What Can We Learn from Records of Past Eruptions to Better Prepare for the Future?

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Abstract

There is a long and rich record of historical observations of volcanic activity that has the potential to enhance current understanding of volcanic eruptions and their impacts, and to inform planning of responses to future events. However, apart from a small number of well documented examples, much of this broader material remains unread and little used. In this chapter, we explore examples of contemporary observations and accounts of volcanic eruptions at Santorini (Greece) and the Soufrière, St. Vincent, in the 18th, 19th and early 20th centuries. We show how these sorts of data could be used to inform and advance our understanding of, and approach to, volcanic crises; and to better understand the roles that communication—of hazards, of past events, or during an emerging crisis—may play in helping to prepare for the future.

1 Introduction

Despite considerable advances in scientific methodologies, monitoring techniques and modelling capacity, many aspects of the science of volcanology remain empirical; in particular the anticipation of 'what may happen next'. This presents a critical challenge to those charged with the management of emerging volcanic events, and those responsible for communications and crisis management as events unfold during an eruptive sequence. At volcanoes with a long legacy of monitored activity, recognising and developing an empirical understanding of the way the volcano behaves, and being able to read the signs of what might be unfolding, is one of the core skills of the staff at the local volcano observatory. However, instrumental records of volcano observation are short compared to the typical intervals between large eruptions; and what about volcanoes not known to have had unrest or activity in the recent past? It is in these contexts that accounts of prior activity, perhaps deep in the past, have particular value, both in providing a qualitative picture of what may have happened in the past; and in forming a narrative

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Advs in Volcanology (2018) 445–462
https://doi.org/10.1007/11157_2017_5

with which to engage communities who may be affected by volcanic activity.

In the context of a volcano which is starting to show unrest, the conventional approach to the understanding of the emerging volcanic hazard still relies to a great extent on a combination of (i) the mapping of the likely hazard, based on the physical deposits of prior eruptions, (ii) assessment of the timing of past eruptions and (iii) effective monitoring of the volcano, whether from ground-based sensors, or by satellite remote sensing, combined with an analysis of instrumental records of past eruptions (e.g. Scarpa and Tilling 1996; Haynes et al. 2007; Pyle et al. 2013; Hicks et al. 2014). The next step is often based around the analysis of likely eruptive scenarios, which will in turn be based on an understanding either of the past eruptive history of that particular volcano; or, in the case of a volcano showing unrest for the first time, may be based on scientists' judgements about the sorts of eruptive scenarios that might be typical of the volcano. In recent years, this process has been developed and applied to great effect. For example at Montserrat, West Indies, an iterative and repeated process of expert elicitation has been used to form a consensus view of the state of the volcano (Aspinall et al. 2002, 2003; Aspinall 2006; Wadge and Aspinall 2014). The development of 'Bayesian Belief Network' approaches represents a valuable tool for using the learning from past events to inform decision making about future events (Hincks et al. 2014).

As other work on Montserrat and elsewhere has also shown, a poorly understood aspect of the response to emerging volcanic events is the role played by communication: not only in terms of the formal pronouncements on hazards, risks and 'alerting' processes (e.g. Barclay et al. 2008, 2015; Wadge and Aspinall 2014; Donovan et al. 2012, 2014), but also in terms of the communications with and within the diverse communities affected by the emerging crisis; and the impacts on those affected by the activity (e.g. Hicks and Few 2015). This is a significant gap which would certainly be worthy of future investigation.

In this chapter, I argue that volcanologists could add considerably to the evidence base relating to past eruptions, and consequently improve our capacity to manage impending or future crises, by seeking out the wider historical records of past eruptions. In particular, there is much to be learned from records (for example contemporary accounts, written by the people who experienced the event) that document not only how the past physical events unfolded, but also the social, economic and political consequences of the event. These same resources may also record the roles played by communication during these past crises: from the immediate response (when, why and how did people affected by events respond?), to the diffusion of news of the events, and the response of external actors and agencies.

2 Volcanic Eruptions and Their Consequences

The rich sources of contextual information around volcanoes and the impacts of their historical eruptions have only rarely been exploited. Three better known examples, where diverse source materials have been brought together for analysis sometime after the primary event, include studies of the eruption of Tambora, in 1815 (e.g. Stommel and Stommel 1983); of Krakatoa in 1883 (Simkin and Fiske 1983); and, on a smaller scale, of Parícutin, Mexico in 1943 (Luhr and Simkin 1993). These examples are briefly described in the following sections.

2.1 Tambora, 1815

The Tambora eruption of April 1815 was one of the largest eruptions of the past 500 years, but was understudied until relatively recently (Self et al. 1984; Self and Gertisser 2015). Eyewitness accounts of the eruption were gathered at the time by the regional Governor, Stamford Raffles, who dispatched a team to deliver emergency relief to affected communities, and collect information on what had happened (see Oppenheimer 2011; Pyle 2017). It was only many decades later that others attempted to assess the wider impacts of the eruption. Heinrich Zollinger, a Swiss botanist, climbed Tambora in 1847, and later documented the scale and severity of the eruption, including the casualties (Zollinger 1855). The extent of the global consequences of the eruption became clearer once the stories of the 'Year without a Summer' of 1816 had been gathered, and linked to the eruption of Tambora (e.g. Milham 1924; Stommel and Stommel 1983; Stothers 1984), while the narratives of links to global health crises and economic collapse are still emerging (e.g. Post 1977; D'Arcy Wood 2014; Oppenheimer 2015). The Tambora event is a case study of a globally-disruptive event; and one that would benefit from further analysis, particularly in the context of communication and crisis management.

2.2 Krakatoa, 1883

Krakatoa was the first volcanic eruption with a global impact where news of the event travelled faster than the spread of the ash cloud. The newly completed international network of submarine telegraph cables ensured that the opening phases of the Krakatau eruption in summer 1883 were reported in *The Times* newspaper in London within 36 h of the event (Simkin and Fiske 1983; Winchester 2003). The aftermath of the climatic phase of the Krakatoa eruption in August 1883 was an early example of the use of crowd-sourcing to gather information about the far-flung impacts of an eruption. George Symons, a British meteorologist, chaired the Royal Society's Krakatoa Committee. The remit of the committee was to collect information on the scientific phenomena attending the eruption, and Symons placed calls in early 1884 for 'the communication of authenticated facts respecting the fall of pumice and dust… unusual disturbances of barometric pressure and sea-level (etc.)' (Symons 1888, p. iv). The final report contained only a very brief outline of the relief efforts that followed the eruption (Symons 1888, p. 2), alongside more extensive eyewitness reports from those both at sea, and on land. To mark the centenary of the eruption, Simkin and Fiske (1983) collected together these and many other accounts, and refined the timeline for the unfolding events. The existence of a telegraph network meant that some of the otherwise transient records of events were recorded for Krakatoa in ways that had never before happened for an eruption of this scale. However, while analysis of this material could provide valuable insights into the nature of emergency communication and response during a large-scale volcanic emergency, the full potential of these records has not yet been realised.

2.3 Parícutin, 1943

The eruption of Parícutin, Mexico, was on a smaller scale, but had dramatic consequences for farming communities of the high Mexican plains. In February 1943, an eruption began without warning in the corner of a corn field. Over the next nine years, the new volcanic cone of Parícutin grew, eventually covering 25 km^2 of land with lava. To mark the 50th anniversary of the eruption, Luhr and Simkin (1993) collected and edited a volume of papers and reports—some contemporary with the eruption; others offering a retrospective analysis of the wider impacts of the events on those affected. Accounts document the first-hand experiences of farmers who first had to cope with the fallout of ash and cinders; then a 'rain of mud', when the rains arrived, and finally resettlement in new locations that had no connection to their original homes, and required them to adapt their farming practices to lower elevations. The value of this volume in bringing together a diverse range of papers on the physical, environmental and social impacts of a one-off eruption was considerable; but, as with the examples of Tambora and Krakatoa, lacked any formal analysis of crisis communications.

