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Reconstructing eruptions from historical accounts: Makaturing *c.* 1765, Philippines

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ABSTRACT

For some volcanoes, the only evidence for past eruption is provided by historical accounts. When interpreted carefully, these have the potential to be a rich source of information, and yet they have so far been under-utilised in reconstructing eruption histories. The navigator Thomas Forrest describes a large eruption at Makaturing volcano, southern Philippines, in approximately 1765 that he considers the catalyst for the local Iranun population transitioning from an agrarian society to long-distance piracy and slave raiding. Within the historical literature, the eruption is attributed to large scale physical impacts around the volcano and disruptions to trading routes and livelihoods that ultimately changed the course of southeast Asia's history. However, no such eruption (or impacts) are recognised in the scientific literature or in eruption databases, and fieldwork to the region remains difficult. Here, we reinterpret the account of Forrest from a multi-disciplinary perspective, with a historian and physical volcanologists working together to incorporate the greatly needed local context into identifying credible volcanic processes and impacts associated with the reported activity. We used a novel approach to eruption reconstruction by cross-referencing deposits and impacts inferred from the historical record with stochastic tephra dispersal modelling that considered multiple eruption sources and characteristics. We found that Forrest's account was best characterised by an eruption of ~VEI 4 between May and October, with plume heights in the range of 12 to 16 km. While at least one eruption of this size was required to reproduce the impacts described in the historical record, it may have formed part of a longer sequence of multiple, repeated eruptions. In this way, such an eruption could have acted as a 'tipping point' for a local population already on the verge of socio-political and economic collapse, disproportionately affecting regions on a much larger scale than the reported deposits suggest. There remains a disconnect between the eruption characteristics recorded in historical accounts and those reproduced by numerical modelling, for which we propose alternative interpretations of the historical record. Unfortunately, given the minimal details available about the eruption, this discordance is unlikely to be resolved, even when geological studies are possible. However, a valuable benefit of the probabilistic modelling approach presented here is that it highlights the likely direction of tephra dispersal and deposition during a future eruption of Makaturing, supporting rapid tephra hazard assessment in the event of future unrest.

1. Introduction

Much of our understanding about past volcanic activity is inferred from two sources: 1) studies of deposits and/or monitoring data; and 2) historical and eyewitness observations of volcanic activity. There are issues with inferring activity from either source: collection of geological or monitoring data is not always possible because of deposit preservation, limited resources and/or restricted or unsafe access, while historical and eyewitness accounts have been found to be unreliable or attributed to the wrong volcano (e.g. Garrison et al., 2018). For some volcanoes, historical accounts may be the only available evidence of past eruptions, and have the ability to provide valuable information about the eruption size, location and associated impacts, when interpreted carefully (Blong, 1982; Cronin and Cashman, 2016; Delfin et al., 1997). They can be used to supplement eruption records and to tackle historical under-recording issues but are typically under-utilised in reconstructing eruption histories (Pyle, 2017).

This study focuses on the historical record of Forrest (1779), which describes a large eruption at Makaturing volcano, southern Philippines, in approximately 1765. As a captain and emissary for the British East India Company, Forrest was tasked with recording the physical features and sociographic context of the area around Makaturing and knew the area and local population – the Iranun – personally and

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intimately, having spent several years learning the language and living in the area. Forrest (1779) hypothesised that the eruption displaced the local Iranun population, resulting in a change from an agricultural-based to a sea-raiding society. This change in livelihood is suggested to have provided the catalyst for slavery and piracy in the neighbouring seas, and tribal conflict across southeast Asia, severely disrupting traditional trade routes. Trade as far afield as China was impacted, ultimately changing the course of southeast Asia's history (Warren, 2018). Except for historical reports of the significant regional consequences of this eruption, made at least ten years after the eruption (Forrest, 1779; Warren, 2018), there is no record of a c.1765 eruption of Makaturing in the scientific or historical literature. Providing a scientific interpretation of historical reports has value in preventing misinterpretations and embellishments on eruption characteristics from gaining traction in the literature and becoming normalised over time (e.g. Delfin et al., 1997; Blong, 2019; Blong and Kurbatov, 2020). For Makaturing, the size and characteristics, or even existence, of a c.1765 eruption remain unknown, despite assertions in the historical literature (Forrest, 1779; Warren, 2018). If any geological evidence of eruption was preserved, studies are currently not possible because of ongoing civil unrest in Mindanao. In such cases, can we make use of the historical accounts even if they cannot be validated through geological studies? And how do we account for the uncertainties inherent in ambiguously written observations that can be interpreted in multiple ways?

Here, we evaluate the available information on the eruption from a multi-disciplinary perspective, with a historian and physical volcanologists working together to source as much spatial information from the historical record as possible. The main aim of our study was twofold: 1) To reinterpret the historical record from a multi-disciplinary perspective; and 2) To constrain the likely characteristics of the eruption, e.g. its size, style and approximate date, which we achieved through the development of a novel modelling technique that filtered our simulations based upon their fit to the proposed impact.

2. Makaturing volcano, Philippines

Makaturing volcano lies in the Bangsamoro Autonomous Region of Muslim Mindanao, in the southern Philippines (Fig. 1). The main summit of Makaturing rises 1908 m above sea level but the area between the summit and the coast of Illano Bay, ~ 25 km to the southwest, is home to a large number of parasitic flank cones (Fig. 1) (PHIVOLCS-LAVA, 2020). Makaturing is situated at the southwestern end of a chain of young volcanoes in central Mindanao (Fig. 1). Very little is known about the primary eruptive composition and hazards of Makaturing volcano, except for the basaltic nature of volcanic bombs and tephra associated with the volcano, which can be found along the coast of Illano Bay from Pollock Harbour to Tubug (Saderra-Masó, 1904; Neumann van Padang, 1953). Other volcanoes in the region include Latukan and Ragang volcano. Latukan has no record of previous eruptions, while Ragang has produced relatively frequent explosive eruptions from the 1800s to the early 1900s (Neumann van Padang, 1953), and is infamously known as "the mountain where smoke or fire rises" within the indigenous Moro community (Saderra-Masó, 1916).

The area around the flanks of Makaturing is dominated by agricultural land, with a number of villages. The closest city, Cotabato, lies approximately 45 km to the south and has a population of ~300,000 according to the 2015 census. Approximately 67% of the region's economy is sourced from agriculture (BTC, 2016). Political tensions and conflict between Muslim separatists in Mindanao and the predominantly

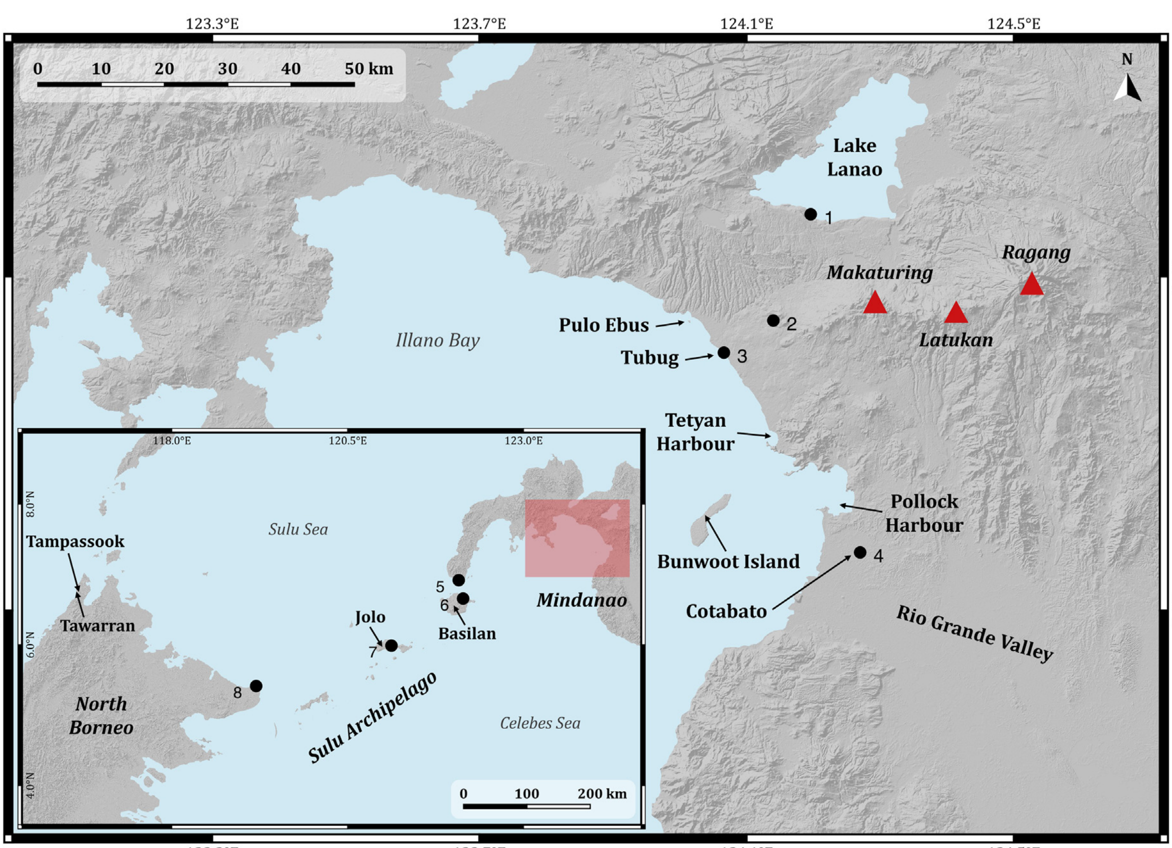


Fig. 1. Location map of the area surrounding Makaturing and its neighbouring volcanoes, with inset showing the area covered by the larger map (red box) and the Sulu Archipelago to the southwest and the north coast of Borneo. Places referred to in the Forrest (1779) text are marked on the figure. Modelled impact points are labelled from 1 through 8: 1. South Lake Lanao, 2. Small cone proposed by Forrest (1779), 3. Coast, 4. Sultanate of Mindanao (modern day Cotabato), 5. Zamboanga, 6. Basilan, 7. Jolo and 8. North Kalimantan. Hillshade digital elevation model is 1 arc-second SRTM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Catholic population of the rest of the Philippines has a long history, and economic growth in Mindanao has been stunted since the early 1970s as a result (Ringuet, 2002). Estimates for the number of people killed or displaced in the conflicts range up to 150,000 and 2 million people, respectively (Project Ploughshares, 2017). At the time of writing, all travel to the region is advised against due to the threat of terrorist attacks and kidnapping.

