

Lightning
No lightning during eruption according to ATDnet of the UK Met Office and WWLLN-system.

Noise
None.

Meltwater

The eruption was 5 km N of the glacier, therefore without a jökulhlaup. No indication of changes in water flow in rivers. The conductivity still remains at the same high level as in the previous days. The size of the cauldrons recently observed on the glacier has been estimated to be 30-40 million m3, but not clear where the meltwater has gone.

Conditions at eruption site

At 00:02 UTC signs of a lava eruption were detected on web camera images from Mila. The web-camera is located at Vaðalda, north-east of the eruption site. Around midnight, weak signs of increased tremor were apparent on IMO’s seismic stations near to the eruption site. At 00:20 UTC scientists in the field from the Icelandic Met Office, Institute of Earth Sciences and Cambridge University confirmed the location of the eruption. The eruption occurred on an old volcanic fissure on the Holuhraun lava field, about 5 km north of the Dyngjujökull ice margin. The active fissure was about 600 m in length. A small amount of lava drained from the fissure and by around 04:00 UTC, lava flow is thought to have stopped. According to seismic data and web-camera imagery, the eruption peaked between 00:40 and 01:00 UTC. Aerial observations by the Icelandic Coastguard show that only steam is rising from the site of the lava eruption. Location of eruption site is at 64°52'N, 16°50'W.

Seismic tremor
Weak eruption tremor seen after midnight that diminished with the eruption. No signs of tremor now.

Earthquakes
At the beginning of the eruption, seismic activity decreased, although seismicity has since returned to levels observed in recent days. An earthquake (4.8) occurred at 11:15 and another (5.2) at
12:21, both on the N-rim of the Bárðarbunga caldera.

GPS deformation
The most recent GPS measurements from stations at Dyngjuháls and Kverkfjöll indicate continuation of magma flowing into the dike. A new GPS station has been set up north of Vonarskarð. In the following days, three new stations will be installed: one at Urðarháls and two south of Askja, on either side of the dike.

Overall assessment
At this moment it is unclear how the situation will develop. However, three scenarios are considered most likely: * The migration of magma could stop, resulting in a gradual reduction in seismic activity and no further eruptions. * The dike could reach the Earth's surface north of Dyngjujökull causing another eruption, possibly on a new fissure. Such an eruption could include lava flow and (or) explosive activity. * The intrusion reaches the surface and an eruption occurs again where either the fissure is partly or entirely beneath Dyngjujökull. This would most likely produce a flood in Jökulsá á Fjöllum and perhaps explosive, ash-producing activity. At 10:00 UTC, IMO changed the Aviation Colour Code for Bárðarbunga to 'orange', signifying that significant emission of ash into the atmosphere is unlikely. The aviation colour-code for the Askja volcano remains at 'yellow'. Other scenarios cannot be excluded. For example, an eruption inside the Bárdarbunga caldera.

6.2: Daily factsheet - 26th September 2014

NATIONAL COMMISSIONER OF THE ICELANDIC POLICE

DEPARTMENT OF CIVIL PROTECTION AND EMERGENCY MANAGEMENT

THE SCIENTIFIC ADVISORY BOARD OF THE ICELANDIC CIVIL PROTECTION		
Date: 26.09.2014	**Time: 09:30**	**Location: Crisis Coordination Centre, Skogarhlid.**
Regarding: Volcanic activity in the Bardarbunga system.		
Attending: Scientists from Icelandic Met Office and the Institute of Earth Sciences University of Iceland along with representatives from the Icelandic Civil Protection and the Directorate of Health.		

Main points
• **Volcanic eruption in Holuhraun**
• **Air quality**
• **Scenarios**

Notes

- The new lava field continues to grow and has now crossed the track (in Flæður) leading into the Holuhraun area.
- The subsidence of the Bardarbunga caldera continues with same rate as before.
- Seismic activity in Bardarbunga continues on similar rate as the last few days. Five earthquakes bigger then M3,0 were recorded since noon yesterday. The biggest one was M5,0 at 16:35 yesterday afternoon.
- Smaller earthquakes were detected in north part of the dyke and around the eruption site.
- GPS measurements show continuing slow movements.
- No change was detected in water monitoring that cannot be explained with changing weather.

Air quality:

- Yesterday a high concentration of SO_2 was measured around lake Myvatn (2000 microgram pr. cubic meter) and last night in Reydarfjordur (2600 microgram pr. cubic meter). The Environmental Agency of Iceland is waiting for shipment of SO_2 meters that will be put up around Iceland.
- Pollution from the eruption is mostly expected to move towards east and southeast today (Friday) and tomorrow. A map showing the gas forecast can be found on the web page of the Icelandic Met Office www.vedur.is/vedur/spar/textaspar/oskufok/ An interactive map showing the gas distribution can be seen at

NATIONAL COMMISSIONER OF THE ICELANDIC POLICE

DEPARTMENT OF CIVIL PROTECTION AND EMERGENCY MANAGEMENT

- Information and any questions on air pollution can be sent to The Environment Agency through the email gos@ust.is. The Environment Agency is especially looking for information from people who have been in contact with high concentrations of gas; where they were, at what time it happened, how the gas cloud looked (colour and thickness of the cloud) and how they were affected by it.

- Three scenarios are considered most likely:
  - The eruption on Holuhraun declines gradually and subsidence of the Bardarbunga caldera stops.
  - Large-scale subsidence of the caldera occurs, prolonging or strengthening the eruption on Holuhraun. In this situation, it is likely that the eruptive fissure would lengthen southwards under Dyngjujokull, resulting in a jokulhlaup and an ash-producing eruption. It is also possible that eruptive fissures could develop in another location under the glacier.
  - Large-scale subsidence of the caldera occurs, causing an eruption at the edge of the caldera. Such an eruption would melt large quantities of ice, leading to a major jokulhlaup, accompanied by ash fall.

Other scenarios cannot be excluded.

- **From the Icelandic Met Office:** The Aviation Colour Code for Bardarbunga remains at 'orange'.
- Next meeting of The Scientific Advisory Board will be held on Monday, 29. September, unless deemed necessary.

The National Commissioner of the Icelandic Police, Department of Civil Protection and Emergency Management
www.almannavarnir.is www.avd.is Twitter: @almannavarnir