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# Lava flow impacts on the built environment: insights from a new global dataset

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**Abstract**

The recent destruction of thousands of homes by lava flows from La Palma volcano, Canary Islands, and Nyiragongo volcano, Democratic Republic of Congo, serves as a reminder of the devastating impact that lava flows can have on communities living in volcanically active regions. Damage to buildings and infrastructure can have widespread and long-lasting effects on rehabilitation and livelihoods. Our understanding of how lava flows interact with buildings is limited and based upon sparse empirical data. Often a binary impact is assumed (destroyed when in contact with the flow and intact when not in contact with the flow), although previous events have shown this to be an oversimplification. Empirical damage data collected after past events provide an evidence base from which to better understand lava flow impacts across a range of building types, environments, and eruption styles, as well as to explore the temporal and spatial trends in these impacts. However, information on lava flow impacts is scattered across literature, reports, and maps; no comprehensive dataset of lava flow impacts exists. In this study, we compile and standardise lava flow impact information from previously compiled data, eruption records, and published literature to create the first comprehensive global dataset of impacts on the built environment from lava flows. We found that since the first recorded event between 5494 yr B.P. and 5387 yr B.P., lava flows from at least 155 events have impacted buildings or infrastructure (e.g., roads, electricity pylons, ski-lifts), with most (47%, $n=73$) recorded as located in Europe. Over the last century, there have been approximately seven lava flow impact events per decade ($n=71$ total). This greatly expands on the past compilations of lava flow impact events. Since ca. 1800 CE, impacts have been consistently documented for less than 14% of recorded eruptions with lava flows globally; prior to 1800 CE, impacts were recorded much more variably (between 0 and 70% of lava flows in any 10-year time bin). The most destructive recorded events were the 1669 CE lava flows at Etna volcano, Italy, which destroyed up to 12 villages and part of the city of Catania, and the 2002 CE lava flows at Nyiragongo volcano, Democratic Republic of Congo, which destroyed up to 14,000 buildings. We found that few studies in the dataset report building typology, damage severity, or hazard intensity at the building-level scale, limiting our ability to assess past building-lava interactions. Future collection of building-level hazard and impact data, supplemented with non-English language records, can be used to inform models that forecast future impacts, support lava flow risk assessments, and develop potential mitigation measures.

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## Introduction

Assessing the impacts of past events is an essential part of understanding the future risks that communities face in volcanically active regions. Global disaster databases compiling past events and impacts have been used as a tool to guide future research and policies in disaster risk reduction (e.g., Emergency Events Database [EM-DAT]: CRED, n.d.; Global Disaster Identifier Number

[GLIDE]: GLIDEnumber, n.d.; Disaster Inventory System [DesInventar]: UNDRR 2015a). More specific databases that document past impacts for natural hazards, including earthquakes (Spence et al. 2011), floods (Gourley et al. 2013), storms (Ciavola et al. 2018), and landslides (Kirschbaum et al. 2010), can be used to identify the range and scale of potential impacts expected for a particular hazard. Having a complete catalogue of past disasters is also fundamental to meeting the priorities of the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR 2015b). These databases provide a baseline for researchers, governments, and communities to assess temporal and spatial trends in risk and can guide future decision-making and investments in mitigation measures (Mazhin et al. 2021; Moriyama et al. 2018). For example, where building-level empirical damage data are available, they can be used to provide insights into the vulnerability of similar buildings in future events in the same region or another region with similar building types (Wilson et al. 2014). With enough data, the relationships between damage and hazard intensity can be used to build robust impact forecasting models (e.g., Chua et al. 2021; Williams et al. 2020; Lallemant et al. 2015; Suppasri et al. 2011; Tomiczek et al. 2017). This analysis can be used to evaluate building vulnerability, improve building design, and give guidance for mitigation measures. It can also be used to issue warnings (Potter et al. 2021; Sai et al. 2018). However, in order to do this, a consistent and comparable catalogue of past impacts is required.

For lava flow impacts, there is no comprehensive dataset of events despite the scale and severity of lava flow impacts on the built environment (Blong 1984; Harris 2015; Jenkins et al. 2017). Lava flow impacts on population centres were previously estimated by Harris et al. (2016) to occur twice every decade. In 2021 CE alone, lava flows from Nyiragongo, Democratic Republic of Congo (DRC), and La Palma, Canary Islands, destroyed 3,629 homes (Global Volcanism Program 2021) and 2,896 buildings (Global Volcanism Program 2022), respectively. Current disaster databases include events based on different classifications for different purposes. For example, the international disaster database EM-DAT (CRED, n.d.) identifies key disasters, defined as events with at least 10 or more fatalities, 100 or more people affected, a state of emergency declared, or a call for international assistance included. It records nine lava flow disasters since 1900 CE, with the first at Fogo volcano, Cabo Verde, in 2014 CE (CRED, n.d.), and two disasters attributed to the 2021 CE Nyiragongo lava flows (in both the DRC and Rwanda). Blong (1984) described 22 case studies of past lava flow events across 15 volcanoes, and their impacts on structures, including their relation to hazard intensity. Recent volcanic studies (e.g., Harris 2015; Jenkins et al. 2017; Meredith et al. 2022) have included some quantification of buildings or villages destroyed in past lava flow events to provide context to their work, but only included events occurring in specific years and/or affecting certain numbers of buildings. Other work has compiled case studies of lava flow crises, including those that do not contact structures (Peltier et al. 2022; Tsang and Lindsay 2020). A key recommendation of Tsang and Lindsay (2020) is the standardisation of past lava flow damage data. In order to assess the extent and range of impacts from lava flows, a more comprehensive catalogue of higher resolution (such as building-level damage information) is required, to better inform policy, decision-making, and prioritisation of future study.

Damage data collection in volcanology has primarily focussed on impacts from tephra fall (Deligne et al. 2022). This study provides the first comprehensive dataset of recorded lava flow events that have impacted the built environment. We compile and standardise hazard and impact information from past lists of lava flow impact events (e.g., Blong 1984; Harris 2015; Jenkins et al. 2017; Tsang and Lindsay 2020; Meredith et al. 2022), Global Volcanism Program (2023) records, and other English-language published literature and newspaper articles. The standardisation of hazard and impact data into one central dataset provides easy comparison between events. We use the dataset to assess temporal and spatial trends in the impact events. The dataset also provides a template for future data collection and guides further study. We use the dataset to identify gaps in current knowledge in terms of the precision and detail of empirical impact data that are recorded. We also assess whether the key lava flow hazard intensity metrics identified by Wilson et al. (2014) are being reported in impact studies. By understanding the gaps in past knowledge, we can assist future volcanology studies to collect more useful and complete data in order to assess building-lava interactions and reduce future lava flow risk.

## Methods

To assess our current knowledge regarding lava impacts on the built environment, we constructed a dataset of past lava flow impact events. A lava flow impact event refers to impacts during a stage of effusive activity (as defined by Jenkins et al., 2007), where at least one lava flow impacted the built environment (buildings and/or infrastructure). This research required an extensive methodology to compile information and capture every impact event possible. For this first compilation, we constrained our search to English-language records only; valuable future work would be to expand beyond this to account for local language records. Records of impacts from lava flows on the built environment were compiled, ranked, and selected to compile the lava flow impact event dataset. For an overview of the methodology used in this study, see Fig. 1.

### Data sources

Data on lava flow impacts in the English language were compiled and interrogated from four sources: 1) Past published global lava impact event lists; 2) Global Volcanism Program (2023) records; 3) English-language newspaper articles; and 4) English-language published studies (Fig. 1). From here, a study refers to a published journal article, book, report, or similar found in our literature search. There may be data on multiple events within a single study or source, and data on a single event may be found across multiple studies or sources.

First, we collated data from six existing published global lava flow impact event lists, which filter events by date and/or scale of impact (Fig. 1A). Blong (1984) listed examples of lava flow damage to buildings from 22 eruptions from 1706 to 1983 CE and explored these, and an additional three, case studies in the text, with information sourced from newspaper articles and other scientific literature. This included 12 events that are not in the other six event lists (Fig. 1A). Harris (2015) and Harris et al. (2016) listed 13 examples of towns or villages completely or partially inundated by lava between 1900 and 2005 CE, updating the list from Blong (1984) by eight events. The lava flow impact assessment of Jenkins et al. (2017) updated Blong (1984) and Harris (2015) by an additional two events, listing eruptions with lava flow impacts of > 20 houses destroyed between 1965 and 2015 CE. Tsang and Lindsay (2020) investigated impacts from 42 basaltic eruptions that have affected surrounding communities since 1950 CE, of which 25 lava flow events have impacted either buildings and/or infrastructure. This included eight eruptions not covered in the other event lists, with information sourced from an English-language literature review and the Global Volcanism Program (2023). Most recently, Meredith et al. (2022) used other scientific literature and the Global

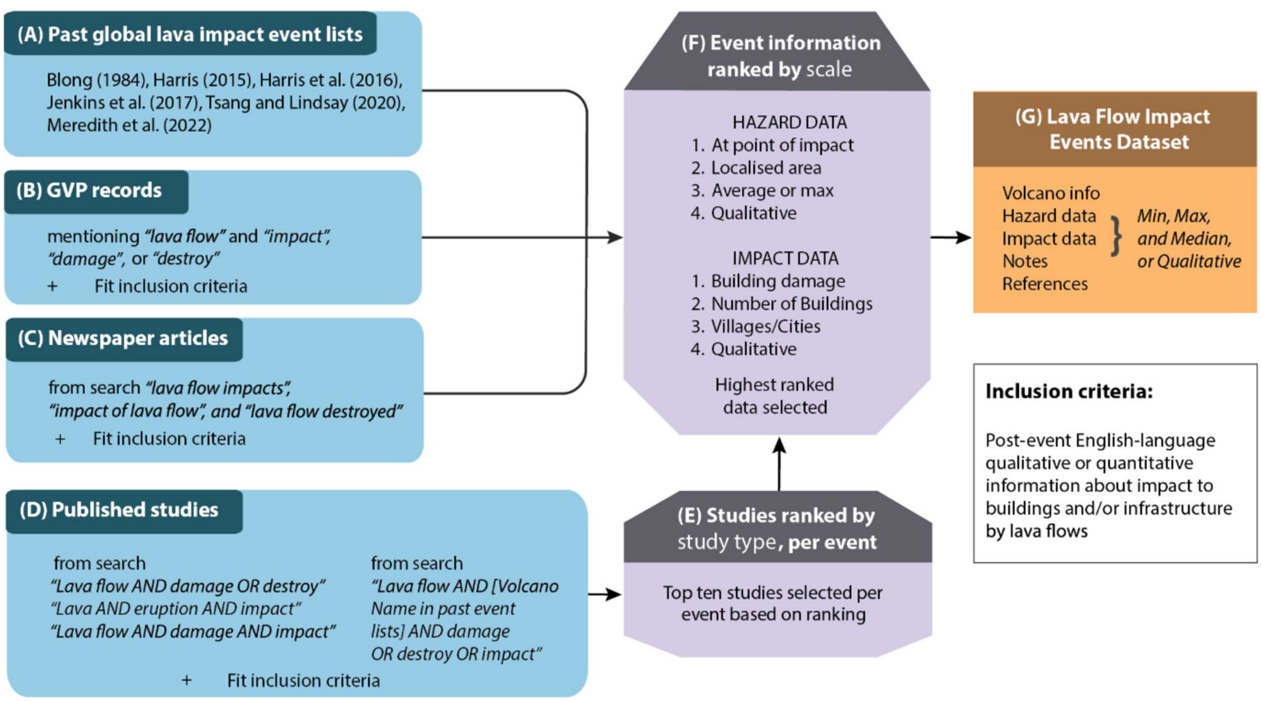


**Fig. 1** An overview of the methodology applied in this research. Four data sources are shown on the left as blue oblongs (**A-D**) and were compiled and filtered by the inclusion criteria stated within the box at the bottom right of the figure. GVP stands for the Global Volcanism Program (Global Volcanism Program 2023). For GVP records, the database Geological Summaries and Bulletin Reports were mined for data. For the published studies with impact data (**D**), for each impact event, each study was ranked by the specificity of study type (**E**; centre lower purple hexagon). The study types (with topic examples in brackets) ranked from highest to lowest are: 1) eruption impact assessment, 2) eruption study (e.g., eruption report, eruption chronology), 3) volcano study (e.g., geology of the volcano, past eruptions), 4) general volcanology study (e.g., other volcano, hazard modelling), and 5) other study (e.g., other natural hazard, disaster risk). Eruption or volcano studies are focussed on the eruption or volcano where the impact occurred. General volcanology studies include those where the focus is on a different volcano. Up to 10 of the highest-ranking studies for each event were selected. The hazard and impact information collated for each event across the four sources were ranked by scale (**F**; centre top purple hexagon) and the highest ranked data for each event were selected for the lava flow impact events dataset (**G**; right orange rectangle)

Volcanism Program (2023) to list 21 eruptions with lava flow impacts from 1970 to 2022 CE to at least one building, four events more than listed previously. These six published event lists resulted in data on a total of 52 lava flow impact events.

In order to update the existing event lists to build a more comprehensive and standardised dataset with as many events as possible, we gathered impact data from three additional sources. The Smithsonian Institution's Global Volcanism Program (2023) compiles records on global Holocene volcanoes and eruptions, with information from scientific literature, observatories, and volcanological bulletins. We refer to these records as GVP records (Fig. 1B). We used web-scaping and programmatically queried the Global Volcanism Program (2023) Bulletin Reports and Geological Summaries for mention of relevant strings (shown in Fig. 1B), ignoring punctuation and capitalisation (the code for this is provided at: https://github.com/elinormeredith/GVPscrape). We manually read those reports and selected those that fit the inclusion criteria (Fig. 1).