2.1. Cultural-ecological setting

The Iranun (Illanun, Illanoons, Lanuns) originally inhabited coastal stretches around Pollock (Polok, Polluc) harbour and the eastern shore of Illano (Illana) Bay (Fig. 1). This coast and Bay, whose shorefront comprised impenetrable mangrove and low-lying swamps, was readily linked to Lake Lanao, which the Iranun considered their stronghold and home. By the early 1600s, thousands had migrated inland to Lake Lanao and the Tiruray highlands to its west. William Dampier, who lived among the Maguindanao, Maranao and Iranun communities during 1686 and 1687 described the Iranun and Maranao communities as prosperous and stable, with a developed commercial life and good ship-building skills. Small bands of men intermittently captured slaves from the interior of Mindanao to work on their lands, but there was reportedly little to no raiding by sea (Dampier, 1697; Warren, 2018).

The Iranun population is thought to have then steadily risen due to the introduction of intensive agriculture made possible by the fertile volcanic soils (Warren, 2018). By the early 1700s, Laarhoven (1989) estimates that the population had grown to around 90,000 to 100,000. At this time, the Iranun were generally regarded with some fear by Maguindanao royalty (Laarhoven, 1989). They were thus portrayed to the Dutch and English in the 1600s and 1700s, in the context of the politics of ethnic inter-relations and state rivalries, as a deceitful, savage people with military prowess, a warlike nature and a willingness to engage in slave-raiding for the Sultanate of Cotabato (Warren, 2018). In the mid-1770s, the first British East India Company traders arrived in the unchartered coastal waters of south-western Mindanao and the Sulu Archipelago, in search of trade goods to take back to China (Warren, 2001). During that time, and over several years, a captain and explorer with the British East India Company, Thomas Forrest, travelled to the Mindanao-Sulu region, learning the language of the Maguindanao and Iranun people and studying their history, customs, nautical skills, and boat building. This was a time of significant social, political and economic flux in the region because of the advent of trading with China (Warren, 2018), which coincided with the sudden emergence and devastating impact of the ‘Lanun slave raiders’ on the region. At this time, rival colonial powers began to collect and study data on piracy and slave raiding, speculating on possible reasons for the rise of the Iranun as regional slave raiders. In 1779, Forrest wrote an account about the Iranun's way of life, approximately 90 years after Dampier (Forrest, 1779), describing some of Jolo's (Sulu) inhabitants as having acquired the necessary expertise for long-distance maritime slave raiding in Southeast Asia. Forrest (1779) was the first to draw a possible link between the rise of the Iranun as saltwater slavers and a c.1765 eruption of Makaturing. In 1792, the increase in slave raiding by people from the Makaturing region was noted in Samar Island in the central Philippines by French naval officer, de Pagès (1792). By the end of the 18th century, the skills of the Iranun in piracy and sailing were well-known across the Sulu Archipelago, Malay peninsula, Bay of Bengal, Philippines, Papua New Guinea and Indonesia. Throughout this region, the Iranun were considered the fiercest and most powerful pirates, frequently boarding ships disguised as traders before stealing valuables. In some cases, crew members on the boarded ship were violently attacked or beheaded, with a particular lack of mercy shown for non-native crew such as the European colonial powers that were reporting on their piracy and slave raiding. The Iranun forcibly took thousands of slaves each year from the coastal villages that they attacked, with most Filipino captives being sold at slave markets in Cotabato or Sulu. An Iranun squadron could contain up to 200 vessels, but more typically comprised 40 large vessels (see Rutter, 1930; Warren, 2007 and McKenna, 1994 for more details on the Iranun).

Spanish colonisers (including the Jesuits) regained a foothold in the area around Makaturing in southwestern Mindanao in the 1800s, after the reported eruption. They labelled maritime raiders at the time, a ‘distinct race’ who inhabited the stretch of coast within the Bay of Illano and were the ‘Illanoon of the Lake’, distinguishing them from other ethnic groups in the area (Admiralty Record Office, 1838). According to the Jesuit seismologists, Makaturing remained, even in the latter part of the 1800s, ‘famous but almost unknown’ and the only mention of the volcano is in the book of Saderra-Masó (1904).

3. Methods

3.1. The search for information

We undertook a comprehensive search for sources of information that may provide detail about eruption products and/or eyewitness accounts associated with a c.1765 eruption of Makaturing.

For historical accounts, we conducted a thorough search of available historical literature that mentions Makaturing, or that provided accounts of important events in Mindanao during the 1700s and 1800s, a broad time period around the reported eruption in c.1765. Additional potential sources that we considered were the oral histories of local Iranun people, and the visiting B'laan people, who lived in the upland areas (beyond Lake Lanao) but travelled to the coastal villages and city of Cotabato to trade.

Geological data for Makaturing and any past eruptions were sourced from PHIVOLCS – the Philippine Institute of Volcanology and Seismology – who are mandated to monitor volcanoes in the Philippines and mitigate their associated hazards and risks. We are indebted to their efforts in tracking down geological maps, papers and reports for Makaturing from their archive in Quezon City, Manila. We also searched the published literature for reference to Makaturing volcano and its eruptions.

We used the Smithsonian Institution's Global Volcanism Program (GVP) and the PHIVOLCS catalog of active volcanoes to trace eruptions recorded in Mindanao around the time of c.1765. By considering other volcanoes and eruption years we hoped to capture any historical or catalog reports that had been mistakenly attributed to a neighbouring volcano or different year.

3.2. Impact mapping

In order to relate historical records with quantitative or qualitative information that describes the eruption characteristics and related dispersal of eruptive phenomena and impacts, there were two main steps:

1) Geolocate the identified areas.

There were challenges associated with directly transcribing the locations from the historical record because of changes in the way that place names have been used over time and in distinguishing between large areas and one location. For example, Iranun people are reported to have been relocated as far as Sooloo (Forrest, 1779), suggesting impacts were limited there. However, Sooloo (Sulu) refers to a set of islands between ~250 and 500 km to the southwest of Makaturing. In addition, the sultanate of Sulu was active during the 1700s and, at its peak, stretched as far afield as the Palawan islands and eastern Kalimantan. In the absence of more specific information, we relied on the judgement and interpretation of our historical expert (JFW).

2) Infer values, where possible, for each location.

One of the key requirements for reconstructing the c.1765 eruption and its eruption products is as comprehensive an understanding of the amount and the spatial distribution of erupted products as possible, given the limited information available. Historical accounts are often quantitatively ambiguous, and so a certain level of volcanological inference was required, based on observations of analogous impacts at other eruptions worldwide.

3.3. Reconstructing the eruption

3.3.1. Identifying the source of the eruption

We cross-referenced the location reported in the historical record with Google Earth imagery, SRTM topographic data and considered the physical volcanology of the area in order to evaluate a number of potential eruption sources within and beyond the Makaturing volcanic complex.

3.3.2. Eruption scenario development and modelling

A range of eruption scenarios of differing explosivity were developed based upon the likely composition of a c.1765 eruption from Makaturing. Given the absence of information for past eruptions at Makaturing, a deliberately broad but credible set of distributions and ranges was used to characterise eruption source parameters, such as plume height and erupted mass. Source parameters and wind conditions were sampled stochastically from within the defined distributions and ranges in order to establish 50,000 different potential eruptions for each simulated source vent. Each simulation of an eruption was therefore characterised by one set of unique eruption source parameters and one wind profile, with each simulation considered equally likely.

We focussed on tephra as a mechanism for causing the reported impacts. Tephra, which includes volcanic ash, is fragmented material generated by explosive activity, propelled upwards in an eruption column before being carried by atmospheric currents and deposited at some distance from source. How tephra is transported and then deposited to form tephra falls depends upon particle characteristics (e.g. sizes and densities), the wind conditions acting on particles as they fall through the atmospheric column, as well as other physical parameters related to particle-atmosphere interactions. A numerical model is required to capture these processes. For our purpose, we used the two-dimensional advection-diffusion model Tephra2 (Bonadonna et al., 2005; Connor et al., 2008), which is an analytical model designed for fast computation of tephra accumulations. Tephra2 has successfully reproduced tephra falls across a spectrum of eruption magnitudes and compositions, from small-volume basaltic eruptions through to Plinian rhyolitic eruptions. Aided by TephraProb (Biass et al., 2016), the model allows for the simulations of many thousands of potential eruptions within a probabilistic framework. Sampling of the source conditions for each simulation was constrained so that the mass eruption rate (MER; a function of plume height, wind speed and eruption duration: see Biass et al., 2016) produced a total erupted mass lying within the assumed mass ranges. This means non-viable combinations such as very large mass but small plume height were not simulated. Input parameters common across all simulated eruptions, along with their rationale for use, are shown in Appendix 1a. For computational reasons, we simulated tephra accumulations only on the selected points shown on Fig. 1. Running the model on selected points makes it possible to run thousands of simulations very quickly and, in turn, ensures a statistically significant sampling of the space of initial conditions. It however limits the ability of visualising the spatial distribution of probabilities of tephra accumulation on a map. To illustrate the likely tephra dispersal, we also modelled individual probabilistic eruption scenarios that can be used to suggest the past or potential future tephra fall hazard given an eruption of Makaturing by running 2000 instances of the model for each scenario on a 5 km grid spanning the volcano and the Sulu islands.

Each location identified in the impact mapping provided a cross-referencing point for our model results. We used these values to filter our simulation outputs and identify the eruption scenarios that best fit the reported tephra dispersal and deposition. For example, scenarios and simulations that produced zero tephra fall where tephra fall was reported could be removed from our suite of likely eruption source parameters and wind conditions. By filtering in this way, we identified the characteristics of the c.1765 eruption that were more, or less, likely.

Current wind conditions at Makaturing provide a preliminary indication of likely tephra dispersal direction, given information on the plume height (Fig. 2). Between ~7 and 16 km above sea level, winds predominantly blow towards the west, but above ~16 km, there is a seasonal split with winds mostly blowing towards the east between November and March, and the west the rest of the year (Fig. 2). Stochastic sampling of wind conditions is therefore required to appropriately represent this variability when simulating tephra dispersal.

