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Volcanic fatalities database: analysis of volcanic threat with distance and victim classification

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Abstract

Volcanoes can produce far-reaching hazards that extend distances of tens or hundreds of kilometres in large eruptions, or in certain conditions for smaller eruptions. About a tenth of the world's population lives within the potential footprint of volcanic hazards and lives are regularly lost through volcanic activity: volcanic fatalities were recorded in 18 of the last 20 years. This paper identifies the distance and distribution of fatalities around volcanoes and the activities of the victims at the time of impact, sourced from an extensive search of academic and grey literature, including media and official reports. We update and expand a volcano fatality database to include all data from 1500 AD to 2017. This database contains 635 records of 278,368 fatalities. Each record contains information on the number of fatalities, fatal cause, incident date and the fatality location in terms of distance from the volcano. Distance data were previously available in just 5% of fatal incidents: these data have been significantly increased to 72% (456/635) of fatal incidents, with fatalities recorded from inside the crater to more than 100 km from the summit. Local residents are the most frequently killed, but tourists, volcanologists and members of the media are also identified as common victims. These latter groups and residents of small islands dominate the proximal fatality record up to 5 km from the volcano. Though normally accounting for small numbers of fatalities, ballistics are the most common cause of fatal incidents at this distance. Pyroclastic density currents are the dominant fatal cause at 5 to 15 km. Lahars, tsunami and tephra dominate the record after about 15 km. The new location data are used to characterise volcanic threat with distance, as a function of eruption size and hazard type, and to understand how certain activities increase exposure and the likelihood of death. These findings support assessment of volcanic threat, population exposure and vulnerabilities related to occupation or activity.

Keywords: Volcanic hazards, Fatalities, Distance, Threat to life, Database

Introduction

Volcanic eruptions can cause loss of life and livelihoods and result in major societal and economic disruption. There are 1508 active volcanoes: that is those with activity suspected or confirmed during the last 10,000 years (Volcanoes of the World 4.5.3 downloaded 19/12/16, Global Volcanism Program, 2013: hereafter referred to as VOTW4.5.3 (GVP, 2013)). They are located in 86 countries and additional territories worldwide (Brown et al. 2015a). Eruptions have the potential for causing regional and global effects, although the relative infrequency of large eruptions (Volcanic Explosivity Index (VEI) ≥4) compared with small eruptions (VEI ≤3) means that effects are mostly local (to tens of kilometres). Over 29 million people worldwide live within just 10 km of active volcanoes, and around 800 million people live within 100 km (Brown et al. 2015b), a distance within which there is potential for devastating volcanic hazards at some volcanoes.

Understanding how volcanic threat varies with distance from the volcano and which groups of people are affected most can contribute to risk reduction by providing empirical data on which to forecast impacts or support evidence-based eruption planning and preparedness. Threat to life is influenced by distribution of both population and the footprint of volcanic products. We

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distinguish 'threat' from 'risk', as the latter incorporates an understanding of the vulnerabilities of the communities, and probabilities associated with the hazard, which is beyond the scope of this paper.

Research into volcanic fatalities has focussed on statistical analysis of the numbers of fatalities over time, by hazard and eruption size. Auker et al. (2013) built on earlier work to develop a fatalities database, combining data from the Smithsonian Institution's Global Volcanism Program (GVP), Witham et al. (2005), CRED EM-DAT and Munich Re. Their database contains brief descriptions of fatal incidents, but does not normally give their location.

In this paper we identify the distance at which fatalities occurred from volcanoes, discriminating between different hazards. We also classify the victims where possible, identifying their activity or occupation that lead to their presence in hazardous zones. These data are sourced from academic literature, media and official reports. We distinguish and discuss both eruptive and non-eruptive fatalities, with hazards being present even when a volcano is in quiescence. This new fatalities data can be used to better understand volcanic threat with distance, eruption size and hazard type, and has application in calculation of population exposure, vulnerabilities and risk.

Methods: Updating the fatalities database and determining fatal incident distance

The fatalities database of Auker et al. (2013) contains fatal incidents from 1600 AD and provides brief incident descriptions, eruption start date and VEI, the number of fatalities and fatal cause. This database has been updated and refined to include additional data and updated or new information on fatal cause, number of fatalities, the fatal incident occurrence date, descriptive details and all fatal incidents to July 2017. Here, we add a new dataset identifying the location and distance of fatalities.

The updated fatalities database is provided as Additional file 1. Google Earth placemarks have been added to show fatal incident locations, enabling the provision of a downloadable dataset containing latitude and longitude (Additional file 2).

In the following sections we introduce fatal causes, describe the identification of distance, and discuss data limitations.

Fatal causes

Volcanoes can produce a number of potentially lethal hazards (Baxter, 1990), referred to here as the fatal cause. Baxter (1990) described common physiological causes of death due to volcanic hazards. However, medical cause of death is rarely identified in available records, so it is the hazard itself that is linked to the fatality. Fatal cause categories are now described below.

Pyroclastic density currents (*PDCs: inclusive of pyroclastic flows, surges and blasts*): PDCs can reach distances of several kilometres and tens of kilometres in large explosive eruptions (Walker, 1983). In general, PDCs move too quickly for people to escape and death is almost certain for those caught by a PDC. Baxter (1990) identified dead:injured ratios as high as 230:1. Deaths commonly result from thermal injury (including laryngeal and pulmonary oedema), asphyxiation and impact or blast trauma (Baxter, 1990).

Tsunamis: These can result from the rapid entrance of debris avalanches, PDCs or other volcanic products into a water body, earthquakes accompanying eruptions, submarine eruptions, caldera collapse, or even volcanic shock waves (Latter, 1981). Tsunamis can devastate distant shorelines and wash kilometres inland.

Lahars: Lahars (volcanic mudflows) can extend tens to hundreds of kilometres (Waythomas, 2014). Death and injury typically result from trauma or asphyxiation (drowning). Lahars can be hot enough to cause burns (Baxter, 1990) and can occur years after an eruption as secondary lahars.

Tephra: Tephra can be transported and deposited hundreds, or even thousands, of kilometres from the volcano. Deaths typically occur in proximal areas of thick deposition, through roof collapse, asphyxiation and burial (Spence et al. 2005). Airborne ash can aggravate pulmonary conditions such as asthma (Horwell and Baxter, 2006).

Ballistics: Ballistics (large ejected clasts of a few cm size or above) are typically restricted to within 5 km of the vent (Blong, 1984) and deaths and injuries are typically due to trauma from direct impacts.

Avalanche (*inclusive of debris avalanches, sector collapse and landslides*): These result from the collapse of unstable edifices due to seismicity, eruption or intense rainfall. Avalanches discharging into lakes or oceans can generate tsunamis; resultant fatalities are classified under tsunami.

Lava flows: Lavas normally advance slowly, allowing escape, but sudden outbursts of very fluid lavas can cause loss of life (Baxter et al. 1982). Deaths and injuries typically arise if escape routes are cut off, or as small explosions occur through interaction with water, vegetation or fuel.

Gas: Various gases are emitted at volcanoes during or between eruptions, including gases that can be harmful to health (e.g. carbon dioxide, hydrogen sulphide, sulphur dioxide, hydrogen chloride, hydrogen fluoride, carbon monoxide) (Hansell and Oppenheimer, 2004). Gases released from volcanic systems between eruptions are hereafter called *quiescent gas*.

Lightning: Volcanic lightning is a common feature of volcanic ash clouds, especially in larger explosive eruptions (McNutt and Williams, 2010).

We also use *Multiple* where fatalities are attributed to more than one cause and *Uncertain* when the cause is not known.

Indirect fatalities include accidents, for example related to evacuation or unsafe driving conditions, heart attacks and cascading hazards such as famine and disease. Indirect deaths can occur over great distances and over considerable time periods after an eruption. The distance involved in indirect fatalities, such as victims of famine, is not easily quantifiable. Indirect deaths can dwarf the numbers of direct deaths. For example, the 1815 VEI 7 eruption of Tambora, Indonesia, resulted in about 12,000 deaths through direct hazards including PDCs, tephra fall and tsunamis during the short-lived cataclysmic stage of the eruption (Oppenheimer, 2003, and references therein). These fatalities occurred on the Sanggar peninsula of Sumbawa at distances up to about 40 km. Following the eruption an estimated further 49,000 fatalities occurred throughout Sumbawa, Lombok and surrounding islands through the indirect causes of famine and disease; widespread crop failure and famine was also reported across Europe, North America and Asia (Oppenheimer, 2003).

Fatalities associated with seismicity are recorded, but it is difficult to distinguish between volcanic and tectonic seismicity-related deaths in the literature. Thus, both indirect and seismicity-related fatalities are excluded from analysis of fatalities and fatal incidents with distance, though are discussed in Fatalities during quiescence and Victim classification.

Determining the dates and distance of fatal incidents and fatalities

The fatality database records eruption dates (i.e. start date of eruption as per GVP, 2013). This is not always the same as the date of the fatal incident within an eruption. Incident dates aid identification of specific incidents and help to avoid duplication. These dates can commonly be obtained from activity bulletins. As an example, during the 1968–2010 eruption of Arenal, Costa Rica, SEAN Bulletin 13:07 07/1988 (GVP, 1988) states: *"On 6 July, a climber died near Arenal's crater rim after being struck in the head by tephra. The victim and a companion had approached to ~3 m from the crater rim when the explosion occurred".*

Unless eruptive activity is typically located in fissure zones or volcanic fields, evacuations and eruption planning commonly focus on the summit of the volcano, and existing population exposure assessment methods are typically centred on the summit. Hence, despite recognising that some hazards originate in areas distal to this (effusive flank vents for example), here the volcano to fatal incident distance is measured from the summit.