2.4 Other Examples

While there are volcanological studies of many past eruptions, there are rather fewer that extend to an analysis of the human impacts and responses. Recent work on historical eruptions of Vesuvius in 1906 and 1944 that explore human impacts, crisis management and emergency response (e.g. Chester et al. 2007, 2015) reveal some important lessons for dealing with future volcanic crises, at Vesuvius and elsewhere.

Deeper in the past, volcanic events and their impacts may only have been recorded in official and other records if the event was of sufficient scale to have required a response (evacuation, aid and assistance, rebuilding or relocation); and if the local governance systems collected and recorded such information. There are extensive records of natural hazard events from the Spanish colonial period of Latin America (e.g. Petit-Breulh Sepúlveda 2004, 2006; Hutchison et al. 2016), but scant records from, for example, Ethiopia (e.g. Gouin 1979; Wiart and Oppenheimer 2000): differences that in part reflect the spatial locations and numbers of chroniclers, and the security of the archives. Beyond this, large-scale natural disasters may be captured in oral histories that require patience, luck and persistence to piece together (e.g. Blong 1982; Johnson 2013).

3 Why the Instrumental Records of Past Eruptions Is Deficient

Two major challenges face scientists in their efforts to extend and develop an evidence-based approach to anticipate the behaviour of less-well-known volcanic systems that are starting to show their first known episodes of unrest. Even for systems where the recent volcanic record is well preserved, challenges include:

- The preserved geological record, and much of the physical observational record, for most volcanoes is almost exclusively a record of past *eruptive activity*. In itself, this is a record biased towards activity of a scale or style, or deposited into an environment that can be preserved (e.g. Pyle 2016). There is often a lack of evidence from which to make inferences about the nature of either non-eruptive unrest, or of long-term precursors to subsequent activity (Moran et al. 2011). Non-eruptive unrest leaves no accessible trace in the geological record, and as result most of our current knowledge about unrest dates from the modern, instrumental, era.
- The catalogued records of past activity are almost exclusively records of eruptions, rather than of non-eruptive unrest (e.g. Siebert et al. 2010); and these records rarely, if ever, document the wider social, political and economic consequences of these past eruptions. While catalogues of volcanic activity have evolved an effective set of tools for recording the totality of an eruption—start date, size, end date—there are as yet no agreed standards for recording, preserving and making accessible the long-termtime-series of measurements (and associated metadata) and observations of volcanic events, and their consequences, beyond the daily, weekly or monthly ‘status’ bulletins; despite valiant efforts by individuals (e.g. Perret 1924), international projects including WOVOdat (Venezky and Newhall 2007), the Global Volcanism Programme (Siebert et al. 2010) and the Global Volcano Model (Loughlin et al. 2015); and a handful of prominent case studies (e.g. Mount St. Helens—Lipman and Mullineaux 1981; Pinatubo—Newhall and Punongbayan 1996; and Montserrat—Druitt and Kokelaar 2002; Wadge et al. 2014). As a result, fine-grained details about the evolution of eruptive activity during a crisis are prone to being lost, and will be hard, if not impossible, to recover after the event. Thus, our understanding of even the ‘volcanic’ part of past volcanic crises (leave alone their social imprint) is far from complete (e.g. Hicks and Few 2015); and our understanding of the run-up to eruptions is even more fragmentary.

Volcanology is now entering a period of time when it is possible to monitor volcanoes globally using satellite remote-sensing; and where near-real-time automated remote detection of changes in behaviour (whether thermal, geodetic, seismic or gas) is becoming a reality (Hooper et al. 2012; Pyle et al. 2013). The challenge will be to match this step change in our *capacity* to monitor changes in behaviour, with our ability to interpret these changes in behaviour, in a way that is useful to those charged with managing volcanic risk.

An indication of the scale of this problem can be seen from an analysis of global patterns of volcano deformation (Biggs et al. 2014). Biggs et al. analysed the published satellite geodetic (InSAR) studies of 198 systematically observed volcanoes in the 18 year period up to 2013, distinguishing between volcanoes that erupted in that same period; and those that did not. Critically, they found that only 44% of detected 'deforming volcanoes' actually erupted during this period; meaning that the majority of deforming volcanoes are not poised to erupt; while 6% of 'non-deforming' volcanoes erupted, meaning that some restless volcanoes may show little sign of being restless, before erupting. This result shows that the successful recognition of pre-eruptive unrest will continue to require multiple sources of observation; while the interpretation of the signals of unrest will continue to require an understanding of the specific attributes of the system that is showing unrest.

4 Retrospective Analysis of Volcanic Crises

Here, we use records from historical eruptions at two typical subduction-zone volcanoes (Santorini, Greece; Soufrière, St. Vincent) to illustrate how retrospective analysis of the wider archives and records of past eruptions might help in the management of ongoing and future crises.

4.1 The Kameni Islands, Santorini, Greece

First we consider post-calderadome-forming eruptions on the Greek island of Santorini; a restless caldera in the Mediterranean. The volcano is well known to the local residents (e.g. Dominey-Howes and Minos-Minopoulos2004), and intimately linked to the deep archaeological history of both Santorini, and the Aegean Bronze Age 'Minoan' culture (e.g. Marinatos 1939). It has a significant transient summer population of tourists; some of whom will have come to see the volcano and its hot springs.

Over the past 3000 years, a series of dacite lava and tephra eruptions have progressively built the Kameni islands; a 4 km^3 edifice which now emerges above sea level within the caldera (Druitt et al. 1999; Nomikou et al. 2014; Table 1; Fig. 1). The first eruptions to form the nascent Kameni islands would have been exclusively submarine, but there have been at least 8 subaerial eruptions since 46 AD which have progressively enlarged the Kameni islands (Fytikas et al. 1990; Pyle and Elliott 2006; Nomikou et al. 2014). Of these eruptions, there are written contemporary accounts of six, and detailed accounts of all known eruptions since 1707.

An eruption from 1707–11 was the first such event on Santorini to be documented in a journal (Box 1, Gorée 1710); and is the earliest eruption of Santorini for which early maps or sketches exist (Fig. 2). 150 years later, from 1866 to 1870, a major dome-forming eruption became the focus of a significant amount of contemporary observation and writing. This eruption led to the first treatise on the medical effects of volcanic eruptions and their gas emissions (da Corogna 1867), and was documented in considerable detail by Ferdinand Fouqué, leading to the modern ideas on the origin and evolution of calderas (Fouqué1879). Contemporary observations of eruptions in 1866–70 and 1925–1928 detail the eruption progress, including rates of dome growth, of explosions, and lava extrusion. These datasets provide the essential quantitative information that underpin later forecasts for the style of future activity (e.g. Watt et al. 2007; Jenkins et al. 2015). The last of the eruptions of Santorini was in 1950, three decades before the installation of the first instrumental monitoring networks on the islands.

Table 1 Historical activity of the Kameni islands, Santorini, Greece

Eruption date	Location	Primary sources
10 Jan–2 Feb 1950	Nea Kameni	Georgalas (1953)
20 Aug 1939–July 1941	Nea Kameni	Georgalas and Papastamatiou (1951)
23 Jan–17 Mar 1928	Nea Kameni	Reck (1936)
11 Aug 1925–Jan 1926	Nea Kameni	Reck (1936)
26 Jan 1866–15 Oct 1870	Nea Kameni	Fouqué (1879)
23 May 1707–14 Sep 1711	Nea Kameni	Gorée (1710)
1570 or 1573	Mikra Kameni	No primary records
1457	Palea Kameni	No primary records
726	Palea Kameni	No primary records
46–47	Palea Kameni (Thia)	No primary records
199–197 BC	Hiera (or Lera)	No primary records

Notes Full sources listed in Fouqué (1879); Stothers and Rampino (1983); Pyle and Elliott (2006); Nomikou et al. (2014)