4. Results and discussion

4.1. The search for information

All of the identified historical sources that mention Makaturing or an eruption in Mindanao in the 1700s or 1800s are shown in Table 1. There

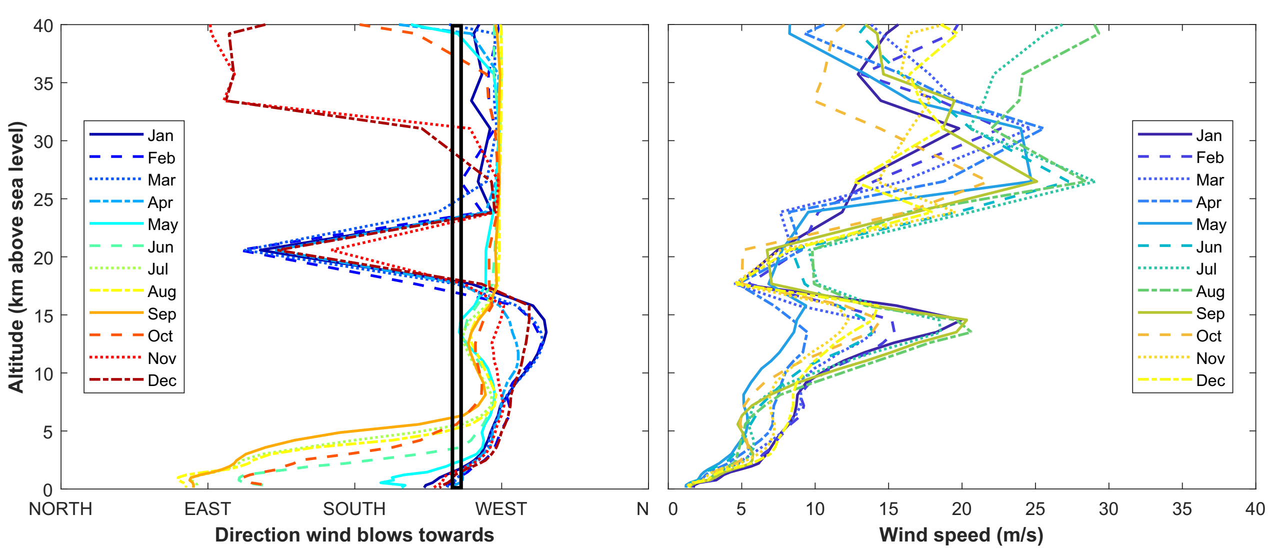


Fig. 2. Median wind directions (blowing towards; left) and speeds (right) for each month at Makaturing with height above sea level. The black solid box in the left plot marks the bearing from the proposed Makaturing vent to Sulu islands, where ash was reported. Wind data source ten years of European Centre for Medium-range Weather Forecasts (ECMWF) ERA-Interim reanalysis data at six-hourly intervals (2000–2018).

Table 1
All sources of historical information, in chronological order, that mention Makaturing eruptions or an eruption in the region of Makaturing around 1765 CE.

Reference	Relevant information
Forrest (1779)	See text.
de Bylandt-Palstercamp (1835)	Notes that a volcano in Mindanao had a violent eruption in 1764 (citing Forrest, 1779), although there is no mention of the source volcano.
Perrey (1860)	Cited de Bylandt-Palstercamp (1835) (who in turn cited Forrest, 1779) for an eruption of a volcano in the bay of Illano in 1765; Also reports an eruption of a volcano in Mindanao and questions if it was the same as the eruption in 1765 at the bay of Illano; Notes that an eruption at Makaturing was observed in 1858, about 8 leagues (~38 km) distant from Pollock.
Becker (1901)	Cited Perrey (1860) for an eruption of Makaturing in 1765; Notes eruptions at Makaturing in 1856, 1865 and 1871.
Saderra-Masó (1904)	Notes reports of three eruptions at 'Macaturin' in 1840, 1856 and 1871.
Saderra Masó (1925)	Raised doubt on the authenticity of historical eruptions (1840, 1858, 1871, 1873) ascribed to Makaturing, believes that the eruptions occurred at Ragang based on the more vegetated state of Makaturing.
Macdonald and Alcaraz (1954)	Only states that the last recorded eruption of Makaturing volcano was in 1871.
Andal and Yambao (1955)	Contradicts Saderra Masó (1925), arguing that historical 19th century eruptions occurred at Makaturing due to the thicker vegetation cover at Ragang.
Wernstedt and Spencer (1967)	Only states that a historical eruption occurred at Makaturing in 1891.

is a distinct lack of information on activities (volcanic or otherwise) on Mindanao much beyond 1755, coinciding with the Jesuits being expelled from the region. We find that all historical records of the eruption can be traced back to Forrest (1779), which in turn is based on the oral record of local Iranun people, leaving these as the only historical accounts describing the occurrence of the c.1765 eruption of Makaturing.

Forrest described a large eruption that was reported to him, while walking over the landscape with key Iranun informants, to have taken place around ten years prior to his visit in 1775 (Forrest, 1779; p.192):

> *"About ten years ago, one of the mountains, six or seven miles inland from this part of the coast, broke out into fire and smoke, with all the fury of a Volcano. It ejected such a quantity of stones, and black sand, as covered great part of the circumjacent country, for several foot perpendicular. Large stones loaded many places, even at the sea side; and at Tubug, near Pulo Ebus, I have seen fresh springs burst out, (at low water) from amongst black stones, of many tons weight, in various parts of that dry harbour. I was told that a river was formerly there, where is not the least appearance of one now."*

> *"During the eruption of the Volcano, the black sand was driven to Mindano, the ashes as far as Sooloo, which is about forty leagues distant, and the Illanon districts suffered so much, that many colonies went to Sooloo, even to Tampassook and Tawarran, on the west coast of Borneo, in search of a better country, where many of them live at this day."*

Note that at that time, 'Mindano' referred to the Sultanate of Mindanao, which was centred on Cotabato to the south of Makaturing.

The strong oral traditions of the B'laan highland people of Mindanao have been used in successfully reconstructing the 1641 Parker eruption (Delfin et al., 1997). However, there is no reference to the c.1765 Makaturing eruption in B'laan oral histories. B'laan people were known to have visited the coastal villages and city of Cotabato in the heart of Iranun territory to trade but it is thought that they were predated upon by the Iranun and so visited only infrequently. The Iranun people also have oral traditions and these are based primarily on formulae (titles and rituals), lists (place names and personal names), and tales (historical-general, local and family). The present-day Iranun of Northwest Kalimantan (Sabah) note in their oral traditions a number of migration events from Mindanao to North Kalimantan from before the 1600s to the late 1800s (Kawashima, 2017). Different stories persist among them concerning their origins in Mindanao, but one of the stories directly links a relocation event with the Makaturing eruption of the mid 1760s (Chin and Smith, 2011).

4.1.1. Why is Forrest (1779) the only written record of the eruption?

As with any data source, multiple historical accounts of the same eruption would provide an increased confidence in any reconstruction of the eruption and associated impacts. However, despite the reported magnitude of impacts, Forrest (1779) provides the only written account of the eruption. Alternative historical sources, e.g. ship's or master's log books, or the Oriental and India Office collections of the British Library, have all been exhaustively checked over the many decades that historical experts have been studying Thomas Forrest. The reader is referred to Warren (2007) for a breakdown of all historical reports that have been investigated from the region around the time of the eruption.

One obvious historical source of eruption and earthquake records in the Philippines are the Spanish Jesuits. Their letters pertaining to the Philippines comprise 20 bound volumes prior to 1768. Within these volumes, they recorded the large VEI 5 eruption of Parker in 1641, but not the proposed Makaturing eruption in 1765, which is proposed to have erupted 124 years later and lies approximately 200 km to the northwest of Parker. The geomorphology of the two volcanoes, and the resulting eruption crater dimensions, suggests that any eruption of Makaturing was much smaller than that of Parker, which may partly explain its absence from the Jesuit record. However, if the impacts were as reported by Forrest (1779), then some mention should be expected. Information in the Jesuit volumes related to local ethnographic and other events ceased from volume 14, in 1755, likely because they were under political pressure from the crown and communication from Mindanao to Manila was difficult, e.g. letters were being intercepted, travel was unsafe. The Jesuits were expelled from Mindanao at the end of 1755 and from the Philippines in 1768 by the crown, not returning until the second half of the 19th century. The entire Philippines section of the Jesuit records therefore contains no reports, volcanic or otherwise, beyond 1755. For a detailed discussion of the sources and references pertaining to the Jesuits in the Philippines see De la Costa (1961).

In addition to the expulsion of the Jesuits, the British occupied Manila from 1762 to 1764 and destroyed many valuable government records, including the Manila archives of the Spanish Crown in the Philippines and the military government in Zamboanga during this time. The remaining Manila collection of the Jesuit record was set on fire during WWII and the European records were also subject to fire. Spanish records from Zamboanga for the 1790s, held in the Archive General de Indias in Seville and the Jesuit archives in Rome, make no mention of the eruption. Potentially the Spanish were by then too preoccupied with the Iranun threat and the collapse of coastal communities. Makaturing was also inaccessible to the Jesuits because it lay in Muslim-controlled territory (Warren, 2018), which may further explain the lack of corroboration of the impacts and eruption noted by Forrest.

The reliability of Thomas Forrest's observations is difficult to objectively prove in the absence of multiple other accounts. We rely here upon historical expertise and the trust that the East India Company's Committee of Secrecy, the most powerful committee of the world's largest trans-national corporation at that point in time, placed in Thomas Forrest as one of their most able Captains. Forrest was considered the only naval officer capable of carrying out difficult and dangerous missions on their behalf to thwart their trade rivals the Dutch in the 'Eastern Seas'. As an East India Company emissary, Forrest was required to know key persons in the Mindanao area, and trained to report upon and describe as accurately and objectively as possible the people and places, as well as the local terrain, distances, weather and potential hazards, he encountered in the course of his journeys.

4.1.2. Geological records and eruption catalogues

If we assume that the historical record of Forrest (1779) is correct, or at least identifies the approximate location and decade, we can search for information from other sources, e.g. geological data and eruption catalogues.

Geological information on Makaturing available from PHIVOLCS comprises a series of geological reports and brief summaries on the historical activity of Makaturing volcano published by the Manila Observatory between 1916 and 1925; the Commission on Volcanology between 1953 and 1955; and PHIVOLCS in 1991. A geological report of Makaturing and Ragang volcanoes by Andal and Yambao (1955), based on a flight reconnaissance of the volcanoes in 1955, states that several vague eruptions credited to Rangang may actually have occurred from Makaturing based on the vegetation cover of the two volcanoes. However, there was no detailed description of eruption products from Makaturing in any of the geological reports or summaries. Similarly, there is no record of an eruption, or associated geological deposits, from a c.1765 eruption in southern Mindanao in the published scientific literature.

