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DATABASE

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# The Volcanic Hazard Maps Database: an initiative of the IAVCEI Commission on Volcanic Hazards and Risk

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**Abstract**

In this work we present the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Commission on Volcanic Hazards and Risk (CVHR) Volcanic Hazard Maps Database and the accompanying volcanichazardmaps.org website. Using input from a series of IAVCEI CVHR Working Group on Hazard Mapping workshops, we developed a classification scheme and terminology framework for categorizing, discussing, naming, and searching for hazard maps. ≥ The database and website aim to serve as a resource for the volcanology community to explore how different aspects of hazard map development and design have been addressed in different countries, for different hazard processes, and for different intended purposes and audiences. Additionally, they act as a tool for presenting hazard map options to stakeholder groups and serve as a learning resource that can be incorporated into educational materials and training courses. In this work, we present the database and website, discuss the classification scheme, explore the enormous diversity of hazard maps, and suggest ways that the database and website can be used by the volcanic hazard mapping community.

**Keywords** Hazard maps, Volcanic hazard, Database

## Introduction

Volcanic hazard maps communicate information about the distribution of potential future volcanic hazard processes, such as tephra fall, pyroclastic flows, and lahars (Crandell et al. 1984). While nearly every volcano observatory around the world has produced hazard maps of one kind or another, there are currently no community guidelines, conventions, or globally consistent approaches for their development. Volcanic hazard maps vary widely in the way both hazard levels and hazard processes are portrayed, the temporal and spatial scales they cover, their hazard zonation methodology, and their cartographic design elements (Calder et al. 2015; Thompson et al. 2017; Charlton 2018;). These variations are due to differences in the volcanoes themselves, the intended map audience and purpose, and the diverse philosophies of the hazard map makers.

While there may not be a one-size-fits-all approach for choosing the exact components of a hazard map, there is consensus that hazard mapping and communication about hazard mapping could be improved through

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community efforts (Calder et al. 2015). The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Commission on Volcanic Hazards and Risk (CVHR) Working Group on Hazard Mapping was formed in 2014 with the goals of 1) constructing a classification scheme for volcanic hazard maps to promote harmonization of terminology; 2) identifying good practices and important considerations for volcanic hazard mapping; and 3) developing a database of volcanic hazard maps (IAVCEI Commission on Volcanic Hazard Risk 2018).

In this contribution, we present the Volcanic Hazard Maps Database, which has collected information from 1780 volcanic hazard maps thus far and presents it as a searchable database. No effort of this scale and breadth has been undertaken previously for volcanic hazard maps. The database catalogs the diversity of existing volcanic hazard maps, classifies those maps so they can be searched and sorted via a web interface, and contains detailed metadata about both map elements and design. The database includes hazard maps for volcanoes around the world from 1937 to 2022. Some of these maps changed through time, so that in many cases there are several hazard map versions for a single volcano. The maps represent a range of original formats (e.g., formal published maps, map sheets or posters, interactive webmaps, inserts in hazard assessments) as well as derivative maps that have been modified for specific audiences (e.g., trail maps, park signs). Some are official (i.e., produced by the responsible government agency) and operational (i.e., the most recent, in-use map) hazard maps; some are research results (e.g., produced through scientific research and published in journal articles); and some are from other sources such as non-governmental organizations (NGOs) or foreign government agencies. The main purpose of the database and its accompanying website (https://volcanichazardmaps.org/) is to serve as a resource for the volcanology community, in particular those engaged with hazard mapping, to explore how common aspects of hazard map development and design have been addressed in different countries, for different hazard processes, and for different intended purposes and audiences. We also envision the website being used as a tool for stakeholder interaction as way to present and explore hazard map options. Additionally, the website and database can be incorporated into educational materials and training courses.

Several previous and related efforts to catalogue and discuss volcanic hazard maps were essential resources in developing the structure and content of the Volcanic Hazard Maps Database. An early version of the hazard map database (HazMap Database, discussed in Calder et al. 2015) classified 120 hazard maps according to a preliminary classification scheme (Calder et al. 2015). The scheme mixed some elements of hazard zonation methodology with hazard presentation style to categorize maps as 1) geology-based; 2) integrated qualitative; 3) administrative; 4) modeling-based; or 5) probabilistic. That database also gathered a great deal of information about the content of the maps, including color scheme, cartographic elements, spatial scale, basemap type, etc. Independently, Charlton (2018) collected and examined 222 hazard maps from around the world and catalogued the temporal scale, basemap type, the hazard processes or phenomena portrayed, the map type from Calder et al. (2015), and map elements (e.g., safety advice, evacuation routes, etc.). The V-hazard Database on Volcanic Hazard Maps and Reference Material (National Research Institute for Earth Science and Disaster Prevention & Volcanological Society of Japan, 2013) contains all volcanic hazard maps published between 1983 and 2013 for 40 active volcanoes in Japan, a total of over 300 maps. Recent work by Forte et al. (2021) compiled information about Latin American hazard maps and proved a valuable resource for discovering additional maps for the Volcanic Hazard Maps Database population.

From 2014–2018 the IAVCEI CVHR Working Group on Hazard Mapping facilitated a series of international community workshops on volcanic hazard assessments as well as 'State of the Hazard Map' meetings around the world, bringing together over 200 participants from over 40 countries (Calder et al. 2018). During these workshops, participants presented hazard maps they had created, similarities and differences between maps were explored, and map-making challenges and solutions were discussed. The intention was to build on past volcanic hazard map typologies (Calder et al. 2015) and extract common approaches, best practices, and key lessons for the development process, content, design, and format of maps.

From these workshops and related initiatives, it became clear that the initial simple rubric for classifying hazard maps presented in Calder et al. (2015) could be refined, extended, and elaborated upon. Indeed, there are many ways in which hazard maps can be classified, including factors such as type of hazard processes portrayed, type of hazard presentation (hazard level-focused or hazard process-focused), temporal and spatial scale, zonation methodology and scenarios considered, and purpose and audience. In addition to these main, multi-perspective map classification categories, it can also be useful to sort and search maps according to their hazard zone and probability definitions, publication format, language, map elements (e.g., evacuation routes, actions to take, alert level schemes, etc.), and map design (e.g., basemap, color scheme, etc.). The new IAVCEI CVHR Volcanic Hazard

Maps Database presented here, which was created with community input through these workshops, considers all these classification possibilities.

The following sections explain the structure of the database and how it was populated (Database construction and content), describe the website that serves as a portal for the database and as a community resource on hazard mapping (Volcanic hazard maps website), and explore the diversity of hazard maps contained in the database and website (The diversity of hazard maps).