Deaths are commonly reported in particular towns or villages, or with relation to the summit or crater. We determine the approximate distances at which fatalities occurred relative to the volcano summit, through combination of these descriptions with additional literature, including from volcano activity bulletins, online news and academic articles. Judgement is required to interpret qualitative descriptions, as described below.

The location is commonly linked to features of the volcano and described as 'at the summit', 'near the crater', or 'at the crater rim'. Although a precise distance is unknown, the location can be quite well constrained and is recorded as <1 km in the database. An example is the 1930 eruption of Asamayama, Japan, where the Japan Meteorological Agency (JMA) Fatality Database confirms the proximity to the crater and fatal cause: *"Volcanic block: August 20, 1930: 6 people were killed near the crater"*, with further confirmation in the National Catalogue of the Active Volcanoes of Japan (NCAVJ), 4th Edition.

Fatalities are commonly described on the cone or during climbs to the summit. In these cases the location is assumed to be on the upper cone. A distance range is approximated based on the radius of this upper cone estimated using Google Earth. An example is the 1992 eruption of Marapi, Indonesia, when *"Bombs killed one person, seriously injured three, and caused minor injuries to two others. The victims had climbed to the summit without consultation with the Mt. Marapi Volcano Observatory or local authorities, although a hazard warning had been in effect since 1987."* (GVP, 1992a, b). Marapi's active cone is about 10 km diameter (5 km radius centre to cone base), with a distinct treeline-upper cone boundary of <2 km diameter. The description thus suggests that the victim was possibly within 1 km, but certainly within 5 km and it is recorded as <5 km in the database.

The town in which deaths occurred is sometimes recorded. When the town is named the approximate town centre or Google Earth marker is used to determine the distance. Minimum and maximum distances are also provided for the town limits. Literature about the volcanic activity and online maps and images help to identify town location. An example is the 1996 eruption of Manam, Papua New Guinea: *"The paroxysm accounted for 13 deaths in a coastal village called Budua Old near SW Valley"* (GVP, 1996). Although this village cannot be located in Google Earth, a map locating the valley allows the approximate location to be defined, and distance calculated (~5 km).

Manam also illustrates the use of island size to constrain the maximum distance within which fatalities occurred. The island is at most 11 km across, with an approximately central volcanic peak. The maximum distance from the centre to the coast on any flank is about 6 km.

Other literature can identify the extent of the fatal cause and identify a distance range. For example, deaths are described through pyroclastic flows in the 1913 eruption of Colima, Mexico. Here, the maximum distance can be constrained to within 8 km, from mapping of ash flow deposits by Luhr and Carmichael (1980).

Data limitations and uncertainties

We consider both fatal incidents (an event with fatalities) and fatalities (number of victims). A single eruption can have multiple fatal incidents and can include fatalities at a range of distances from a range of fatal causes. Fatalities are recorded as separate incidents when: (1) they are due to different fatal causes; (2) they occurred at different times. Fatalities are recorded as single incidents with sub-incidents when they are due to the same fatal cause at a range of distances. For example, the 57 direct fatalities at St. Helens, USA in 1980 can be considered as one incident. However, we separate these into sub-incidents as we record 26 separate distances where the fatality locations could be identified from the literature (e.g. Eisele et al. 1981). To average the distances in such an incident would not be appropriate, therefore individual distances are recorded and can be counted in multiple distance bins in analysis.

The database is prone to errors related to incorrect or unreliable reporting. Multiple information sources and specifics such as incident date or victim details are used wherever possible to improve reliability. Ultimately, judgement is applied about whether a report is reliable enough to include. A quality level index is introduced to evaluate data reliability (Table 1).

Fatal incidents recorded at specific distances are considered data quality level 1 (QL 1), such as those mapped precisely in the St. Helens eruption. Where the fatal incident cannot be restricted to an exact distance, a distance range is identified (QL 2). For example, about 3000 fatalities occurred in the 1951 eruption of Lamington, Papua New Guinea, when PDCs devastated the volcano's north flank to a distance of up to 13 km (Gorshkov, 1963). The majority of destroyed villages were at approximately 5 to 10 km (Taylor, 1958). The distribution of fatalities between villages is unknown, thus all fatalities are recorded as one incident at <13 km. QL 3 data have no distance information available.

QL 1 and 2 data are combined in our analysis. The maximum distance recorded in QL 2 incidents is used as this represents a conservative estimation of threat. If the QL 2 midpoint was used then this could underestimate the reach of the hazard. For example in the case of the 1951 eruption of Lamington, a midpoint of 6.5 km would not adequately represent the distribution of fatalities, which dominantly occurred at distances greater than this.

Distances of fatal incidents can be used to characterise distribution of threat with distance from a volcano and to understand the hazardous extent of different volcanic phenomena. The former requires measurement from the summit, while the latter requires measurement from the active vent, noting the occurrence of satellite vents. However, the location of the active vent is not always recorded. Many hazard, exposure and risk assessments

Table 1 Assessing uncertainty in the determination of location of fatal incidents

Data Quality Level (QL)	Conditions	Distance data	Percentage of database records
1	Location of the fatality is identified - Distance of fatality is given in literature - Position of fatality relative to eruptive crater (e.g. 'crater rim', 'near crater', 'at summit') - Town/village is identified and located - Precise location is known - Small distance range is accurately identified (mid-point used). This also applies to towns where the centre is used and outskirts represent uncertainty	Distance of fatality is precisely identified (e.g. 350 m, 7.2 km, 12 km, 400–600 m)	34%
2	Distance within which the fatality occurred is constrained by: - Size of cone (e.g. fatality described as on cone: radius taken for upper cone from summit to clear change in slope using elevation profile tool in Google Earth) - Extent of the lethal flow as given in literature or identified on Google Earth (n.b. distance is measured from the distal flow end to the summit) - The maximum distance from the summit crater to the coast (normally applicable to island volcanoes) - The destructive radius/distance as described in literature (e.g. blast zones, PDC extents) - Town is named or described but not precisely located	A distance range within which the fatality occurred is identified (e.g. <5 km, 8–14 km). The maximum distance vis used for analysis.	40%
3	No information is provided on fatality location and none can be inferred from the description or edifice/island size	Distance is unknown	26%

consider distance rings around a central volcano (e.g. Ewert and Harpel, 2004; Aspinall et al. 2011; Brown et al. 2015b). Our analyses use distance measured from the summit, unless stated otherwise.

In calderas or volcanic fields lacking a central edifice, measurement is from fatal incident to the volcano coordinates in Google Earth from GVP (2013). These measurements therefore have larger uncertainties than for stratovolcanoes.

The database uses the same enumeration method of Auker et al. (2013) and Simkin et al. (2001) where qualitative statements regarding the number of fatalities are given numeric values to permit analysis (Table 2).

Results

The updated fatalities database contains 635 records and 278,368 fatalities recorded since 1500 AD through any fatal cause. These records comprise 581 incidents, 19 of which are further subdivided into 73 sub-incidents, where fatalities are identified at multiple distances. Sub-incidents are hereafter combined under incidents for analysis. Of the total, 64 incidents and 61,612 fatalities are due to indirect fatal causes or seismicity: these are excluded and discussed separately in our analysis.

The difference in number of incidents and fatalities compared with Auker et al. (2013) arises from the updates to the data, which included both addition and removal of fatal events and adjustments to the number of fatalities recorded in some incidents.

Fatalities are recorded at 194 volcanoes in 38 countries (Fig. 1), with the highest number of incidents recorded in southeast and east Asia (~50%).

A distance is identified for 456 of the 590 fatal incident records in the database; a major improvement on the 27 of 533 fatal incidents reported in Auker et al. (2013). Distances are either well-defined (n = 210, QL 1) or constrained to a distance range (n = 246, QL 2). Results are presented here with some contextual discussion; more focussed discussion is provided in Discussion.

Variation in fatal incidents and fatalities with distance

Our analysis with distance excludes fatal incidents due to indirect fatal causes or seismicity unless otherwise stated, and combines incidents and sub-incidents. Therefore, we consider 571 incidents with 216,756 fatalities. Of these incidents, 413 have a distance recorded.

The number of fatal incidents decreases with distance from volcanoes (Fig. 2). About a third of incidents (149/413) are recorded within 5 km, 63% (259/413) are recorded within 10 km, and 83% (343/413) within 20 km from the volcano (grey dashed line, Fig. 2). The data approximately fit a logarithmic trend (R^2 = 0.91), but there is an inflection in the number of incidents recorded at about 10 km distance. This may be an artefact of the recording process when distances are constrained to a range: 43 QL 2 incidents are recorded at <10 km. The largest number of fatal incidents in any 5 km bin around the volcano occurs closest to the volcano, in the first 5 km. Despite this, these incidents only account for 6268 fatalities (<3% of total). Indeed, at 5 km to about 10 km the number of fatalities increases dramatically (Fig. 2), despite the lower number of incidents. About 47% of fatalities are recorded within 20 km. Over 50% of fatalities occur more than 20 km from the volcano, and are attributed to just 17% of the fatal incidents.

The number of fatalities with distance is more variable (Fig. 2). Single incidents can account for large losses of life at different distances, resulting in markedly stepped appearance to the cumulative curves in Fig. 2. Just seven incidents (Table 3) account for a combined total of over 125,000 fatalities (about 58% of total fatalities). Lahars, tsunami and PDCs (and potentially tephra fall) caused these large losses of life; indirect and seismicity-related fatal causes are excluded. If these major incidents are excluded from the analysis about 70% of fatalities are recorded within 20 km.

Distance and fatal cause

Fatal incidents are recorded across a range of distances for all fatal causes, and these ranges are variable between hazards (Fig. 3, Table 4). Despite a range of distances recorded up to 170 km, the median incident distance (for all eruptive hazards) is 8.4 km, with an arithmetic mean of 13.2 km.