The Smithsonian Institution's Global Volcanism Program (GVP) lists four eruptions for Makaturing - 1856, 1858, 1865 and 1882, of which the first two are flagged as 'uncertain' (Global Volcanism Program, 2013). The PHIVOLCS - Local Active Volcanoes Archive (PHIVOLCS-LAVA) lists eleven eruptions, which includes four additional years with eruption to those listed by GVP: 1765, 1840, 1855 and 1871, with one extra eruption in 1856 and two in 1858. Seven of the same eruptions – 1765, 1840, 1856, 1858, 1865, 1871 and 1882 - are listed under neighbouring Ragang by the Catalog of Active Volcanoes of the World (Neumann van Padang, 1953). The GVP lists a 1765 eruption for Ragang and notes that the eruption was at one time attributed to Makaturing by the Catalog of Active Volcanoes of the World (Neumann van Padang, 1953). Latukan volcano, which lies between Makaturing and Ragang, has no record of previous eruptions in the GVP or PHIVOLCS-LAVA.

4.2. Impact mapping

The primary account of Forrest (1779) was interpreted through a volcanological lens in order to constrain the likely eruptive products, their reach and intensity. The resulting inferred values and their correlated sources are summarised in Table 2 and serve as the main evidence to filter our simulation outputs, as described in Section 3.3.2. The key interpretations from the historical record are that basaltic tephra from the eruption reached the Sulu islands ~220 km to the southwest and the Sultanate of Mindanao ~40 km to the south, and that impacts from the eruption displaced communities near Lake Lanao and the coast. We identified four filtering points, in order of decreasing confidence based on the historical record and our interpretations in Table 2:

1. Basilan: The report of ash reaching 'Sooloo' has been used to consider a minimum tephra threshold of 0.1 mm (trace amounts of tephra) for Basilan (Point 6), as the closest of the Sulu islands and the location most likely being referred to in Forrest (1779). We also considered the potential for ash on Jolo island (Point 7), as the capital of the province of Sulu, and Zamboanga (Point 5), a small Spanish garrison on the mainland, but their inclusion did not change our key findings.
2. Cotabato: Black sand was reported to have fallen in 'Mindano', which at the time referred to the Sultanate of Mindanao, approximately 40 km to the south of Makaturing and close to present-day Cotabato. Given the larger grain size ('sand') relative to Sulu ('ash'), we considered an increased tephra thickness threshold of 1 mm for Point 4.
3. Coast: The 'Iranun districts' around the coast adjacent to Makaturing (Point 3) and the south of Lake Lanao (Point 1) are reported to have suffered so much that communities abandoned the area and settled elsewhere (Chin and Smith, 2011; Forrest, 1779). Further evidence that communities living on the southern coast of Lake Lanao were affected by a c.1765 eruption has been proposed by Warren (2018) by contrasting the reports of Dampier (1697), who visited Mindanao in 1687, and Forrest (1779), who was there for several years nearly a century later (1770s). In the intervening time between these two reports, the population around Lake Lanao is reported to have become 'fragmented' and seemingly shrunk from ~100,000 (Dampier, 1697) to ~61,300 (Forrest, 1779). Warren (2018) uses this information to suggest that the eruption significantly affected agriculture, as the main activity and source of livelihoods in these areas at the time. Forrest (1779) describes "large stones [that] landed many places, even at the seaside", implying that the coast was affected by the ejection of ballistic blocks, or perhaps volcanic flows, in addition to tephra fall. We discuss the validity of these assumptions in Section 6, but in the interests of considering all available historical

Table 2
The information gathered and the related information derived from the historical accounts of Forrest (1779), in order of increasing levels of inference required. The inferred values and locations formed part of our impact mapping and were used to filter simulation results.

Primary text	Information inferred	
"About ten years ago, one of the mountains, six or seven miles inland from this [Tubug] part of the coast, broke out into fire and smoke, with all the fury of a Volcano"	Vent location	The eruption was reported to have originated from a vent/s 6 to 7 miles (9.6 to 11.3 km) inland from Tubug.
	Eruption style	'Fire and smoke; fury' implies an explosive component – perhaps incandescence at night, ash during the day.
"It ejected such a quantity of stones, and black sand, as covered great part of the circumjacent country, for several foot perpendicular"	Proximal thickness	Thicknesses of more than 2 m proximally.
	Proximal grain size	Black tephra 0.25 to 2 mm diameter deposited in the surrounding area. Lapilli and potentially bombs (> 2 mm and > 64 mm) impact the surrounding area.
"Large stones landed many places, even at the seaside"	Ballistics extent	Tephra of 64 to 256 mm diameter landed at least 10–12 km from the vent (the closest distance to the sea). An alternative interpretation is that the large stones were carried to the seaside within volcanic flows such as lahars.
"During the eruption of the Volcano, the black sand was driven to Mindano, the ashes as far as Sooloo, which is about forty leagues[a] distant"	Ash thickness	At least traces (≥ 0.1 mm thickness) of fine-grained tephra <0.25 mm diameter reached as far as the closest island of Sulu, Basilan, >220 km to the southwest.
	Grain size	Tephra of diameter 0.25 mm to 2 mm was deposited on the Sultanate of Mindanao (Cotabato).
	Magma composition and eruption style	The eruption was most likely mafic but explosive because of the black colouring of the tephra (supported by the predominantly mafic composition of the volcanic complex).
"…the Illanon districts suffered so much, that many colonies went to Sooloo, even to Tampassook and Tawarran, on the west coast of Borneo, in search of a better country, where many of them live at this day"	Tephra thickness	The Illanon districts are considered as areas to the southwest of Lake Lanao and in the floodplains near Pulo Ebus. Suggests large enough thicknesses to significantly disrupt livelihoods. Zero to minimal (few mm) thicknesses in Sulu and the west coast of Borneo. Potential implication that the east coast of Borneo was affected if people went to the west coast.

[a] Forty nautical leagues is approximately equal to 220 km.

evidence we keep the Coast and south Lake Lanao impact points in our study, assigning them our lowest level of confidence. Warren (2018) considered the coast to have been much more severely impacted than south Lake Lanao and so, conservatively, we apply a minimum thickness threshold of 100 mm to the Coast and 10 mm to south Lake Lanao following established relationships between tephra thickness and agricultural impact (Jenkins et al., 2015). We recognise the large uncertainty in this estimate and discuss this in more detail in Section 6.

4. South Lake Lanao: A minimum thickness threshold of 10 mm is considered, as discussed above.

Filtering our simulations through layered impact points (i.e. considering only our most robust point, then our two most robust points, and so on) allowed us to evaluate filtered eruption source parameters (ESPs) without the less robust points, if preferred. For example, as historical records of population counts are not always reliable, we considered the impact points of the Coast and south Lake Lanao as the least robust and as a result, model outputs can be interpreted without them.

Here, we have related impacts uniquely to the thickness of tephra deposits, the interpretation of which has proven to be challenging. We acknowledge that impacts are also a function of other properties of the deposit (e.g. chemical) and multiple other aspects (e.g. the full duration of the eruptive episode, the time of year, environmental conditions, and the socio-economic context at the time of impact). Since these additional parameters could not be estimated from historical reports, conservative minimum tephra thickness thresholds have been applied.

4.3. Reconstructing the eruption

4.3.1. Identifying the source of the eruption

The cone identified by Forrest (1779) as being responsible for the c.1765 eruption lies *"six or seven miles inland"* (9.6 to 11.3 km) from the Tubug coast (Fig. 1) where parasitic cones from Makaturing lie. There are two cones "*6 to 7 miles*" inland from Tubug, and these rise approximately 250 m above the surrounding landscape with the classical morphometry of scoria cones (Wood, 1979). The cones are around the same height, slope and volume as well-known recent basaltic eruptions, e.g. Cerro Negro (Nicaragua); Paricutin (Mexico), and andesitic eruptions, e.g. Tavurvur, Vulcan (Papua New Guinea). Historical eruptions produced plume heights of up to 7 km at Cerro Negro (Connor et al., 2001) and 8 km above the vent at Paricutin, with Paricutin eruptions depositing tephra in Mexico City, approximately 300 km away (Pioli et al., 2008). The 160 m high cone of Vulcan, albeit in a different tectonic setting to Makaturing, produced plume heights up to 30 km (McKee et al., 2018). It is therefore possible for such small cones to produce and disperse tephra that reaches hundreds of kilometres from the vent, e.g. as far as the Sulu islands; however, they are very unlikely to produce, in a single short-lived eruption, deposits sufficiently thick as to cause impacts of the magnitude reported in Forrest (1779). This is especially true in a tropical environment such as the Philippines, where tephra can be easily remobilised by rain and where vegetation recovery will be relatively rapid. The dispersal of tephra across large distances and the magnitude of the impacts reported by Forrest (1779) are better suited to a more explosive (and potentially more silicic) eruption. We therefore chose to consider multiple eruption sources along a profile approximately 40 km long stretching from the small cone reported by Forrest (1779) in the west (hereafter referred to as the 'small cone') through the Makaturing – Latukan - Ragang complex to the summit of Ragang in the east: the reported source of the 1765 eruption in volcanic catalogues (Fig. 3). As wind conditions are very similar across the volcanic complex, there was no added value in simulating additional points between the three vents – results can be reliably interpolated. We chose not to consider volcanic sources farther afield: the next closest volcanoes are 100 km or more from the reported vent in Forrest (1779) and are thus even less likely to produce the reported impacts within the relatively limited spatial area of the Iranun stronghold (along the coast and to south Lake Lanao), because of the increased distance that eruptive products would need to be transported.