We extended our event search to English-language newspaper articles using online article databases Elephind, Google News Archive, and Gale NewsVault to search for mention of relevant strings (shown in Fig. 1C). We filtered up to the first 50 articles for each of the search terms for each website, as most search terms resulted in less than 50 results and any results over 50 results became repetitive. From these, we selected newspaper articles that fit the inclusion criteria.

The final data source was other published English-language studies (Fig. 1D). We conducted a systematic literature search, using Google Scholar, of published research papers, books, reports, and grey literature to identify studies mentioning lava flow impacts on the built environment (Fig. 1D). This was conducted by one author (EM) in September 2021 and repeated in December 2022 for any additional studies. For the initial search using the terms listed in Fig. 1D, we filtered through the top 100 results ranked by relevance. We did not filter beyond the 101st result for each search as the studies became repetitive and less relevant. Our inclusion criteria were studies that report past or current lava flows and focus on or mention qualitative or quantitative information about impacts to buildings (e.g., homes, villages, cities) or infrastructure (e.g., roads, ski-lifts, electricity network) (Fig. 1). To capture as much information as possible from these events, we conducted a further literature search (Fig. 1D). Using Google Scholar, we searched terms, shown in Fig. 1D, including the volcano name from each event compiled. The volcano names are provided in the Supplementary Material, including additional names of the eruptive fissures or cones, and/or alternate spellings for the volcano, that were included in the search. The first 30 results were selected, except for Etna, Kīlauea, and Vestmannaeyjar volcanoes where we selected the first 50 results, as results beyond these became repetitive or irrelevant. We removed repeated results or studies that did not fit the inclusion criteria. We also removed from subsequent analysis studies that were unavailable online, even through our institutional online subscription services.

Many of these studies reference other sources when mentioning impact information. For any studies that cited another study when referring to lava flow impacts, these cited studies were added if available and filtered by the inclusion criteria. This process was repeated until the information did not have a citation. Information found in cited studies was duplicated in studies citing this source. This was done so that all impact information was captured and any information from unavailable studies would still be included.

For each study, we collated information, including the publish date and type of publication (e.g., eruption impact assessment, eruption chronology, non-volcanology study). Studies were classified into different types (listed in Fig. 1) based on their relevance to the eruption or volcano where the impact occurred. For each event, we ranked the studies by specificity of study type (listed in Fig. 1) and selected the highest-ranking studies for each impact event. We based these rankings on study topic relevance. This means that the potentially less specific or relevant sources (e.g., general volcanology, other sources) were only included if there were less than 10 studies for a specific lava flow impact event. If multiple studies of a certain study type resulted in more than 10 records for an event the most relevant records were selected. In total, we collated 536 records of lava flow impacts within 299 studies. The list of studies is given in the Supplementary Material.

### Inclusion criteria

In order to compile events on lava flow impacts, we created criteria to determine if the record of impact should be used in the dataset. We defined that there must be reference to hazard, asset, and impact information; Table 1 gives examples of the terminology used to determine whether the information was used in the dataset. There must be reference to lava, and we did not include impacts from block-and-ash flows, nuées ardantes, or lava domes. We included information with phrases that refer to direct impact, such as damaged or destroyed (e.g., Jenkins et al. 2017; Bonaccorso et al. 2016; Siebe 2000), and also those that refer to the mechanism of damage, such as engulfed, buried, or covered (e.g., Ramírez-Uribe et al. 2021; Brown et al. 2017; Chester et al. 1985), as these imply impact.

However, we did not include phrases not implying contact, such as threatened (e.g., 1959 CE Mount Cameroon, Cameroon: Jennings 1959; 1832 CE Piton de la Fournaise, La Réunion: Stieltjes and Moutou 1989; 1986 CE Izu-Oshima, Japan: Global Volcanism Program 1986). For the asset, we retained all information referring to impacts on human-made physical structures on a large scale (e.g., villages, settlements, cities) or individual structures (e.g., buildings, ski-lifts, ancient structures such as pyramids). If only impact on people or agriculture, and not structures, was recorded, these events were not included unless there was reference to structures such as farmhouses or farmsteads (Table 1). We also did not include impacts on hiking trails (e.g., 2018 CE Piton de la Fournaise, La Réunion: Global Volcanism Program, 2018a). Events where lava flows were recorded to have severed, cut across, or traversed roads were included (e.g., 1979 CE Etna, Italy: Chester et al. 1985; 2004 and 2007 CE Piton de la Fournaise, La Réunion: Peltier et al. 2022, Tsang and Lindsay 2020; 1959 and 1982 CE Mount Cameroon, Cameroon: Wantim et al. 2018), as contact of lava with roads results in impact (Hayes et al. 2022; Mossoux et al. 2019; Wilson et al. 2014). If the phrase used was ambiguous, we used other studies to verify if lava flow hazard was present during the eruption (Table 1). For example, "lava reached" may not imply contact and "impact to populations" may not include structures.

In total, from all four sources of data (Fig. 1A-D), there were data across 155 lava flow impact events between ~ 3491 BCE and 2022 CE.

#### Creating the lava flow impact event dataset

For the structure of the lava flow impact event dataset (Fig. 1G), we followed the structure of Brown et al. (2017), with the aim of simplifying the information from different sources on each lava flow impact event into one standardised dataset, whilst preserving the original data. Each row in the dataset (as a lava flow impact event) corresponds to an event, referring to a stage of activity with lava flow impact on the built environment. For example, the 1983 – 2018 CE Kīlauea eruption, USA, is classified as two events: the Puʻuʻōʻō effusion (1983 – 2018 CE) impacting Kalapana and Royal Gardens, and the lower East Rift Zone effusion (3 May – 4 August 2018 CE). The impacts of the Puʻuʻōʻō effusion stage (1983 – 2018 CE) can be split into further episodes, which are included in an additional sheet in the Supplementary Material. If recorded, the year of impact was added, otherwise, the start year of the episode of activity was selected from the Global Volcanism Program (2023). Any record of uncertainty around the impact year is added to the Stage of Activity column. For example, if there is an uncertainty range around the starting year, we selected the mean average starting year (e.g., 5494 yr B.P. to 5387 yr B.P. Etna, Italy, was entered as -3491 in the events dataset). To provide context for each lava flow impact event, we added information from the Global Volcanism Program (2023) including the volcano number, volcano name, country, region, latitude, longitude, start and end eruption dates, volcano type, and tectonic setting.

For all sources of data compiled (Fig. 1A-D), we noted the information regarding any qualitative or quantitative hazard metrics or characteristics (e.g., lava thickness, velocities, field volume, field area) and impact (e.g., number of buildings or villages destroyed, qualitative impact descriptions, amount of infrastructure destroyed). We also recorded the scale of both hazard data (e.g., maximum, average, point data at one location) and impact data (building-level, settlement-level, infrastructure only).

To select the most precise data for the dataset, for each event, we filtered the hazard and impact

**Table 1** Examples of hazard, impact, and asset terminology in the record of impact used to determine inclusion or rejection of the information in this research. There must be reference to hazard, impact, and asset/s (each row). However, for each row, if there is only reference to a term in the fourth column, the information is not included. For example, if impact from lava and block-and-ash flows damaging villages is recorded, this is used in the dataset compilation; however, if it only refers to impacts from block-and-ash flows damaging villages, it is not included. Other sources were used to verify the impact from lava flows on the built environment if only a term in the third column was used. For example, lava flows reaching a town would be verified with other sources

| Term type | Included | Verified with other sources / marked as uncertain | Not included |
|---|---|---|---|
| Hazard | Lava, lava flow | | Lava mud, lava flood, cold lava, lava avalanche, block-and-ash flow, lava dome, nuée ardente, PDCs |
| Impact | Damaged, destroyed, engulfed, buried, covered, severed, cut, traversed, impacted, razed, invaded, into, enveloped | Reached | Threatened, toward |
| Assets | Villages, settlements, cities, towns, buildings, houses, roads, ski-lifts, pyramids, farmsteads, railways, spas, base camps, water tanks | Populations, areas, regions, properties | Farms, farmland, agriculture, fences, hiking trails |

information by scale (i.e., prioritising those on a building-level scale over a settlement-level scale) (Fig. 1F). For quantitative data, where different sources gave multiple values, we selected the median value and provided the range of values in the Range column. For example, if various records for an impact event showed impacts of 10, 13, 20, and "many" buildings impacted, the data will be entered as 13 in the Median Buildings Destroyed column, and 10 – 20 in the Range of Buildings Destroyed column. All impact information and references were included in the Damage Notes column. This is also the same for the lava flow Area and Volume columns. For qualitative impact data we listed all information; however, this was only entered when no quantitative data were available. Other information such as impacts to infrastructure (e.g., roads, ski-lifts, electricity pylons), agriculture ($km^2$ of land), and people (numbers of fatalities or evacuations) were also added to the dataset. If fatalities were recorded, we added information about the fatalities from Brown et al. (2017), if available. Hazard data such as the lava flow area, volume, length, or velocity were also noted in the dataset if recorded. Data were converted into the same comparable unit in the lava flow impact event dataset, using the metric system. To establish a comprehensive dataset, we used additional English-language literature sources and the Global Volcanism Program (2023) records to fill in any missing hazard information if available, referenced in the dataset. If the Global Volcanism Program (2023) records state that the lava flow entered water, and/or the episode of activity exhibited other hazards, these were added. The data source references for hazard and impact information were added in separate columns. This resulted in a dataset with a total of 155 recorded lava flow impact events (Fig. 1G; Supplementary Material).

This research focussed on impacts on physical structures. The dataset solely presents the recorded impacts of lava flow impact events on the built environment (buildings and/or infrastructure) and relevant information associated with these events (e.g., agriculture impacts, fatalities, evacuations). The dataset does not include the many other events that have caused evacuations, fatalities, or impacts on the natural or agricultural environment but that have not impacted the built environment. Wider cascading impacts or impacts on aviation or climate are not included. Whilst we recognise that these impacts and impacts recorded in non-English-language sources, as well as other social and economic impacts, are important and should be expanded upon in a future update of the dataset, these are out of our research scope.

### Uncertainty of impact events

We noted in the Uncertainty of Events column if there were any uncertain information used in the compilation of the dataset. However, all events were included in subsequent analysis. The four sources of uncertainty are as follows:

A) *Grouping of impact data*. Impacts from additional hazards such as tephra fall or pyroclastic density currents (PDCs) may be included within the total number of impacted structures. In some instances, it is difficult to distinguish the cause of the initial impact when studies report total eruption impacts (1914 CE Sakurajima, Japan: Omori 1916). If the type of additional hazard is known, this was added to the Uncertainty of Events column.

B) *Inference of impacts.* For eruptions where there were no direct observations of impact, some studies have inferred lava flow impacts based on archaeological evidence, or the presence of nearby settlements (e.g., 1075 CE San Francisco Volcanic Field, USA: Elson et al. 2002; 2670 BCE Harrat Ash Shaam: Trifonov 2007; 5494 yr B.P. and 5387 yr B.P. Etna, Italy: Magli et al. 2022).

C) *Contradictory evidence.* For a few examples, other studies provided evidence to imply that the event or impact may not have occurred, had occurred at a different time, or was caused by another hazard (e.g., 1902 CE Savai'i: Taylor and Talia, 1999; 1814 CE Mayon: Bankoff et al., 2020). For these case studies, contradictory evidence was noted in the Uncertainty of Events column. If the sources referencing the hazard mark the event as uncertain this is added to the Uncertainty column (1883 CE Karthala, Comoros: Morin et al. 2009). If there were events where later studies disproved the occurrence of the impact event these were detailed in the Later Proved Invalid column (e.g., 253 CE Etna, Italy: Branca et al. 2016; 1631 CE Vesuvius, Italy: Arnò et al. 1987).

D) *Ambiguous terminology*. There are sometimes multiple or no local language translations of English volcanological terms (Harris et al. 2017); this may lead to the term "lava" used in records to represent other hazards. Difficulty in determining the cause and result of the impacts may be apparent for the more andesitic eruptions in Indonesia, the Philippines, and South America, where deposits of block-and-ash flows, lahars, or PDCs are often referred to as lava (Orense and Ikeda 2007). In these potential cases, alternate studies were used, and any photographs provided were analysed to clarify the role that different hazards, such as lahars or PDCs, had in the recorded impact, and any contradictory evidence was noted in the dataset (1814 Mayon, Philippines: Bankoff et al. 2021). If the impact or asset information is vague, for example, the words "area" or "reached" are used (Table 1), these events are marked as uncertain, and to be included, other studies are used to verify the event.

## Results

There are two main components of our results: first, we present the sources used to build the dataset and an assessment of the gaps in the amount and detail of the information being recorded, then we present the lava flow impact event dataset and investigate temporal and spatial trends in the lava flow impact events (see Supplementary Material).

### Recorded lava flow impact information

The lava flow impact event dataset used four main sources of data (Fig. 1A-D; Fig. 2). A total of 41 GVP reports with lava flow impact information were used, with the first published in 1969 CE, and 32 newspaper articles were used with the first published in 1868 CE. There has been a marked increase in the number of English-language references to lava impact used in this research (Fig. 2). The first study included is Hamilton (1795), and the secondary sources cite back to studies as early as 1542 CE. The studies collated from our literature search include 7 studies published from 1795 to 1895 CE, 54 studies published from 1895 to 1995 CE, and since 1995 CE there have been 238 studies published. Approximately half of all studies included in this research ($n=148$) have been published since 2011 CE (Fig. 2). Whilst impact events prior to 1900 CE ($n=71$) are predominantly reported qualitatively, mostly on a settlement-level scale, impacts post-1900 CE ($n=84$) include more quantitative information on a building-level scale (Figs. 2 and 3).