## Database construction and content

The hazard map data are stored in a MySQL (Oracle, 2022) relational database in 12 main tables (Fig. 1), which capture the following information:

- the basic map data (e.g., title, year, citation, URL, publication format, temporal scale, purpose, and audience);
- bibliographic information about map sets;
- the name of the volcano(es) depicted, unique Volcano Numbers (VNUMs), country, and volcano characteristics such as volcano morphology type, primary rock type, tectonic setting, and nearby population statistics from the Global Volcanism Program's (GVP) Volcanoes of the World (VOTW) database (Global Volcanism Program, 2013);
- the name(s) of the map-making institution(s);
- information about the basemap (e.g., basemap type, dimensionality, spatial scale);
- hazard zonation information (e.g., hazard processes included in each zone, zonation methodology, scenarios considered, probability definition);
- information about any models used to simulate hazardous phenomena;
- cartographic and design elements (e.g., color scheme, uncertainty depiction, version number); and
- any additional information depicted on the map (e.g., hazard and impact descriptions, eruptive history, past deposits, hazardous phenomena arrival times, evacuation routes, population information, etc.).

Link tables are used to connect tables which have many-to-many relationships between them (e.g., maps may depict multiple volcanoes and each volcano may be represented on multiple maps). A series of dictionary tables (not shown in Fig. 1) define the options for many of the columns in the database (e.g., map publication, scenario, or basemap type).

The database was constructed by first importing data from two existing hazard map databases (HazMap, Calder et al. 2015; unnamed Charlton 2018 hazard map database), and updating those entries with the additional data types identified during the State of the Hazard Map Workshops and being captured by the new database. About 1500 additional maps were then added to the database, with a concerted effort to include maps from the widest possible variety of countries, languages, volcanoes, hazard process types, publication types, and publication years.

Database data entry was straightforward for most fields; values could be read directly off the map or found in attached documentation. However, map purpose, audience, and some aspects of zonation methodology were not explicitly stated on many maps; where absent, these values were inferred from other map elements or entered as unknown where inference was not possible. In order to catalog data from non-English-language maps, a combination of the authors' language knowledge (Spanish and Japanese), online translation applications, geologic language dictionaries, and professional translations were used. For entries that are incorrect or incomplete due to lack of information or difficulty in translation, the website includes mechanisms for users to submit corrections to any of the collected data.

## Volcanic hazard maps website

The website front-end for the database (Fig. 2, https://volcanichazardmaps.org/) includes basic and advanced search functions that allow users to find maps based on basic map metadata (title, author, year, etc.), and a variety of map classifications and design elements. Maps can also be searched using volcano characteristics from the GVP, such as volcano type, composition, maximum eruption Volcanic Explosivity Index (VEI, Newhall & Self 1982), and nearby populations, etc. Users can also browse by volcano or country or can select maps spatially on a global volcano map. A number of informational pages describe the ways in which hazard maps can be classified (similar to the information presented in The diversity of hazard maps). Other pages include links to hazard mapping institutions and a blog.

Individual map pages include a thumbnail image of the map (which links to the full-size image as hosted by the original source, where available), the map citation, a selection of the most pertinent map classification data (Fig. 3), and links to other maps if part of a set.

This website was created for educational and research purposes. Importantly, we do not intend the website to serve as the source for hazard maps as sought by stakeholders during a crisis. Prominent disclaimers on all website pages make it clear that the site is for informational, educational, and archival purposes only, and that during an emergency users should seek out the operational hazard map (i.e., the most recent, in-use map produced