4.3.2. Eruption scenario development and modelling

The predominantly mafic composition of the Makaturing - Latukan - Ragang complex (Global Volcanism Program, 2013) and the 'black sand' described by Forrest (1779) suggest that the c.1765 eruption was likely basaltic, or perhaps basaltic-andesite, and explosive. Explosive basaltic eruptions can range from Violent Strombolian to sub-Plinian eruptions with VEI 2 to 4, e.g. Cerro Negro, 1992 (Connor et al., 2001); Tecolote (Mexico), ~27 ka (Zawacki et al., 2019); Sunset Crater (USA), 1085 CE (Alfano et al., 2018). Potentially larger (VEI 5) Plinian eruptions of basaltic composition have occurred in the past (e.g. Coltelli et al., 1998; Walker et al., 1984; Williams, 1983), but they are rare and often imply

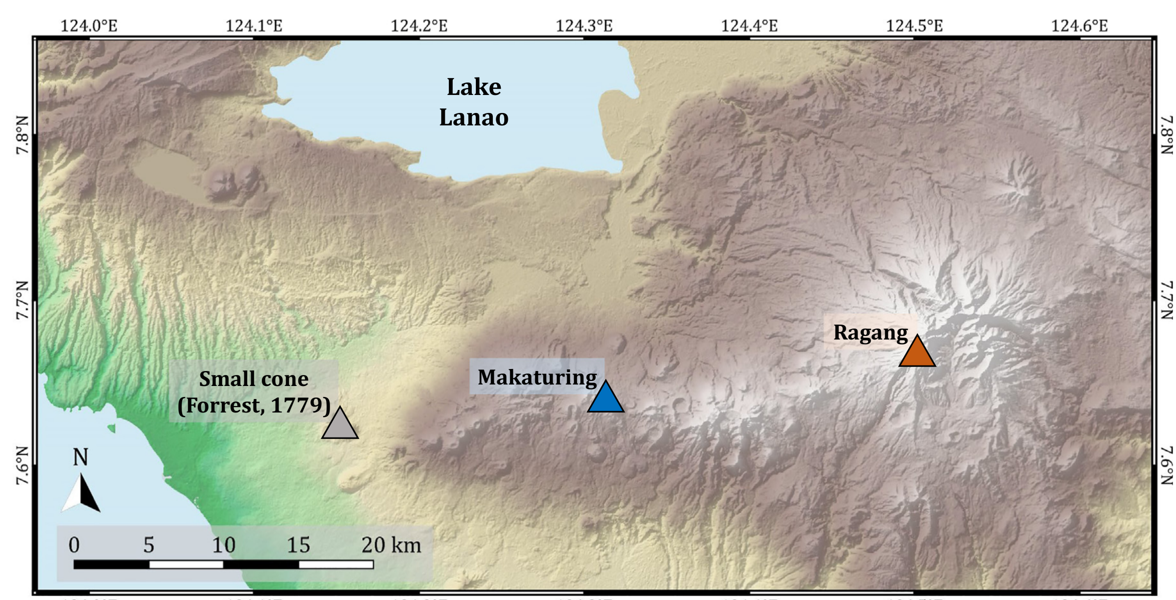


Fig. 3. Digital elevation map (1 arc-second SRTM) of the coast through the Makaturing - Latukan - Ragang volcanic complex, with the simulation source vents noted by coloured triangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

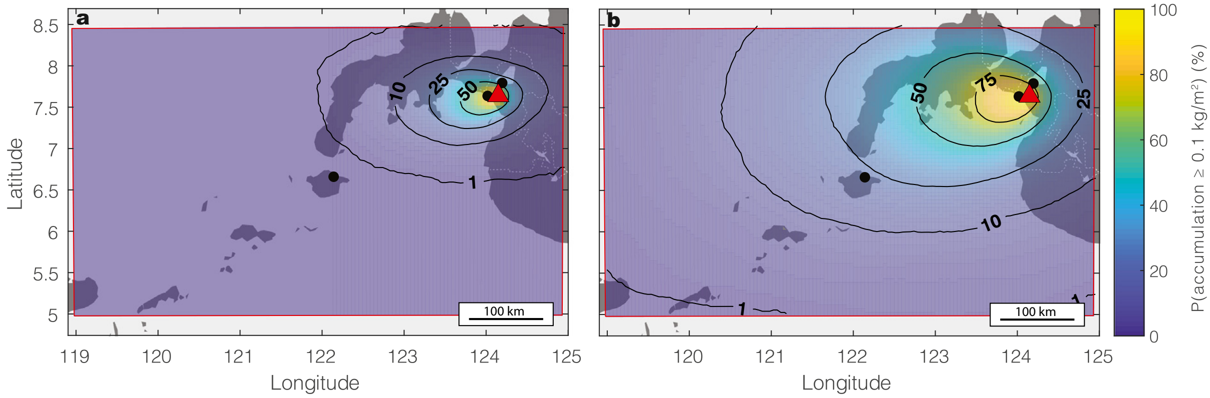


Fig. 4. Probability (as a %) to exceed tephra accumulations of 0.1 kg/m^2 (~ equivalent to 0.1 mm, or trace thicknesses) for a) a VEI 3 and b) a VEI 4 eruption. The map from Makaturing summit is shown, but the distribution is very similar across the three source locations. Each map is the result of 2000 model runs with the two scenarios having initial mass ranges of 0.1 to 1×10^{11} kg (VEI 3) and 1 to 10×10^{11} kg (VEI 4). Wind conditions from the entire year are considered. Black dots represent the impact mapping points of Basilan, Cotabato, the Coast and south Lake Lanao used to filter our simulation outputs.

some level of magma-water interaction, which typically results in large crater diameters that are not observed here.

We assumed that the impacts reported by Forrest (1779) were caused by the largest discrete explosive phase of what could have been a longer, multi-stage sequence. Given the observation of tephra falls in the Sulu Islands, at least 220 km from source and to account for the majority of eruptive styles produced by basaltic explosive eruptions, we chose to simulate eruptions across ranges of source parameters covering VEI 3 and 4. The ranges of eruption source parameters stochastically sampled during the modelling, and their rationale for use, are shown in Appendix 1b. We investigate various eruption intensities by defining broad initial ranges of plume heights (4 to 30 km) and erupted masses (1×10^{10} to 1×10^{12} kg). We first simulated 50,000 eruptions for each of the three identified source vents and computed their resulting tephra accumulations on the points of interest derived from impact mapping. Accumulation is output in the model as tephra load (kg/m^2) and we use a reasonable 1:1 conversion between load and thickness, in mm, which implies assuming a bulk deposit density of 1000 kg/m^3. Those simulations that produced the required impact conditions (e.g. tephra accumulations of ≥0.1 mm (or kg/m^2) over Basilan island plus ≥1 mm in Cotabato, ≥100 mm at the Coast and ≥10 mm at south Lake Lanao) were used to analyse the combination, and associated likelihood, of eruptive and atmospheric conditions responsible.

The report of ash being dispersed as far as the Sulu islands is key in estimating the size of the eruption. The probabilities of observing traces of tephra (i.e. loads exceeding 0.1 kg/m^2 or 0.1 mm) are shown in Fig. 4 for a VEI 3 and VEI 4 scenario from Makaturing. In agreement with the wind analysis of Fig. 2, tephra is preferentially dispersed in a west-southwest direction, with low-level winds oriented towards the east allowing a wide distribution of probabilities around the vent. Such probabilistic maps highlight the likely direction of tephra dispersal and deposition during a VEI 3 or VEI 4 eruption of Makaturing. As we consider modern-day wind conditions, these maps can also be useful in supporting rapid tephra hazard assessment in the event of any future unrest at the volcanoes.

Table 3 shows the probabilities of exceeding accumulations of 0.1 (i.e. 0.1 mm or a trace), 1 and 10 kg/m^2 (approximately 1 mm and 1 cm, respectively) independently at the identified impact points. Although plume heights were initially sampled from a uniform distribution, the indirect sampling of the mass from the combination of mass eruption rate and eruption duration suggests that plume heights ≥18 km are less likely to produce a mass in the VEI 3 to 4 range for the selected eruption durations. Similarly, the associated masses are skewed towards the higher boundary. As a consequence, about 40% of the 50,000 eruptions simulated for each source are VEI 3 and 60% are VEI 4 (Table 3). This is a result of the relatively wide range of plume heights deliberately selected here, which was larger than the range proposed by Newhall and Self (1982) for VEI 3 to 4 eruptions. The bias towards VEI 4 simulations does not affect the individual VEI 3 and VEI 4 scenario probabilities as they are conditional on the eruption occurring. Unless specified, probabilities discussed here are normalised over all simulations.

Our simulations agree with the report of Forrest (1779) suggesting that only traces of ash travelled as far as Basilan, the first island in the Sulu Archipelago. Considering the eruption sources of the small cone, Makaturing and Ragang, trace amounts of ash (≥0.1 mm or 0.1 kg/m^2) in Basilan were produced by 13, 13 and 12% of all simulations for the respective sources (Table 3). No simulation from any source produced accumulations ≥10 mm and less than 1% produced ≥1 mm. As the simulated source vent moves to the east along the volcanic complex, the elevation of the vent increases such that Ragang is approximately 2 km higher than the small cone. Assuming the same plume height, an increasing vent elevation will disperse tephra farther from source, which may explain the minimal differences in accumulations modelled in Basilan. All remaining impact points lie within 55 km of the vents and are associated with probabilities of occurrence above 30, 9 and 0.5%, for the ≥0.1, 1 and 10 mm (kg/m^2) thresholds, respectively (Fig. 1; Table 3).

Table 3
Probabilities (as a %) associated with tephra accumulations equal or greater than 0.1, 1 and 10 kg/m^2 (considered equal to 0.1, 1 and 10 mm) independently at each of the considered impact points, i.e. not considering simultaneous impact at multiple points. Probabilities are conditional on the occurrence of each eruption scenario: both VEIs together ('All'), and VEI 3 and VEI 4 separately. For each simulated vent source, the impact points are ordered by their distance from vent, and so the order may change between vents.

	Distance (km)	Bearing	Probability (%) to exceed tephra accumulation (mm or kg/m^2)								
			All			VEI 3			VEI 4		
	From the vent		0.1	1	10	0.1	1	10	0.1	1	10
Cone identified by Forrest (1779)			*Simulation count:*			*19,960*			*30,040*		
Coast	11	WSW	93	88	75	87	78	55	97	94	88
S Lake Lanao	18	NNE	56	31	10	40	14	2	67	42	16
Cotabato	41	SSE	31	9	0.7	13	1	0	43	14	1
Basilan	247	SW	13	0.2	0	0.2	0	0	22	0.4	0
Makaturing			*Simulation count:*			*19,914*			*30,086*		
S Lake Lanao	21	NNW	80	54	22	64	27	3	91	72	35
Coast	28	WSW	86	72	44	74	49	12	94	87	65
Cotabato	40	SSW	46	17	2	25	3	0	60	27	4
Basilan	264	SW	13	0.2	0	0.1	0	0	21	0.4	0
Ragang			*Simulation count:*			*19,797*			*30,203*		
S Lake Lanao	36	WSW	85	63	30	70	34	3	94	82	48
Cotabato	52	SW	52	20	2	27	2	0	69	31	3
Coast	50	WSW	79	53	20	59	20	0.5	91	75	33
Basilan	285	SW	12	0.1	0	0	0	0	20	0.2	0

When considering the individual VEI scenarios separately, probabilities of exceeding the assumed thresholds across all reference points are much greater given a VEI 4 scenario over a VEI 3 scenario, for all impact points and all source vents (Table 3), owing to the increased mass and higher plume height associated with a VEI 4 eruption. Thus, our modelling of the impacts reported in Forrest (1779) suggests that the Makaturing c.1765 eruption was most likely VEI 4.