Eruption impact assessment and lava impact reviews, which include those with their own event lists (Fig. 1A), are few ($n=16$) and all published post-1979 (Fig. 2). Some specifically assess post-event lava impacts (e.g., Branca et al. 2015; Jenkins et al. 2017; Meredith et al. 2022). The majority of studies ($n=224$; 60%) are eruption studies (e.g., Allard et al. 2002; Coltelli et al. 2012; Macdonald 1962; Wantim et al. 2018), or volcano studies (e.g., Branca and Abate 2019; Isshiki 1964; Le Moigne et al. 2020), and include impact information in the eruption chronology or literature review, with most generalising impacts qualitatively or on a settlement-level scale (e.g., village, town, city) (Fig. 3). These types of studies often either cite earlier work or do not include a citation or method of impact data collection. Other studies cite eyewitness accounts, newspaper articles, personal communication, or first-hand journal notes from volcanologists (e.g., Cubellis et al. 2016; Harkin 1960; Thordarson 1990). Hazard information was recorded alongside the impact information for 108 of the impact events, with eruption parameters volume and area as the most common. Other

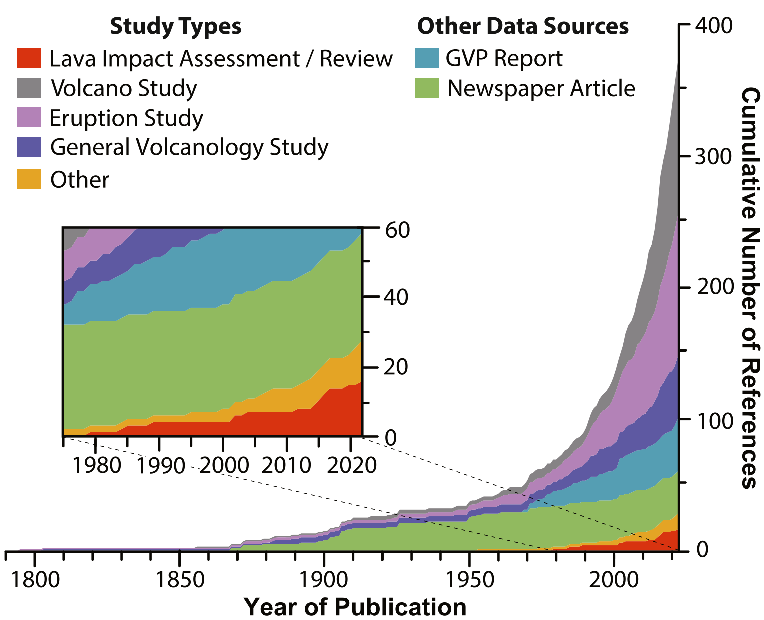


**Fig. 2** The sources of information used to build the lava flow impact event dataset shown as a stacked area chart timeline of the cumulative number of references that mention lava flow impacts based on the publication date, classified by type. The studies with past lava impact event lists (Fig. 1A) are included as lava flow impact assessments/reviews. Impact assessments can include both field and/or remote assessments

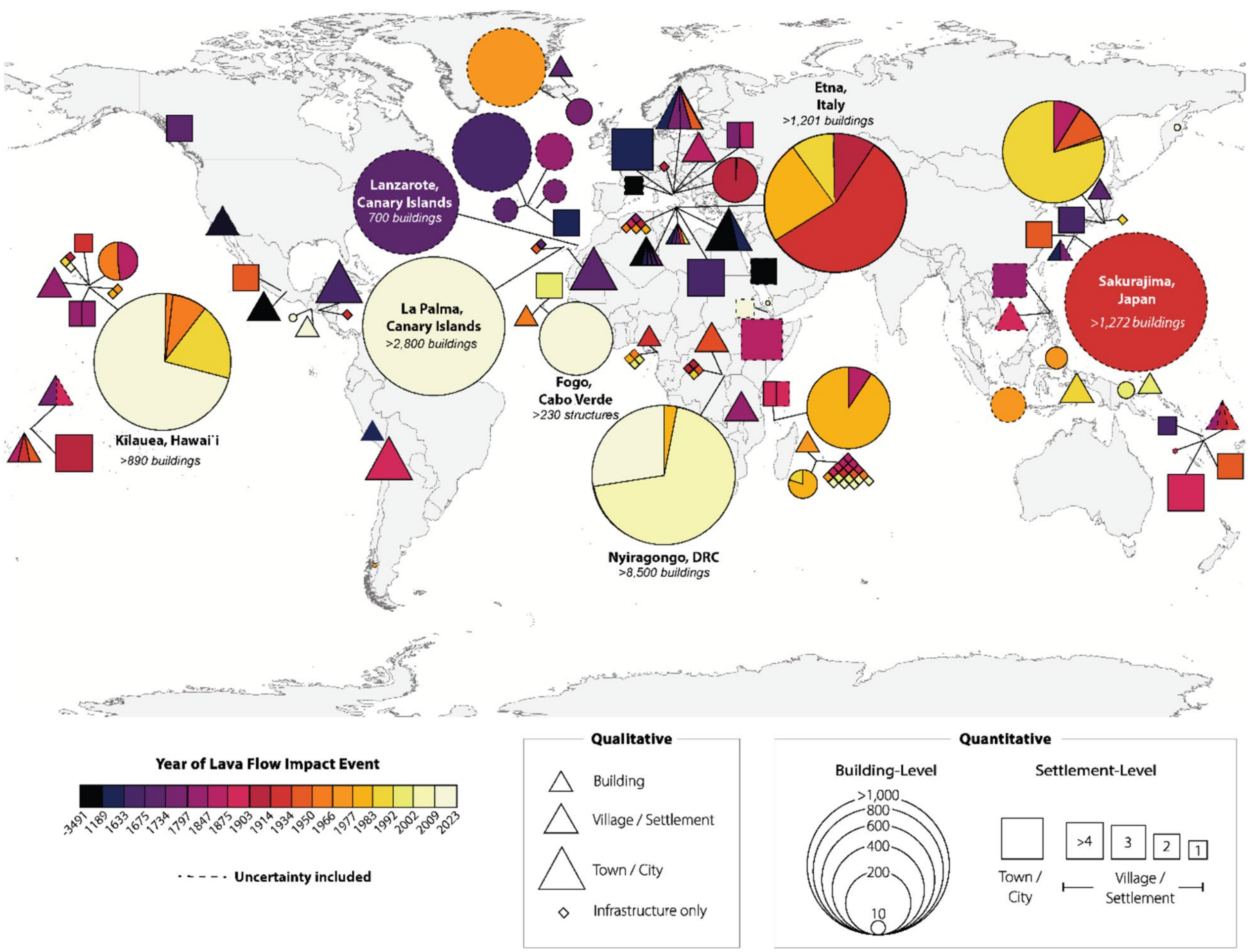


**Fig. 3** Global map of lava flow impact events at each volcano showing impacts where data are available quantitatively as the minimum number of buildings (circles), or settlements (squares) recorded, or where only qualitative data are available (triangles). Each portion of the icon represents each individual event. The icon is coloured by the year of the impact event, and the size represents the scale of impacts. Impact events where only infrastructure impacts are recorded are indicated as diamonds, and events including uncertainty (e.g., other hazard impacts included) are shown with a dashed line. The older events pre-1900 CE (darker colours: pink to purple to black) are predominantly recorded qualitatively and on a settlement-level scale, whilst the relatively recent events post-1900 CE (lighter colours: red to orange to yellow) are predominantly recorded quantitatively and on a building-level scale

information, such as the lava flow front velocities and lava flow lengths for some events, were supplemented by other sources (e.g., Calvari 2019; Walker et al. 1973, Global Volcanism Programme 2023).

### Lava flow impact events

In total, we identified 155 recorded lava flow impact events (see Supplementary Material), with the earliest event in ~ 3491 BCE (5494 yr B.P. and 5387 yr B.P. Etna, Italy) with impact inferred from presence of local settlements, and the latest in 2022 CE, at Mauna Loa, Hawai'i (Figs. 3 and 4). There are 42 events with impacts only recorded to infrastructure (e.g., roads, ski-lifts, water tanks). Of the total lava-flow-producing eruptions recorded during or after 1 CE until December 2022 CE ($n=2{,}072$) in the Global Volcanism Program (2023), only 7% ($n=144$) have associated impacts, recorded in the lava flow impact events dataset (Fig. 4B). The number of recorded lava flow impact events has increased through time, as has the number of recorded lava flows, with 68% ($n=1{,}402$) of recorded lava-flow-producing eruptions and 76% ($n=109$) of recorded lava-flow-producing eruptions with impacts occurring during or after 1800 CE (Fig. 4A), compared to 1 CE to 1800 CE. Prior to ~ 1800 CE, impacts were recorded variably (representing between 0 and 70% of lava flows in any 10-year time bin), which decreased to consistently less than 14% after 1800 CE (Fig. 4B).

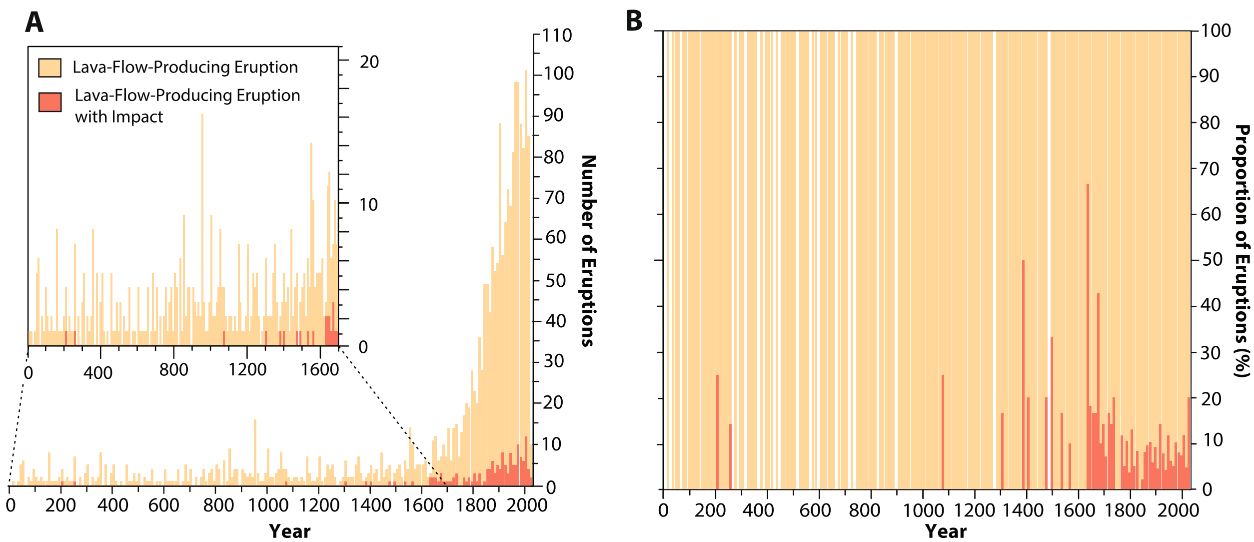


**Fig. 4** Lava-flow-producing eruptions (yellow) ($n$ = 2,072) recorded as an eruption with at least one lava flow event in the Global Volcanism Program (2023), and eruptions with associated lava flow impact events (orange) ($n$ = 144) from this study between years 1—2022 CE, binned by 10-year periods, and based on the eruption start year. For example, the impact events during the 1983 – 2018 CE Kīlauea eruption are presented as one eruption in this figure, in 1983 CE. Shown as (**A**) an overlay bar chart (not stacked) and (**B**) the proportion of all recorded lava-flow-producing eruptions with documented impacts in our dataset. The final bin contains eruptions starting between 2020—2022 CE, where two out of ten eruptions with lava flows had impacts. Five lava flow impact events prior to 1 CE are not shown

Lava flow impact events are recorded at 51 volcanoes, across a range of GVP-defined volcano types and tectonic settings (Global Volcanism Program, 2023), most commonly at stratovolcanoes ($n$ = 25; 49%) and subduction zones ($n$ = 25; 49%). The greatest proportion of recorded lava flow impact events has been recorded in Europe ($n$ = 73; 47%) at 14 volcanoes (Fig. 5), where eruptions at Etna volcano, Italy, have led to the most impact events ($n$ = 26), accounting for 17% of the dataset, including two later proven invalid. Lava flows at Etna have also impacted the highest number of settlements (12 villages and part of Catania city) recorded at a volcano during a single event in 1669 CE (Table 2). While the recording of impact events at the regional scale remained relatively constant prior to 1600 CE, there has been a marked increase in the proportion of impact events recorded in Africa since 1800 CE (Fig. 5), when the first impact event was recorded at Kyejo volcano, Tanzania, in 1800 CE. Recorded African ($n$ = 23) and Oceanian ($n$ = 15) lava flow impact events currently account for 15 and 10% of the dataset, respectively. If events are classified geographically using the Global Volcanism Program (2023) region instead, with Hawaiian volcanoes classified as part of Oceania, and Piton de la Fournaise volcano, La Réunion, in Africa, there is also an increase in the proportion of impact events recorded in Africa with 28% ($n$ = 44) of events at 9 volcanoes, and Oceania accounting for 19% ($n$ = 30) of the dataset at 10 volcanoes, since the first record at Ambae volcano, Vanuatu, in 1670 CE (Fig. 5). The highest recorded number in our dataset of buildings destroyed results from lava flows at Nyiragongo volcano, DRC, with at least 8,529 buildings destroyed (50% of the minimum total number of buildings recorded as destroyed in the dataset) across three events (Fig. 3). Nyiragongo volcano also has the highest number of recorded buildings destroyed by a single impact event in our dataset, with up to 14,000 buildings destroyed during the 2002 CE lava flows (Table 3). The 2002 CE Nyiragongo lava flows are also the deadliest, killing 47 people directly and 60 – 100 people during an explosion of a petrol station surrounded by lava (Brown et al. 2017). Off the coast of Africa, Piton de la Fournaise volcano, La Réunion, has also produced a large quantity of lava impact events ($n$ = 21), including events that impacted the main coastal highway.