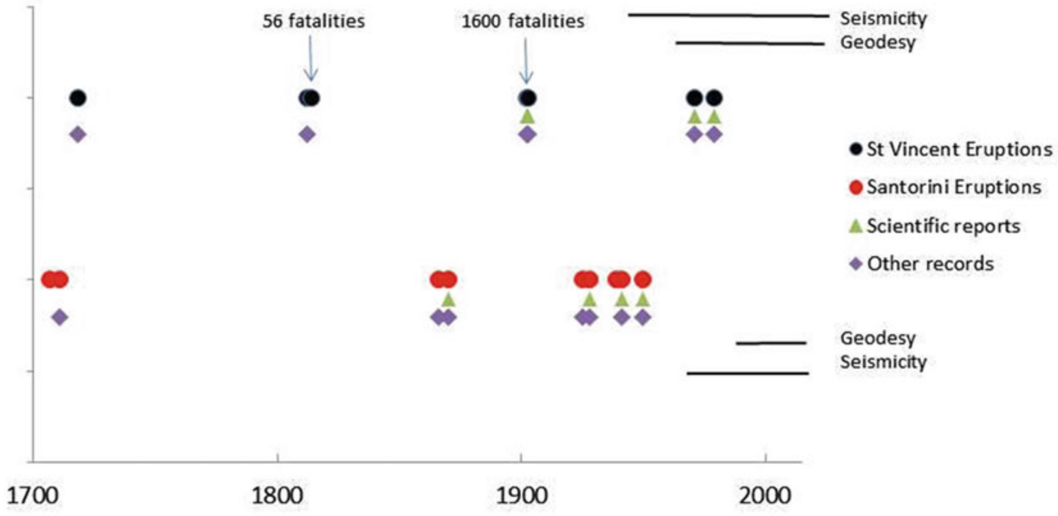

Fig. 1 Summary timeline of eruptions of the Kameni islands, Santorini, and the Soufriere, St. Vincent, since 1700 AD, showing those events for which contemporary records (including newspaper reports, or sketches, or diaries, or official reports) and scientific reports exist. In contrast to the ca. 300 year-long record of contemporary observations, the scientific instrumental monitoring record (e.g. seismicity, or ground deformation/geodesy) is much shorter. There are no systematic instrumental monitoring records of the most significant eruptions of either system (1902–3 eruption of St. Vincent; 1866–1870 eruptions of Santorini)

Box 1: The 1707 eruption of Nea Kameni, Santorini

Excerpt from Gorée Fr (1710) ‘A relation of a new island, which was raised up from the bottom of the sea on the 23rd of May 1707, in the Bay of Santorin, in the Archipelago’.

‘Five days before it appeared, viz on the 18th of May between one and two of the clock in the afternoon, there was at Santorini an earthquake, which was not violent and continued but a moment; and in the night between the 22nd and 23rd there was also another, which was yet less sensible

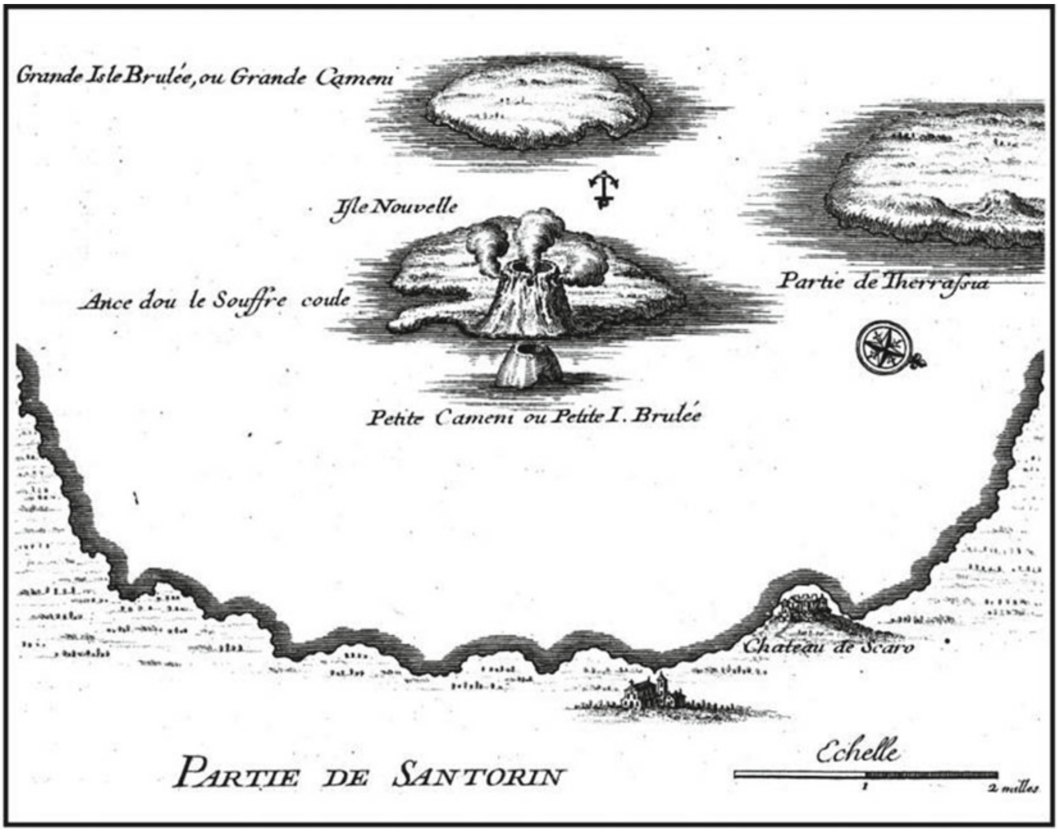

Fig. 2 Map of the Santorini caldera, showing the Kameni islands during the eruption of 1707–1711. The Ile Nouvelle (new island) is the lava dome and flow formed during the 1707 eruption. This now forms a part of the island of Nea Kameni. From Tarillon (1715)

> than the former […] Add to this, that a long time before the earthquakes the fishermen perceived an ill smell every time they passed by that place […] Notwithstanding it is very certain that there have not been any other earthquakes at Santorini than those which, 14 or 15 years ago, continued for several days and were very violent. However it was, some seamen discover'd this island early in the morning, but not being to distinguish what it was they imagined it to be some sort of vessel that had suffered shipwrack.
>
> The smoak appeared first upon the 16th of July: at which time there rose up a ridge of black stones and which was afterwards not only the centre of the while island, but also of the fire, and smoke and great noise that was heard some time after. The smoak which issued out of this ridge of stones […] was very thick and white.'

4.2 Eruption Progress

Work on the Kameni islands since the mid-1800s documenting both the nature of eruptions and the petrology of the erupted products meant that by the early 21st century, volcanologists were able to develop a simple but detailed conceptual model of what a future eruption might look like. The key factors that fed into the model were:

- The observations that the compositions of the erupted products, and the style of eruption

have varied very little over the past 500 years (e.g. Nicholls 1971);
- The observation that many of these eruptions may have been 'triggered' by the influx of hot, volatile-rich magma some short time before (e.g. Higgins 1996; Martin et al. 2006);
- The observation that there is an apparent linear relationship between the period elapsed since the last eruption, and the volume erupted in the next eruption (Pyle and Elliott 2006).

This led to the hypothesis that the next eruption of the Kameni islands would be preceded by 'general uplift of the edifice and discoloration of the sea, and anticipated some days to weeks in advance. The eruption would involve the early formation of lava domes, which would later act as a focus for vigorous, intermittent explosive activity' (Pyle and Elliott 2006, p. 266).

The recognition of a relationship between eruption length and the interval between eruptions for the last 4 large eruptions of the Kameni islands, consistent with a model of a constant time-averaged deep supply of magma, also meant that it was possible to forecast the duration of a future eruption. While this analysis is entirely empirical—based on collation of observations from eruptions over the past 300 years—this approach is typical of the way in which much modern volcanology still operates; this analysis would not have been possible without the depth and breadth of contemporary descriptive materials accompanying the historical eruptions.