About 40% of fatal incidents in the first 5 km are caused by ballistics (Fig. 4a). These have the most proximal average distances (Table 4), with just one ballistics incident recorded beyond 5 km (Fig. 5). Typically, each ballistics incident involved a small number of fatalities (Fig. 4b). The largest loss of life recorded through ballistics was recorded at Asama, Japan, in 1596, when 'many' (n = 100, Table 2) were killed (NCAVJ 4th Edition). More recently, 57 people lost their lives through ballistics at the summit of Ontake, Japan in 2014. Ballistics account for <1% of fatalities (367/216,756).

Gas and quiescent gas emissions are typically a proximal hazard (Table 4, Figs. 3, 4) with the greatest distances to

Table 2 Enumeration of qualitative statements about number of fatalities, after Simkin et al. (2001) and Auker et al. (2013)

Qualitative description	Numerical value
Few	3
Some	3
Several	5
Unknown	15
Many	100
Hundreds	300

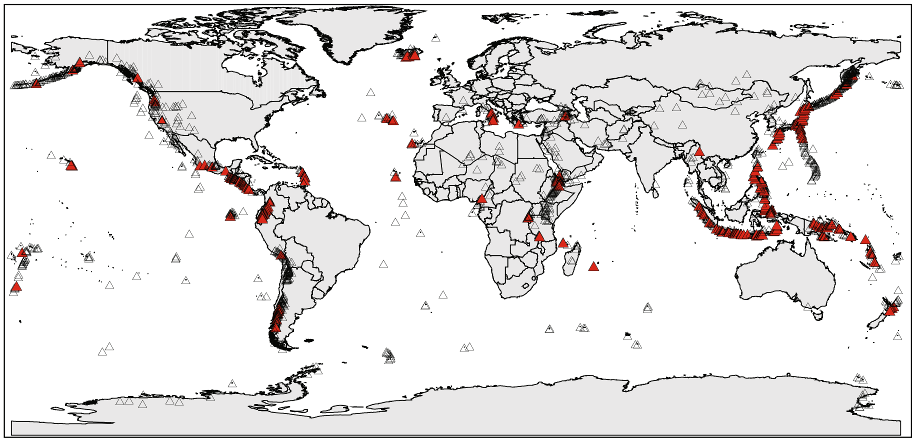

Fig. 1 The distribution of Holocene volcanoes and those with fatal incidents recorded since 1500 AD

the volcano recorded when gas emission occurred from a satellite vent. Distances from these satellite vents are provided in the database where known. Gas and quiescent gas are responsible for both individual casualties and incidents in which many died. The greatest loss of life (>1565) is recorded at Lake Nyos in 1986 (e.g. Barberi et al. 1989, Baxter 1989; see Section 3.4). Volcanic gas, inclusive of quiescent gas, accounts for 2283 fatalities (1%).

Although fatal incidents through PDCs are recorded over a large distance range (Table 4, Fig. 3), 50% of incidents are recorded up to 10 km and about 90% within 20 km (Fig. 5), demonstrating the relative rarity of extensive PDCs. The greatest extent recorded in our dataset is 80 km during the 1883 Krakatau eruption, when PDCs travelled across the sea to southern Sumatra and West Java (Carey et al. 1996). Although too old for inclusion in this database, earlier examples of human impacts at distances beyond this are known. Maeno and Taniguchi (2007) described human settlements in southern Kyushu as devastated by PDCs, which had reached at least 100 km during the 7.3 ka Kikai eruption, Japan. Single PDC incidents have accounted for large loss of life in the database: about half of the PDC-related deaths (~28,000) occurred in just one incident: the 1902 Mont Pelée eruption, Martinique. Within 10 km of the vent, PDCs contribute the largest proportion of fatalities (Fig. 4). PDCs account for 59,958 fatalities (28% of the total recorded). It is also likely that many of the fatalities in the *Multiple* category were due to PDCs, including a majority of the 12,000 direct fatalities at Tambora, Indonesia in 1815.

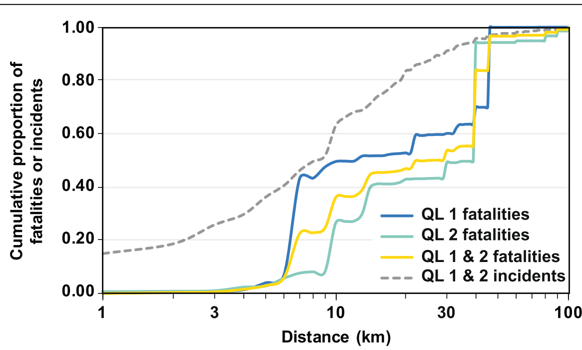

Fig. 2 Cumulative proportion of fatalities and fatal incidents with distance. QL 1 and QL 2max data are represented and shown for all fatal causes excluding indirect and seismicity. Data are binned in 1 km width bins at the maximum distance (e.g. incidents from 1.1 to 2 km are in 2 km bin)

Fatal incidents from lavas occur at greater distances on average than PDCs (Table 4, Fig. 3), at least in part due to the measurement of distance from the volcano summit rather than the eruptive vent. The greatest distance recorded was during the 1823 eruption of Kilauea, Hawaii, when lavas emitted from a 10 km-long section of the rift rapidly inundated a village (Stearns, 1926) 29 km from the summit. The largest loss of life (~100–130) occurred during the 2002 eruption of Nyiragongo, Democratic Republic of Congo, when lava flows inundated the city of Goma (e.g. Komorowski et al. 2002–3). Lava flows account for 659 fatalities (< 1%).

Few explosive hydrothermal incidents are recorded (n = 6). These explosions (typically VEI 1) have localised effects around the explosion vent but can be located in geothermal areas away from the summit. Measured from the volcano summit, the farthest fatal incidents occurred at 20 km at Okataina, New Zealand; measured from the vent these occurred at <1 km (Table 4). The greatest number of fatalities in any one incident is recorded at Dieng Volcanic Complex, Indonesia, in 1939, when steam explosions caused ten deaths. Fatalities in explosive hydrothermal incidents will occur through the ejection of boiling water, mud,

Table 3 Seven largest incidents in terms of loss of life (not including indirect or seismicity-related fatal causes)

Volcano name	Year	Number of fatalities	Fatal cause
Krakatau, Indonesia	1883	36,000	Tsunami
Pelée, Martinique	1902	28,000	PDCs
Nevado del Ruiz, Colombia	1985	24,000	Lahars
Tambora, Indonesia	1815	12,000	Multiple (PDCs, Tephra, Tsunami)
Unzendake, Japan	1792	10,139	Tsunami
Kelut, Indonesia	1586	10,000	Lahars
Kelut, Indonesia	1919	5110	Lahars

The largest incidents are those with over 5000 fatalities

steam and ballistics, but are considered separately to other eruptive ballistics.

Tephra, lahars and tsunami become the dominant fatal causes for incidents and fatalities after about 15 km (Fig. 4).

Tephra fall is commonly the most widespread volcanic hazard (Jenkins et al. 2012). Despite the wide reach, about 80% of fatal incidents occur within 20 km (Figs. 3, 5), reflecting thicknesses of tephra that can threaten life (e.g. due to roof collapse) are deposited quite close to source. Occasionally, tephra can cause fatalities at great distances, typically through exacerbation of existing heart or lung conditions (Horwell and Baxter, 2006), as in a fatality recorded at 170 km during the 1912 eruption of Novarupta, U.S.A. (Hildreth and Fierstein, 2012). The largest loss of life due to tephra occurred during the 1902 eruption of Santa María, Guatemala, when an estimated 2000 died due to burial, building collapse and suffocation. The distance at which this burial occurred is unknown; however, Church et al. (1908) describes tephra at about 10 km of 2.1 to 3.7 m depth. Tephra accounts for 4315 fatalities (2%). Lightning is a frequent component of volcanic ash clouds and nine fatalities are recorded through lightning strikes (<1%).

The majority of fatal incidents at distances greater than 15 km are due to lahars (primary and secondary). Distance measurement from the summit can be misleading, as lahars can be generated away from the summit and bulk up and entrain water and debris along the flow, making the source dispersed along the flow. The greatest recorded

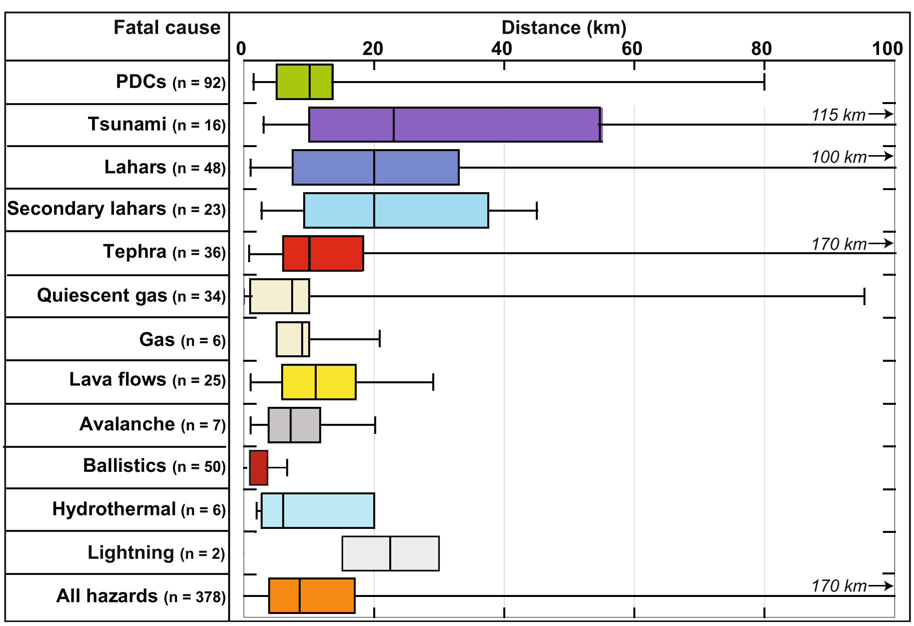

Fig. 3 Box and whisker plot showing the range of distances recorded for fatal incidents by fatal cause. The graph combines QL1 and QL2max data. Each box marks the 25th to 75th percentile distances, with the black line marking the 50th percentile. Whiskers extend to the minimum and maximum distances recorded. All hazards includes all eruptive hazards, including where multiple or unknown, and excludes non-eruptive, seismic and indirect. The count *n* is the number of incidents with distance data