We found little relationship between the size of the lava flow (either by volume or area) and the scale of impacts (Fig. 6A-D). For example, one of the largest lava flows by volume, the 1783 – 1784 CE Lakagígar eruption at Grímsvötn volcano, Iceland, inundated ~ 14.7 km$^3$ and destroyed ~ 34 structures, while one of the smallest flows by volume, the 2002 CE Nyiragongo ~ 0.025 km$^3$ lava flows destroyed up to 14,000 buildings (Fig. 6A-D; Table 3). This disparity between lava flow size and impact scale is also evident at the individual volcano scale. For example, at Kīlauea, Hawai‘i, the 1983 – 2018 CE Pu‘u‘ō‘ō lava flows inundated 144.10 km$^2$ in just over three decades and destroyed up to 215 structures, while the 2018 CE lower East Rift Zone flows inundated 35.5 km$^2$ but damaged and/

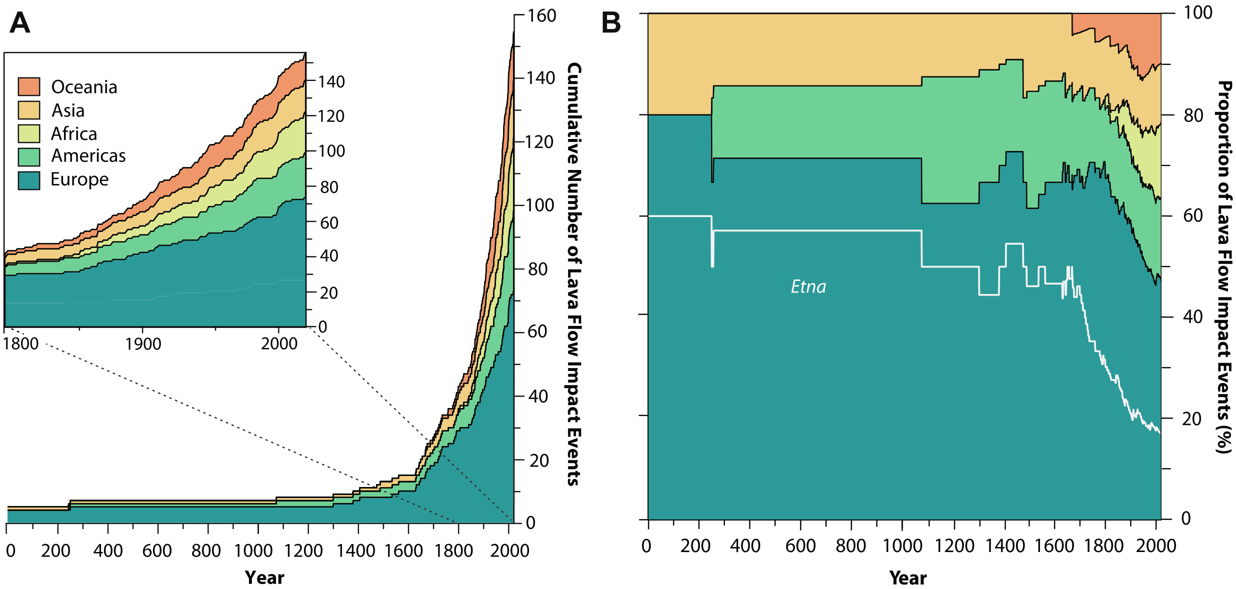


**Fig. 5** (**A**) Cumulative frequency of recorded lava flow impact events classified by region from 1 to 2022 CE. The inset box shows lava flow impact events occurring after 1800 CE, which represent ~ 71% of the total number of lava flow impact events. Lava flows starting prior to 1 CE are included in the cumulative count but not shown on the x-axis. (**B**) The proportion of cumulative lava flow impact events classified by region from 1 to 2022 CE. Etna lava flow impact events are highlighted. In 2022 CE, the greatest proportion of the recorded lava flow impact events is in Europe (47%; $n=73$), followed by the Americas (17%; $n=26$), Africa (15%; $n=23$), Asia (12%; $n=18$), and Oceania (10%; $n=15$). Regions are defined based on the UN Geoschemes (United Nations 1999) location of the GVP country in the dataset, e.g., Hawaiian volcanoes are classified as Americas and Piton de la Fournaise, La Réunion, is classified as Europe. If Hawaiian volcanoes and Piton de la Fournaise were classified by geographic location (Oceania and Africa, respectively), for 2022 CE, Oceania and Africa would represent a higher proportion in the dataset, with 28% ($n=44$) in Africa and 19% ($n=30$) in Oceania. There are no recorded lava flow impact events in Antarctica

**Table 2** Lava flow events with the greatest impacts to the built environment, where impacts are recorded quantitatively on a settlement level. Events are ranked by the maximum number of recorded impacts to settlements. Events with inferred impacts or contradictory evidence are not included

**Settlements**

| Rank | Start Year | Volcano | Maximum # Impacted |
|---|---|---|---|
| 1 | 1669 | Etna, Italy | 12 settlements and part of city |
| 2 | 1888 | Ambrym, Vanuatu | 9 villages |
| 3 | 1905 | Matavanu (Savai'i), Samoa | 5 villages |
| 4 | 1700 | Tseax, Canada | 3 villages |
| 5 | 1944 | Vesuvius, Italy | 2 towns |
| 6 | 1643 | Miyakejima, Japan | 2 towns |
| =7 | 2011 | Nabro, Eritrea | 2 villages[a] |
| =7 | 1995 | Fogo, Cabo Verde | 2 villages |
| =7 | 1946 | Sakurajima (Aira), Japan | 2 villages |
| =7 | 1943 | Parícutin (Michoacán-Guanajuato), México | 2 villages |
| =7 | 1939 | Lopevi, Vanuatu | 2 villages |
| =7 | 1855 | Vesuvius, Italy | 2 villages |
| =7 | 1563 | Pico, Azores, Portugal | 2 villages |

[a]Includes earthquake and tephra damage

**Table 3** Lava flow events with the greatest impacts to the built environment, where impacts are recorded quantitatively on a building level. Events are ranked by the maximum number of recorded impacts to buildings. Events with inferred impacts or contradictory evidence are not included

**Buildings**

| Rank | Start Year | Volcano | Maximum # Impacted |
|---|---|---|---|
| 1 | 2002 | Nyiragongo, DRC | 14,000 |
| 2 | 1914 | Sakurajima (Aira), Japan | 4,500[a] |
| 3 | 2021 | Nyiragongo, DRC | 3,644 |
| 4 | 2021 | La Palma, Canary Islands, Spain | 3,126 |
| 5 | 1977 | Nyiragongo, DRC | 800 |
| 6 | 1928 | Etna, Italy | 750 |
| 7 | 2018 | Kīlauea, Hawai'i, USA | 716[b] |
| 8 | 1730 | Lanzarote, Canary Islands, Spain | 700[a] |
| 9 | 1983 | Miyakejima, Japan | 423 |
| 10 | 1672 | Fayal, Azores, Portugal | 307[c] |
| 11 | 1973 | Eldfell (Vestmannaeyjar), Iceland | 300[a] |
| 12 | 1977 | Karthala, Comoros | 293 |

[a]includes tephra damage; [b]1,929 including water tanks and other structures; [c]includes earthquake damage

or destroyed up to 1,929 structures in several months (Fig. 6A-D). There is also a disparity between the numbers of impacts reported for single lava flow impact events, in terms of scale and precision, resulting in the range shown by the blue lines in Fig. 6. For example, the 1955 CE Kīlauea lava flow is reported in different studies as impacting 17 (Blong 1984; Macdonald 1962), and over 60 buildings (Gregg 2005).

Twenty-eight impact events are noted as having some uncertain information included, mostly because impact data are grouped into impacts from multiple hazards or events ($n=13$). For example, buildings recorded as destroyed during the 1914 CE Sakurajima eruption, Japan, and the 2011 CE Nabro eruption, Eritrea, were also impacted by tephra as well as lava flows (Goitom et al. 2015; Kotô, 1916; Omori 1916). In seven cases, there is ambiguous language about the hazard or asset, and in another five cases, impacts are inferred. For some events, other studies help to confirm or reject the occurrence of the impact, and seven events have contradictory evidence against the impact event occurring. An account of the destruction of a church and town (Azaïs and Chambard 1931) by a 13th Century eruption of Fentale, Ethiopia, could be related to 19th Century lava flows (Fontijn et al. 2018). Two events at Etna were classified as later proven invalid, for example, Monaco et al. (2010) stated that 252 – 253 CE Etna, Italy, lava flows reached the amphitheatre in Catania, referencing Sciuto Patti (1872); however, this impact was disputed by Branca et al. (2016).

## Discussion

### Trends in lava flow impact events

The dataset of 155 recorded lava flow impact events is more comprehensive than previous published lists of lava flow impacts. This is primarily because the dataset includes infrastructure impacts and starts from the first recorded lava flow impact event in ~ 3491 BCE at Etna, Italy, whereas other studies are limited to smaller time ranges and/or to events impacting only certain numbers of structures (e.g., Harris 2015; Jenkins et al. 2017; Tsang and Lindsay 2020). For example, Jenkins et al. (2017) listed seven eruptions filtered to between 1965 and 2015 CE with more than 20 buildings affected by lava flows. Our dataset shows that the frequency of events is higher than previously estimated. For example, Harris et al. (2016) estimated two lava flow impact events to population centres per decade, whilst our dataset presents at least 31 impact events to settlements or > 20 buildings in the past 100 years, equating to three events per decade (and five in the last decade). For the total dataset, there are approximately seven events per decade (including < 20 structures impacted and infrastructure-only impacts) with 71 in the past 100 years and six in the last decade. Our dataset also greatly exceeds those of global disaster databases such as the EM-DAT database ($n=9$ between 1900 and 2022 CE). Our dataset gives a more comprehensive representation of past impactful lava flow events and thus insights into the risk posed by lava flows.

The increased rate of recorded impact events over time may relate to higher population exposure around volcanoes (Chester et al. 2000; Freire et al. 2019), exemplifying an increasing risk from lava flows. The increased rate of impact events may also be due to more impact data collection and recording, and a potential lack of preservation of older records (Burgos et al. 2022), highlighted by fewer recorded events prior to ~ 1800 CE (Fig. 4). The rise in lava flow impact events after ~ 1500 CE (Fig. 5) corresponds to an increase in eruption recording in the Atlantic region related to expansions of populations during the Age of Discovery, with the first impact event recorded in the Azores in 1563 CE (Burgos et al. 2022). The increase in African impact records after 1800 CE, predominantly in the East African Rift System (EARS), is consistent with findings of Wadge et al. (2016), whereby eruption records of 21 EARS volcanoes that have erupted historically (since 1800 CE) extend back to the 1840s, with oral accounts of eruptions since 1800 CE.

Of those lava flow impact events recorded before 1800 CE, no events include solely impacts to infrastructure (Fig. 3), and all other impacts are recorded at a settlement level or for multiple buildings, except for a medicinal and thermal spa recorded to have been destroyed at La Palma, Canary Islands, in 1677 CE (Longpre and Felpeto 2021; Carracedo et al. 1996). The first impact event post-1800 CE where only infrastructure damage is recorded is during the 1843 CE Etna lava flows, Italy. This suggests that the events with large impacts are more likely to be recorded and/or passed on through oral accounts. Indeed, the 1800 CE Sarabwe eruption of Kyejo volcano, Tanzania, that destroyed several villages, is the only eruption in the Rungwe Volcanic Province that is recorded (Fontijn et al. 2012).