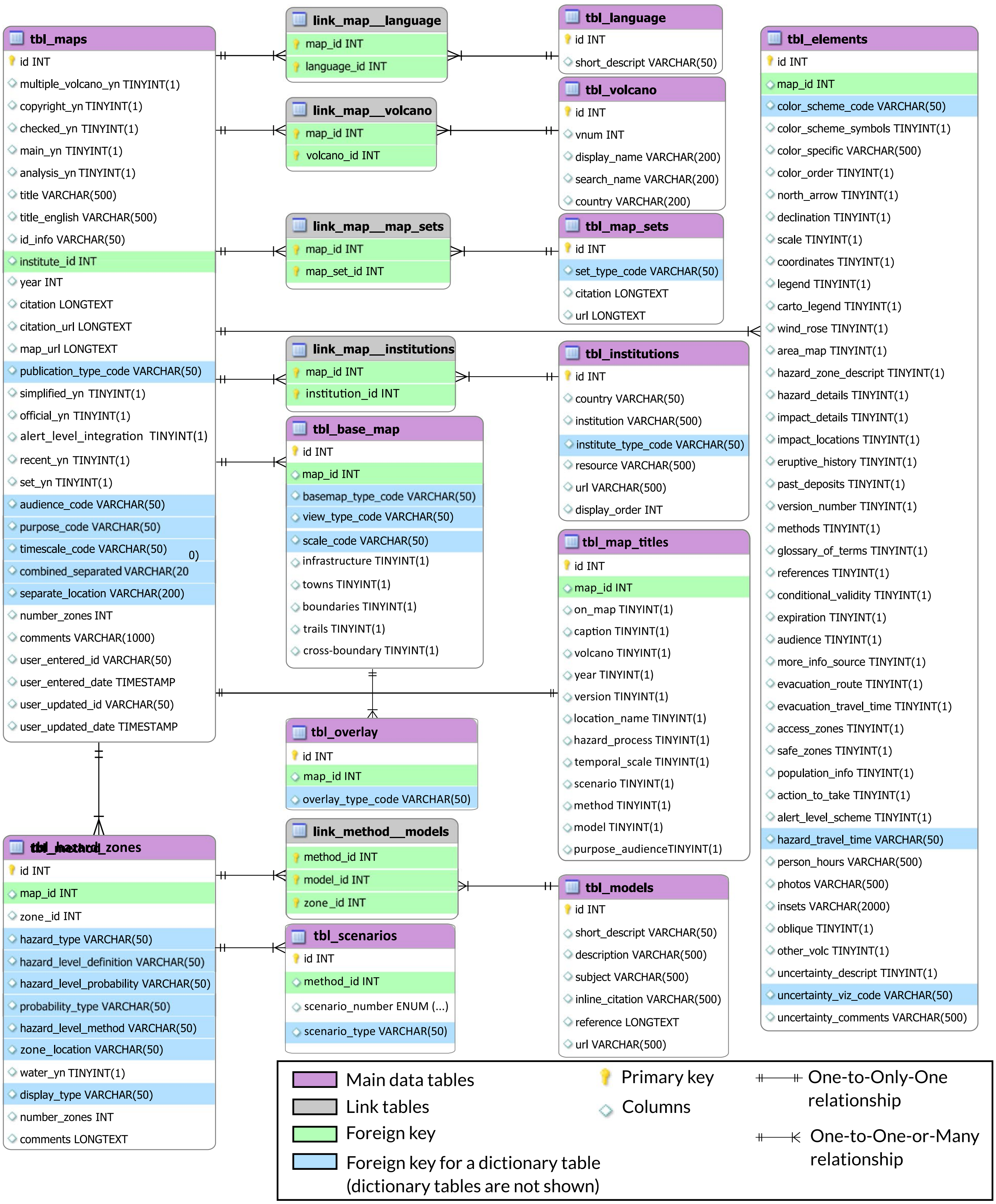



**Fig. 1** Simplified schema diagram of the Volcanic Hazard Maps Database. Main data tables and link tables are shown (purple and gray, respectively). Column names are followed by the data type with the length in parentheses (e.g., VARCHAR(50)). The data type TINYINT is used to indicate yes/no values. Definition tables, which define the options available for a particular column, are not shown to make the schema readable. Each definition table consists of an ID or code as the primary key, a short description, and a long description

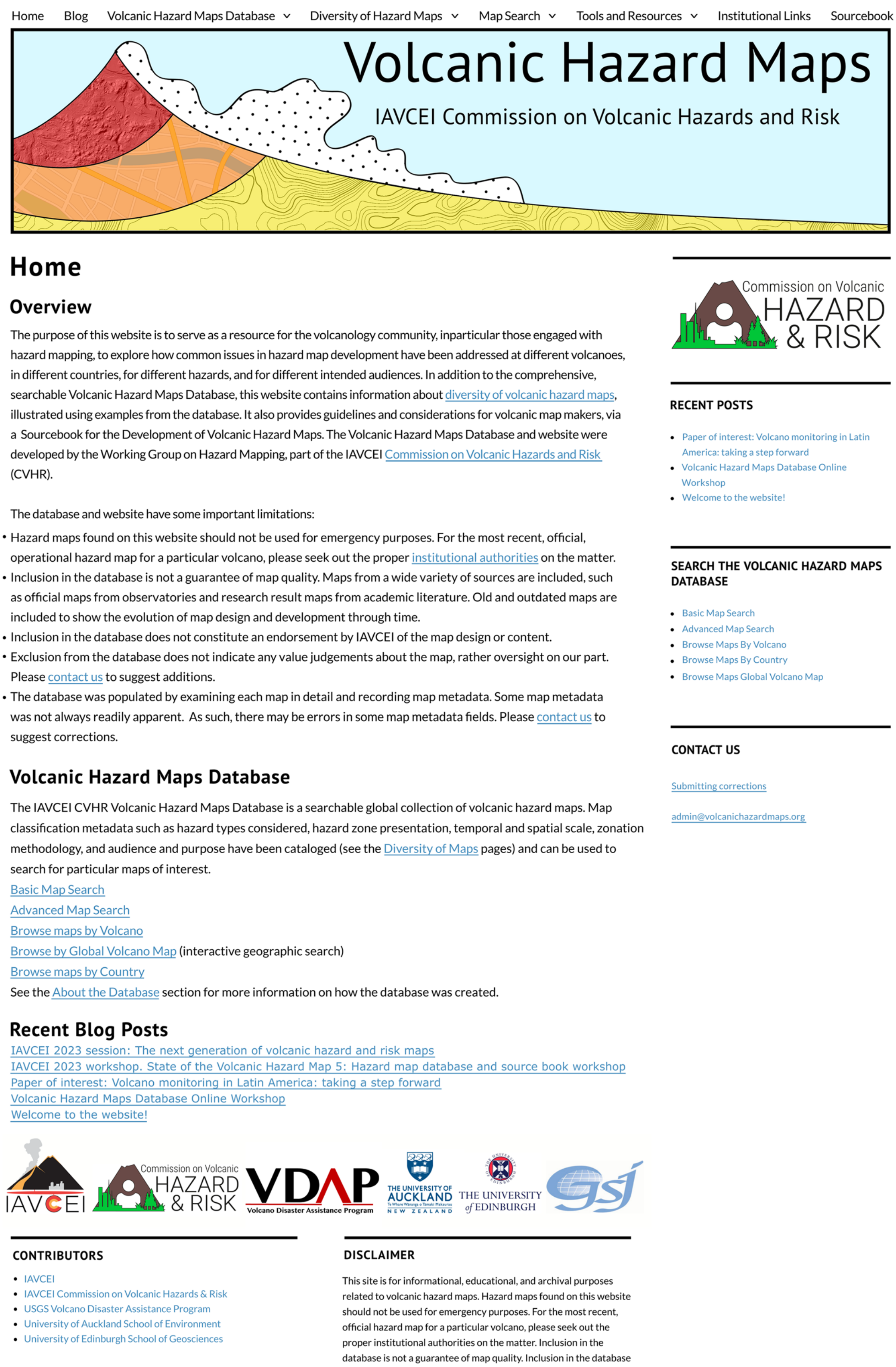



**Fig. 2** The IAVCEI Commission on Volcanic Hazard and Risk (CVHR) Volcanic Hazard Maps website homepage and database front end. https://volcanichazardmaps.org/

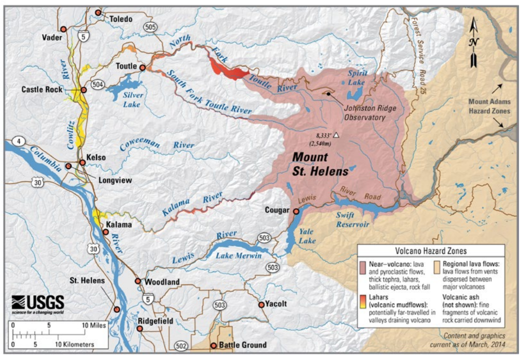
← Back to Search Results

**Simplified volcano hazards map of Mount St. Helens, Washington**

**Mount St. Helens (St. Helens), United States (2014)**

Wolfe, E.W., Pierson, T.C., Driedger, C.L., Scott, W.E., Iverson, R.M., and Faust, L.M. (2014). Simplified volcano hazards map of Mount St. Helens, Washington (modified from U.S. Geological Survey Open-File Report 95-497). U.S. Geological Survey, *Mount St. Helens, Washington Simplified Hazards Map.*

*This map was produced by an official agency, but may not be the most recent, most complete, or main operational map. For the current operation hazard map, please consult the proper institutional authorities.*




Click on image for full size map.