Table 4 Statistics for distance of fatal incidents by fatal cause, ordered by decreasing number of fatalities

Fatal Cause	Number of incidents	Number of fatalities	Min. distance (km)	Max. distance (km)	Mean distance (km)	Median distance (km)	2σ (km)
PDC	102	59,958	1.5	80	10.7	10.0	19.0
Tsunami	23	56,822	3.0	115	37.3	23.0	74.0
Lahars	72	49,938	1.0	100	24.1	20.0	38.9
Secondary lahars	41	6377	2.7	45	22.9	20.0	30.0
Tephra	52	4315	0.5	170	18.6	10.0	61.8
Avalanche	9	3525	1.0	20	8.3	7.0	13.2
Quiescent Gas	50	1698	0.1	74	10.9	7.5	30.8
Quiescent gas from vent	–	–	*0.0*	*13*	*5.4*	*6.8*	*9.0*
Lava flows	25	659	1.0	29	12.2	11.0	15.8
Lava flows from vent	–	–	*1.0*	*29*	*11.6*	*10.0*	*15.8*
Gas	16	585	5.0	21	9.8	9.0	13.1
Gas from vent	–	–	*1.0*	*21*	*7.2*	*5.0*	*15.1*
Ballistics	57	367	0.0	7	1.7	1.0	3.0
Hydrothermal	7	62	1.5	20	9.3	6.0	17.5
Hydrothermal from vent	–	–	0.8	3	1.6	1.3	1.7
Lightning	4	9	15.0	30	22.5	22.5	21.2
All eruptive hazards	515	214,004	0.0	170	13.5	8.6	35.6

Data include QL 1 and QL 2max. Gas, quiescent gas, lava flows and hydrothermal bursts are sometimes recorded with distance from their source vent as well as distance from the summit. In these cases we present all data under the parent category (e.g. quiescent gas) and substitute in the distance from vent data in the subcategory (e.g. quiescent gas from vent). We do not double count the fatalities and fatal incidents. All eruptive hazards includes the 'Multiple' and 'Eruption – unknown element' fatal cause categories: quiescent hazards are excluded. Note that the incident count includes sub-incidents

(QL1) distance occurred in the 1985 eruption of Nevado del Ruiz, Colombia, when lahars inundated the town of Armero 46 km from the volcano. Approximately 25,000 people lost their lives in Armero and Chinchiná (~34 km from Nevado del Ruiz). Lahars and secondary lahars are responsible for 56,315 fatalities (26%).

Tsunami can also have widespread impacts. However, the identification of the location and numbers of tsunami-related fatalities is problematic. The incidents for which distance is identified occur from close to the volcano to distances beyond 100 km. The greatest recorded number of fatalities through volcanogenic

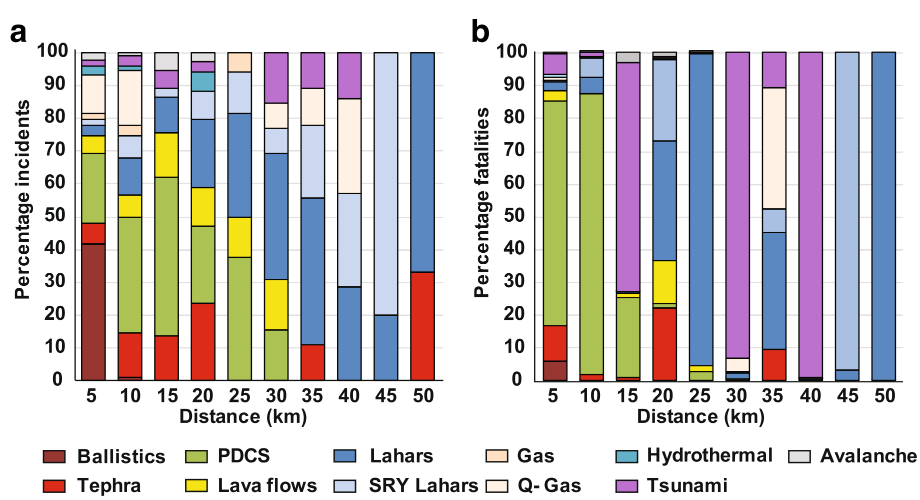

Fig. 4 Percentage of incidents (**a**) and fatalities (**b**) per fatal cause in 5 km bins to 50 km. Data include QL 1 and QL 2max categories. Q-gas is quiescent gas, SRY lahars is secondary lahars

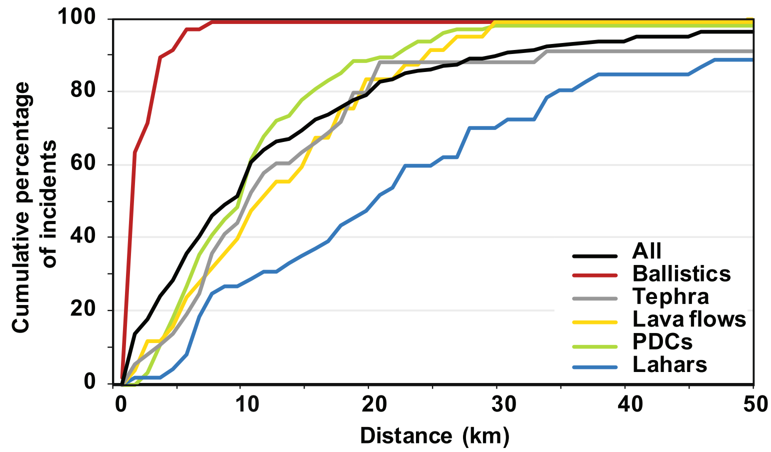

Fig. 5 The cumulative percentage of fatal incidents by selected eruptive hazard with distance. Data include QL 1 and QL2max categories. Incidents are counted in 1 km bins. The curve for 'all' represents all eruptive hazards as per Fig. 4

tsunami was 36,000 in the 1883 eruption of Krakatau, Indonesia, at distances of up to 40 km. Tsunamis account for 56,822 fatalities (26%).

Distance, eruption VEI and fatal cause

The fatal incidents data are dominated by small-magnitude (VEI 3 and below) eruptions of fatal incidents, 69% are associated with VEI 1–3 eruptions, 18% at VEI 4, and 13% at VEI 5–7. This dominance of smaller events reflects at least three main factors related to: the short time period of recording; systematic changes in recording of both eruptions and fatal incidents back in time that depend on eruption magnitude; and rapid population growth. Issues of incompleteness and under-recording are discussed further below. Unravelling these complexities will be challenging and will require a major modelling study which is well beyond the scope of this study. Here we analyse the data without any corrections and so our approach is empirical. The tendency for fatal incident distances to increase with eruption explosivity is illustrated in Fig. 6 for eruptions of VEI 5 and 6. Incidents in eruptions of VEI 4 show a less convincing increase in distance. There is no evidence for distance dependence for VEI ≤3.

Incidents individually accounting for over 100 fatalities are recorded in all VEI bands from 1 to 7: an increasing proportion of such incidents in each band is seen with increasing VEI. These incidents are recorded up to tens of kilometres from the volcano. There is no convincing relationship between VEI, the number of fatalities per incident and distance or fatal cause (Fig. 7).

Fatalities during quiescence

Fatal incidents are recorded in periods of quiescence primarily due to secondary lahars (41 incidents, 6377 fatalities), quiescent gas emissions (50 incidents, >1600 fatalities) and indirect accidents (28 incidents, 30 fatalities).

The largest recorded loss of life from secondary lahars occurred in 1998 at Casita (San Cristóbal), Nicaragua. During Hurricane Mitch a debris avalanche transformed into a lahar which killed over 2500 in the towns of El Porvenir and Rolando Rodriguez (Scott et al. 2004) located at about 9 to 10 km from the volcano summit.

Quiescent gas emission was responsible for large numbers of fatalities in two events. Both occurred at volcanic lakes in the extensive Oku Volcanic Field, Cameroon: 37 fatalities at Lake Monoun in 1984 and >1565 fatalities at Lake Nyos in 1986. Both events involved non-eruptive lake-overturn (for Lake Monoun see Sigurdsson et al. 1987; for Lake Nyos see Kling et al. 1987), which released large volumes of carbon dioxide that flowed as dense currents into populated areas. Fatalities occurred at about 1 km from Lake Monoun. Baxter et al. (1989) and Barberi et al. (1989) showed that the majority of the Nyos fatalities occurred within 3 km of the lake, and all within 15 km.