Although impact is likely to be highly related to exposure, cataloguing of impact events provides examples of the range and scale of potential impacts to both buildings and infrastructure from lava flows. The size of lava flow fields is not correlated to the number of impacted buildings (Fig. 6); for example, the high number of lava flows in Iceland (Thordarson and Höskuldsson, 2008), including the 1783 – 1784 CE Lakagígar lava flows with a ~ 14.7 km$^3$ volume (Grímsvötn volcano, Iceland; Thordarson and Self 1993), only resulted in ~ 34 structures destroyed (Fig. 6) due to low building exposure. A small effusive event at the highly exposed Nyiragongo volcano, Democratic Republic of Congo, or Vesuvius

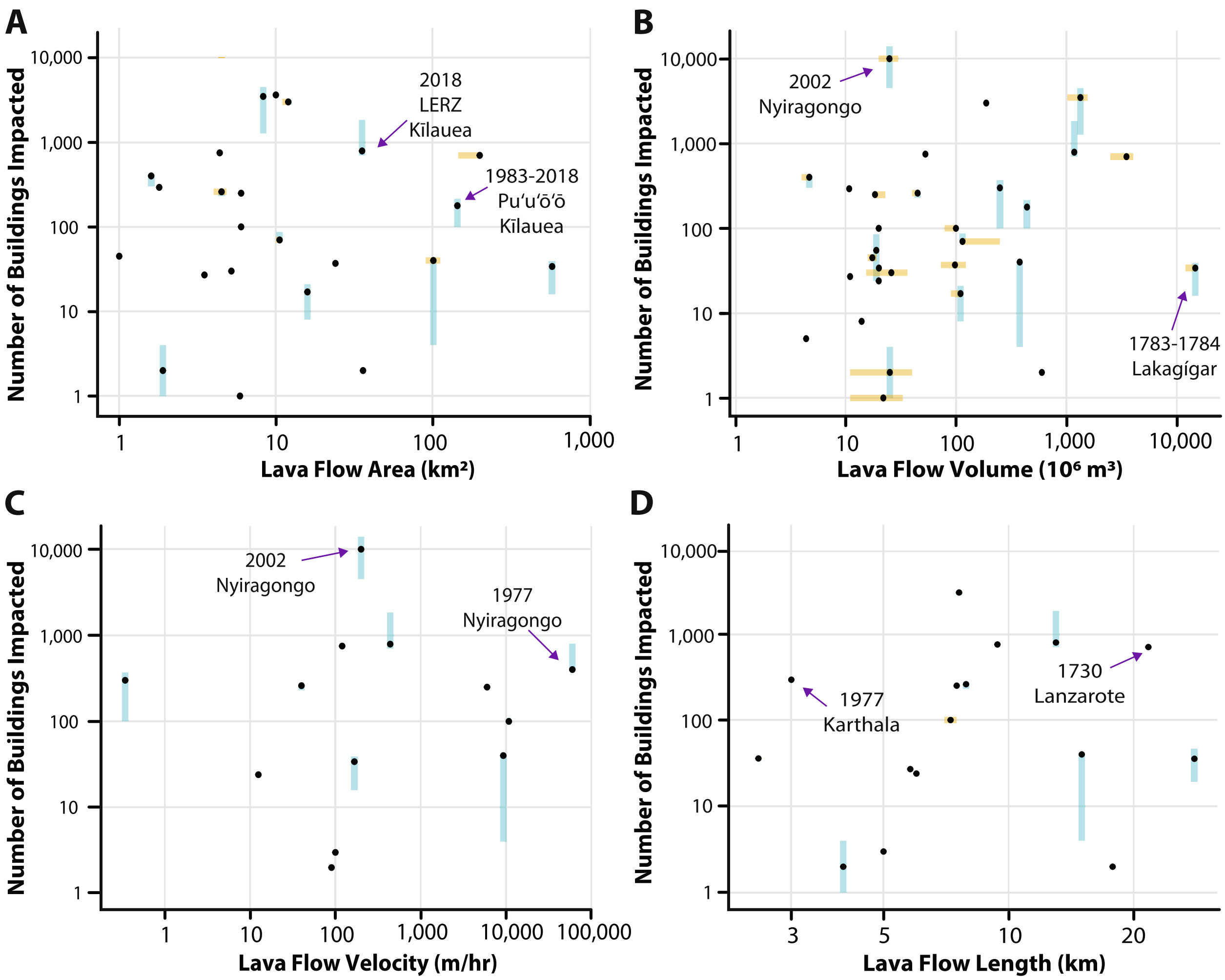


**Fig. 6** The median of reported impacted structures for each lava flow impact event where quantitative building-level data are known, plotted against (**A**) lava flow area, (**B**) lava flow volume, (**C**) maximum recorded lava flow velocity, and (**D**) lava flow length. Recorded channel velocity is not included. Each lava flow impact event is represented as a dot. Error bars show the range of recorded lava flow area, volume, velocity, or length (yellow) and impact data (blue), in different records. Both x- and y-axes are on a log scale. There is little correlation between the number of buildings impacted and lava flow area ($R^2 = 0.0079$), volume ($R^2 = 0.0004$), front velocity ($R^2 = 0.001$), and length ($R^2 = 0.0013$). Key lava flow impact events are highlighted with purple arrows

volcano, Italy, is likely to pose a much greater risk than a flood basalt erupted at the remote Katla volcano, Iceland, or a high-effusion rate lava flow at Mauna Loa volcano, Hawai'i. Indeed, lava has also erupted from fissures opening within settlements (2018 lower East Rift Zone lava flows, Kīlauea, Hawai'i: Meredith et al. 2022; 1853, 1946 Niuafo'ou, Tonga: Taylor 1991). Although most (93%, $n = 1{,}928$) lava-flow-producing eruptions since 1 CE (Fig. 4) have no record of impacts on the built environment, all lava flows are likely to have impacted the local natural environment and may also have impacted local communities in other ways, for example, by causing fatalities (Brown et al. 2017), restricting access, burying farmland, affecting air quality, closing roads, or prompting evacuations (Tsang and Lindsay 2020).

The majority ($n = 82$, 57%) of the lava flow impact events have other examples of hazards, such as tephra fall, volcanic bombs, gases, and cracks/fissures, with examples of impact to structures prior to, during, or after lava effusion. Secondary hazards may extend the potential impact area beyond the lava flow margin (Meredith et al. 2022). For example, flooding from rivers dammed by lava flows occurred during the 1658 CE San Salvador eruption, El Salvador (Ferrés et al. 2011), and famine was caused by lava inundation of agricultural land during the 1730 CE Lanzarote lava flows, Canary Islands (Carracedo et al. 1992). Both flooding and famine were caused by the 1783 – 1784 CE Lakagígar eruption, Grímsvötn volcano, Iceland (Boreham et al. 2020). One recurring impact among at least five events is the explosion of liquid tanks or petrol stations (e.g., 1843 CE Etna, Italy: Thomaidis et al. 2021; 1944 CE Vesuvius, Italy: Carlino 2021; 2002 CE Etna, Italy: Ancione et al. 2015; 2002 CE Nyiragongo, DRC: Baxter et al. 2002; 2014 – 2015 CE Fogo, Cabo Verde: Jenkins et al. 2017). Other examples of secondary hazards associated with lava flow events recorded in the dataset include collapsing lava flow fronts, fire spread, laze (a hydrochloric acid mist at ocean entry), or explosions at contact with water. There are also records of localised tsunamis (e.g., 1905 – 1911 CE Matavanu, Samoa: Simanjuntak et al. 2020). Collapsing lava flow fronts can trigger damaging block-and-ash flows, which are not included in this dataset as we consider the damaging hazard to be PDCs (1922 CE Santa Maria, Guatemala: Alvarado et al. 2007; Harris et al. 2002; 2018 CE Mayon, Philippines: Global Volcanism Program 2018b). This highlights the potential additional hazards associated with lava flow events that extend the impacts beyond those captured in a lava flow inundation map.

### Damage information

For eruptions prior to ~ 1800 CE, 26 events record damage data on an island or settlement-level scale (e.g., 1669 CE Etna, Italy; 1706 CE Teide, Canary Islands; 1643 CE Miyakejima, Japan), compared to 14 at a building-level scale (Fig. 3). Studies reporting impacts from post-1800 CE lava flows more often identify the total numbers of buildings destroyed or give details of building-level damage ($n=43$) than those on a settlement-level scale ($n=30$). Building-level, rather than settlement-level, data are important for local recovery and crisis management during and after the eruption, particularly as there are examples of buildings used after lava flow contact (1973 Vestmannaeyjar lava flows, Iceland: Williams and Moore 1983). They also allow for a better understanding of the scale of impacts and allow for quantified impact assessments (e.g., Hayes et al. 2019; Spence et al. 1996; Williams et al. 2020).

Very few studies ($n=16$) are post-eruption impact assessments or reviews, with only a small number ($n=3$) of those focussing solely on building damage assessment from a single lava flow event at a building-level scale (Branca et al. 2015; Jenkins et al. 2017; Meredith et al. 2022). This is fewer than the post-eruption impact studies or reviews identified by Deligne et al. (2022) that included tephra fall ($n=39$), lahar ($n=15$), projectile ($n=13$), or PDC impacts ($n=13$). The greater focus on tephra fall may be because lava flows typically cover smaller areas closer to vents than tephra falls, and so the likelihood of affecting a built-up area is lower, providing fewer opportunities to collect lava flow damage data (Deligne et al. 2022). Lava flows also pose a lower threat to life than tephra fall (lava flows account for < 1% of global volcanic fatalities compared to ~ 8% for tephra fall: Brown et al. 2017).

Lava flow damage assessments may also not have been prioritised in the past as lava flows were considered as a binary impact (buildings destroyed or intact) in risk assessments (e.g., Centorrino et al. 2021; Favalli et al. 2012; Jenkins et al. 2014; Lirer and Vitelli 1998), while tephra fall impacts are considered as gradational leading to a wider spectrum of perceived impacts (Deligne et al. 2022). This may be appropriate for wooden structures that are destroyed (e.g., 1977 CE Piton de la Fournaise, La Réunion: Peltier et al. 2022; 2018 CE Kīlauea, Hawai'i: Meredith et al. 2022). However, most studies follow this binary approach for all structure types, reporting numbers of buildings destroyed, but there are also some records, damage assessments, and photographs that provide evidence that structures were not completely destroyed (e.g., Taylor and Sapolu 2016; Jenkins et al. 2017; Meredith et al. 2022). For example, stone churches were damaged but were not destroyed during the 1905 – 1911 CE Matavanu lava flows, Samoa (Anderson 1910); 1906 CE Vesuvius lava flows, Italy (Chester et al., 1985); 1943 CE Parícutin lava flows, México (Nolan 1972); and the 1977 CE Piton de la Fournaise lava flows, La Réunion (Global Volcanism Program 1977). A potential method to standardise future impact data collection is to use a set of damage states to classify damage severity from lava flows, such as those proposed in Meredith et al. (2022).

### Hazard information

Finding relationships between damage and the characteristics or intensity of the lava flow could be used to forecast the scale or severity of future impacts. Wilson et al. (2014) proposed six hazard intensity metrics that can influence damage severity, which ideally would be useful metrics to collect when conducting an impact assessment: the presence of lava, depth of flow, velocity, dynamic pressure, temperature, and cooling time. The presence of lava, as a lava flow footprint, is an output of lava flow models and is currently used to forecast whether structures will be destroyed by flows. Whether the lava flow is in contact with a building or infrastructure can be observed in the field or through remote imagery on a building level, for example, Copernicus (2021a and 2021b) classified buildings in contact with the lava flow as destroyed and buildings along the lava flow margin as damaged. However, this approach does not explain the observations of damage severity variation both within and beyond the flow margin.

Eruption parameters giving the size of the lava flow (lava flow area, length, and volume) are often reported with generalised event impact information, and can serve as hazard intensity metrics; however, there is not a clear relationship with damage scale (Fig. 6). To assess building-lava interactions, building-level measurements of lava flow metrics like those given by Wilson et al. (2014), such as thickness, temperature, or pressure, may be useful, particularly as thickness, velocity, and temperature are outputs of lava flow forecasting models (de' Michieli Vitturi and Tarquini 2018; Cappello et al. 2016; Fujita and Nagai 2016). The lack of these hazard intensity metrics in records may be due to these data being difficult or dangerous to collect at a building-level scale and/or at the time of impact, or potentially because it is not yet recognised as important to collect. For example, some studies record lava temperatures (e.g., Macdonald 1954; Hume, 1946; Aramaki et al., 1986). As the lava flow crust contacts the structure (Blong 1984), the radiant heat around the flow margin may be more important than the lava core temperature (Meredith et al. 2022; Wilson et al. 2014), but it is difficult to access the lava flow to measure temperature at the site and time of impact.

The relation between lava flow pressure and subsequent damage has not yet been explored, as it has for other flows, such as PDCs or lahars (Jenkins et al., 2013; Jenkins et al., 2015). However, this relation has been suggested as a potential influence on damage severity (Blong 1984; Jenkins et al. 2017; Wilson et al. 2014). Pressure from a mass flow includes a dynamic component (Eq. 1) and a static component (Eq. 2).

$$P_D = \frac{1}{2} \cdot \rho \cdot v^2 \tag{1}$$

$$P_S = \rho \cdot g \cdot h \tag{2}$$

where $P_D$ is the dynamic pressure (Pa), $P_S$ is the static pressure (Pa), $\rho$ is the lava flow density (kg/m$^2$), $v$ is the lava flow front velocity (m/s), g is the gravitational acceleration (9.81 m/s$^2$), and h is the flow depth (m).

If the flow front advance rate is known, the dynamic pressure of the flow can be estimated based on typical lava densities using Eq. 1 (Fig. 7). The static pressure may also play an important role in influencing damage severity, which can be calculated if the lava flow thickness is known using Eq. 2 (Fig. 7). These could be later updated if the lava density is measured. Flow front velocities can be measured syn-eruption with aerial monitoring (de Graffenried et al. 2021). Lava flow velocities have also been estimated using lava in contact with trees (Chevrel et al., 2019). However, often lava flow front velocities are averaged as advance rates over a period of time, and lava density is often an estimate for the entire flow field. As density and flow front velocities can vary through time and across the lava flow field, this means that pressure varies temporally throughout the lava effusion, and spatially across the flow front. Once a relationship between pressure and/or velocity at time of impact with damage severity is established, it can then ideally be used in real-time forecasts and risk assessments, if measurements of velocity are measured through aerial monitoring syn-eruption, and density is estimated or known.