*If link seems broken, try the archived version*

**Map Data**

| | |
|---|---|
| **Map ID** | 1112 |
| **Hazard Process(es)** | Ballistics; Lahars; Lava flows; PDCs; Proximal hazards; Regional hazards; Rockfalls; Tephra fall |
| **Hazard Presentation** | Hazard process-focused; Grouped by location (e.g. proximal/distal zones) on a main map panel |
| **Temporal Scale** | Background, or long-term, map |
| **Spatial Scale** | Volcano and surrounding area |
| **Publication Format** | Map on website |
| **Zonation Method(s)** | Derived/simplified from another map |
| **Zonation Model(s)** | |
| **Scenario Type(s)** | Size, VEI, or intensity-based; Source location- or direction-based; Style, eruption-type or trigger-based |
| **Hazard Zone Label(s)** | Hazard name; Location or source name |
| **Probability Definition(s)** | Qualitative relative probability (e.g. high-medium-low) |
| **Purpose** | Hazard awareness: Intended for educating the audience about the extent and probability of volcanic hazard |
| **Audience** | General public and/or media |
| **Language(s)** | English |
| **Basemap(s)** | Hillshade |
| **Basemap overlay(s)** | Street map |
| **Dimensionality** | Planimetric (map) view |
| **Color Scheme** | Red to Yellow |

**Fig. 3** Example map data displayed on the page for the simplified volcano hazards map of Mount St. Helens, Washington (Wolfe et al. 2014)

by the responsible government agency) for a particular volcano. Additionally, non-operational maps, including outdated versions or maps from diverse sources (such as figures in academic journal articles), are clearly marked as such in both the search results and the individual map pages. Inclusion (or exclusion, for that matter) in the database does not constitute an endorsement of map quality or design.

## The diversity of hazard maps

At the time of writing, the Volcanic Hazard Maps Database contains 1780 hazard maps at 612 volcanoes in 53 countries (Fig. 4). The database currently includes maps published from 1937 (Ruang and Cereme, Indonesia; Neumann van Padang 1937a, 1937b) to 2022. Many volcanoes have hazard maps that have changed considerably through time; all map versions that could be identified are included and can be used to explore the evolution of hazard maps, hazard process understanding, and communication strategies through time.

The maps are in 14 different languages, with the majority in English (53%), Spanish (30%), or Japanese (13%) due to the language proficiency of the database population team, the relative abundance of volcanoes in English-, Spanish-, and Japanese-speaking countries, and because the majority of maps from journal articles are published in English-language sources. About 6% of maps display text in multiple languages; notably, official Indonesian maps display all map text in both Bahasa Indonesia and English. Maps from Vanuatu also give all map information in English, French, and Bislama, or have multiple versions of the same map in different languages.

Many maps form part of a set or a series. Map sets and series may contain multiple maps that differ only in language, location (different flanks or drainages of the same volcano), or forecast window (for repeatedly revised crisis maps during one eruption, e.g., daily ashfall forecasts). If we count only one map from these types of sets or series, the database contains 1596 unique maps. All further discussion in this paper references these 1596 unique maps.

Our classification scheme categorizes hazard maps according to hazard process portrayed, hazard zone presentation (e.g., hazard process-focused or hazard level-focused), temporal and spatial scale, purpose and audience, zonation methodology (including scenarios considered), and hazard zone and probability definitions (how zones are labelled and/or assigned probabilities). We can also classify maps according to their cartographic and design elements, including publication format, color scheme, uncertainty portrayal, etc. The following sections explore these classifications and the frequency of each map type in the database. For specific examples of selected map types, see Table 1.

### Hazard processes portrayed

A variety of hazard processes or phenomena are depicted on volcanic hazard maps (Fig. 5). The specific hazard processes displayed on any map depend upon the nature

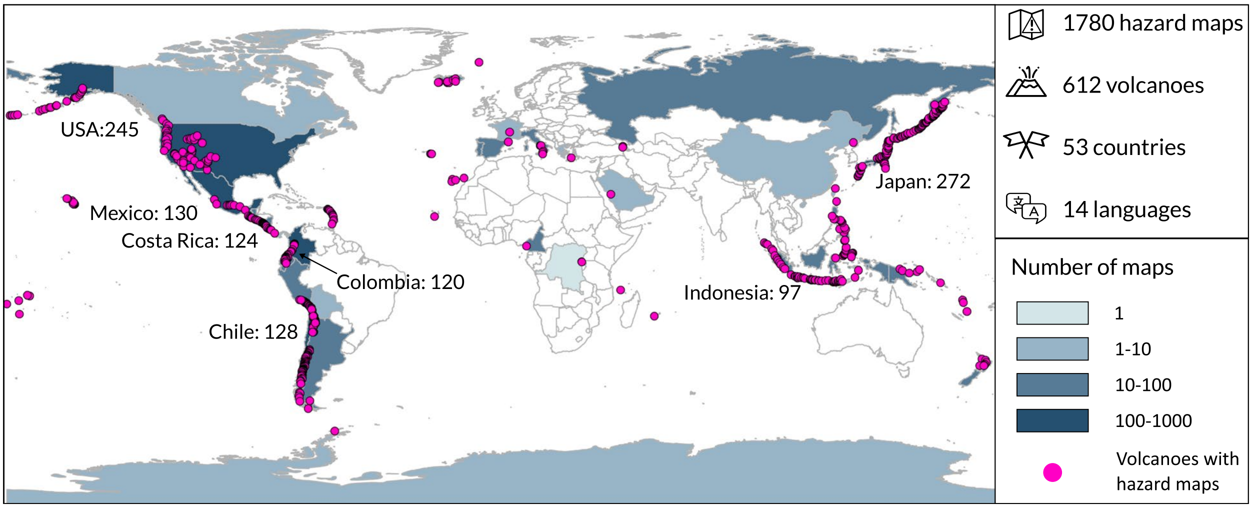



**Fig. 4** Number of unique volcanic hazard maps in the database sorted by Global Volcanism Program (GVP) country. Note that the high number of hazard maps from Costa Rica is primarily due to a large number of maps from a few hazard assessments, theses, and journal articles

of the particular volcano, the temporal and spatial scale the map covers, and on the map purpose and audience. Maps may focus on a single hazard process (e.g., lahars) or hazard process type (e.g., flowage hazards), may strive to depict all possible hazards, or may refer to hazard processes collectively or indirectly through the use of access, danger, or exclusion zones.

The most commonly considered hazard processes (Fig. 5) in the database include tephra (52%); pyroclastic density currents (PDCs) of different types (48%; including pyroclastic flows, base surges, and ash-cloud surges); lahars (46%); ballistics (37%); and lava flows (37%). Less commonly considered hazard processes include low-probability, high-impact events, such as debris avalanches and lateral blasts; and secondary hazards, such as floods, tsunamis, fire, and littoral blasts.