The remaining quiescent gas emission incidents resulted in 96 fatalities. Many of these incidents involved

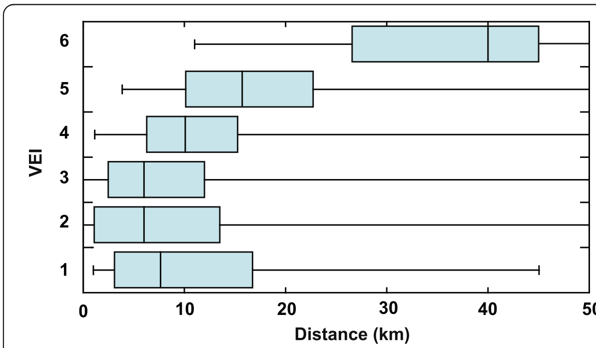

Fig. 6 VEI and distance of fatal incidents across all fatal causes; non-eruptive, indirect and seismicity excluded. Data include QL 1 and QL2 max categories

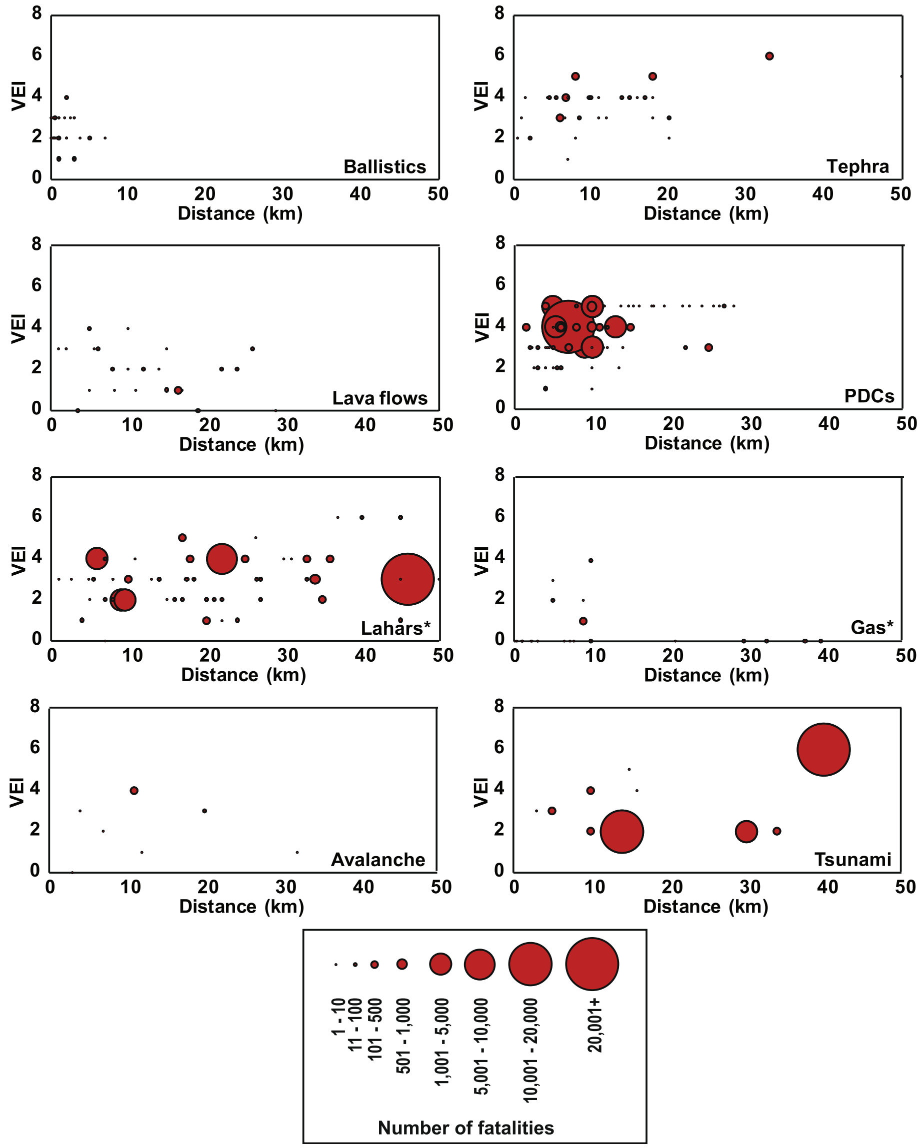

Fig. 7 The relationship between eruption size (VEI), the fatal cause, number of fatalities (bubble size) and fatal incident distance. Data include QL 1 and 2max categories. *Lahars includes secondary lahars, and Gas includes quiescent gas

small groups of recreational visitors close to craters and bathers in geothermal pools (Table 5, see section 3.5).

Single fatalities occurred in 27 incidents through falls or misadventure. These incidents include a fall into the acidic crater lake at Kelimutu, Indonesia, a fall into a thermal mudpot at Mutnovsky, Russia, one incident at Rotorua, New Zealand and 23 incidents at Yellowstone, U.S.A., where the victims fell or jumped into thermal pools. Falls during eruptions, for example during tephra clean-up are considered separately.

Ten fatal incidents through seismicity are recorded. In most incidents there is ambiguity as to whether these were volcanic or tectonic events. Earthquakes have generated tsunamis resulting in fatalities in both eruptive and non-eruptive events.

At least two instances of fatalities associated with non-eruptive avalanches (e.g. flank collapse) and floods are recorded. An avalanche occurred at Mombacho, Nicaragua, during a storm in 1570 resulting in 400 fatalities. One hundred fatalities are recorded at Parker, Philippines, in 1640 after the caldera wall was breached draining the lake.

Victim classification

Information about the occupation, activities or place of residence of the fatalities can highlight vulnerabilities.

Table 5 Fatalities due to quiescent volcanic gas emission

Volcano, Country	Year	Fatalities	Fatal distance from volcano (from gas source)	References
Oku Volcanic Field, Cameroon (Lake Nyos)	1986	>1565 villagers: 1196 300 52 17	33 km (2.5 km) 30 km (11 km) 38 km (7 km) 40 km (13 km)	1
Oku Volcanic Field, Cameroon (Lake Monoun)	1984	37 villagers	74 km (1.1 km)	2
Karthala, Comoros	1903	17 camping	<10 km	3
Kusatsu-Shiranesan, Japan	1971	6 skiers	?	4, 5
Rabaul, Papua New Guinea	1990	3 gathering eggs 3 retrieving bodies	<1 km	6
Salak, Indonesia	2007	6 campers	<1 km	7
Adatara, Japan	1996	4 hikers	In crater	8
Kusatsu-Shiransan, Japan	1976	3 hikers/climbers	2.3 km	4
Hakkoda Group, Japan	1997	3 soldiers	<10 km	4
Mammoth Mountain, USA	2006	3 ski patrollers (inc. one during rescue)	<1 km (in vent)	9
Hakoneyama, Japan	1951	2 bathers	?	10
Daisetsu, Japan	1958	2 climbers	<1 km	4
Daisetsu, Japan	1961	2 climbers	<1 km	4
Rotorua, New Zealand	1962	2 residents	?	11
Midagahara, Japan	1967	2 campers	?	4, 10
Hakoneyama, Japan	1972	2 (unknown)	?	10
Vulcano, Italy	1980s	2 children	?	12
Rotorua, New Zealand	1987	2 tourists	?	11
Kirishimayama, Japan	1989	2 bathers	?	10
Asosan, Japan	1997	2 tourists	0.1 km	13
Nasudake, Japan	1919	2 (unknown) 1 (unknown)	?	10
Rotorua, New Zealand	1946	1 bather	?	11
Rotorua, New Zealand	1948	1 in sewer	?	11
Hakoneyama, Japan	1952	1 bather	?	10
Rotorua, New Zealand	1954	1 digging hole 1 bather 1 in septic tank	? ? ?	11
Midagahara, Japan	1954	1 bather	?	10
Rotorua, New Zealand	1962	1 unknown	?	11
Naruko, Japan	1969	1 bather	?	10
Midagahara, Japan	1970	1 in cabin	?	10
Midagahara, Japan	1972	1 spa worker	?	10
Midagahara, Japan	1975	1 (unknown)	?	10
Midagahara, Japan	1985	1 (unknown)	?	10
Akita-Yakeyama	1986	1 (unknown)	?	10
Asosan, Japan	1989	1 tourist	<250 m	13
Asosan, Japan	1990	1 tourist	<250 m	13
Asosan, Japan	1990	1 tourist	<250 m	13
Dieng Volcanic Complex, Indonesia	1992	1 (unknown)	3 km	14
Asosan, Japan	1994	1 tourist	<250 m	13

Table 5 Fatalities due to quiescent volcanic gas emission *(Continued)*

Mammoth Mountain, USA	1998	1 skier	2.2 km (in zone of diffuse degassing)	15
Rotorua, New Zealand	2000	1 tourist	?	11
Rotorua, New Zealand	2003	1 bather	6.5 (within caldera)	16
Rotorua, New Zealand	2007	1 bather/tourist	7.2 (within caldera)	17
Rotorua, New Zealand	2008	1 bather/tourist	7.3 (within caldera)	17
Rotorua, New Zealand	2013	1 bather/tourist	7.7 (within caldera)	18

Data from fatalities database and 1) Barberi et al. (1989); 2) Sigurdsson et al. (1987); 3) Blong (1984); 4) Japan Meteorological Agency Fatality Database (2013); 5) NCAVJ; 6) GVP (1990); 7) GVP (2007); 8) GVP (1997); 9) Cantrell and Young (2009); 10) Hayakawa (1999); 11) Collins (2003); 12) Granieri et al. (2014); 13) Ng'Walali et al. (1999); 14) GVP (1992b); 15) Hill (2000); 16) Brown (2003); 17) Bassindale and Hosking (2011); 18) Bathgate (2016). Distance data Oku Volcanic Field is given both for the distance from the volcano coordinates and distance from the source of gas

Most fatal incident descriptions do not include such information about the victims. However, for those that do, several groups of victim occupation or activity stand out (Table 6): tourists, scientists (typically volcanologists), journalists, emergency responders and miners working in or near craters. Although rarely explicitly stated, the vast majority of fatalities are assumed to be local residents. We describe our findings in more detail for tourists, scientists, media and emergency response personnel in the following sections.

Tourists

One hundred and thirteen incidents with 561 fatalities are associated with tourism or recreation, including tourists, spectators, tourism-related park employees, climbers, campers, students, religious pilgrims and other recreational visitors to volcanoes. These are hereafter grouped as *tourists*. Fatal incidents occurred in both times of eruption and quiescence.