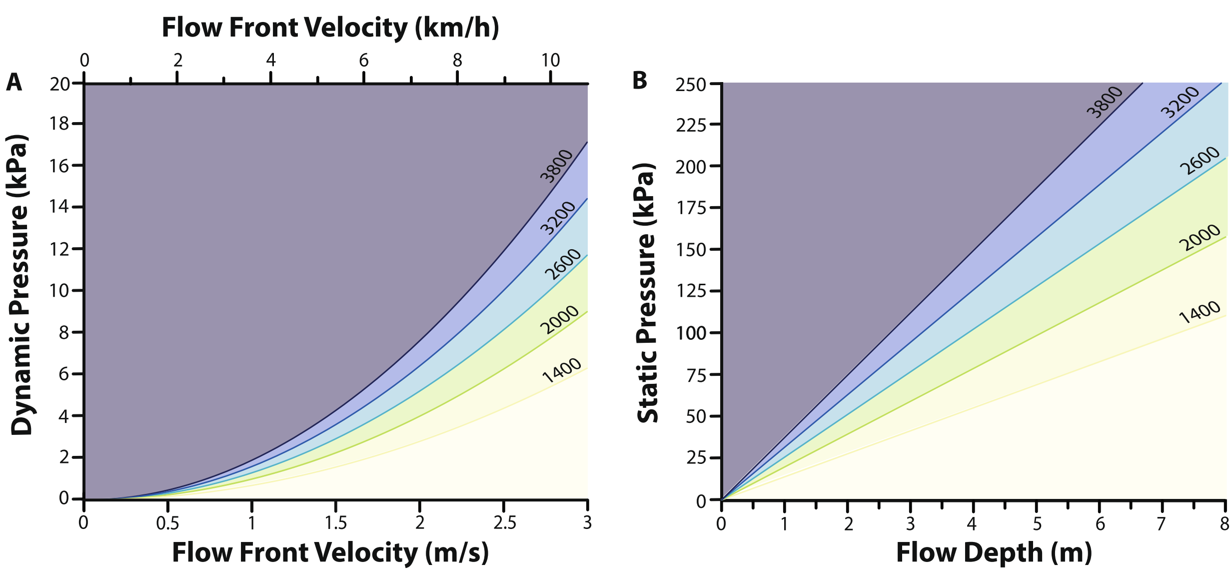


**Fig. 7** Lava flow dynamic pressure as a function of lava flow front velocity (**A**) and static pressure as a function of flow depth (**B**), calculated using Eq. 1 and Eq. 2. The lines represent typical lava flow densities (kg/m$^2$). Lava flow depth and velocity measured at the site of impact can be used to estimate pressure exerted on a building

Final lava flow thicknesses can be used as a proxy for hazard intensity (Meredith et al. 2022; Wilson et al. 2014) and used to calculate static pressure (Fig. 7). The lava flow thickness is often presented as an average or maximum for the flow field, but it could also be measured through observations at the site of impact. Where hazard intensity metrics are recorded, the method of how these values are measured is not always included; for older papers, these may be rough estimates across the whole flow. However, without measurements in the centre of the flow, estimates made from the flow margins are prone to error (Stevens et al. 1997). For example, the journals of Jón Steingrímsson give observations of lava flow thickness (e.g., 60 fathoms [100 m] next to the farm Skál: Thordarson et al., 2003) during the 1783 – 1784 CE Lakagígar eruption, Grímsvötn volcano, Iceland, which are greater than estimates and measurements from later fieldwork (e.g., average of lava flow sections between 10 and 74 m: Thordarson and Self 1993). For more recent lava flows, thickness maps created using comparison of pre- and post-eruption topography derived from LiDAR or photogrammetric methods (e.g., Favalli et al. 2010; Richter et al. 2016; Zoeller et al. 2020) allow for specific thicknesses to be identified at individual structures. As lava flow thickness is an output of some lava flow models, it can potentially be used to forecast damage in future lava flow scenarios.

### Future expansions of the dataset

Our study provides a new dataset of recorded lava flow impact events. The dataset can be used to highlight the frequency, scale, and range of potential impacts for communities at risk of lava flows. This can be used to inform decision-making and frame conversations around lava flow vulnerability when considering future lava flow risk in volcanically active regions. The dataset can be updated as future studies reveal past lava flow impact events, or when future lava impact events occur. Where there are examples of events with finer-resolution data, the dataset can be expanded to include a building-level impact component. This allows for post-event building-level damage data collection at future events to be added, or past impacts can be added with enough building-level data. With enough data, correlations of damage data with lava flow attributes such as thickness will allow for the exploration of building-lava interactions and to forecast future damage.

A dataset of past events has its limitations, may not capture every event, and can be expanded further (Lin et al. 2021). Through our study, we had difficulty accessing some primary sources, and the methodology was constrained to English-language sources. Whilst the methodology includes studies that cite non-English and inaccessible sources, such that information from primary and non-English studies is collected through secondary sources, there may be missed impact events, for example through indigenous knowledge passed down through oral tradition and not captured in English sources. The data in the current dataset can be verified and/or updated with a systematic literature search of other sources, reports, or newspaper articles in local languages. For example, the impacts of the 1987 CE Piton de la Fournaise eruption, La Réunion, are detailed by Bertile (1987) in French, and the lava flows of Etna in 1669 and 1879 CE are explored in Donato et al. (2009), Manitta (2010), and Manitta (2016) in Italian. Such expansion of impact datasets to include local sources was recognised as important in Peltier et al. (2022). We invite any additions of lava flow impact events to the dataset so it can capture as many impact events as possible. There could also be an analysis of the source reliability, for example in terms of the uncertainty surrounding the terminology of events that were included or excluded. For example, studies reporting impacts on farms may have affected buildings, but have not been included in our collation of events (Table 1). Studies may not have used the word "lava" to describe the hazard, such as if there is only a photograph or translation from another language. Future study can ascertain the presence of lava in order to clarify the inclusion of these uncertain events.

## Conclusion

Our dataset comprises 155 lava flow events that have impacted the built environment between ~ 3491 BCE and 2022 CE. We used 372 Global Volcanism Program (GVP) records, newspaper articles, or other studies published between 1795 and 2022 CE. Our findings show a higher frequency of impact events than previously estimated. Whilst Harris et al. (2016) estimated the occurrence of approximately two events of lava flow impact to population centres every decade, we identify 31 events with impacts to settlements or > 20 buildings in the past 100 years, and five in the last decade, equating to approximately three events per decade. If including all events, these are approximately seven events per decade ($n = 71$ in the last 100 years, $n = 6$ in the last decade). The most comprehensive source of lava flow impacts on the built environment prior to this study was Blong (1984) reporting 22 lava flow impact events between 1800 and 1983 CE. The impacts from 28 of the events in our dataset were compiled with some uncertainty, with two classified as later proved invalid, mostly due to the grouping of impact data with other hazards.

The global lava flow impacts dataset presented here provides a basis for temporal and spatial analysis of trends at the global or local scale. Whilst most documented impact events from English-language sources occurred at European volcanoes, primarily at Etna volcano, Italy, in recent years there has been a rise in the reporting of impact events at African and Oceanian volcanoes, with these regions representing 21 and 8% of the impact events recorded in the last 100 years. The number of lava flow impact events recorded has increased through time with ~ 50% of all impact events recorded within the last 110 years; likely reflecting an increase in recording through time, rather than a real increase in the number of events, as well as population growth around volcanoes through time increasing the exposure to lava flows. On average, the proportion of lava-flow-producing eruptions that have impacts recorded for them is less than 14% since 1800 CE. The highest number of buildings recorded as destroyed by lava flows is in 2002 CE at Nyiragongo volcano, Democratic Republic of Congo (at least 4,500), and the highest number of settlements recorded as destroyed by lava flows is during the 1669 CE Etna lava flows (12 villages and part of Catania city).

The dataset compiles eruption parameters and hazard intensity, and quantifies the impacts to buildings/settlements and infrastructure from published sources that record lava impacts. Whilst studies mostly report binary impacts to buildings (destroyed or intact), there is little relationship between the number of buildings impacted and the size of the lava flow (area or volume), which is often the most common lava flow measurement reported. This lack of relationship is largely due to differing exposure amount and distribution around the volcano, as exemplified by different lava flows from Kīlauea, which impacted up to 1,929 structures in 2018 CE from a 35.5 $km^2$ lava field, and up to 215 buildings between 1983 and 2018 CE from a ~ 144 $km^2$ lava field. Hazard data at the site and time of impact such as syn-eruption flow front velocity (for dynamic pressure) or ambient temperature, may be more appropriate and useful to collect for impact assessment. However, these data are difficult to collect at the time and location of impact. Post-event measurements of the hazard, such as thickness, could be used as a proxy for hazard intensity. Within the dataset, there are examples of building-level damage (not destruction) information and resistance of structures to the flows, further supporting that lava flow impacts are not always binary. Thus, future collection of precise impact and hazard data, such as lava flow thickness, on a building-level scale would allow for the assessment of potential relationships of the hazard intensity and impact information. A key requirement of future building-lava interaction, and the increased collection of empirical impact data, is the development of the standardised dataset presented here, which provides a guide and template for what data are useful to collect (Deligne et al. 2022). The dataset provides a standardised format for future data collection as part of post-event impact assessments. With enough damage and hazard data on a building level, we will be able to analyse building-lava interactions in order to develop impact forecasting models and mitigation measures in efforts to reduce lava flow risk.

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**Authors' contributions**
E.S.M. conceived the project and developed the methodology, with support from J.H.L. and S.F.J. N.R.X.T. conducted data collection from newspapers and E.S.M. conducted the data collection from literature and the GVP database. E.S.M. conducted data analysis, made figures, and drafted the manuscript, with support from J.H.L., S.F.J., D.L., and N.I.D. All authors reviewed the manuscript.

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**Availability of data and materials**
Research data presented in this study are available at the NTU Data Repository: https://researchdata.ntu.edu.sg/privateurl.xhtml?token=15ef9833-4f29-43bb-a649-b1e9a660cf03

## Declarations

**Ethics approval and consent to participate**
Not applicable.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare no competing interests.

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**References**

Allard P, Baxter P, Halbwachs M, Komorowski JC (2002) The January 2002 eruption of Nyiragongo volcano (Dem. Repub. Congo) and related hazards: observations and recommendations. Final Report of the French–British Team, Paris

Alvarado GE, Soto GJ, Pullinger CR, Escobar RÜ, Bonis SA, Escobar DE, Navarro MA (2007) Volcanic activity, hazards, and monitoring. In: Bundschuh J, Alvarado GE (ed) Central America: geology, resources and hazards. Taylor and Francis, London

Ancione G, Milazzo MF, Lisi R, Maschio G (2015) Consequences of liquid tank explosions caused by lava flow. Chem Eng Transact 43:2071–2076. https://doi.org/10.3303/CET1543346

Anderson T (1910) The volcano of Matavanu in Savaii. Quart J Geol Soc 66:621–639

Aramaki S, Hayakawa Y, Fujii T, Nakamura K, Fukuoka T (1986) The October 1983 eruption of Miyakejima volcano. J Volcanol Geotherm 29:203–229. https://doi.org/10.1016/0377-0273(86)90045-4