With regards the more likely source of the eruption, reference points aligned with the preferential dispersal axis (i.e. Basilan and the Coast: Fig. 4) show an inverse correlation between probability and distance, such that higher probabilities are associated with the closest source (small cone), and lower probabilities with the farthest source (Ragang). However, Cotabato and south Lake Lanao lie upwind of the main dispersal axis for the small cone and progressively more crosswind and then downwind as the source vent moves from west to east. As a result, the probability of independent tephra deposition on Cotabato and south Lake Lanao increases as the source vent moves eastward. By considering the simultaneous deposition of tephra across multiple reference points over the next subsection, we can further constrain the likely source, with the underlying assumption that tephra was deposited at multiple reference locations during the same eruptive phase.

4.3.3. Likely eruption characteristics

Sampled distributions for key eruption characteristics (plume height, erupted mass, median grain size and eruption month) across the 50,000 eruptions for each simulated source (150,000 total) are shown in the first row (all ESP) of Fig. 5. The subsets of simulated eruption source parameters when considering impacts on Basilan (second row), Basilan and the Sultanate of Mindanao (Cotabato: third row), Basilan, Cotabato and the Coast (fourth row) and Basilan, Cotabato, the Coast and south Lake Lanao (fifth row) are also shown. The three overlain histograms for each plot represent each of the simulated source vents. In what follows, we describe the evolution of the ESP distributions reproducing the inferred tephra accumulations as successive conditional constraints are applied to filter the model outputs.

Condition 1. Traces of ash on Basilan: For the three sources, the subset of simulated eruption source parameters that produced traces of ash on Basilan (~12 to 13% of simulations) suggest that a VEI 4 scenario (i.e. masses $\geq 10^{11}$ kg) with plume heights >10 km (maximum likelihood at 12–16 km) and fine total grain-size distributions was the most likely eruption. We associate the distal dispersal of ash to Basilan, 220 km or more away from the source, to two factors. Firstly, an altitude of between 12 and 16 km corresponds to the tropopause region, where wind speeds are the fastest in the troposphere (Fig. 2), thus increasing the dispersal power at the upper region of the plume. Secondly, the occurrence of ash in Basilan is the result of eruptions with relatively fine total grain-size distributions, which require efficient fragmentation mechanisms that are commonly associated with sub-Plinian to Plinian, rather than Vulcanian or violent Strombolian, eruption styles (Rust and Cashman, 2011). An increasing distance of the eruption source from Basilan (from the small cone to Makaturing to Ragang) slightly reduces the likelihood of a simulation producing tephra traces on Basilan as it lies directly downwind, but the difference in probability is small compared to that for other reference points, potentially because of increasing vent elevation.

Condition 2. Traces of ash on Basilan and ≥1 mm at Cotabato: By also considering the 'black sand' driven to the sultanate of Mindanao in Cotabato (second row of Fig. 5), the likely eruption characteristics remain the same as for impact on Basilan but the source vent is now much less likely to be the small cone proposed by Forrest (1779). This reflects the difficulty in tephra being dispersed both downwind

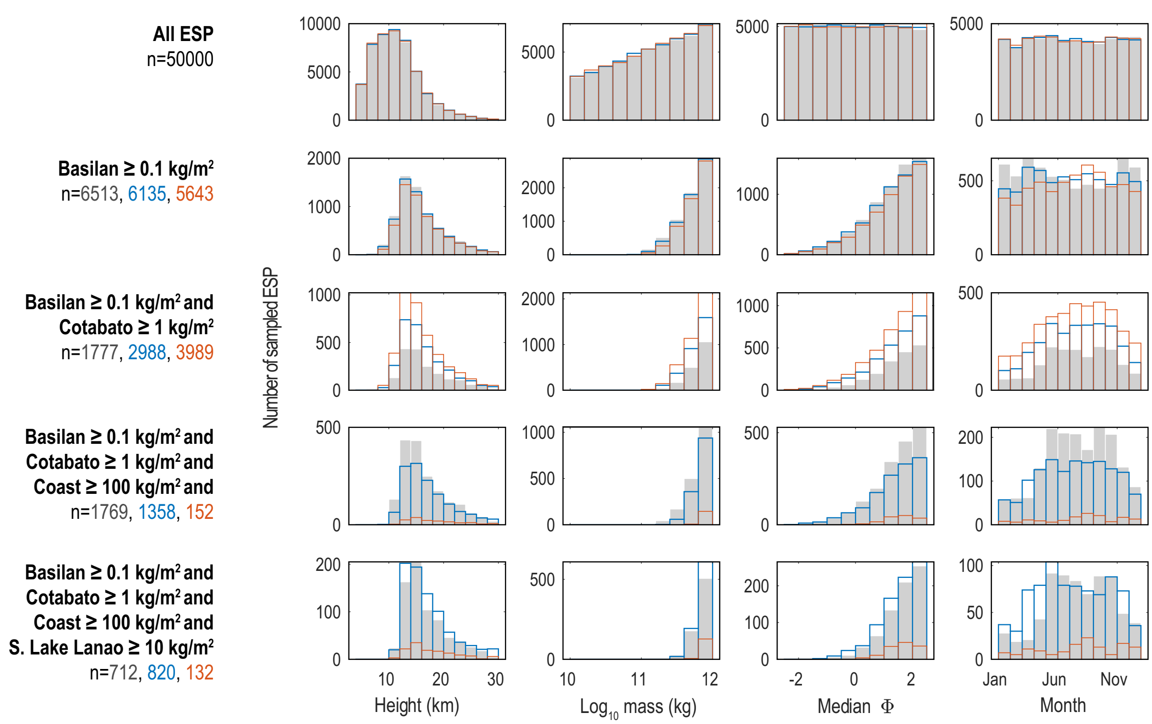


Fig. 5. Ranges and distribution of sampled (columns, left to right): plume height, erupted mass, median grain size and eruption month. The first row shows the total sampled distribution for the 50,000 simulations for each source. Results for the three simulated source vents are represented by the bar colours: filled grey for the small cone proposed by Forrest (1779), blue outline for Makaturing and orange outline for Ragang. Rows 2 through 5 show the distributions for eruption source parameters that reproduce tephra accumulations of ≥0.1 kg/m² (0.1 mm or trace ash) over Basilan island, and also accumulations of ≥1 kg/m² (1 mm) at Cotabato, ≥100 kg/m² (~100 mm) at the Coast, and ≥10 kg/m² (~10 mm) over south Lake Lanao. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for hundreds of kilometres and crosswind (assuming the small cone). As the simulated vent moves eastward, Cotabato moves closer to the main dispersal axis of tephra making source vents towards the east more likely sources. While no pattern in eruption month exists for deposition of tephra on Basilan alone, there is a clear preference for an eruption in the rainy season (May through October) when Cotabato is also considered.

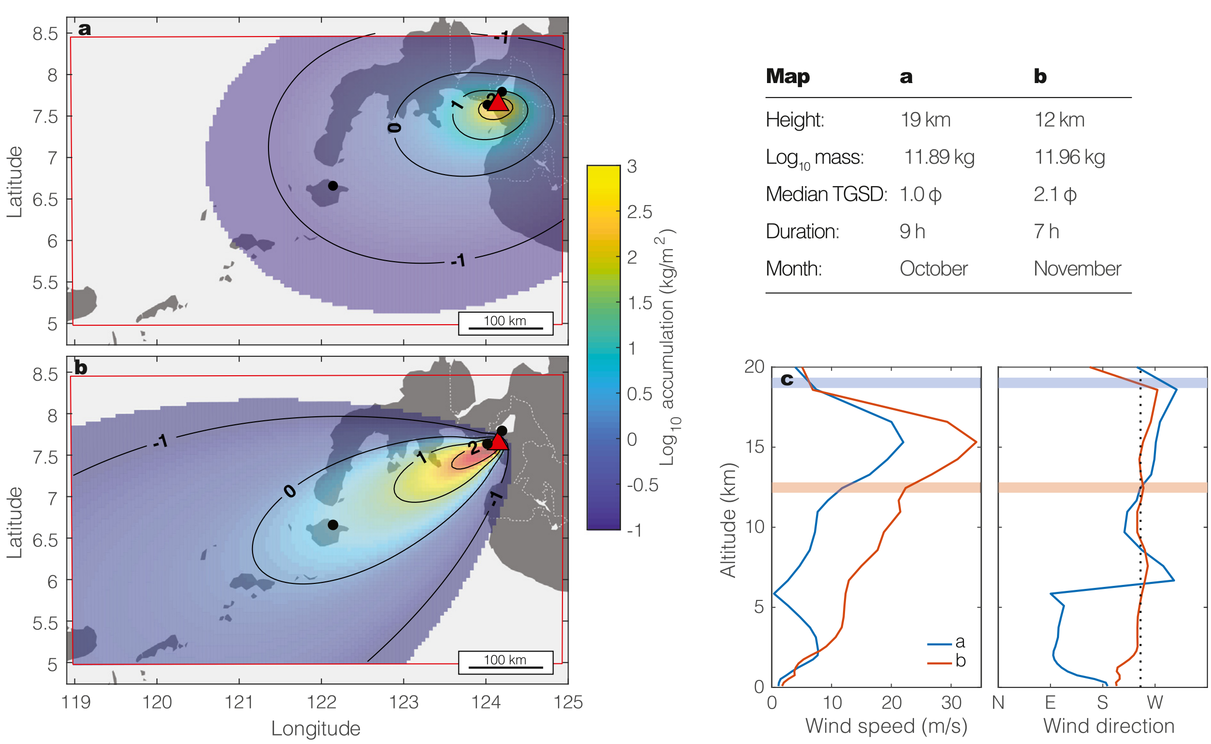
Condition 3. Traces of ash on Basilan, ≥1 mm at Cotabato and ≥100 mm at the Coast: The Coast impact point is directly aligned with the bearing of Basilan island, such that any tephra that reaches Basilan is also expected to impact the coast. For the small cone, all simulated eruptions that produce traces of ash on Basilan also produce ≥10 mm at the Coast, and many (42% of all simulations) also produce ≥100 mm at the Coast. However, very few (3.5%) also deposit tephra on Cotabato. As the source vent moves inland, the probability of tephra ≥100 mm at the Coast decreases, e.g. Makaturing has 11% probability and Ragang, <1% probability, with simultaneous deposition of tephra at the Coast, Basilan and Cotabato, becoming very unlikely for the most eastward source (Ragang: 0.3%).