In times of eruption 480 fatalities are recorded in 69 fatal incidents. 55% of these incidents involved more than one fatality. All of the victims were outside at the time of eruption. Forty-seven of these incidents and 88% of fatalities (424/480) occurred within 5 km of the volcano. Ballistics were the most common fatal cause (31 incidents (45%), 164 deaths (34%)).

Persistent volcanic activity can result in hazard footprints that rarely extend beyond the crater. Such regular activity can engender complacency in tourists and guides, although small changes in activity, topography or wind direction can change the hazard footprint. At least 22 eruptive (and 5 indirect) fatal incidents occurred more than 1 year after the eruption start date, commonly at volcanoes known for regular activity. Long-lived eruptions affect analysis of relationships with VEI, as the VEI in GVP (2013) normally represents the tephra volume over the full length of the eruption. Ninety-one of the 113 incidents (81%) occurred during quiescence or low-explosivity eruptions of VEI 0–2.

Table 6 Groups identified as being involved in numerous fatal incidents. Note that local residents will be the largest group by far

Group	Incidents	Number of fatalities
Tourists or tourism-related	113	561
Scientists	22	67
Miners	6	108
Media	6	30
Emergency response personnel	5	57

Eighty-one fatalities occurred in 44 fatal incidents in periods of quiescence of which only 10 incidents involved more than one death. Non-eruptive fatal causes are gas (56 fatalities, 19 incidents) and indirect (25 fatalities, 25 incidents). These latter data are, however, strongly biased by data from Yellowstone, USA, which includes 23 incidents involving singular fatalities.

In times of quiescence hazards can be less obvious, with gas in particular representing a potentially invisible hazard. A good example is the six tourists who died in five incidents through quiescent degassing at Asosan, Japan, between 1989 and 1997 (Table 5). Ng'Walali et al. (1999) found that most of these victims had pre-existing pulmonary conditions, highlighting the increased risk to those with chronic lung disease. Gas monitoring devices and warnings were introduced in 1996. The two deaths in 1997 and the work of Ng'Walali et al. (1999) resulted in adjustments to the sulphur dioxide levels required to restrict access to the crater: no quiescent gas-related fatalities have been recorded at Asosan since.

Tourist co-operation is a requirement for safety in any volcanic setting, with visitors being relied upon to heed warnings and exercise appropriate caution. The 23 fatalities at Yellowstone occurred between 1890 (Whittlesey, 1995) and 2016 (Mettler, 2016), where deaths resulted from immersion in the near boiling water of thermal pools. Whittlesey (1995) describes these as accidental falls and misadventure – where the victims believed the pools swimmable. Of these fatalities, nine (36%) were children younger than 10 years old. Educational and safety information is provided and safe boardwalks through thermal areas have been installed, yet injuries are still frequent as visitors choose to engage in risky behaviour (Lalasz, 2013). Despite the frequency of injuries, only two fatalities are recorded in the last 30 years at Yellowstone, suggesting safety measures have been largely successful and the visitor population has become more risk averse at this volcano. Seventeen deaths are recorded at Rotorua, New Zealand since 1946, of which at least seven were tourists. These fatalities occurred primarily at hot pools through quiescent gas emissions. The decrease in incidents over time seen at Yellowstone is not seen here, with seven incidents since 2000. Recommendations were made in 2010 aimed at improving safety at geothermal pools (Bassindale and Hosking, 2011).

Scientists

Twenty-two incidents are identified in which 67 volcanologists, other field scientists and those supporting their work died (Table 7). This includes volcano observers, field assistants, ship's crew, geology students (on fieldwork), and a U.S. Fish and Wildlife Service volunteer. The latter two events are classed as indirect having resulted from falls into thermal features. The largest loss of scientists' lives (31) occurred with the sinking of the research ship Kaiyo-maru. The ship and her crew had been dispatched with seven scientists to observe the submarine eruption of Bayonnaise Rocks, Japan, which struck and sank the ship (Minakami, 1956).

All known scientist fatalities occurred within 11 km of volcanoes. Two locations are unknown, and the 1930 death of the volcano observer at Merapi, Indonesia, is located <15 km based on the extent of pyroclastic flows (Thouret et al. 2000). Including those killed over the submarine eruption, 49 fatalities (73% of the scientist fatalities) occurred in or near the crater (within 1 km), highlighting the danger to field scientists visiting the summit of active volcanoes.

As with tourists, the most commonly identified fatal cause for scientists is ballistics (7 incidents, 15 fatalities). Four PDCs resulted in nine fatalities, despite this being the dominant fatal cause for all volcanic fatalities (Table 4; Auker et al. 2013). About 75% of scientist fatalities (50% of incidents) occurred in eruptions of VEI 0–2.

Emergency response personnel

Disaster prevention and response personnel, military and emergency services working to evacuate, rescue or recover victims have also lost their lives: 32 soldiers died alongside a geologist in the 1982 eruption of El Chichón,

Table 7 Incidents in which volcanologists or field scientists died

Volcano, Country	Year	Fatalities include:	Fatal cause	Fatal distance	Reference
Bayonnaise Rocks, Japan	1952	7 scientists and 24 crew	? – Ship sunk	Over dome	1, 2
Galeras, Colombia	1993	6 volcanologists	Ballistics	In crater	3
Kelut, Indonesia	1951	3 from Department of Volcanology	Lahar?	Crater observatory, <6.5 km	4, 5
Unzendake, Japan	1991	3 volcanologists	PDCs	4 km	6
St.Helens, U.S.A.	1980	2 volcano watchers 1 volcanologist 1 volcanology PhD student	PDCs	7 km 8.6 km 10.5 km	7, 8
Azuma, Japan	1893	2 geologists	Ballistics	Crater rim	1
Awu, Indonesia	1966	2 volcano officers	Pyroclastic flows or lahars	<5 km?	4
Karkar, Papua New Guinea	1979	2 volcanologists	Ballistics	~0.8 km	9
Guagua Pichincha, Ecuador	1993	2 volcanologists	? – Phreatic explosion	Dome rim	10
Semeru, Indonesia	2000	2 volcanologists	Ballistics	~0.3 km	11
Papandayan, Indonesia	1923	1 volcano observer	Gas	?	
Merapi, Indonesia	1930	1 volcano observer	PDCs	<15 km	12
Hekla, Iceland	1947	1 scientist	Lava	<10 km	13, 14
Mutnovsky, Russia	1960	1 geology student	Indirect	?	
Klyuchevskoi, Russia	1977	1 glaciologist	Ballistics	Near summit	
Klyuchevskoi, Russia	1982	1 geophysicist	Ballistics	3.5–4 km	
El Chichón, Mexico	1982	1 geologist	PDCs	5 km	15
Lokon-empung, Indonesia	1991	1 volcanologist	Ballistics	Near crater	16
Kilauea, U.S.A.	1992	1 volunteer US Fish & Wildlife Service	Indirect	0.8 km	17
Raoul, New Zealand	2006	1 from Department of Conservation	?- Eruption	<1 km	18

Data from fatalities database and additionally 1) Japan Meteorological Agency Fatality Database (2013); 2) Minakami (1956); 3) Baxter and Gresham (1997); 4) CVGHM (2014); 5) Bourdier et al. (1997); 6) Nakada (1999); 7) Olson (2016); 8) Hunter (2012a); 9) Johnson (2013); 10) GVP (1993); 11) GVP (2000); 12) Thouret et al. (2000); 13) Walker (1973); 14) Thorarinsson (1950); 15) GVP (1982); 16) GVP (1991); 17) Seattle Times (1992); 18) GVP (2006)

Mexico, when a pyroclastic flow overran the town of Francisco León, about 5 km from the summit (Bulletin SEAN 07–05, GVP, 1982); 12 disaster prevention personnel and two policemen died in the 1991 Unzendake eruption (Ministry of Land, Infrastructure and Transport 2007) 4 km from the summit; eight rescuers were killed in a helicopter crash at Dieng Volcanic Complex, Indonesia, during evacuation efforts in 2017 (Jakarta Globe 2017); and two rescuers died in 2006 at Merapi, Indonesia, after taking shelter in a bunker which was buried by pyroclastic flows about 4 km from the summit (Wilson et al. 2007). A radio operator reporting on the activity of St. Helens in 1980 for the Washington Department of Emergency Services died in the PDC at about 12 km (Hunter, 2012b).

Although not classified as emergency responders, fatality records exist for individuals who perished during rescue and recovery efforts. At Rabaul, Papua New Guinea, in 1990, three were killed whilst attempting to recover the bodies of three friends and relatives who were overcome by volcanic gases in a vent (GVP, 1990). At Mammoth Mountain, USA, in 2006, two ski patrollers fell into a fumarole and were asphyxiated. Rescue efforts saw the further death of one colleague and hospitalisation of seven others (Cantrell and Young, 2009).

Media

Thirty media employees died in six incidents: within 1 km of the vent at Semeru (Indonesia), Santa María (Guatemala) and Pacaya (Guatemala); within 3 km at Sinabung (Indonesia); 4 km at Unzendake (Japan) and at about 13 km at St. Helens (USA). The lava dome collapse at Unzendake generated a PDC in 1991 (Nakada, 1999), resulting in the deaths of 43 people, including 16 journalists and four of the journalists' drivers (Ministry of Land, Infrastructure and Transport, 2007). Victims at Unzendake, Sinabung, Pacaya and Semeru were within the declared danger zones.

Discussion

Data completeness and variation of fatal incidents with time

Catalogue completeness is a key issue for volcanic databases. Under-recording increases further back in time and varies considerably between regions and with eruption size (e.g. Jenkins et al. 2012). Auker et al. (2013) found that the average number of fatalities per fatal incident increases back in time over the last four centuries, indicating that small events were less well recorded than large ones. Our data (Fig. 8) show a general increase in the percentage of fatal incidents with available distance data per century towards present. This observation indicates the increasing availability of more detailed eruption impact records with time as well as improving recording of eruptions. The largest increases in percentage with distance data are seen from the 16th to 17th centuries and 19th to 20th centuries. This pattern is similar to that observed in eruption records where recording undergoes significant improvements at about 1500 and 1900 AD, attributed to colonisation, increased written record keeping and technological improvements in communication (e.g. Furlan, 2010, Rougier et al. 2016).