Arnò V, Principe C, Rosi M, Santacroce R, Sbrana A, Sheridan MF (1987) Eruptive history. In: Santacroce R (ed) Somma-Vesuvius 114, vol 8, CNR Roma, pp 53–104
Azaïs RP, Chambard P (1931) Cinq années de recherches archéologiques en Ethiopie. Geuthner, Paris.
Bankoff G (2020) Under the volcano: Mount Mayon and co-volcanic societies in the Philippines. Environ Hist Camb 26:7–29. https://doi.org/10.3197/096734019x15755402985532
Bankoff G, Newhall C, Schrikker A (2021) The charmed circle: mobility, identity and memory around Mount Mayon (Philippines) and Gunung Awu (Indonesia) volcanoes. Hum Ecol 49:147–158. https://doi.org/10.1007/s10745-021-00225-0
Baxter PJ, Allard P, Halbwachs M, Komorowski J-C, Woods AW, Ancia A (2002) Human health and vulnerability in the Nyiragongo volcano crisis Democratic Republic of Congo, 2002. Acta Vulcanol 14:109–114
Bertile W (1987) Des coulées volcaniques à Saint Philippe (Mars 1986): gestion d'une catastrophe naturelle. Edition Conseil Général de La Réunion, Saint Denis, pp 60
Blong RJ (1984) Volcanic hazards: a sourcebook on the effects of eruptions. Academic Press, Sydney, Orlando, Fla
Bonaccorso A, Calvari S, Boschi E (2016) Hazard mitigation and crisis management during major flank eruptions at Etna volcano: reporting on real experience. Geol Soc London Spec Publ 426:447–461. https://doi.org/10.1144/SP426.4
Boreham F, Cashman K, Rust A (2020) Hazards from lava–river interactions during the 1783–1784 Laki fissure eruption. GSA Bull 132:2651–2668. https://doi.org/10.1130/B35183.1
Branca S, Abate T (2019) Current knowledge of Etna's flank eruptions (Italy) occurring over the past 2500 years. From the iconographies of the XVII century to modern geological cartography. J Volcanol Geoth Res 385:159–178. https://doi.org/10.1016/j.jvolgeores.2017.11.004
Branca S, Azzaro R, De Beni E, Chester D, Duncan A (2015) Impacts of the 1669 eruption and the 1693 earthquakes on the Etna Region (Eastern Sicily, Italy): an example of recovery and response of a small area to extreme events. J Volcanol Geoth Res 303:25–40. https://doi.org/10.1016/j.jvolgeores.2015.07.020
Branca S, Branciforti MG, Chiavetta AF, Corsaro RA (2016) The geology of the 2nd century AD amphitheater area of Catania, Italy: historical eruptions affecting the urban district. Geoarchaeology 31:3–16. https://doi.org/10.1002/gea.21534
Brown SK, Jenkins SF, Sparks RSJ, Odbert H, Auker MR (2017) Volcanic fatalities database: analysis of volcanic threat with distance and victim classification. J Appl Volcanol 6. https://doi.org/10.1186/s13617-017-0067-4
Burgos V, Jenkins SF, Bebbington M, Newhall C, Taisne B (2022) A new perspective on eruption data completeness: insights from the First Recorded EruptionS in the Holocene (FRESH) database. J Volcanol Geoth Res 431:107648. https://doi.org/10.1016/j.jvolgeores.2022.107648
Calvari S (2019) Understanding basaltic lava flow morphologies and structures for hazard assessment. Ann Geophys 61. https://doi.org/10.4401/ag-8048
Cappello A, Hérault A, Bilotta G, Ganci G, Del Negro C (2016) MAGFLOW: a physics-based model for the dynamics of lava-flow emplacement. Geol Soc London Spec Publ 426:357–373. https://doi.org/10.1144/sp426.16
Carlino S (2021) Brief history of volcanic risk in the Neapolitan area (Campania, southern Italy): a critical review. Nat Haz Earth Syst Sci 21:3097–3112. https://doi.org/10.5194/nhess-21-3097-2021
Carracedo JC, Badiola ER, Soler V (1992) The 1730–1736 eruption of Lanzarote, Canary Islands: a long, high-magnitude basaltic fissure eruption. J Volcanol Geoth Res 53:239–250. https://doi.org/10.1016/0377-0273(92)90084-q
Carracedo JC, Day S, Guillou H, Badiola ER (1996) The 1677 eruption of La Palma, Canary Islands. Estud Geol 52:103–114. https://doi.org/10.3989/egeol.96523-4258
Centorrino V, Bilotta G, Cappello A, Ganci G, Corradino C, del Negro C (2021) A particle swarm optimization–based heuristic to optimize the configuration of artificial barriers for the mitigation of lava flow risk. Environ Modell Softw 139. https://doi.org/10.1016/j.envsoft.2021.105023
Chester DK, Degg M, Duncan AM, Guest JE (2000) The increasing exposure of cities to the effects of volcanic eruptions: a global survey. Global Environmental Change Part B: Environmental Hazards 2:89–103. https://doi.org/10.1016/s1464-2867(01)00004-3
Chester DK, Duncan AM, Guest JE, Kilburn CRJ (1985) Mount Etna: the anatomy of a volcano. Chapman Hall, London
Chevrel MO, Harris A, Ajas A, Biren J, Gurioli L, Calabrò L (2019) Investigating physical and thermal interactions between lava and trees: the case of Kīlauea's July 1974 flow. Bull Volcanol 81:1–19. https://doi.org/10.1007/s00445-018-1263-8
Chua CT, Switzer AD, Suppasri A, Li L, Pakoksung K, Lallemant D, Jenkins SF, Charvet I, Chua T, Cheong A, Winspear N (2021) Tsunami damage to ports: cataloguing damage to create fragility functions from the 2011 Tohoku event. Nat Hazards Earth Syst Sci 21:1887–1908. https://doi.org/10.5194/nhess-21-1887-2021
Ciavola P, Harley MD, den Heijer C (2018) The RISC-KIT storm impact database: a new tool in support of DRR. Coast Eng 134:24–32. https://doi.org/10.1016/j.coastaleng.2017.08.016
Coltelli M, Marsella M, Proietti C, Scifoni S (2012) The case of the 1981 eruption of Mount Etna: An example of very fast moving lava flows. Geochem Geophys Geosyst 13. https://doi.org/10.1029/2011gc003876
Copernicus Emergency Management Service (© 2021a European Union), [EMSR513] Mount Nyiragongo: Grading Product, Monitoring 2. Available Online: https://emergency.copernicus.eu/mapping/list-of-components/EMSR513. Accessed 1 Oct 2022
Copernicus Emergency Management Service (© 2021b European Union), [EMSR546] La Palma: Grading Product, Monitoring 63. Available Online: https://emergency.copernicus.eu/mapping/list-of-components/EMSR546. Accessed 1 Oct 2022
CRED (Centre for Research on the Epidemiology of Disasters) (n.d.) EM-DAT: The emergency events database. Brussels: CRED. Available online: https://www.emdat.be/database. Accessed 19 May 2023.
Cubellis E, Marturano A, Pappalardo L (2016) The last Vesuvius eruption in March 1944: reconstruction of the eruptive dynamic and its impact on the environment and people through witness reports and volcanological evidence. Nat Hazards 82:95–121. https://doi.org/10.1007/s11069-016-2182-7
de Graffenried R, Hammer J, Dietterich H, Perroy R, Patrick M, Shea T (2021) Evaluating lava flow propagation models with a case study from the 2018 eruption of Kīlauea volcano, Hawai'i. Bull Volcanol 83:1–19. https://doi.org/10.1007/s00445-021-01492-x
Deligne NI, Jenkins SF, Meredith ES, Williams GT, Leonard GS, Stewart C, Wilson TM, Biass S, Blake DM, Blong RJ, Bonadonna C, Calderon BR, Hayes JL, Johnston DM, Kennedy BM, Magill CR, Spence R, Wallace KL, Wardman J, Weir AM, Wilson G, Zuccaro G (2022) From anecdotes to quantification: advances in characterizing volcanic eruption impacts on the built environment. Bull Volcanol 84:7–9. https://doi.org/10.1007/s00445-021-01506-8
de' Michieli Vitturi M, Tarquini S (2018) MrLavaLoba: a new probabilistic model for the simulation of lava flows as a settling process. J Volcanol Geotherm Res 349:323–334. https://doi.org/10.1016/j.jvolgeores.2017.11.016
Donato S, Di Mauro R, Puliafito F (2009) Catania la citta e le mura: analisi dei processi di formazione e trasformazione della realita urbana di Catania. Jason Editrice, Reggio Calabria, Italy
Elson MD, Ort MH, Hesse SJ, Duffield WA (2002) Lava, corn, and ritual in the northern Southwest. Am Antiq 67:119–135. https://doi.org/10.2307/2694881
Favalli M, Tarquini S, Papale P, Fornaciai A, Boschi E (2012) Lava flow hazard and risk at Mt. Cameroon Volcano. Bull Volcanol 74:423–439. https://doi.org/10.1007/s00445-011-0540-6
Favalli M, Fornaciai A, Mazzarini F, Harris A, Neri M, Behncke B, Pareschi MT, Tarquini S, Boschi E (2010) Evolution of an active lava flow field using a multitemporal LIDAR acquisition. J Geophys Res: Solid Earth 115. https://doi.org/10.1029/2010jb007463
Ferrés D, Delgado Granados H, Hernández W, Pullinger C, Chávez H, Castillo Taracena CR, Cañas-Dinarte C (2011) Three thousand years of flank and central vent eruptions of the San Salvador volcanic complex (El Salvador) and their effects on El Cambio archeological site: a review based on tephrostratigraphy. Bull Volcanol 73:833–850. https://doi.org/10.1007/s00445-011-0465-0
Fontijn K, Williamson D, Mbede E, Ernst G (2012) The Rungwe volcanic Province, Tanzania: a volcanological review. J Afr Earth Sc 63:12–31. https://doi.org/10.1016/j.jafrearsci.2011.11.005

Fontijn K, McNamara K, Tadesse AZ, Pyle DM, Dessalegn F, Hutchison W, Mather TA, Yirgu G (2018) Contrasting styles of post-caldera volcanism along the Main Ethiopian Rift: implications for contemporary volcanic hazards. J Volcanol Geoth Res 356:90–113. https://doi.org/10.1016/j.jvolgeores.2018.02.001
Freire S, Florczyk AJ, Pesaresi M, Sliuzas R (2019) An improved global analysis of population distribution in proximity to active volcanoes, 1975–2015. ISPRS Int J Geo Inf 8:341. https://doi.org/10.3390/ijgi8080341
Fujita E, Nagai M (2016) LavaSIM: its physical basis and applicability. Geol Soc London Spec Publ 426:375–386. https://doi.org/10.1144/sp426.14
GLIDEnumber (n.d) GLIDEnumber V2.0. Available Online: https://glidenumber.net. Accessed 15 Sept 2022
Global Volcanism Program (2023) [Database] Volcanoes of the World (v. 5.0.4; 30 May 2023). Distributed by Smithsonian Institution, compiled by Venzke, E. https://doi.org/10.5479/si.GVP.VOTW5-2022.5.0
Global Volcanism Program (1977) Report on Piton de la Fournaise (France). In: Squires D (ed) Natural Science Event Bulletin, 2:4. Smithsonian Institution. https://doi.org/10.5479/si.GVP.NSEB197704-233020
Global Volcanism Program (1986) Report on Izu-Oshima (Japan). In: McClelland L (ed) Scientific Event Alert Network Bulletin, 11:11. Smithsonian Institution. https://doi.org/10.5479/si.GVP.SEAN198611-284010
Global Volcanism Program (2022) Report on La Palma (Spain). In: Bennis KL, Venzke E (eds) Bulletin of the Global Volcanism Network, 47:2. Smithsonian Institution. https://doi.org/10.5479/si.gvp.bgvn202202-383010
Global Volcanism Program (2018a) Report on Piton de la Fournaise (France). In: Crafford AE, Venzke E (eds) Bulletin of the Global Volcanism Network, 43:9. Smithsonian Institution. https://doi.org/10.5479/si.GVP.BGVN201809-233020
Global Volcanism Program (2018b) Report on Mayon (Philippines). In: Crafford AE, Venzke E (eds) Bulletin of the Global Volcanism Network, 43:4. Smithsonian Institution. https://doi.org/10.5479/si.GVP.BGVN201804-273030
Global Volcanism Program (2021) Report on Nyiragongo (DR Congo). In: Bennis KL, Venzke E (eds) Bulletin of the Global Volcanism Network, 46:6. Smithsonian Institution. https://doi.org/10.5479/si.GVP.BGVN202106-223030
Goitom B, Oppenheimer C, Hammond JO, Grandin R, Barnie T, Donovan A, Ogubazghi G, Yohannes E, Kibrom G, Kendall J, Carn SA (2015) First recorded eruption of Nabro volcano, Eritrea, 2011. Bull Volcanol 77:1–21. https://doi.org/10.1007/s00445-015-0966-3
Gourley JJ, Hong Y, Flamig ZL, Arthur A, Clark R, Calianno M, Ruin I, Ortel T, Wieczorek ME, Kirstetter P-E (2013) A unified flash flood database over the US. Bull Am Meteor Soc 94:6. https://doi.org/10.1175/BAMS-D-12-00198.1
Gregg CE (2005) Natural hazards in Hawai'i: Some studies of awareness, risk perceptions and preparedness. University of Hawai'i at Manoa.
Hamilton W (1795) IV. An account of the late eruption of Mount Vesuvius. Philos Transact Royal Soc London 85:73–116
Harkin DA (1960) The Rungwe volcanics at the northern end of Lake Nyasa. Mem Geol Surv Tanganyika 2:1–172
Harris AJL, Flynn LP, Matías O, Rose WI (2002) The thermal stealth flows of Santiaguito dome, Guatemala: implications for the cooling and emplacement of dacitic block-lava flows. Geol Soc Am Bull 114:533–546. https://doi.org/10.1130/0016-7606(2002)1142.0.co;2
Harris AJL, Belousov A, Calvari S, Delgado-Granados H, Hort M, Koga K, van Wyk de Vries B (2017) Translations of volcanological terms: cross-cultural standards for teaching, communication, and reporting. Bull Volcanol 79:1–10. https://doi.org/10.1007/s00445-017-1141-9
Harris AJL, De Groeve T, Garel F, Carn SA (eds) (2016) Detecting, Modelling, and responding to effusive eruptions. Geological Society of London, London
Harris AJL (2015) Basaltic lava flow hazard. In: Shroder JF, Paple P (eds) Volcanic hazards, risks and disasters. Elsevier. https://doi.org/10.1016/B978-0-12-396453-3.00002-2
Hayes JL, Calderón R, Deligne NI, Jenkins SF, Leonard GS, McSporran AM, Williams GT, Wilson TM (2019) Timber-framed building damage from tephra fall and lahar: 2015 Calbuco eruption, Chile. J Volcanol Geoth Res 374:142–159. https://doi.org/10.1016/j.jvolgeores.2019.02.017
Hayes JL, Biass S, Jenkins SF, Meredith ES, Williams GT (2022) Integrating criticality concepts into road network disruption assessments for volcanic eruptions. J Appl Volcanol 11:1–21. https://doi.org/10.1186/s13617-022-00118-x
Hume EE (1946) The 1944 eruption of Vesuvius. The Military Surgeon 98:369–383. https://doi.org/10.1093/milmed/98.5.369
Isshiki N (1964) Mode of eruption of Miyake-jima volcano in historic times. Bull Volcanol 27:29–48. https://doi.org/10.1007/bf02597505
Jenkins S, Komorowski JC, Baxter PJ, Spence R, Picquout A, Lavigne F (2013) The Merapi 2010 eruption: An interdisciplinary impact assessment methodology for studying pyroclastic density current dynamics. J Volcanol Geotherm 261:316–329. https://doi.org/10.1016/j.jvolgeores.2013.02.012
Jenkins SF, Day SJ, Faria BVE, Fonseca JFBD (2017) Damage from lava flows: insights from the 2014–2015 eruption of Fogo. Cape Verde. J Appl Volcanol 6. https://doi.org/10.1186/s13617-017-0057-6
Jenkins SF, Magill CR, McAneney KJ (2007) Multi-stage volcanic events: A statistical investigation. J Volcanol Geotherm 161:275–288. https://doi.org/10.1016/j.jvolgeores.2006.12.005
Jenkins SF, Phillips JC, Price R, Feloy K, Baxter PJ, Hadmoko DS, de Bélizal E (2015) Developing building damage scales for lahars: application to Merapi volcano, Indonesia. Bull Volcanol 77:1–17. https://doi.org/10.1007/s00445-015-0961-8
Jenkins SF, Spence RJS, Fonseca JFBD, Solidum RU, Wilson TM (2014) Volcanic risk assessment: quantifying physical vulnerability in the built environment. J Volcanol Geoth Res 276:105–120. https://doi.org/10.1016/j.jvolgeores.2014.03.002
Jennings JH (1959) The eruption of Mount Cameroon, 1959. Geogr: J Geograph Assoc 44:207
Kirschbaum DB, Adler R, Hong Y, Hill S, Lerner-Lam A (2010) A global landslide catalog for hazard applications: method, results, and limitations. Nat Hazards 52:561–575. https://doi.org/10.1007/s11069-009-9401-4
Kotô B (1916) The great eruption of Sakurajima in 1914. J Col Sci Imp Univ Tokyo 38:1–237
Lallemant D, Kiremidjian A, Burton H (2015) Statistical procedures for developing earthquake damage fragility curves. Earthquake Eng Struct Dynam 44(9):1373–1389. https://doi.org/10.1002/eqe.2522
Le Moigne Y, Williams-Jones G, Russell K, Quane S (2020) Physical volcanology of Tseax volcano, British Columbia, Canada. J Maps 16:363–375. https://doi.org/10.1080/17445647.2020.1758809
Lin YC, Khan F, Jenkins SF, Lallemant D (2021) Filling the disaster data gap: lessons from cataloging Singapore's past disasters. Int J Disas Risk Sci 12:188–204. https://doi.org/10.1007/s13753-021-00331-z
Lirer L, Vitelli L (1998) Volcanic risk assessment and mapping in the Vesuvian area using GIS. Nat Hazards 17:1–15. https://doi.org/10.1023/A:1007977110144
Longpré MA, Felpeto A (2021) Historical volcanism in the Canary Islands; part 1: a review of precursory and eruptive activity, eruption parameter estimates, and implications for hazard assessment. J Volcanol Geoth Res 419:107363. https://doi.org/10.1016/j.jvolgeores.2021.107363
Macdonald GA (1954) Activity of Hawaiian volcanoes during the years 1940–1950. Bull Volcanol 15:119–179. https://doi.org/10.1007/bf02596001
MacDonald GA (1962) The 1959 and 1960 eruptions of Kilauea volcano, Hawaii, and the construction of walls to restrict the spread of the lava flows. Bull Volcanol 24:249–294. https://doi.org/10.1007/bf02599351
Magli A, Branca S, Speranza F, Risica G, Siravo G, Giordano G (2022) Paleomagnetic dating of prehistoric lava flows from the urban district of Catania (Etna volcano, Italy). GSA Bulletin 134:616–628. https://doi.org/10.1130/b36026.1
Manitta G (2010) L'Etna e le sue eruzioni attraverso i documenti raccolti e ordinati da Guglielmo Manitta. Catania, Il Convivo Editore, p 399
Manitta G (2016) L'eruzione dell'Etna del 1879 problema dell'Italia unita. Catania, Il Convivo Editore, p 619
Mazhin SA, Farrokhi M, Noroozi M, Roudini J, Hosseini SA, Motlagh ME, Kolivand P, Khankeh H (2021) Worldwide disaster loss and damage databases: A systematic review. J Educ Health Promot 7:3–4. https://doi.org/10.4103/jehp.jehp_1525_20
Meredith ES, Jenkins SF, Hayes JL, Deligne NI, Lallemant D, Patrick M, Neal C (2022) Damage assessment for the 2018 lower East Rift Zone lava flows of Kīlauea volcano, Hawai'i. Bull Volcanol 84. https://doi.org/10.1007/s00445-022-01568-2
Monaco C, De Guidi G, Ferlito C (2010) The morphotectonic map of Mt. Etna. Ital J Geosci 129:408–428. https://doi.org/10.3301/ijg.2010.11