4.3 Precursors

Although the eruption record of the Kameni islands is well known, the record of anything that may have happened in between eruptions is almost non-existent. We know of precursors, or pre-eruption changes, for several eruptions (see Box 1), but apart from a mention of an earthquake swarm a few years prior to the 1707 eruption, there are no known reports or records of any sort of unrest that wasn't subsequently followed by an eruption. This lack of evidence for 'precursory behaviour that didn't culminate in an eruption' (non-eruptive unrest) is likely to be a common feature of many volcanic systems (Moran et al. 2011)—and likely to explain the poor correlation between 'run up' and eruption scale that is evident in the most recent analysis of these sorts of datasets (e.g. Passarelli and Brodsky 2012).

The lack of documented non-eruptive unrest and the volcanological model for 'the next eruption' was brought into sharp relief in 2011, with the start of the first modern volcano-seismic crisis on Santorini since the eruption of 1950. In January 2011, the first small earthquakes located within the caldera were detected by the local seismic network. This was clearly anomalous, since most of the detected seismicity in the region since systematic measurements began in the late 1980s has been associated with structures *outside* the caldera, most notably the submarine Kolombos volcano (Dimitriadis et al. 2005; Nomikou et al. 2012).

The event was readily identifiable as a period of volcano-seismic unrest, due to localisation of shallow earthquakes along a well-known fault system thought to have been responsible for the delivery of magma to the surface during previous eruptions; and from the patterns of uplift and ground deformation detected from the network of continuous GPS instruments and analysis of satellite radar interferograms (e.g. Newman et al. 2012; Parks et al. 2012). Later, field evidence also showed changes in the nature of the diffuse degassing around the summit craters. In early 2012, the authorities convened a Special Scientific Committee for the Monitoring of Santorini Volcano, and oversaw the deployment of a host of new instruments across and around Santorini, but fairly soon the unrest came to an end and nothing further happened (Aspinall and Woo 2014). No formal notice of the unrest was declared by the authorities until the event was effectively over (see Vougioukalakis et al. 2016), and although there are now a dozen or more scientific papers describing these events, there was no eruption and there is no record of the event in the Smithsonian Institution's Global

Volcano Programme dataset or associated reports.

Best estimates of the scale of the magmatic anomaly associated with the 2011–2012 unrest suggest that the shallow magmatic pressure source increased in volume by ca. 14–23 million cubic metres (Parks et al. 2015); equivalent to a couple of decade's worth of 'steady state magma accumulation'. This presents a challenge to the previous consensus model for the volcano: here was evidence for a large, shallow intrusion which did not lead to eruption. Whether this is the typical behaviour of the system, or not, is something that cannot yet be determined—because although the rich documentary record of past events furnishes us with the evidence for how the next eruption *might* proceed, it provides us with no information, one way or the other, about the frequency and style of episodes of unrest. However, the episode of unrest has stimulated new work on conceptual physical models for repeated eruptions driven by pressurisation and failure of the shallow magma reservoir by intrusion (e.g. Browning et al. 2015; Degruyter et al. 2016), and stimulated retrospective analysis of bathymetric maps, that chart the ups and downs of the volcano since the 1850s (Watts et al. 2015). The unrest has also opened up a public discussion of how the scientific community, civil defence and local authorities should plan for a future crisis; including how to manage hazards, risk and communications (Vougioukalakis et al. 2016).

4.4 The Soufrière, St. Vincent

The Soufrière, St. Vincent, is another example of a lava-dome forming volcano in a subduction-zone setting. In contrast to the Kameni islands, recent and historical eruptions of St. Vincent have been of a more mafic magma (basaltic andesite, rather than dacite), and eruptions have tended to be significantly more explosive than those of the Kameni islands, with much more serious consequences (Fig. 1; Table 2). Below, we briefly introduce the chronology of the St. Vincent eruptions, and their broader consequences, before discussing the challenges for the future.

4.5 Eruptive History and Impacts

St. Vincent lies in the eastern Caribbean, and is one of the southern islands of the Lesser Antilles Arc. The eruptive history of the presently active volcano—the Soufrière, a complex of craters at the top of the Morne Garou—is not well known prior to about 1700. Since then, St. Vincent has

Table 2 Historical activity of the Soufrière, St. Vincent

Date	Notes	Phenomena
	Summit crater is dry, with an exposed lava dome	
13 April–October 1979	Explosive eruptions, and dome extrusion	P, E, L
17 May 1971–1972	Minor effusive eruption	L
	Summit crater is water filled	
6 May 1902–1903	Major explosive eruptions	P, E
1880	Crater lake level increases, temperatures rise	
	Summit crater is water filled	
1814	Possible minor eruption	E?
27 April–6 May 1812	Major explosive eruption	P, E
ca. 1784?	Possible minor eruption	L?
26 March 1718	Major explosive eruption	P, E

P precursor seismicity; *E* explosive eruption; *L* lava dome Compiled from Shepherd (1831), Anderson and Flett (1903), Robertson (1995) and Richardson (1997) experienced four major explosive eruptions, and at least one minor dome-forming eruption (Fig. 1; Table 2; Robertson 1995). Eruptions in 1718, 1812 and 1902–3 each had major consequences for the northern sectors of the island—with widespread tephra fallout, explosive ejection of ballistic blocks, column-collapse pyroclastic density-currents, and lahars deposited across or coursing down the flanks of the volcano. Each of these explosive eruptions led to significant ash fallout across other islands of the Caribbean; notably Barbados.

The eruptions of 1812 (at least 56 fatalities; Robertson 1995) and 1902–3 (1600 fatalities) were severe, with much damage to properties, many associated with the sugar plantations in the northern parts of the island; and deaths in the communities which provided labour for those plantations (Anderson and Flett 1903; Smith 2011; Pyle et al. 2017). The details of the social and economic consequences of these eruptions can be reconstructed in an extraordinarily fine-grained way, principally because of the preservation of official correspondence and reports from the time in colonial archives (Gullick 1985; Smith 2011; Richardson 1997; Pyle et al. 2017).

There are no known reports, however, of the consequences of the explosive eruption of 1718 for the inhabitants of St. Vincent. The only written record of the eruption was gathered from the descriptions of European mariners, and published anonymously in a pamphlet that declared ‘the entire desolation of the island of St. Vincent’, and that ‘the island was no more’ (Box 2; Defoe 1718). This account was not mentioned by Shepherd (1831) in his history of St. Vincent, even though by that time the 1718 eruption would have been well known to natural historians from the works of de Humboldt and Bonpland (1825).

Box 2: The 1718 eruption of St. Vincent

Daniel Defoe ‘The destruction of St. Vincent’ from Mist’s Journal, July 5, 1718.

‘On the 27th [March] in the morning the air was darkened in a dreadful manner; which darkness by all accounts seems to have extended over all the colonies and the islands which were within 100 miles of the place […] The sum of [reports from ships] ‘they saw in the night that terrible flash of fire and after that innumerable clashes of thunder […] a thousand times as loud a thunder or cannon. As the day came on, still the darkness increased.

In the afternoon they were surprised with the falling upon them as thick as smoke, but fine as dust and yet solid as sand; this fell thicker and faster as they were nearer or farther off—some ships had it nine inchers, others a foot thick, upon their decks. The island of Martinico is covered with it at about seven to nine inches thick; at Barbadoes it is frightful, even St. Christopher’s is exceeded four inches’.’

The eruption of April–May 1812 and its consequences were recorded in detail in a range of primary contemporary sources (letters and diaries) and published reports and accounts (see Smith 2011, for a detailed analysis). The diaries and reports of a British barrister and plantation owner, Hugh Perry Keane (Box 3) are thought to also have provided the materials for *The Times* leader story on the eruption, published six weeks later in late June (Smith 2011). Keane’s sketches of the eruption were later used by JMW Turner to inform his 1815 painting of the volcano in eruption. One notable feature of this eruption is the contrast between the published accounts that stress the ‘dreadful’ scale of the eruption, and the apparent light loss of life (Smith 2011). Estate owner Alexander Cruikshank wrote that ‘there has [not] been so violent an Eruption recorded since the destruction of Herculaneum and Pompeii’ (Blue Book 1813, p. 4), and a committee of landowners petitioned the Crown for compensation, on the basis that these ‘distressed Memorialists [had suffered a] severe visitation of Divine

Providence… unexampled in any of His Majesty's dominions for much more than a century' (Blue Book 1813, p. 9). These accounts were presumably motivated by a desire for financial recompense, and stress the physical impacts of the eruption on their crops, estate lands and property. In contrast, the same reports are very thin on the consequences of the eruption either for their enslaved workers (one sugar estate owner appended the brief statement 'but most providentially not many lives were lost'; Blue Book 1813, p. 4), or for the island's native residents. Reports suggest that many people from the Carib communities who lived around the flanks of the volcano evacuated spontaneously within a couple of days of the eruption starting, but before the eruption reached a climax (Blue Book 1813; Smith 2011). It is not known whether this reflected a response based on oral histories of prior eruptions; or that the effects of the tremor and tephra fallout had become intolerable.