Condition 4. Traces of ash on Basilan, ≥1 mm at Cotabato, ≥100 mm at the Coast and ≥10 mm at south Lake Lanao: By additionally considering a tephra accumulation of ≥10 mm at south Lake Lanao, the likely eruption characteristics remain the same, and the most likely source is located around the summit of Makaturing. The number of potential simulations reduces significantly (<2% of all simulations for any source) suggesting that the simultaneous deposition of tephra on all four reference points is a very unlikely, but not impossible, outcome. This does not rule out the possibility that two or more distinct explosions affected the different areas at different times during the eruption, a point we return to in Section 5, or that the report of Forrest (1779) has some inaccuracies, as we discuss in Section 6.

To summarise, the distributions of sampled eruption source parameters suggest that simultaneous accumulation of tephra at Basilan, Cotabato, the Coast and south Lake Lanao is the result of eruptions with plume heights of preferentially 12 to 16 km. Although infrequent, plume heights between 10 and 30 km can also reproduce these observations, no plume height below 10 km can. In adding constraints that filter simulation outputs (i.e. from top to bottom row of Fig. 5), the centre of the distribution of mass gradually shifts towards higher values and finer total grain-size distributions. The sampled eruption dates (last column of Fig. 5), and thus the sampled wind conditions, suggest that the months of May–October are the most likely to deposit tephra on the identified impact points.

Probability maps (Fig. 4) show that Cotabato and south Lake Lanao are located crosswind or, for the small cone upwind, and on opposite sides of the preferential dispersal axis suggested by local wind profiles (Fig. 2). The independent occurrence of tephra at these two locations could be the result of an eruption occurring in atypical wind conditions, but its simultaneous occurrence requires explanation. We propose two different theories: 1) bi-directional wind profiles with height, which support tephra being dispersed in different directions as it falls through the atmosphere; and 2) the formation of an umbrella cloud associated with a large sustained eruption column that can support upwind and crosswind tephra deposition.

Changes in wind direction with altitude occur at Makaturing during May to October, with winds preferentially blowing towards the west above 7 km and towards the east below that. The sedimentation of tephra in such an atmospheric regime can result in simultaneous deposition at Basilan and the Coast to the southwest, as well as at Cotabato to the south and south Lake Lanao to the north. Fig. 6 illustrates the effect of wind conditions on tephra deposition using two of our simulations from Makaturing: Fig. 6a shows the simulation with one of the largest



Map	a	b
Height:	19 km	12 km
Log$_{10}$ mass:	11.89 kg	11.96 kg
Median TGSD:	1.0 ϕ	2.1 ϕ
Duration:	9 h	7 h
Month:	October	November

Fig. 6. Mapped simulations extracted from the 50,000 runs resulting in the highest accumulation on Basilan when a) accumulations of ≥10 mm (~10 kg/m^2) are required on south Lake Lanao and ≥1 mm at Cotabato and b) when considering accumulation on Basilan only. The key eruption source parameters are also displayed as are the associated wind profiles (c), for which the respective plume heights (orange and blue bars) and the bearing of Basilan from the vent (black vertical dotted line) are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tephra accumulations on Basilan that also deposits tephra at the Coast (≥100 mm) and at south Lake Lanao (≥10 mm), while Fig. 6b shows the simulation resulting in the highest accumulation in Basilan without constraining accumulations on other locations. The two simulations are characterised by comparable erupted masses (~ 10×10^{12} kg), durations (7 to 9 h) and times of the year (October to November) but different plume heights, grain size distributions and wind profiles. The simulation shown in Fig. 6a is the product of a relatively high plume height (19 km) and a median total grain-size distribution of 0.5 mm (1φ) combined with a bi-directional wind profile (Fig. 6c). The simulation of Fig. 6b is characterised by a significantly lower plume height (12 km) and finer total grain-size distribution (0.25 mm; 2.1φ) combined with a high-speed wind profile oriented directly and constantly towards Basilan (Fig. 6c). The resulting eruption footprint is much more elongated and results in higher accumulations at Basilan but lower accumulations in proximal areas compared to the solution in Fig. 6a.

Proximal upwind and crosswind sedimentation of tephra can also occur when an eruption produces strong, sustained and steady plumes that have a plume rise velocity greater than the wind speed (Carey and Sparks, 1986; Degruyter and Bonadonna, 2012). Under such conditions, the eruption column can reach a neutral buoyancy level where gravity currents produce an 'umbrella cloud' that spreads laterally and can cause upwind sedimentation (Bonadonna and Phillips, 2003; Costa et al., 2013). In the case of the c.1765 eruption of Makaturing, an umbrella cloud that permits tephra accumulations in cross- and upwind locations favours a sub-Plinian over a Strombolian eruption scenario and supports the VEI 4 eruptions identified by our modelling approach, although we appreciate that eruptions of this size are rare from basaltic volcanic centres.

All our findings point towards the c.1765 eruption of Makaturing most likely being a sub-Plinian VEI 4 eruption with plume heights in the range 12 to 16 km occurring between May and October. With regards the eruption source vent, the small cone suggested by Forrest (1779) is unlikely to have produced an eruption of this size, with historical plume heights at Cerro Negro and Paricutin reaching a maximum of 8 km above the vent, at least 50 to 100% lower than the height most likely to disperse tephra to the reported impact points in our study. The simultaneous deposition of tephra on Basilan and Cotabato, as our two most reliable references, is also least likely given the small cone vent, with a source towards the east more likely. Considering tephra deposition for all impact points together, a vent around the summit of Makaturing is found to be most likely. This is approximately 20 km farther inland than the small cone, and nearly 30 km from the coast. While a Makaturing source is more compatible with the reported tephra falls, it is less compatible with the "large stones …" that are reported to have "… landed many places, even at the seaside", if we consider that "landed" implies a ballistic transport mechanism, rather than having been carried to the coast within a lahar for example (Table 2; Forrest, 1779). Reconstructing the simultaneous deposition of tephra at our reference points thus requires us to question some of Forrest's observations (the source vent and the large clasts "landing" at the coast) whilst assuming that the reported impacts are valid and true, a point that we return to in Section 6.

5. Challenges

There are numerous challenges associated with translating brief and ambiguous historical records into quantitative eruption scenarios; the necessary reliance in this study on one written record obtained 10 years after the eruption led to relatively high uncertainty in quantified eruption characteristics. Although we rely upon decades of historical investigation and analyses of the Sulu area (Warren, 2007) when considering the accuracy and reliability of Forrest's account, we cannot rule out that it may be flawed. The written account of Forrest (1779) can be validated to some degree by his exceptional accuracy in mapping and reporting locations in the complex, and at the time unchartered, archipelago around Makaturing as they were later proven correct; however, there may have been exaggerations, mislocations or inaccuracies within the recounting of the eruption to Forrest by key Iranun informants. Historical expertise suggests that the time Forrest spent living with the Iranun would ensure that he could identify, and account for, any such embellishments, but it is impossible to know with absolute surety. This highlights the importance of including appropriate expertise when interpreting historical records, for example to understand the context within which historical records are created and recounted and to interpret their validity and subtleties accordingly.

One method for reducing our uncertainty, in the absence of extra records, would be to search for geological deposits in the field, which could be used to better constrain the eruption characteristics. For tephra, it is unlikely that distal or thin deposits remain given the tropical high-weathering environment, but any associated flow deposits may remain and could potentially be dated. Unfortunately, fieldwork in southern Mindanao is not currently possible because of ongoing conflict. Another source of uncertainty lies in assuming a relationship between the reported impact and the hazard intensity, e.g. the tephra thickness, as very few empirical impact data from past eruptions exist (Jenkins et al., 2014). This relatively high uncertainty required a conservative interpretation of the minimum thresholds of tephra accumulation causing impacts, and also the pragmatic development of a reasonably simple and conceptual eruption scenario. As a result, our modelling approach considers relatively intense, sustained and steady eruption dynamics lasting for a few hours. However, no evidence provided in the historical account of Forrest (1779) can rule out the occurrence of a longer-lasting (e.g. months-years) eruption sequence. For comparison, eruptions at the Paricutin cinder cone lasted for nine years (Pioli et al., 2008). In this context, impacts on south Lake Lanao to the north and Basilan to the south are perhaps the result of two distinct explosive phases occurring in different wind conditions, rather than the single one considered in our modelling approach. The occurrence of ash in Basilan however requires an eruption of around a VEI 4. Thus, the c.1765 eruption of Makaturing, although potentially being a long-lasting eruptive sequence, produced at least one relatively large event able to impact populations at a regional scale.

6. Alternative scenarios

The historical record of Forrest (1779) discusses the impacts and dynamics of the eruption in minimal detail and so there are multiple non-exclusive interpretations that may produce the reported impacts, each requiring a small variation in the inferences made. For example, while the oral record from the Iranun people directly connects their relocation to an eruption from a small cone at Makaturing, the full inventory of reported impacts cannot reasonably be reproduced by an eruption from this source. This suggests that either i) the source reported by Forrest is inaccurate and the vents lie farther inland; ii) the eruption dynamics are not as described in the historical literature; or iii) there was an unexpectedly large socio-economic response to the eruption. In the following, we describe these three variations, and the effect they have on our findings, in more detail.

Variation 1. The eruption source reported in Forrest (1779) is inaccurate: Forrest (1779) directly links the c.1765 eruption of Makaturing with the relocation of the Iranun. Warren (2018) further describes the volcanic processes that could have led to this relocation, suggesting that the impact of the eruption on agriculture, as the main source of livelihoods at the time, likely caused the Iranun to turn to maritime activities. Thus, in the historical literature at least, the c.1765 Makaturing eruption is associated with significant physical impacts that led to far-ranging societal consequences. From a volcanological perspective, the small scoria cone identified by Forrest (1779) is incompatible with the reconstructed eruption scenario. More likely candidates for a source vent that produces tephra at all the reference points are found farther inland and include the larger volcanoes of Makaturing and Ragang. There is little morphological evidence for a very explosive recent history across the dominantly basaltic Makaturing - Latukan – Ragang volcanic complex, although it is possible that the morphological evidence for a very explosive eruption has since been obscured, e.g. by a later eruption.