Morin J, Lavigne F, Bachèlery P, Finizola A, Villeneuve N (2009) Insitutional and social responses to hazards related to Karthala volcano, Comoros: Part I: Analysis of the May 2006 eruptive crisis. Int J Res Island Cultures 3:33–53
Moriyama K, Sasaki D, Ono Y (2018) Comparison of global databases for disaster loss and damage data. J Disaster Res 13:1007–1014. https://doi.org/10.20965/jdr.2018.p1007
Mossoux S, Kervyn M, Canters F (2019) Assessing the impact of road segment obstruction on accessibility of critical services in case of a hazard. Nat Hazards Earth Syst Sci 19:1251–1263. https://doi.org/10.5194/nhess-19-1251-2019
Nolan ML (1972) The towns of the volcano: a study of the human consequences of the eruption of Parícutin volcano. Doctoral dissertation, Texas A&M University
Omori F (1916) The Sakurajima eruptions and earthquakes II. Bull Imp Earthq Invest Comm 8:152–179
Orense RP, Ikeda M (2007) Damage caused by typhoon-induced lahar flows from Mayon volcano Philippines. Soils Foundations 47:1123–1132. https://doi.org/10.3208/sandf.47.1123
Peltier A, Chevrel MO, Harris AJL, Villeneuve N (2022) Reappraisal of gap analysis for effusive crises at Piton de la Fournaise. J Appl Volcanol 11:1–17. https://doi.org/10.1186/s13617-021-00111-w
Potter S, Harrison S, Kreft P (2021) The benefits and challenges of implementing impact-based severe weather warning systems: perspectives of weather, flood, and emergency management personnel. Weather Climate Soc 13:303–314. https://doi.org/10.1175/WCAS-D-20-0110.1
Ramírez-Uribe I, Siebe C, Chevrel MO, Fisher CT (2021) Rancho Seco monogenetic volcano (Michoacán, Mexico): petrogenesis and lava flow emplacement based on LiDAR images. J Volcanol Geoth Res 411:107169. https://doi.org/10.1016/j.jvolgeores.2020.107169
Richter N, Favalli M, de Zeeuw-Van Dalfsen E, Fornaciai A, da Silva Fernandes RM, Pérez NM, Levy J, Victória SS, Walter TR (2016) Lava flow hazard at Fogo volcano, Cabo Verde, before and after the 2014–2015 eruption. Nat Hazards Earth Syst Sci 16:1925–1951. https://doi.org/10.5194/nhess-16-1925-2016
Sai F, Cumiskey L, Weerts A, Bhattacharya B, Haque Khan R (2018) Towards impact-based flood forecasting and warning in Bangladesh: A case study at the local level in Sirajganj district. Nat Haz Earth Syst Sci Discuss 1–20. https://doi.org/10.5194/nhess-2018-26
Sciuto Patti C (1872) Carta geologica della città di Catania e dintorni. Atti dell'Accademia Gioenia di Scienze Naturali di Catania, ser. III, vol. VII, Catania
Siebe C (2000) Age and archaeological implications of Xitle volcano, southwestern Basin of Mexico-City. J Volcanol Geoth Res 104:45–64. https://doi.org/10.1016/S0377-0273(00)00199-2
Simanjuntak EM, Ginting JWR, Putra IAIDR (2020) A simple run-up calculation of tsunami Krakatau 1883 for the evaluation of NCICD seawall design. Jurnal Teknik Hidraulik 11:53–66. https://doi.org/10.32679/jth.v11i1.633
Spence R, So E, Jenkins S, Coburn A, Ruffle S (2011) A global earthquake building damage and casualty database. Human Casualties in Earthquakes. Springer, Dordrecht, pp 65–79. https://doi.org/10.1007/978-90-481-9455-1_5
Spence RJS, Pomonis A, Baxter PJ, Coburn AW, White M, Dayrit M, Field Epidemiology Training Program Team (1996) Building damage caused by the Mount Pinatubo eruption of June 15 (1991). In: Newall CG, Punongbayan RS (eds) Fire and 529 Mud: eruptions and lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology, University of Washington Press, Seattle, pp 1055–1061
Stevens NF, Murray JB, Wadge G (1997) The volume and shape of the 1991–1993 lava flow field at Mount Etna, Sicily. Bull Volcanol 58:449–454. https://doi.org/10.1007/s004450050153
Stieltjes L, Moutou P (1989) A statistical and probabilistic study of the historic activity of Piton de la Fournaise, Reunion Island, Indian Ocean. J Volcanol Geoth Res 36:67–86. https://doi.org/10.1016/0377-0273(89)90006-1
Suppasri A, Koshimura S, Imamura F (2011) Developing tsunami fragility curves based on the satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand. Nat Haz Earth Syst Sci 11:173–189. https://doi.org/10.5194/nhess-11-173-2011
Taylor PW, Sapolu F (2016) Volcanic hazards in Samoa. In: Taylor PW (ed) Volcanic hazards and emergency management in the Southwest Pacific. SPC Technical Bulletin SPC00017.
Taylor PW, Talia L (1999) Volcanic Hazards Assessment of Savai'i, Samoa. SOPAC Technical Report 295
Taylor PW (1991) The geology and petrology of Niuafo'ou Island, Tonga: subaerial volcanism in an active back-arc basin. Doctoral dissertation, Macquarie University.
Thomaidis K, Troll VR, Deegan FM, Freda C, Corsaro RA, Behncke B, Rafailidis S (2021) A message from the 'underground forge of the gods': history and current eruptions at Mt Etna. Geol Today 37:141–149. https://doi.org/10.1111/gto.12362
Thordarson T (1990) The eruptive sequence and eruption behaviour of the Skaftá Fires, 1783-1785, Iceland: Characteristics and distribution of eruption products. Doctoral dissertation, The University of Texas at Arlington.
Thordarson T, Höskuldsson Á (2008) Postglacial volcanism in Iceland. Jökull 58:197–228. https://doi.org/10.33799/jokull2008.58.197
Thordarson T, Larsen G, Steinthorsson S, Self S (2003) The 1783–1785 AD Laki-Grímsvötn eruptions II: Appraisal based on contemporary accounts. Jökull 53:11–47. https://doi.org/10.33799/jokull2003.53.011
Thordarson T, Self S (1993) The Laki (Skaftár fires) and Grímsvötn eruptions in 1783–1785. Bull Volcanol 55:233–263. https://doi.org/10.1007/bf00624353
Tomiczek T, Kennedy A, Zhang Y, Owensby M, Hope ME, Lin N, Flory A (2017) Hurricane damage classification methodology and fragility functions derived from Hurricane Sandy's effects in coastal New Jersey. J Waterw Port Coast Ocean Eng 143:04017027. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000409
Trifonov VG (2007) The bible and geology: destruction of Sodom and Gomorrah. Geol Soc London Special Publ 273:133–142. https://doi.org/10.1144/GSL.SP.2007.273.01.12
Tsang SWR, Lindsay JM (2020) Lava flow crises in inhabited areas part I: Lessons learned and research gaps related to effusive, basaltic eruptions. J Appl Volcanol 9. https://doi.org/10.1186/s13617-020-00096-y
UNDRR (United Nations Office for Disaster Risk Reduction) (2015a) DesInventar. DesInventar Sendai. Available Online: https://www.desinventar.net/DesInventar/. Accessed 10 Nov 2022
UNDRR (United Nations Office for Disaster Risk Reduction) (2015b) Sendai framework for disaster risk reduction. UNDRR, Geneva. Available Online: https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030. Accessed 20 June 2022
United Nations (1999) Composition of macro geographical (continental) regions, geographical sub-regions, and selected economic and other groupings. Available Online: https://unstats.un.org/unsd/methodology/m49/. Accessed 25 Nov 2022
Wadge G, Biggs J, Lloyd R, Kendall JM (2016) Historical volcanism and the state of stress in the East African rift system. Front Earth Sci 4:86. https://doi.org/10.3389/feart.2016.00086
Walker GPL (1973) Mount Etna and the 1971 eruption - Lengths of lava flows. Phil Trans R Soc Lond A 274:107–118. https://doi.org/10.1098/rsta.1973.0030
Wantim MN, Bonadonna C, Gregg CE, Menoni S, Frischknecht C, Kervyn M, Ayonghe SN (2018) Forensic assessment of the 1999 Mount Cameroon eruption, West-Central Africa. J Volcanol Geoth Res 358:13–30. https://doi.org/10.1016/j.jvolgeores.2018.06.007
Williams RS, Moore JG (1983) Man against volcano: the eruption on Heimaey, Vestmannaeyjar, Iceland. US Department of the Interior, Geological Survey. https://doi.org/10.3133/7000025
Williams GT, Jenkins SF, Biass S, Wibowo HE, Harijoko A (2020) Remotely assessing tephra fall building damage and vulnerability: Kelud Volcano, Indonesia. J Appl Volcanol 9:10. https://doi.org/10.1186/s13617-020-00100-5
Wilson G, Wilson TM, Deligne NI, Cole JW (2014) Volcanic hazard impacts to critical infrastructure: A review. J Volcanol Geotherm Res 286:148–182. https://doi.org/10.1016/j.jvolgeores.2014.08.030
Zoeller MH, Perroy RL, Wessels R, Fisher GB, Robinson JE, Bard JA, Peters J, Mosbrucker A, Parcheta CE (2020) Geospatial database of the 2018 lower east rift zone eruption of Kilauea Volcano, Hawaii. US Geol Surv Data Release. https://doi.org/10.5066/P9S7UQKQ

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