Box 3: The 1812 eruption of St. Vincent Excerpts from the diary of Hugh Perry Keane [Virginia Historical Society mss1 k197 a23], transcribed in Smith (2011), Hamilton (2012) and Pyle (2017).

Weds 29 [April] Then to see the Soufrier, involved in dark clouds and vomiting black sands. Landed at Wallilabou. Spent the evening in contemplation of the volcano, and slept there.

Thurs 30th in the afternoon the rousing of the Mountain increased and at 7 o'clock the flames burst forth and the dreadful eruption began. All night watching it between 2 and 5 o'clock in the morning showers of stones and earthquakes threatened our immediate destruction.

May 1 The day did not give light till nearly 9—the whole island involved in gloom. The mountain was quiet all night.

May 2 Rose at 7, Drawing up my narrative for the register.

Sun 3rd Rose at 7 and after gathering some Bfast… Proceeded to Wallibu—strange and dismal sight, the river dried up and the land covered with cinders and sulphur. Morne Ronde Hid in smoke and ashes—the track covered with trees and a new formation given to it—burnt carcasses of cattle lying everywhere.

Mon: 4 rose at 6 and took a cup of coffee… and returned to town. Kingston in great confusion.

Wed 6 the volcano again blazed away from 7 till 1/2 past 8.

The catastrophic eruptions of 1902–3, in which about 1600 people were killed, left dense records of official and other communications during both the immediate crisis, and the relief and recovery efforts (Blue Book 1903, 1904; Anderson and Flett 1903). Eyewitness accounts of the build up to the eruption again suggest that significant numbers of people from communities living on the flanks of the volcano evacuated spontaneously during the 24 h before it reached a climax (Pyle et al. 2017). Indeed, by the time the scale of the eruption became apparent to colonial officials in Kingstown, telephone lines to the north of the island had already been interrupted and submarine telegraph lines from St. Vincent to the neighbouring island of St. Lucia had been severed (Report of Edward Cameron, Administrator; Blue Book 1903). A combination of the infrastructure of the Colonial Government; the relative ease of international communication (telegrams) and the coincidence of the devastating eruption of Mont Pelée, Martinique, just one day after the eruption of the Soufrière of St. Vincent meant that these two volcanic disasters in the Caribbean attracted world-wide interest at the time, and a rapid international relief effort (Pyle et al. 2017). Scientists and journalists arrived with some of the relief boats, and dramatic reports of the aftermath of the eruption were soon widely available (e.g. Russell 1902; Morris 1903; Anderson 1903; Hovey 1903a, b). Since that time, though, little of this material has been re-considered by volcanologists; and a full analysis of both the entire eruption sequence, and the recovery process has yet to be completed.

Fig. 3 Sketch map of the summit crater of the Soufrière of St. Vincent in 1784, showing a steaming lava dome (*top*, *centre*) within a steep-sided summit crater, flanked by two small crater lakes (Anderson and Yonge 1785). The image was drawn by Frederick Nodder, from a sketch by J. Anderson. Image RS 9780, Map of Morne Garou, reproduced by permission of the Royal Society

In between these eruptions, each of which were preceded by many months of felt seismicity in areas close to the volcano, there may well have been other small to moderate eruptions which were non-explosive, and which produced few noticeable consequences—whether in terms of detectable seismicity, or other manifestations. There has been speculation that an eruption in 1784 formed a lava dome which was subsequently described after the first known ascent by a European in late 1784. Anderson, who was then keeper of the newly established Botanic Station on St. Vincent, describes the nature of the crater in detail, along with a sketch map of the summit area (Fig. 3). This can readily be interpreted as a lava dome with actively degassing fumaroles—not greatly different from the current status of the dome, which extruded in 1979.

During the ‘modern era’ there were two eruptions of St. Vincent, both of which were

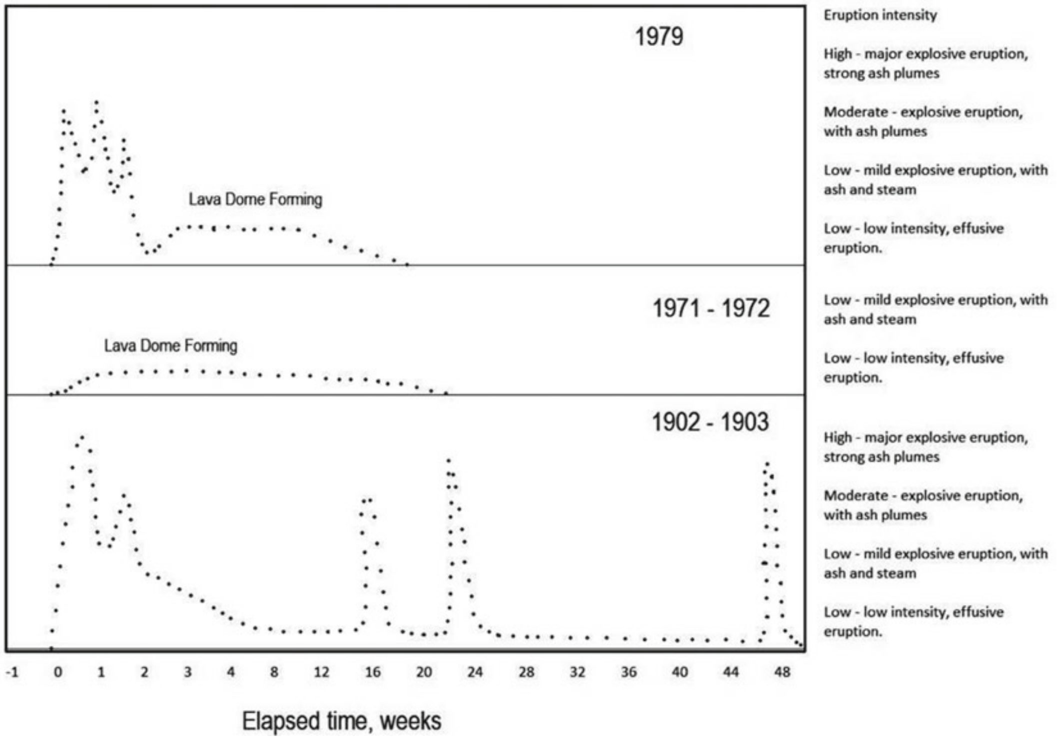

Fig. 4 Schematic timelines of the eruptive sequences at St. Vincent for each of the last 3 eruptions, based on contemporary reports (Blue Book 1902, 1903; Aspinall et al. 1973; Shepherd and Aspinall 1982; Shepherd and Sigurdsson 1982)

closely observed and documented. In 1971–1972 a ‘quiet’ effusive eruption led to the emplacement of a lava dome within the summit crater-lake. This was followed, just 8 years later, by a short but violent series of explosive eruptions (from April 13–26, 1979), followed by six months of the emplacement of a lava dome (Aspinall et al. 1973; Shepherd et al. 1979; Shepherd and Sigurdsson 1982; Huppert et al. 1982).

4.6 Challenges for the Future

In the context of anticipating future events, the detailed records of these past eruptions and their timelines (Fig. 4), would certainly inform the development of future eruption scenarios. But our understanding of the nature of any precursors is, as with the case of Santorini, rather limited, with just the two most recent eruptions having any instrumental monitoring record—the first of which made barely a trace in terms of detectable precursory seismicity (Aspinall et al. 1973).