Some hazard zones involve unspecified hazard processes, as is the case with access, exclusion, or danger zones. Other unspecific hazards include vent-opening hazards, unspecific eruption or explosion hazards, dome-related hazards, flowage hazards, location-based hazards (i.e., proximal, distal, or regional hazards) and hazards related to caldera formation. Some hazardous phenomena are more commonly described in text (gray bars in Fig. 5) than displayed on the map in a hazard zone (colored bars in Fig. 5), e.g., fire, lightning, and geothermal hazards.

## Hazard zone presentation

Hazard maps can be classified according to whether they are hazard level-focused, with different hazard processes integrated into combined hazard level zones (Fig. 6a-b) or whether they are hazard process-focused, and thus separated into hazardous phenomena-specific zones or groups (Fig. 6c-f).

Hazard level-focused maps (Fig. 6a**)** combine all or most hazard processes into integrated hazard zones (often resembling a 'bulls-eye'), which are commonly defined by the relative level or degree of hazard (e.g., high-medium–low or specific probability ranges) rather than the type of hazardous phenomena. Commonly, hazard level-focused hazard maps indicate, in text, which hazard types might be expected in each of the zones; sometimes only the relative hazard level is communicated. Some maps of this type display only one hazard zone (e.g., a single exclusion or danger zone). Distal tephra fall hazards are sometimes displayed separately from the rest of the hazards on these maps due to the difference in scale of the hazard zones.

Administrative hazard maps (Fig. 6b) are a special type of hazard level-focused map, where the shape and level of the zones is determined through a combination of hazard information and administrative concerns regarding risk to lives and infrastructure (e.g., civic boundaries, life-safety-thresholds). Often, administrative zone boundaries remain static, but access to zones changes with changing conditions or alert level.

Hazard process-focused hazard maps (Fig. 6c-f) portray distinct hazard zone boundaries for each hazard process under consideration, where the zones are usually defined by the hazard type (e.g., 'tephra hazard zone' or 'lava flow hazard zone'). Some maps show only one hazard process (Fig. 6d), often as part of a set of different maps which show a single hazardous phenomenon per map. On some hazard process-focused maps, hazards are grouped by location; for example, the map may have

**Table 1** Selected example maps for the different map classification categories. The Map ID can be appended to the URL https://volcanichazardmaps.org/map/?id=Map ID to view specific map information pages. Note that the maps listed here do not necessarily represent "type examples" or imply any judgement about map quality; rather these are merely examples of map classification categories. For more extensive examples, links are proved to the website map classification information pages. Where the volcano name on the map differs from the Global Volcanism Program (GVP) volcano name, the GVP volcano name is given in parentheses

| Map classification category | Map ID | Volcano or Region | Country | Map Ref |
|---|---|---|---|---|
| ***Hazard Zone Presentation*** (https://volcanichazardmaps.org/hazard-presentation/) | | | | |
| Hazard level-focused | 456 | Micotrin (Morne Trois Pitons) | Dominica | Page 32 in: Lindsay et al. (2005) |
| Hazard level-focused (Administrative) | 462 | Soufrière Hills | Montserrat | Montserrat Volcano Observatory (2014) |
| Hazard process-focused | 455 | Micotrin (Morne Trois Pitons) | Dominica | Page 31 in: Lindsay et al. (2005) |
| Hazard process-focused (grouped by location) | 594 | Crater Lake | United States | Plate 1 in: Bacon et al. (1997) |
| Hazard process-focused (grouped by process type) | 582 | California [regional] | United States | Plate 1 in: Miller (1989) |
| Hazard process-focused (single hazard) | 3352 | San Salvador | El Salvador | Figure 107 in: Ferrés López (2014) |
| ***Temporal scale*** (https://volcanichazardmaps.org/timescale/) | | | | |
| Background, long-term | 474 | Osorno | Chile | Moreno (1999) |
| Crisis, short-term | 646 | Te Maari (Tongariro) | New Zealand | GNS Science (compiler) (2012) |
| Crisis, very short-term | 1379 | Holuhraun (Askja) & Bárdarbunga | Iceland | Iceland Meteorological Office (IMO) (2014) |
| ***Spatial scale*** (https://volcanichazardmaps.org/spatial-scale/) | | | | |
| Entire island | 487 | Mt. Scenery (Saba) | Saba | Page 189 in: Smith et al. (2005) |
| Flank or drainage | 1529 | Tenerife | Spain | Sheet 1088-III in: Instituto Geológico y Minero de España (IGME) (2006) |
| Multiple/user selectable | 963 | Colima | Mexico | Universidad de Colima (2017) |
| Regional | 730 | Chile [regional] | Chile | Lara et al. (2011) |
| Summit | 3493 | Ruapehu | New Zealand | GNS Science (compiler) (2020) |
| Volcano edifice and area | 890 | Egon | Indonesia | Sutawidjaja et al. (2005) |
| ***Zonation Methodology*** (https://volcanichazardmaps.org/method/) | | | | |
| Community participation | 663 | Ambae | Vanuatu | Figure 4 in: Cronin et al. (2004) |
| Derived or simplified | 1112 | Mount St. Helens (St. Helens) | United States | Wolfe et al. (2014) |
| Geological history | 511 | Villarrica | Chile | Moreno (2000) |
| Probabilistic modeling | 945 | Etna | Italy | Figure 3 in: Del Negro et al. (2013) |
| Scenario-based modeling | 1554 | Fuego | Guatemala | Instituto Nacional de Sismología, Vulcanologia, Meteorologia e Hidrología (INSIVUMEH) et al. (2018) |
| ***Scenarios*** (https://volcanichazardmaps.org/scenario-types/) | | | | |
| Analog volcano(es) | 1084 | Mount Adams (Adams) | United States | Plate 1 in: Scott et al. (1995) |
| Composition | 586 | Lassen Volcanic Center | United States | Plate 1 in: Clynne et al. (2012) |
| Eruption or hazard process size | 1000 | El Misti | Peru | Mariño et al. (2008) |
| Eruption or hazard process style | 657 | Soufrière Volcanic Center (Qualibou) | Saint Lucia | Pocket Insert in: Lindsay (2005) |
| Hypothetical | 1466 | Savai'i | Samoa | Figure 4 in: Cronin et al. (2006) |
| Location or direction | 1398 | Vesuvius | Italy | Figure 9 in: Tierz et al. (2017) |
| Most-likely | 423 | Dominica | Dominica | Page 43 in: Lindsay et al. (2005) |
| Season or weather | 749 | Mentolat | Chile | Kraus (2012) |
| Specific or current conditions | 1221 | Villarrica | Chile | Servicio Nacional de Geología y Minería (SERNAGEOMIN) Observatorio Volcanológico de los Andes del Sur (OVDAS) (2015) |
| Specific past eruption(s) | 812 | Nevado del Ruiz | Colombia | Parra et al. (2007) |
| Worst-case | 3455 | Popocatépetl | Mexico | Figure 121 in: Martin Del Pozzo et al. (2017) |
| ***Basemap*** (https://volcanichazardmaps.org/map-design/#basemap) | | | | |
| Contour lines or topographic map | 1613 | Ticsani | Peru | Figure 15 in: Mariño & Thouret (2003) |
| DEM | 468 | Nevado del Ruiz | Colombia | World Food Programme (2012) |