Variation 2. Alternative eruption dynamics: The small cone eruption source reported in Forrest (1779) is more compatible with the report of 'large stones being deposited at the coast as ballistics than a source vent farther inland. However, should the reported source be correct, then the account of simultaneous deposition of tephra at all of the reference points, within the one major eruption, is unlikely to be accurate. The small cone is more likely to be associated with a multi-phase cone-building event comprising episodes of fountaining, lava flow/s and short-lived Vulcanian (and potentially sub-Plinian) explosions. As mentioned previously, we cannot rule out the possibility that the eruption comprised sustained but unsteady plumes lasting for days to weeks (e.g. 2010 eruption of Eyjafjallajökull, Iceland). While their final magnitudes can equal those of sub-Plinian and Plinian eruptions, the lower intensities of these eruptions typically result in the development of weak, bent-over plumes whose dynamics and interactions with the atmosphere are more difficult to capture in numerical models. The characteristic unsteadiness of such eruptions is not accounted for in our approach, and although its influence on the inferred impacts are not clear, these lower and longer-lived plumes would have interacted with different regions of the atmosphere and would have been influenced by atmospheric conditions changing through time and in space. Although the ash observed in Basilan requires a VEI 4 phase, this may have formed part of a long-lived sequence of eruptive phases that could have lasted for weeks, months or even years. A long-lived eruption with multiple explosions, and associated volcanic hazards and impacts, would have imposed a persistent stress on the local population (e.g. Barclay et al., 2019). Relocation of the Iranun population and their reported change in livelihoods may therefore be the consequence of recurrent impacts, rather than one discrete impact, in combination with strong opportunities to re-orientate activities. In this way, a sequence of small to moderate eruptions could seemingly have effects across regions much larger than the physical deposits.

Variation 3. Pre-existing stress factors influenced the Iranun's response to eruption: The disconnect between the reconstructed eruption scenario, the reported tephra impacts and the Iranun's response may be related to the agricultural or socio-economic context at the time. There are very few studies of the response of agriculture to tephra fall in a tropical environment (Ayris and Delmelle, 2012). Impacts are a function of the tephra and crops themselves, the environmental conditions, and the timing of the eruption, with episodes of tephra fallout having a more significant impact if they coincide with critical points in the growing cycle. In theory, we would expect relatively rapid remobilisation of tephra and recovery of vegetation in a hot, humid tropical environment such as Mindanao.

Cultural response to previous basaltic eruptions ranges from complete collapse of society, through multi-decadal relocation to little apparent change (Ort et al., 2008; Cronin and Neall, 2000), with the socio-economic context at the time of eruption critical to the nature and magnitude of the response. Populations around Makaturing were in flux socially, politically and economically around the time of the reported c.1765 eruption because of the advent of trade with China (Forrest, 1779; Warren, 2018). The migration of the Iranun from Lake Lanao to the coast, and their rise to prominence as sea raiders across the region was directly connected with the c.1765 eruption of Makaturing by the oral records of the Iranun people (Forrest, 1779; Chin and Smith, 2011; Warren, 2018). How a community responds to an eruption is non-linear, and not solely related to the physical impact. The response also varies by timeframe, across different social groups and depends on availability of alternative livelihoods or opportunities at the time (e.g. Hicks and Few, 2015; Few et al., 2017) with an eruption often acting to catalyse social adjustments already underway (Blong, 1984). Many other communities in the eastern archipelago (east of Java) re-orientated their activities from agricultural and short-range raiding to long-distance slave raiding and trade by sea around the time of the c.1765 eruption, but not at the same scale as the Iranun. Potentially the Iranun re-orientated more quickly because their agricultural livelihoods became untenable as a consequence of the eruption, because they already had well-developed boat-building skills and/or to take advantage of increasing opportunities in sea-trading and raiding at the time. There is some evidence that populations around Makaturing were moving in the years prior to the eruption (Rennell, 1763); the eruption may therefore have acted as a 'tipping point', catalysing a change in livelihood and shift in population distribution that was already happening, but not directly causing it, or perhaps the eruption had little to no effect on the relocation of a population that was already underway.

If the eruption impacts were exaggerated, then our modelling remains valid on the basis of the tephra reaching Sulu, and a sub-Plinian eruption is thus still the most likely scenario. If the spatial extent of the tephra (e.g. ash to Sulu) was exaggerated, then the conclusions drawn from our modelling approach are flawed. However, this study does provide a probabilistic assessment of the likely future hazard given a VEI 3 or 4 eruption at Makaturing or Ragang. If there are inaccuracies in the historical record as a result of insufficient detail, we cannot know whether they arose from the Iranun recounting of the eruption, and/or the written record of Forrest (1779), or perhaps a miscommunication between the two, but this work provides a valuable cross-check of historical accounts and reinforces that they should always be interpreted from a multi-disciplinary perspective.

7. Conclusions

Evidence for a c.1765 eruption of Makaturing volcano, southern Philippines, is limited to one written record: that of British East India company captain and explorer Forrest (1779), which was in turn based upon reports from the Iranun population living near the volcano. Forrest (1779) directly linked the eruption and its impacts on the Iranun with their rapid emergence as long-distance slave-raiders, who disrupted trade routes across Asia from the late 1700s with devastating impact. However, there is no other record (geological or otherwise) of the eruption, and fieldwork to the region remains difficult. The exact size and style of the eruption thus remains unknown. In this study, we have re-evaluated the historical record of Forrest (1779) from a multi-disciplinary perspective, aiming to source as much information from the text as possible in order to reconstruct the eruption and constrain its likely characteristics. Better characterising the eruption is important because, within the historical literature, it is being attributed to large scale physical impacts around the volcano, and changes in the trading routes and livelihoods across southeast Asia, and yet no such eruption (or impacts) are recognised in the scientific literature.

We used a novel approach to eruption reconstruction based upon a combination of inference of the deposits from historical notes and stochastic tephra dispersal modelling that considers multiple eruption sources and characteristics. The resulting simulations were filtered according to their potential to reproduce the impacts reported in Forrest (1779). Forrest's account of the c.1765 eruption was found to be best characterised by a VEI 4 eruption between May and October. To deposit tephra at least 220 km to the southwest in the Sulu islands, ~40 km to the south in Cotabato, while also severely impacting more local communities, ~10 km to the southwest and ~20 km to the north, required plume heights in the range 12 to 16 km. While our most likely eruption scenario is a sub-Plinian eruption, the impact conditions can be recreated with a plume height as low as 10 km. The bi-directional deposition of tephra within the one eruption can be explained by either varying wind conditions with height, as observed at the volcano, and/or an umbrella cloud associated with a sustained, intense eruption. There are a number of challenges with this identified scenario. Firstly, we find that the small cone source reported in Forrest (1779) is hard to reconcile with an eruption scenario of this magnitude. A source vent farther up the volcanic chain where larger explosion craters are found is more likely; however, the increased distance of such a source from the coast would then render the reported 'large stones' at the coast less likely. An alternative credible interpretation of the historical record is that the bi-directional deposition of tephra was the result of multiple different phases of tephra dispersion into varying wind conditions, which together formed part of a longer-lived multi-phase event that would have placed a chronic, rather than acute, stress on the surrounding populations.

The exact nature of the eruption, its impacts and the local population's response will likely always remain unknown. Was the eruption responsible for the major shift in Iranun activities in the late 1700s, as suggested by Forrest (1779) and Warren (2018)? Or did it have little to no effect on what was an inevitable change in Iranun circumstances already in motion before the eruption (Rennell, 1763), bought on by external factors such as increasing trade with China? Or was it somewhere in-between whereby the eruption acted as a 'tipping point' for a local population already stressed by the turbulent socio-political and economic context at the time? While we can't answer these questions with just one historical record and no field data, the modelling carried out here provides an indication of the likely eruption style and size that, for the first time, is grounded in volcanological reason. A valuable additional benefit of our modelling is that it provides a preliminary hazard assessment for a future explosive eruption in the Makturing – Latukan – Ragang volcanic complex, highlighting the likely dispersion and deposition of tephra in the region.

Re-interpreting historical records that are limited in quantitative detail has its challenges and its benefits. For example, where deposits can no longer be studied because of preservation or access issues, historical records may remain the only evidence of an eruption. Ideally, the evaluation of historical records of volcanic activity should be undertaken from a multi-disciplinary approach, where historical expertise provides the greatly needed local context and volcanological expertise the credible volcanic processes and impacts associated with the reported activity.

CRediT authorship contribution statement

Susanna F. Jenkins: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization, Supervision. **Marcus Phua:** Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization. **James F. Warren:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Sébastien Biass:** Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Caroline Bouvet de Maisonneuve:** Conceptualization, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Tephra modelling inputs

Appendix Table 1a
Input parameters for Tephra2 and TephraProb that are common across all simulated eruptions.

		Value	Rationale
Parameters common to all scenarios			
Vent 1	Location	626,650 E, 844700 N UTM zone 51 N	Small cone vent identified by Forrest (1779)
	Elevation	720 m asl	
Vent 2	Location	645,270 E, 845160 N UTM zone 51 N	Makaturing summit (GVP)
	Elevation	1818 m asl	
Vent 3	Location	666,200 E, 850430 N UTM zone 51 N	Ragang summit (GVP)
	Elevation	2790 m asl	
Eddy constant		0.04	Standard for small particles in Earth's atmosphere
Plume	Steps	100	Typical number of integration steps
	Model	1	Mass distribution within the plume follows a Beta distribution
	Distribution	Alpha: 3 Beta: 1.5	A plume where the majority of the tephra is emitted at around 80% of the maximum plume height
Wind data		Stochastically sampled from 19 years (2000 to 2018) of six-hourly ECWMF ERA-Interim reanalysis data (Dee et al., 2011) at Makaturing.	
Number of simulations		50,000 total for each vent, where the wind conditions, and source parameters, e.g. erupted mass, plume height, grain size distribution, were varied between credible ranges for each eruption scenario.	

Appendix Table 1b
Input parameters for Tephra2 and TephraProb for the full simulated range of VEI 3 to 4 eruptions.

		Value		Rationale
		Minimum	Maximum	
Plume height (km above vent)		4	30	Derived from the lower and upper confidence bound of an empirical mass:height relationship (Mastin et al., 2009), matching data from Cerro Negro 1992 (minimum height) and Sunset Crater c.1085 (maximum height).
Erupted mass (kg)		1.0×10^{10}	1.0×10^{12}	Following the VEI 3 to 4 classification of Newhall and Self (1982) and a deposit density of ~1000 kg/m^3.
Particle	Median size	0.2 mm (2.5 φ)	6 mm (−2.5 φ)	Deliberately wide ranges of potential, but credible, grain size characteristics were chosen. Densities follow Connor et al. (2001).
	Std. dev. size	8 mm (3 φ)	2 mm (1 φ)	
	Density	900 kg/m^3	1200 kg/m^3	
Duration		0.5 h	24 h	Used to calculate mass from MER. Range spans very short-lasting and intense phase to longer tephra emission scenarios.
Diffusion coeff.		4900 m^2/s		Best fit inversion values for the 1979 eruption of Fuego, Guatemala (Biass et al., 2016).
Fall-time thresh.		5000 s		
Number of simulations		50,000 per vent source		A large enough number to sample a statistically significant number of combinations.

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