Each of the last four explosive eruptions were preceded by felt earthquakes in the north of the island; each of the eruptions for which the crater was flooded also showed short-timescale changes in the nature of the lake waters. There are no quantitative data on the nature of any pre-eruption gas emissions, since the most recent eruptions in 1979 occurred only just in time for the satellite monitoring era (Carn et al. 2016), and before the widespread adoption of volcanic gas measurement technologies. Nonetheless, there have been local crises on St. Vincent triggered by the appearance of sulfurous odors and haze. The most recent of these events occurred in mid-February 2005, and was detected both on the island of St. Vincent and on the Grenadines (50–75 km S). In the event, Seismic Research Unit scientists and the Soufrière Monitoring Unit determined that the cause of the event was purely meteorological in origin: the typical winds in the area take the fumarole emissions out to sea, and this event was ascribed to an unusual wind field (Weekly Report, Smithsonian Global Volcanism Project, March 2005).

5 A 'Typology' for Volcanoes?

Until we have accumulated a few more decades of instrumental monitoring and global survey data for both restless and erupting volcanoes, volcanologists will of necessity have to fall back on the empirical approach of trying to understand how individual volcanoes might behave in the lead up to a future eruption. With larger and longer-term datasets, we should soon be able to make progress developing quantitative 'typologies' of volcano behaviour (c.f. Hone et al. 2007; Grosse et al. 2014), and also to test whether the concept of an 'eruption cycle' for volcanoes can usefully be developed and applied more generally (e.g. Luhr and Carmichael 1980; Luhr 2002; Pyle et al. 2013).

Until that time, statistical approaches to managing both long-term activity and poorly-constrained future activity might best be developed by building on the 'evidence-based learning' approaches to managing volcanic unrest developed by Aspinall and others, (Aspinall et al. 2003; Aspinall 2012; Hicks et al. 2014). This approach has been widely used on Montserrat as an element of the regular external scrutineering of the state of the volcano. Advances in machine learning and the use of the 'crowd' to harness the potential of citizen science volunteer communities for collecting, analysing and interpreting digital data of all sorts (both structured, and unstructured; quantitative and qualitative) have already begun to make an impact in the area of rapid disaster response (e.g. Ramchurn et al. 2015). The new field of 'human agent interaction' offers significant potential for developing new ways of converting contextual information on past volcanic events (including that currently buried in archives) into a form that can be used to develop and test conceptual and quantitative models of hazard and risk; and as a way of beginning to analyse the networks of people, agencies and organisations affected by or responding to volcanic events.

Both approaches have the potential to deepen understanding of what happens to volcanoes when they enter into a new phase of unrest or eruption, and to aid the detection and diagnosis of these changes in time-series of observations. They also have potential to feed into the processes of communication of hazards and risk, by providing a framework within which to understand the parallels between volcanoes. For example, connecting with the narratives of past events at a re-activating volcano, or of past hazard events at a volcano with shared characteristics, will be important elements in helping to frame discussions and decision-making processes about how to prepare for and mitigate the effects of a future event.

6 Conclusions

To make the best use of evidence-based approaches to the management of emerging volcanic unrest, volcanologists would benefit from making fuller use of the wider contextual 'data' that may exist that documents the consequences of prior volcanic activity, or unrest, at that volcano. Retrospective analysis both of the formal scientific literature, and reading of a wider range of contemporary sources that document the broader personal, social, economic and political impacts of prior events will enrich and add to our capacity to anticipate, prepare for and mitigate the consequences of future events; and to advance the ways in which these learnings may be communicated.

Acknowledgements This work has been supported by the NERC-ESRC funded STREVA project, 'strengthening resilience in volcanic areas', and has benefitted enormously from discussions with Jenni Barclay, Teresa Armijos Burneo, Paul Cole, Anna Hicks, Chris Kilburn, Sue Loughlin, Tamsin Mather, Richie Robertson, Mel Rodgers, Simon Smith, Jon Stone, Caroline Williams, Emily Wilkinson and many others. I thank St. Anne's College and the University of Oxford for permitting a period of sabbatical leave; Cambridge University Library, the Bodleian Libraries, Oxford, and the British Library for access to their archives; the Bodleian Libraries

Exhibitions Team for providing a creative outlet and focus for some of this work; and Carina Fearnley and the editors for their patience.

References

Anderson A, Yonge G (1785) An account of Morne Garou, a Mountain in the Island of St. Vincent, with a description of the volcano on its summit. Phil Trans R Soc London 75:16–31

Anderson T (1903) Volcanic studies in many lands. John Murray, London, p 202

Anderson T, Flett J (1903) Report on the eruptions of the Soufriere, in St. Vincent, in 1902, and on a visit to Montagne Pelée, in Martinique. Part I. Phil Trans R Soc London A 200:353–553

Aspinall WP (2006) Structured elicitation of expert judgement for probabilistic hazard and risk assessment in volcanic eruptions. In: Mader HM et al (eds), Statistics in volcanology, IAVCEI Proc Volcanol 1:15–30

Aspinall WP (2012) Comment on "Social studies of volcanology: knowledge generation and expert advice on active volcanoes" by Amy Donovan, Clive Oppenheimer and Michael Bravo. Bull Volcanol 74:1569–1570

Aspinall WP, Woo G (2014) Santorini unrest 2011–2012: an immediate Bayesian belief network analysis of eruption scenario probabilities for urgent decision support under uncertainty. J Appl Volcanol 3:12

Aspinall WP, Sigurdsson H, Shepherd JB (1973) Eruption of Soufriere volcano on St. Vincent Island, 1971–1972. Science 181:117–181

Aspinall WP, Loughlin SC, Michael FV et al (2002) The Montserrat volcano observatory: its evolution, organization, role and activities. In: Druitt TH, Kokelaar BP (eds) The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, Geol Soc London Mem 21:71–92

Aspinall WP, Woo G, Voight B, Baxter PJ (2003) Evidence-based volcanology: application to eruption crises. J Volcanol Geotherm Res 128:273–285

Barclay J, Haynes K, Mitchell T, Solana C, Teeuw R, Darnell A, Crosweller HS, Cole P, Pyle D, 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. In: Liverman DGE, Pereira CPG, Marker B (eds) Communicating environmental geoscience, Geol Soc London Spec Pub 305:163–177

Barclay J, Haynes K, Houghton B, Johnston D (2015) Social processes and volcanic risk reduction. In: Sigurdsson H et al (eds) The encyclopedia of volcanoes, 2nd ed, pp 1203–1214

Biggs J, Ebmeier SK, Aspinall WP et al (2014) Global link between deformation and volcanic eruption quantified by satellite imagery. Nat Comms 5:3471

Blong RJ (1982) The time of darkness. University of Washington Press, USA, 242 pp

Blong RJ (1982) The time of darkness: local legends and volcanic reality in Papua New Guinea. University of Washington Press, Seattle

Blue Book (1813) Report from committee on petition of persons interested in estates in the Island of Saint Vincent. Parliamentary paper by command 182, house of commons, London

Blue Book (1903) Correspondence relating to the volcanic eruptions in St. Vincent and Martinique in May 1902, with map and appendix. parliamentary paper by command 1201, HMSO, Darling and Son, London

Blue Book (1904) Further correspondence relating to the volcanic eruptions in St. Vincent and Martinique in 1902 and 1903. Parliamentary paper by command 1783, HMSO, Darling and Son, London

Browning J, Drymoni K, Gudmundsson A (2015) Forecasting magma-chamber rupture at Santorini volcano, Greece. Sci Rep 5:15785

Carn SA, Clarisse L, Prata AJ (2016) Multi-decadal satellite measurements of global volcanic degassing. J Volcanol Geoth Res 311:99–134

Chester DK, Duncan AM, Wetton P, Wetton R (2007) Responses of the Anglo-American military authorities to the eruption of Vesuvius, March 1944. J Hist Geogr 33:168–196