**Table 1** (continued)

| Map classification category | Map ID | Volcano or Region | Country | Map Ref |
|---|---|---|---|---|
| Hillshade | 3836 | Momotombo | Nicaragua | Figure 18 in: Sistema Nacional de Prevención y Atención de Desastres (SINAPRED) (2009) |
| Photograph | 3493 | Ruapehu | New Zealand | GNS Science (compiler) (2020) |
| Satellite image | 1008 | Sabancaya | Peru | Instituto Geológico Minero y Metalúrgico (INGEMMET) (2019) |
| Simple | 495 | St. Catherine | Grenada | Page 61 in: Robertson (2005) |
| Street map | 582 | California [regional] | United States | Plate 1 in: Miller (1989) |
| Trail or hiking map | 3229 | Adatarayama | Japan | Adatarayama Volcanic Disaster Management Council (2019) |
| ***Dimensionality or Map View*** (https://volcanichazardmaps.org/map-design/#view) | | | | |
| Cross-sectional view | 1472 | Lascar | Chile | Figure 8 in: Bertin (2017) |
| Oblique/3D/perspective view | 1597 | Ambae | Vanuatu | Vanuatu Meteorology & Geo-Hazards Department (2020) |
| Planimetric/2D/map view | 873 | Agung | Indonesia | Kusnadi et al. (2015) |
| ***Hazard Zone Uncertainty*** (https://volcanichazardmaps.org/hazard-zone-uncertainty/) | | | | |
| Buffer zones | 1564 | Pinatubo | Philippines | Figure 5 in: Punongbayan et al. (1996) |
| Color gradation | 1135 | Three Sisters | United States | Scott et al. (2014) |
| Confidence bounds | 3315 | Rincón de la Vieja | Costa Rica | Figure 9 in: Alpízar Segura (2018) |
| Fuzzy boundaries | 3490 | Ruapehu | New Zealand | GNS Science (compiler) (2022) |
| Symbology | 547 | Haleakala | United States | Plate 1 in: Crandell (1983) |
| Versions | 1467 | Savai'i | Samoa | Figure 6 in: Cronin et al. (2006) |

distal and proximal lahar hazard zones (Fig. 6e). Other maps group hazards by process type (Fig. 6f); for example, lava flows, lahars, and pyroclastic density currents might be combined into one 'flowage hazard zone,' with tephra and ballistics grouped into a 'fall hazard zone.'

Some maps show a series of single-hazard insets in addition to the main hazard level-focused map. Other maps may show one location-based zone (e.g., proximal hazard zone) while separating other hazards into different hazard process-focused zones (e.g., distal lahar hazard zone).

When considering all unique maps in the database, single hazard process-focused maps are the most common hazard zone presentation (45%; Fig. 7a). This is due to the inclusion of maps in the database from academic literature that are often focused on developing or testing models for specific hazards. Official hazard maps (Fig. 7b) tend to be hazard process-focused (27%), hazard level-focused (22%), or group hazards by process type (e.g., fall and flowage hazards) (19%).

### Temporal scale

Hazard maps can be classified into two main categories based on the timescale the map intends to cover: background or crisis hazard maps. Background, or long-term, hazard maps are usually created in advance of volcanic unrest. They are intended to show the possible distribution of volcanic hazards over long (years to decades) time frames and to be used without revision over similar timescales. They are commonly based on a combination of methods and may be based on either specific scenarios (e.g., most likely, worst-case) or on all possible activity. Because of the long timescales of these maps, low-likelihood but high-impact hazards are sometimes included. Background hazard maps are the most common map timescale (93%), often accompany long-term hazard assessments produced by geological surveys, and are most suited to general hazard awareness and planning purposes.

Crisis, or short-term, hazard maps are usually created at the start of volcanic unrest or during an eruption. They are often intended for crisis-management purposes and show the likely distribution of hazards based on current conditions over short (usually hours to months) time frames. They may be revised multiple times as conditions change, or understanding is improved. Crisis hazard maps often incorporate more information about the current state of unrest or eruption into hazard zonation boundary placement and often employ modeling in the map-making process. Many modeling-based crisis maps serve as forecasts with very short (hours to days) time frames (e.g., short-term tephra dispersal maps for air traffic). These maps may be regularly generated on a fixed time frame (e.g., daily crisis hazard maps). Instead