We use data since 1900 to investigate whether there has been a reduction in the number of incidents and therefore an improvement in saving lives over time.

In the early part of the twentieth Century the rate of recording of fatal incidents is reasonably steady (Fig. 9). During World Wars I and II there is a drop in recordings: in the years 1914 to 1918 just three incidents are recorded, compared with 17 in the preceding 5 years; nine are recorded from 1939 to 1945, compared with 16 in the preceding 7 years. This may be attributed to fewer non-war-related scientific and humanitarian activities and less record keeping (Simkin, 1993; Siebert et al. 2010). From 1950 the rate of fatal incidents increases to present, with the early 1990s showing a particular peak in incidents and a return to the levels of the mid-century from about 2000.

The number of fatal incidents involving tourists is variable throughout the period. However, the rate also shows a significant increase in the 1990s and for about a decade from 1924. Fatal incidents involving scientists show a general increase in rate since about 1950, with particular increases in recorded incidents in the early-1980s and early-1990s, before a return to the levels of the mid-century.

The increase in numbers of incidents post World War II could suggest there is a worsening volcanic safety record, but alternatively this may reflect improved reporting and changes in population size and distribution. The increased number of incidents involving scientists may reflect

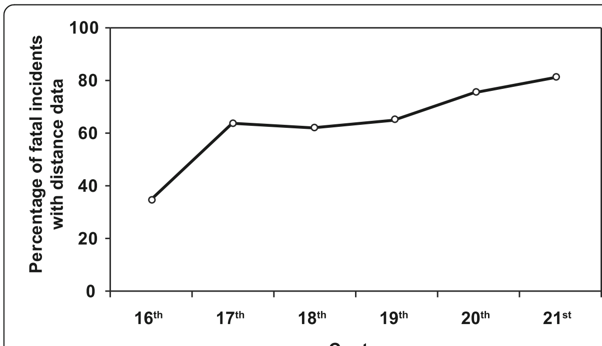

Fig. 8 The percentage of all fatal incidents per century for which we have identified the fatal distances. Note that the data for the twenty-first century only represent up to 2017. Both QL 1 and QL 2max data are represented

increased deployment of scientists globally, with many volcanoes becoming increasingly accessible. The recent decline in fatal incidents in the last 20 years may reflect factors such as more risk averse societies, improved monitoring and early warning and more attention being paid to health and safety. Despite this, volcano fatalities are recorded in each year from 1997 to 2017, with the exception of 2009 and 2012.

Variation of fatal incidents and fatalities with distance

Up to 5 km

More fatal incidents (149) are recorded within the first 5 km of the volcano than any other 5 km zone beyond. The total number of fatalities at ≤5 km of 6268 gives an average of 80 fatalities per km^2, equivalent to 0.54 fatalities per km^2 per incident.

Just over half (78/149) of fatal incidents within 5 km involved visitor groups (inclusive of tourists, scientists, media, miners and emergency response personnel). The remaining 71 incidents have no data explicitly stating the involvement of such groups, and are therefore considered to have been dominantly local residents.

Thirty-six of the incidents within 5 km (24%) and about a third of the fatalities (2129/6268) occurred on volcanic islands of ≤ ~ 5 km radius. In such locations the whole population and all critical infrastructure lies within a few kilometres of the volcano. Such high exposure increases the likelihood of fatalities and has serious implications for evacuation, post-disaster recovery and the severity of the social and economic impact on the island. This identification of a large proportion of proximal volcanic fatalities being located on small islands lends credence to the use of the proportional volcanic threat ranking of Brown et al. (2015c), which highlights the relative threat to small island nations.

5 to 10 km

Between >5 and ≤10 km the number of incidents decreases (110), but the number of fatalities increases significantly to 61,842: 3% of fatalities are recorded within 5 km, 29% at >5 to 10 km. These percentages increase to 6% and 35% respectively with removal of the incidents claiming over 5000 lives. These incidents accounting for large losses of lives are reflected in the average number of fatalities per incident (Table 8). The average number of fatalities increases to 262 per km^2 in this distance range (143 per km^2 if incidents over 5000 fatalities are removed), equivalent to an average of 2.4 fatalities per km^2 per incident. At this distance there are few of the identified fatality groups (e.g. tourists), with residents being the primary victims.

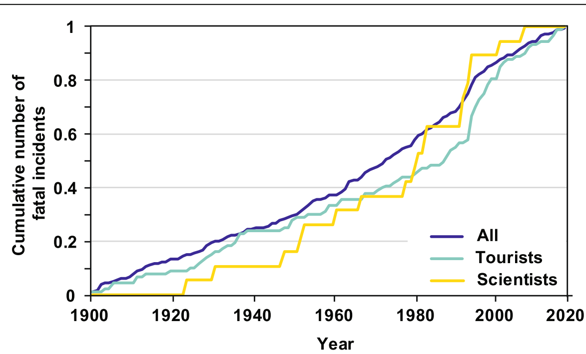

Fig. 9 Number of fatal incidents recorded over the last century, 1917 to 2017. Shown for all data (blue line), and separately for tourists (green), and scientists (yellow)

Beyond 10 km

On average there is an increase in population density around historically active volcanoes beyond 10 km. However, at this distance there is a general decrease in the number of fatalities and the number of incidents, with fewer volcanic hazards reaching this distance. Incidents individually accounting for large losses of lives are observed at this distance, with many tens of thousands lost in incidents at tens of kilometres distance, as reflected in the difference between mean and median fatalities per incident in Table 8. The average number of fatalities at 10 to 30 km is 13 per km^2, equivalent to 0.12 fatalities per km^2 per incident. At 30 to 100 km this decreases to 3 fatalities per km^2, equivalent to 0.08 fatalities per km^2 per incident.

Eruption size

The fatality database is dominated by incidents associated with eruptions of VEI ≤3, with 363 fatal incidents (64% of total). Despite this, only a third of fatalities are recorded with these small eruptions (78,348 fatalities; 36% of total). Larger eruptions are relatively infrequent.

Small eruptions affect a range of distances: 90% of incidents within 5 km were in eruptions of VEI 1–3. At 5–10 km nearly 60% of incidents were recorded at VEI 1–3, this drops to 50% at 10–15 km and 40% at distances beyond this. Just two fatal incidents in VEI ≥5 eruptions are recorded within 5 km of volcanoes. There are several possible reasons for the absence of proximal fatal incidents in large magnitude eruptions: the use of the maximum distance in QL 2 data will in some instances over-estimate the fatality distance, particularly when constrained by the maximum flow length; volcanoes capable of large magnitude eruptions may have unsuitable proximal topography or enforced exclusion zones for the establishment of populations; or evacuations of proximal zones prior to large eruptions have proven successful. Additionally, the higher frequency of smaller events overwhelm the data at this distance. Thus, rather than proximal fatal incidents from large-magnitude eruptions being absent, within this

Table 8 Number of fatalities per incident in different distance bins. The median is a better measure of average given the relative rarity though dominating presence of incidents with large losses of lives

		Distance bin		
		≤5 km	>5 – ≤10 km	>10 km
Number of fatal incidents		149	110	154
Number of fatalities		6268	61,842	119,717
Number of fatalities per incident	Minimum	1	1	1
	Maximum	2000	28,000	36,000
	Mean	39	562	777
	Median	3	15	15

distance bin they are just relatively less likely than those from small-magnitude eruptions.

Major losses of lives

Here we arbitrarily take incidents of 1000 fatalities or greater as a major event to illustrate trends with distance. Only about 5% of incidents individually account for over 1000 fatalities. Just 1% (seven incidents) individually account for over 5000 fatalities, yet this represents nearly 60% of all fatalities. These events in which large numbers of fatalities occur typically reflect PDC, lahar or tsunami impact on towns and cities. Only two incidents of over 1000 fatalities are recorded at ≤5 km, the greatest being 2000 in the El Chichón, Mexico, eruption of 1982: large urban areas are comparatively rare in this distance interval. At 5 to 10 km, 13 incidents had more than 1000 fatalities, the largest being 28,000, when the city of St Pierre, 7 km from Mont Pelée, was destroyed by PDCs in 1902. Beyond 10 km, 12 incidents have over 1000 fatalities each, with the 1883 Krakatau, Indonesia, eruption accounting for 36,000 through widespread tsunami.

Victim classification

The identification of visitor groups in which fatalities are high is key for improving safety and reducing deaths and injuries in these groups. With few exceptions, the recorded deaths of volcanologists or other scientists, tourists, journalists and eruption response personnel were within 5 km of the volcano in incidents resulting in small numbers of casualties. While volcanologists and emergency response personnel may have valid reasons for their approach into hazardous zones, the benefits and risks must be carefully weighed. Baxter and Gresham (1997) provide recommendations on safety measures for volcanologists following the 1993 eruption of Galeras, Colombia. The media should observe exclusion zones and follow direction from the authorities and volcano observatories. The dominance of tourist fatalities at some volcanoes (e.g. Yellowstone, Rotorua and Kilauea) suggests that visitors unfamiliar with the hazards are more vulnerable than local residents. Tourist fatalities could be reduced with appropriate access restrictions, warnings and education.

The dominant classification of victims within 5 km may reflect bias in the data recording. At this distance small numbers of casualties are usually involved, making reports more likely to include detailed information regarding the victims. The volcanology community makes it unlikely for volcanologist deaths to go unremarked at any distance when due to volcanic activity.