Chester DK, Duncan A, Kilburn C, Sangster H, Solana C (2015) Human responses to the 1906 eruption of Vesuvius, southern Italy. J Volcanol Geoth Res 296:1–18

da Corogna L (1867) De l'influence des emanations volcaniques sur les etres organises, particulierement etudiée a Santorin pendant l'eruption de 1866. Adrien Delahaye, Paris (In French)

D'Arcy Wood G (2014) Tambora: the eruption that changed the world. Princeton University Press, USA, 312 pp

Defoe D (1718) An account of the island of St. Vincent in the West Indies and of its entire destruction on the 26th March last, with some rational suggestions concerning the causes and manner of it. Mist's Wkly J, Issue 82, July 5. [Reprinted in Aitken, ed., 1895, Romances and Narratives vol. 15]

Degruyter W, Huber C, Bachmann O, Cooper KM, Kent AJR (2016) Magma reservoir response to transient recharge events: the case of Santorini Volcano (Greece). Geology 44:23–26

Dimitriadis IN, Panagiotopoulos DG, Papazachos CB et al (2005) Recent seismic activity (1994–2002) of the Santorini volcano using data from local seismological network. In: Fytikas M, Vougioukalakis GE (eds) South Aegean Volcanic Arc, Dev Volcanol 7:185–203

Dominey-Howes D, Minos-Minopoulos D (2004) Perceptions of hazard and risk on Santorini. J Volcanol Geotherm Res 137:285–310

Donovan AR, Oppenheimer C, Bravo M (2012) Social studies of volcanology: knowledge-generation and expert advice on active volcanoes. Bull Volcanol 74:677–689

Donovan A, Oppenheimer C, Bravo M (2014) Reflexive volcanology: 15 years of communicating risk and uncertainty in scientific advice on Montserrat. In: Wadge G, Robertson REA, Voight B (Eds), Eruption of Soufrière hills volcano, Montserrat from 2000 to 2010, Geol Soc London Mem 39:457–470

Druitt TH, Edwards L, Mellors RM et al (1999) Santorini Volcano. Geol Soc London Mem 19:1–178

Druitt TH, Kokelaar BP (eds) (2002) Eruption of Soufrière hills volcano, Montserrat from 2000 to 2010. Geol Soc London Mem 39:457–470

Fouqué F (1879) Santorin et ses éruptions. Masson et compagnie, Paris (In French)

Fytikas M, Kolios N, Vougioukalakis G (1990) Post-Minoan activity of the Santorini volcano: volcanic hazard and risk, forecasting possibilities. In: Hardy DA, Keller J, Galanopoulos VP et al (eds) Thera and the Aegean world III, vol 2. The Thera Foundation, London, pp 183–198

Georgalas GC (1953) L'éruption du volcan de Santorin en 1950. Bull Volcanol 13:39–55

Georgalas GC, Papastamatiou J (1951) Uber den Ausbruch des Santorinvulkanes von 1939–1941. Der Kténas Ausbruch. Bull Volcanol 11:1–37

Gorée F (1710) A relation of a new island, which was raised up from the bottom of the sea on the 23rd of May 1707, in the Bay of Santorin, in the Archipelago. Phil Trans Roy Soc London 27:354–375

Gouin P (1979) Earthquake history of Ethiopia and the Horn of Africa. IDRC, Ottawa, vol 118, 259 pp

Grosse P, Euillades PA, Euillades LD, van Wyk de Vries B (2014) A global database of composite volcano morphometry. Bull Volcanol 76:784

Gullick CJMR (1985) Myths of a minority: the changing traditions of the Vincentian Caribs. Studies of Developing Countries, vol 30, van Gorcum, Assen, Netherlands

Hamilton J (2012) Volcano: nature and culture. Reaktion books, London, p 208

Haynes K, Barclay J, Pidgeon N (2007) Volcanic hazard communication using maps: an evaluation of their effectiveness. Bull Volcanol 70:123–238

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. Nat Hazards Earth Syst Sci 14:1871–1887

Hicks A, Few R (2015) Trajectories of social vulnerability during the Soufrière Hills volcanic crisis. J Applied Volcanol 4:10

Higgins MD (1996) Magma dynamics beneath Kameni volcano, Thera, Greece, as revealed by crystal size and shape measurement. J Volcanol Geotherm Res 70: 37–48

Hincks TK, Komorowski J-C, Sparks RSJ, Aspinall WP (2014) Retrospective analysis of uncertain eruption precursors at La Soufrière volcano, Guadeloupe, 1975–77: volcanic hazard assessment using a Bayesian Belief Network approach. J Appl Volcanol 3:3

Hone DWE, Mahoney SH, Sparks RSJ, Martin KT (2007) Cladistic analysis applied to the classification of volcanoes. Bull Volcanol 70:203–220

Hooper A, Prata F, Sigmundsson F (2012) Remote sensing of volcanic hazards and their precursors. Proc IEEE 100:2908–2930

Hovey EO (1903a) An American report upon the West Indian eruptions. Nature 67:256–259

Hovey EO (1903b) Bibliography of literature of the West Indian eruptions published in the United States. Bull Geol Soc America 15:562–566

de Humboldt A, Bonpland A (1825) Personal narratives of travels to the equinoctial regions of the new continent during the years 1799–1804, 2nd ed, Translated by Williams HM, vol 4. Longman et al, London, p 573

Huppert HE, Shepherd JB, Sigurdsson H, Sparks RSJ (1982) On lava dome growth, with application to the 1979 lava extrusion of the Soufrière of St. Vincent. J Volcanol Geotherm Res 13:119–130

Hutchison AA, Cashman KV, Williams CA, Rust AC (2016) The 1717 eruption of Volcán de Fuego, Guatemala: cascading hazards and societal response. Quatern Int 394:69–78

Jenkins SF, Barsotti S, Hincks TK, Neri A, Phillips JC, Sparks RSJ, Sheldrake T, Vougioukalakis G (2015) Rapid emergency assessment of ash and gas hazard for future eruptions at Santorini Volcano, Greece. J Appl Volcanol 4:16

Johnson RW (2013) Fire mountains of the islands—a history of volcanic eruptions and disaster management in Papua New Guinea and the Solomon Islands. Australian National University ePress, Australia

Lipman PW, Mullineaux DR (eds) (1981) The 1980 eruptions of Mount St. Helens, Washington, US geological survey professional paper 1250, 844 pp

Loughlin SC, Sparks RSJ, Brown SK, Jenkins SF, Vye-Brown C (2015) Global Volcanic hazards and risk. Cambridge University Press, UK, 410 pp. doi:10.1017/CBO9781316276273

Luhr JF, Carmichael ISE (1980) The colima volcanic complex, México: part I. Post-caldera andesites from Volcán Colima. Contrib Mineral Petrol 71:343–372

Luhr JF, Simkin T (1993) Paricutín: the volcano born in a Mexican cornfield. Geoscience Press, Phoenix, Arizona, p 427

Luhr JF (2002) Petrology and geochemistry of the 1991 and 1998–1999 lava flows from Volcán de Colima, México: implications for the end of the current eruptive cycle. J Volcanol Geotherm Res 117:169–194

Marinatos S (1939) The volcanic destruction of minoan crete. Antiquity 13:425–439

Martin VM, Holness MB, Pyle DM (2006) Textural analysis of magmatic enclaves from the Kameni islands, Santorini, Greece. J Volcanol Geotherm Res 154:89–102

Milham WI (1924) The year 1816—the causes of abnormalities. Mon Weather Rev 52:563–570

Moran SC, Newhall C, Roman DC (2011) Failed magmatic eruptions: late-stage cessation of magma ascent. Bull Volcanol 73:115–122

Morris C (1903) The volcano's deadly work: from the fall of Pompeii to the destruction of St. Pierre, WE Scull, 448 pp

Newhall CG, Punongbayan RS (Eds) (1996) Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines, University of Washington Press, USA, 1126 pp

Newman AV, Stiros S, Feng L et al (2012) Recent geodetic unrest at Santorini Caldera, Greece. Geophys Res Lett 39:L06309. doi:10.1029/2012GL051286