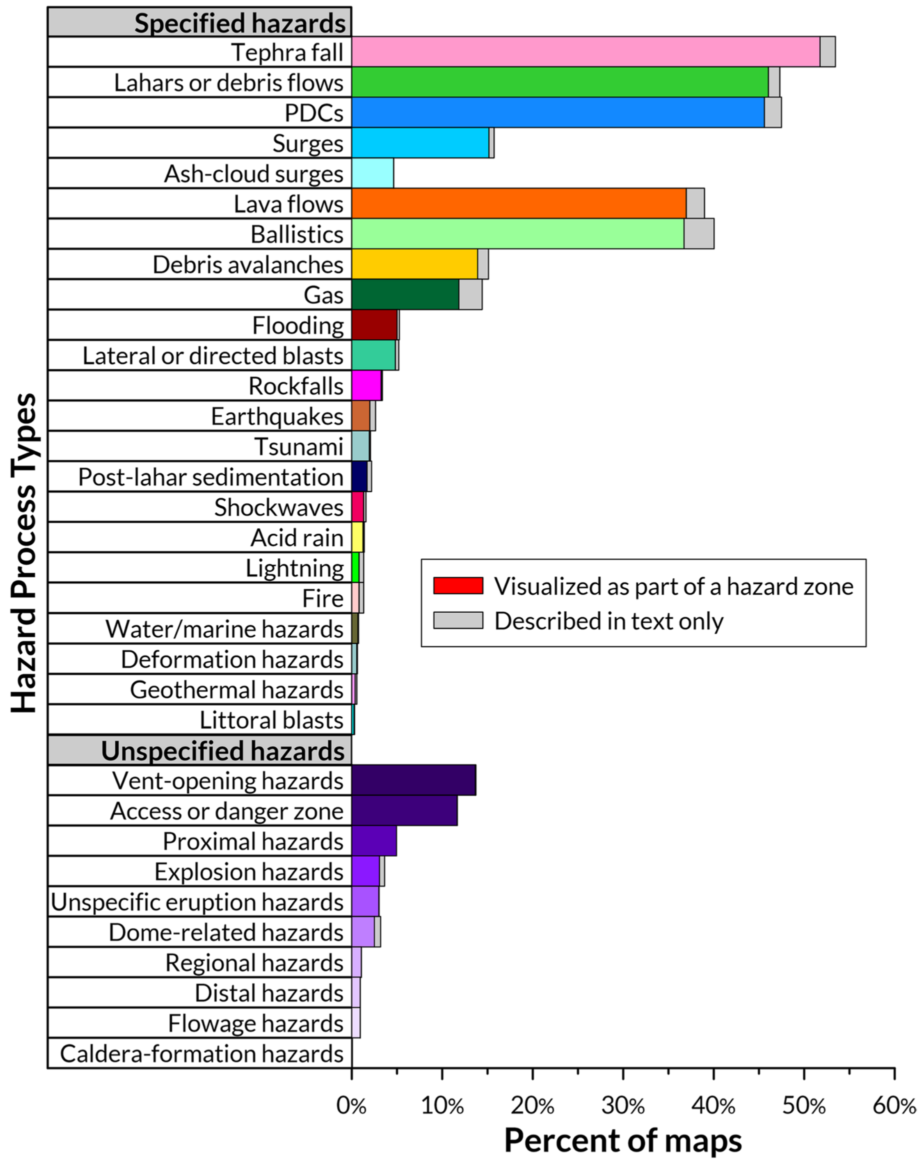



**Fig. 5** Percent of unique maps in database that consider different hazard processes. Colored bars depict hazards that are visualized on the map as hazard zones, while gray bars depict hazard processes that are described only in the map text. Unspecific hazards (purple shades) are shown at the bottom of the graph. Note: PDC = pyroclastic density current

of entering hundreds of nearly identical daily or sub-daily forecast maps in the database, we have included only representative examples of these maps.

### Spatial scale

Hazard maps can be classified according to the spatial scale of the map (Fig. 8). Most commonly (71% of unique maps), hazard maps depict the volcano edifice and the surrounding area (Fig. 8a). For some maps (13%), this may include an entire island (Fig. 8b) and can, therefore, involve special considerations, such as the inclusion of maritime hazard zones. These volcano-scale maps tend to be all- or multi-purpose (see next section). Other hazard maps (7%) focus only on particular flanks or drainages of the volcano (Fig. 8c). These maps tend to show more local infrastructure detail than those at other scales and are often tailored for specific communities at risk and crisis management purposes. They are often part of a series or set of maps focusing on different flanks or drainages of the volcano (each set is counted only once in these statistics). Regional-scale hazard maps (5%) depict a large area, commonly showing only distal hazards (Fig. 8d). Many

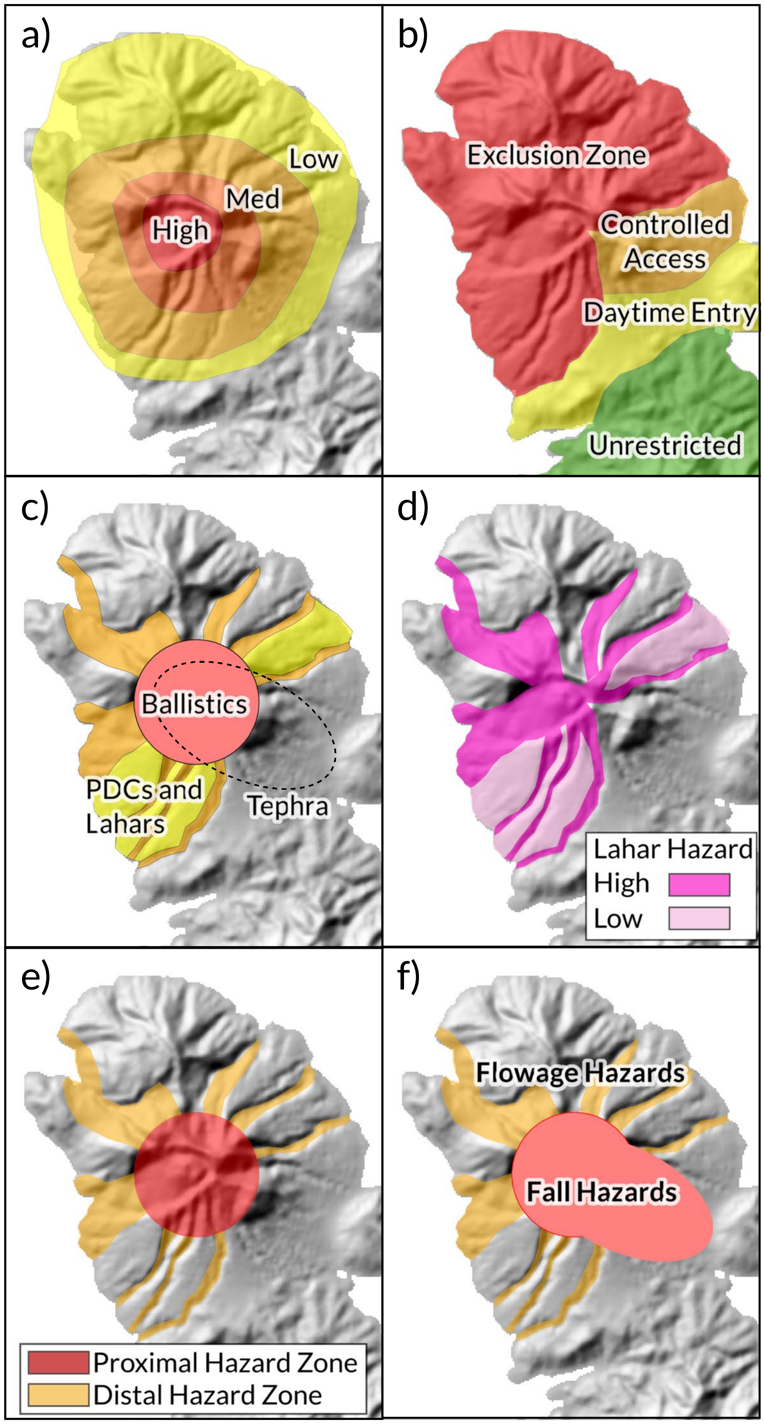



**Fig. 6** Schematic illustrations of different hazard presentation types including **a** hazard level-focused map; **b** administrative hazard zones (a special type of hazard level-focused map); **c** hazard process-focused hazard zones; **d** a single hazard (often with a set of different maps for each hazard); **e** hazard process-focused zones grouped by location (e.g., proximal, distal, regional zones); and **f** hazard process-focused zones grouped by process type (e.g., flow or fall)