Data limitations and uncertainties

Distance measurement

The location of the eruption vent can be difficult to identify, as eruptions can occur at the volcano summit or at flank vents and fissures. Most population exposure and risk assessments are centred on the summit of volcanoes, unless activity is expected from fissure zones. Hence, here the volcano to fatal incident distance is measured from the summit. This is appropriate for our analysis, but should be recognised as a limitation if focussed on particular hazards. For example, lahars may initiate at some distance from the summit, lavas are commonly effused from fissure zones on volcano flanks, and gases and hydrothermal systems may be widespread beyond the summit.

There is an obvious human influence on the data, with both numbers of fatalities and distances being preferentially recorded to whole numbers and often tens (i.e. 10 km, 12,000). Where possible exact figures are used, however, distances should be considered as approximations.

Indirect deaths

The exclusion of distal, indirect fatalities in the analysis can make the lethal range of hazards appear restricted to areas close to volcanoes. However, the difficulty in identifying distance ranges in these incidents can distort the results and complicate analysis. This is also a difficulty in tsunami incidents, where the impacts are widespread. Volcanic areas are prone to cascading hazards where one hazard triggers the occurrence of another, and indirect fatalities can be extensive in area affected, numbers of fatalities and time after eruption. An example of post-eruption indirect fatalities is the 1902 Santa Maria eruption Guatemala, when a malaria epidemic "cost more lives than the eruption itself – many times more" with an estimated 2000 fatalities as the ash had killed the birds, but not the mosquitoes (Church et al. 1908). The potential for such indirect fatalities should be recognised in community planning and preparedness efforts.

Care should be taken in maintenance of the database to ensure the fatal cause is clearly identifiable and volcanic in origin.

Data availability

There are known issues with data completeness in the eruption record, with under-recording affected by factors including time and location. The fatality dataset is relatively small and is likely incomplete. The distance determinations aid the understanding of volcanic fatalities but there are many other factors that should be considered and should be a focus of future work and database improvements. Healthcare facilities hold data on volcano-related fatalities that is not easily accessible and may not be reported elsewhere. For example, indirect fatalities through falls from roofs during tephra clean-up or mental health complications are likely under-reported in the scientific literature and activity bulletins. Future updates to and development of the database would benefit from collaboration with in-country sources such as volcano observatories, geosciences agencies and healthcare facilities to widen the data available and ensure data completeness.

Our analysis is undertaken across the world's volcanoes, irrespective of local population size and topography. Such factors have some control over the location and occurrence of fatalities, and as such may impact the recorded distribution of fatalities. We do not consider the effects of exclusion zones, evacuations and emergency management which have helped save many thousands of lives. For example, the 2010 eruption of Merapi, Indonesia, claimed nearly 400 lives, however an estimated 10,000 to 20,000 lives were saved by timely evacuations (Surono et al. 2012).

To better understand eruptions and their impacts and to reduce disaster risk we need comprehensive, systematic data collection as data are highly variable with time and location. Amongst other aims, the UN's Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations, 2015) seeks a reduction in lives lost. Data availability and accessibility make measurement of such a factor challenging. Sendai should be viewed as a call to spur advancement in data collection and accessibility and international collaboration. One of the desired aims of the UN is to better understand victim demographics, to aid identification of vulnerable groups: data crucial to this aim are gender, disability, age, fatal cause, fatality location, occupation and residence type.

Applications of the data

Population Exposure Index

An application of the new fatality distance data is in the weighting of population data in the Population Exposure Index (PEI; Aspinall et al. 2011; Brown et al. 2015b). The exposed population living around a volcano and within the footprint of potential hazards is a major factor in volcanic risk. Ewert and Harpel (2004) calculated populations in increasing radii circles centred on volcanoes to define Volcano Population Indices (VPI). However, it is preferable to have a single index for risk estimation. A rational way of developing such an index is to recognise that threat decreases in a general way with distance and to use the fatality distance data as an empirical basis for weighting.

The PEI was introduced by Aspinall et al. (2011) and was amended and applied globally by Brown et al. (2015b). Aspinall et al. (2011) weighted VPI_{10} and VPI_{30} (population within 10 and 30 km) by area of rings of 10 and 30 km and the historic occurrence of fatalities within these distances. Brown et al. (2015b) included distances to 100 km, to capture the majority of hazards in the majority of eruptions. Both Aspinall et al. (2011) and Brown et al. (2015b) used the distance described in 27 fatal incidents in the database of Auker et al. (2013) to determine the weighting. Our new dataset expands the number of incidents with a recorded distance to 413, improving confidence in weightings. Indirect fatalities and fatalities through seismicity are excluded from this count. Of these, 175 are QL1 data. As QL2 data represents a range over which fatalities occurred it is excluded for the purposes of PEI calculation.

Despite a six-fold increase in the fatalities dataset there is little change in the weightings and resultant PEI scores due to the overriding occurrence of fatal incidents in the first 10 km: 91 incidents at ≤10 produces a weighting of 0.941; 63 incidents at >10 to ≤30 produces a weighting of 0.057; 19 incidents at >30 to ≤100 gives a weighting of 0.002. VPI_{10}, VPI_{30} and VPI_{100} are weighted by these results at each volcano to produce a PEI score. Eight hundred twenty-five volcanoes are given a low PEI, 295 a moderate PEI and 384 a high PEI. It is this latter group where population exposure is particularly high.

A companion paper will further explain and explore the PEI, and provide the PEI classifications for the world's volcanoes.

Future of the fatalities database

The fatalities database will be available and free to use through the Global Volcano Model (GVM), via http://www.globalvolcanomodel.org/. The database provided as per this paper is Version 1. Periodic updates will be made as new data becomes available and new versions will thus be released. Readers are invited to contribute to the database via the corresponding author. The fatalities dataset will also be incorporated into Volcanoes of the World database through the GVP.

Conclusions and final remarks

The updated fatalities database holds 635 records with 278,368 fatalities in total, considering all fatal causes. The distance at which fatalities occurred from the volcano is identified in 456 incidents, ranging from inside the crater to over 100 km. The removal of indirect and seismicity-related fatal incidents leaves 216,756 fatalities in 571 incidents: distance is recorded in 413 of these incidents. Distances are recorded from within the volcanic vent to 170 km, but nearly half of the fatal incidents are recorded within 10 km (259 incidents, 45%) and 67,680 fatalities (31%). The distribution of fatalities with distance is highly dependent on the occurrence of major incidents in which thousands die. These occur at distances beyond 5 km and to tens of kilometres, typically due to hazardous flows or tsunamis. Ballistics dominate the proximal incident record, PDCs the medial, and lahars, tsunami and tephra the distal record.

Residents make up the largest number of fatalities but visitor groups including scientists, tourists, the media and emergency responders are involved in 152 fatal incidents resulting in 823 fatalities, 76% of which occurred within 5 km or inside the caldera and many in eruptions of low VEI or during times of quiescence.

Reducing mortality from disasters is a priority target of the Sendai Framework for Disaster Risk Reduction. As such, systematic fatality data collection is crucial. In line with the requirements of Sendai, we recommend that future volcanic fatalities are recorded with at least a basic level of detail covering: gender, location, date of death and fatal cause. Further desirable data include the victim's name (this prevents record duplication, but should not be made publically accessible), age, occupation or activity at time of death (e.g. tourist) and place of residence. A better understanding about the lethal range and lethal elements of volcanic hazards could be gained if the physiological cause of death was also recorded (e.g. pulmonary oedema). If volcano-related injuries were recorded in a similar manner, this would provide empirical data for the further development of safety recommendations, equipment and less vulnerable structures.

The distribution of fatalities and quantification of fatal distances enables an analysis of volcanic threat to life around volcanoes, and permits more robust calculations of population exposure to volcanic hazards. The weightings in the Population Exposure Index proposed and applied by Aspinall et al. (2011) and Brown et al. (b) were found to be similar in our much larger dataset.

The ever-growing population exposed to volcanic hazards is a significant factor increasing risk. Risk can be reduced with improvements in forecasting and monitoring, together with increased societal resilience achieved through raising awareness and development of volcanic emergency management plans. Exposure can be reduced through timely evacuations and restrictions on development of urban areas in potential volcanic hazard footprints. Such mitigation measures can be improved upon and supported by the fatality dataset and the understanding of threat with distance.

Additional files

Additional file 1: Excel spreadsheet of the fatalities database, version 1. (XLSX 231 kb)

Additional file 2: KML file for use in Google Earth with the locations of fatal incidents. (KML 205 kb)

Abbreviations

Fatal Cause: The volcanic hazard responsible for the loss of life; Fatal incidents: The occurrence of a fatality or fatalities with one fatal cause identified and one date; Fatal sub-incidents: The occurrence of a fatality or fatalities with one fatal cause identified and one date but listed separately due to the identification of multiple distances; Fatalities: Number of victims; GVM: Global Volcano Model; GVP: Global Volcanism Program; JMA: Japan Meteorological Agency; LaMEVE: Large Magnitude Explosive Volcanic Eruptions database; NCAVJ: National Catalogue of the Active Volcanoes of Japan; PEI: Population Exposure Index; Q-gas: Quiescent gas; QL1 data: Quality level 1 data where distance is precisely known; QL2 data: Quality level 2 data where distance is constrained to a range and the maximum distance is used; SRY lahars: Secondary lahars; VEI: Volcanic Explosivity Index; VHI: Volcanic Hazard Index; VOTW: Volcanoes of the World: the catalogue of holocene volcanoes of the Global Volcanism Program; VPI: Volcano Population Index

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Availability of data and materials

The updated fatalities database is provided as additional material to this paper.

Authors' contributions

SKB conceived of the study with input from SFJ and RSJS. Data collection and analysis was undertaken by SKB. The final manuscript was prepared by SKB with input from SFJ, RSJS, HO and MRA. All authors read, reviewed and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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