Nicholls IA (1971) Petrology of Santorini volcanic rocks. J Petrol 12:67–119

Nomikou P, Carey S, Papanikolaou D et al (2012) Submarine volcanoes of the Kolumbo volcanic zone NE of Santorini Caldera, Greece. Global Planet Change 90–91:135–151

Nomikou P, Parks MM, Papanikolaou D et al (2014) The emergence and growth of a submarine volcano: the Kameni islands, Santorini, Greece. GeoResJ 1–2:8–18

Oppenheimer C (2011) Eruptions that shook the world. Cambridge University Press, USA, 392 pp

Oppenheimer C (2015) Eruption politics. Nat Geosci 8:244–245

Parks MM, Biggs J, England P et al (2012) Evolution of Santorini Volcano dominated by episodic and rapid fluxes of melt from depth. Nat Geosci 5:749–754

Parks MM, Moore J, Papanikolaou X, Biggs J, Mather TA, Pyle DM, Raptakis C, Paradissis D, Hooper A, Parsons B, Nomikou P (2015) From quiescence to unrest—20 years of satellite geodetic measurements at Santorini volcano, Greece. J Geophys Res 120:1309–1328

Passarelli L, Brodsky EE (2012) The correlation between run-up and repose times of volcanic eruptions. Geophys J Int 188:1025–1045

Perret FA (1924) The Vesuvius eruption of 1906: study of a volcanic cycle, Carnegie Institution of Washington, USA, 151 pp

Petit-Breulh Sepúlveda ME (2004) La historia eruptiva de los volcanes hispanoamericanos (siglos XVI al XX): el modelo Chileno. Casa de las Volcanes 8, Cabildo de Lanzarote

Petit-Breulh Sepúlveda ME (2006) Naturaleza y desastres en Hispanoamérica. La visión de los Indíginas, Silex Ediciones, Madrid, p 160

Post J (1977) The last great subsistence crisis. The Johns Hopkins University Press, Baltimore, p 256

Pyle DM, Elliott J (2006) Quantitative morphology, recent evolution, and future activity of the Kameni Islands volcano, Santorini, Greece. Geosphere 2:253–268

Pyle DM, Mather TA, Biggs J (2013) Remote sensing of volcanoes and volcanic processes: integrating observation and modelling—introduction. In: Pyle DM, Mather TA, Biggs J (eds) Remote sensing of volcanoes and volcanic processes: integrating observation and modelling, Geol Soc London Spec Pub 380:1–13

Pyle DM (2016) Field observations of tephra fallout deposits. In: Cashman K, Ricketts H, Rust A, Watson M, Mackie S (eds) Volcanic Ash: Hazard Observation. Elsevier, Netherlands, pp 25–37

Pyle DM (2017) Volcanoes: encounters through the ages. Bodleian Publishing, England, 224 pp

Pyle DM, Barclay J, Armijos MT (2017) The 1902–3 eruptions of the Soufrière, St. Vincent: impacts, relief and response. J Hist Geogr (in review)

Ramchurn SD, Wu F, Jiang W, Fischer J, Reece S, Roberts S, Rodden T, Greenhaigh C, Jennings NR (2015) Human-agent collaboration for disaster response. J Auton Agents Multi-Agent Syst 30:82–111

Reck H (ed) (1936) Santorin. Das Werdegang eines Inselvulkans und sein Ausbruch, 1925–1928. Ergebnisse einer deutsch-grieschischen Arbeitgemeinschaft. Berlin. 3 vols. (In German)

Richardson BC (1997) Economy and environment in the Caribbean: Barbados and the Windwards in the late 1800s. Univ West Indies Press, West Indies

Robertson REA (1995) An assessment of the risk from future eruptions of the Soufrière volcano of St. Vincent, West Indies. Nat Hazards 11:163–191

Russell IC (1902) The recent volcanic eruptions in the West Indies. Nat Geogr Mag 13:267–285

Scarpa R, Tilling RI (1996) Monitoring and mitigation of volcano hazards. Springer, Berlin, p 841

Self S, Rampino MR, Newton MS, Wolff JA (1984) Volcanological study of the great Tambora eruption of 1815. Geology 12:659–663

Self S, Gertisser R (2015) Tying down eruption risk. Nat Geosci 8:248–250

Shepherd C (1831) An historical account of the island of Saint Vincent. W Nicol, London

Shepherd JB, Aspinall WP (1982) Seismological studies of the Soufrière of St. Vincent, 1953–1979: implications for volcanic surveillance in the Lesser Antilles. J Volcanol Geotherm Res 12:37–55

Shepherd JB, Aspinall WP, Rowley KC et al (1979) The eruption of Soufrière volcano, St. Vincent, April–June 1979. Nature 282:24–28

Shepherd JB, Sigurdsson H (1982) Mechanism of the 1979 explosive eruption of Soufrière volcano, St. Vincent. J Volcanol Geotherm Res 13:119–130

Siebert L, Simkin T, Kimberly P (2010) Volcanoes of the world, 3rd edn. University of California Press, Berkeley

Simkin T, Fiske RS (1983) Krakatau 1883: the volcanic eruption and its effects. Smithsonian Institution Press, Washington, DC, p 464

Smith SD (2011) Volcanic hazard in a slave society: the 1812 eruption of Mount Soufrière in St. Vincent. J Hist Geogr 37:55–67

Stommel H, Stommel E (1983) Volcano weather: the story of 1816, the year without a summer. Seven Seas Press, Newport RI, 177 pp

Stothers RB, Rampino MR (1983) Volcanic eruptions in the Mediterranean before A.D. 630 from written and archaeological sources. J Geophys Res 88:6357–6371
Stothers RB (1984) The great Tambora eruption in 1815 and its aftermath. Science 224:1191–1198
Symons GJ (ed) (1888) The eruption of Krakatoa and subsequent phenomena. Trübner, London
Tarillon (1715) Relation en forme de journal de la nouvelle isle sortie de la mer dans le Golfe du Santorin, in, Fleurian D'Armenonville, Th. C., editor, Nouveaux memoires des missions de la compagnie de Jesus, dans le Levant, Paris: Nicolas Le Clerc, pp 126–161. (In French)
Venezky DY, Newhall CG (2007) WOVOdat design document; the schema, table descriptions, and create table statements for the database of worldwide volcanic unrest (WOVOdat Version 1.0): US geological survey open file report 2007–1117, 184 pp
Vougioukalakis G, Sparks RSJ, Pyle D, Druitt T, Barberi F, Papzachos C, Fytikas M (2016) Volcanic hazard assessment at Santorini volcano: a review and a synthesis in the light of the 2011–2012 Santorini unrest. In: Proceedings of the 14th international conference of the geological society of Greece, Bull Geol Soc Greece L: 274–283
Wadge G, Aspinall WP (2014) A review of volcanic hazard and risk-assessment praxis at the Soufriere Hills Volcano, Montserrat from 1997 to 2011. In: Wadge G, Robertson REA, Voight B (eds) Eruption of Soufrière Hills volcano, Montserrat from 2000 to 2010. Geol Soc London Mem 39:439–456
Wadge G, Robertson REA, Voight B (eds) (2014) Eruption of Soufrière Hills volcano, Montserrat from 2000 to 2010, Geol Soc London Mem 39:501 pp
Watt SFL, Mather TA, Pyle DM (2007) Vulcanian explosion cycles: patterns and predictability. Geology 35:839–842
Watts AB, Nomikou P, Moore JDP, Parks MM, Alexandri M (2015) Historical bathymetric charts and the evolution of Santorini submarine volcano, Greece. Geochem Geophys Geosystems 16:847–869
Wiart P, Oppenheimer C (2000) Eruptive history of Dubbi volcano, northeast Afar (Eritrea), revealed by optical and SAR image interpretation. Int J Remote Sensing 21:911–936
Winchester S (2003) Krakatoa: the day the world exploded, 27 August 1883. Viking, London, p 432
Zollinger H (1855) Besteigung des Vulkanes Tambora auf der Insel Sumbawa, und schilderung der Erupzion desselben im Jahr 1815. Winterthur, Switzerland, p 22