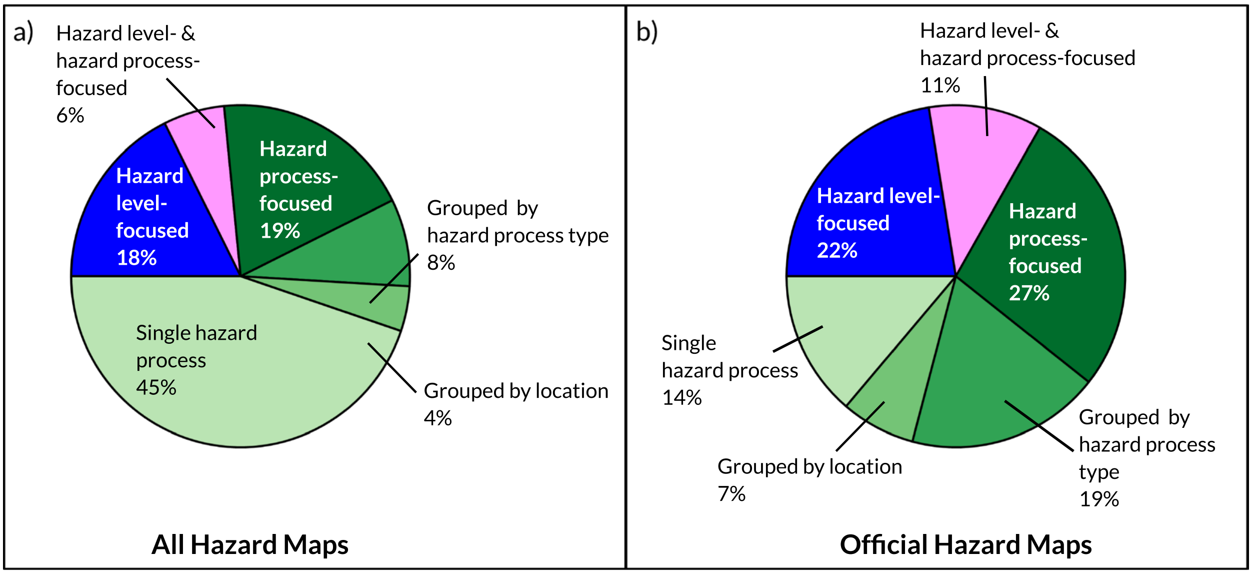



**Fig. 7** Relative frequency of hazard level-focused hazard maps (blue), hazard process-focused hazard maps (green shades), and hazard maps with both hazard level- and hazard process-focused components (pink) for **a** all hazard maps in the database and **b** only official hazard maps

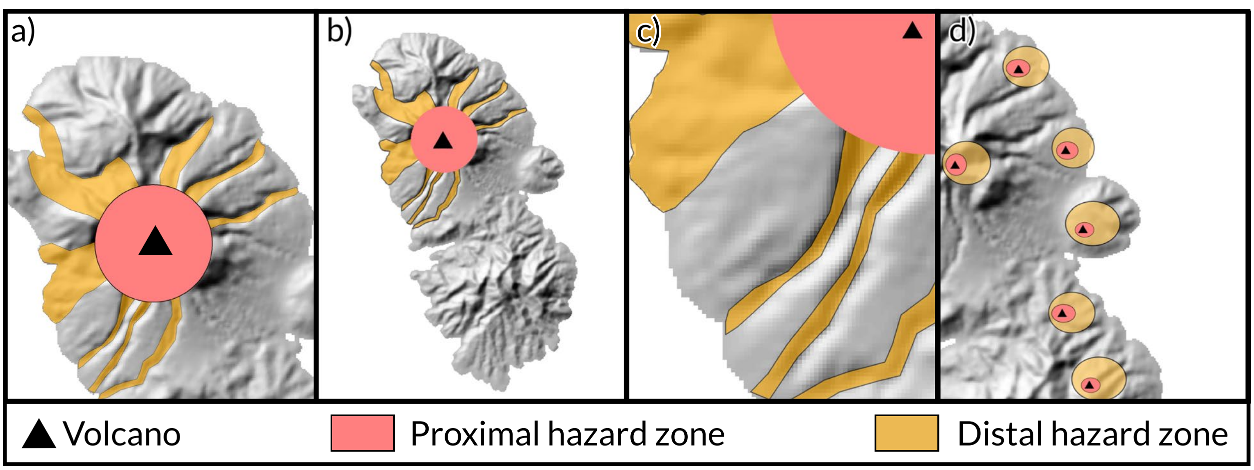



**Fig. 8** Schematic illustrations of different map spatial scales, including **a** volcano-scale; **b** entire island; **c** flank or drainage; and **d** regional scale

regional hazard maps depict the hazards from many volcanoes and may cover entire countries. These maps are commonly used for large-scale land-use and critical infrastructure planning. Some interactive maps, or maps with multiple small insets, may show the same hazards at multiple scales (3%), often selectable by the user. A few maps show only the summit of the volcano (< 1%).

### Purpose and audience

Hazard maps can also be classified according to their primary intended purpose, though it can often be difficult to ascertain the map purpose unless explicitly stated or unless certain obvious design choices were made. As such, most maps with unknown purpose were designated as multi-purpose.

Indeed, many of the maps in the database (47%) were deemed to be multi-purpose maps; that is, they are intended (or assumed to be intended) to aid in general hazard awareness (i.e., educating the audience about the extent and probability of volcanic hazard), crisis management, and land-use planning; or they were not created with any specific intended purpose. Crisis management maps (including short-term forecast-type maps) make up 15% of the database. These maps are intended for managing, responding to, and taking action during a crisis and/or eruption; they often include evacuation routes, access restrictions, recommended actions, etc. Land-use planning maps (11%) inform the citing of facilities, building restrictions, resource management, and infrastructure development. Maps specifically and only intended for hazard awareness make up 6% of the database. The database includes quite a few (20%) maps published in academic journals for illustrating applied research results and general scientific interest. It would not be unreasonable to assume that a common intention of the authors of these maps is for these research results to help inform the broader hazard assessments undertaken by the institutions actually charged with hazard assessment in the relevant countries. In some cases, scientists from official institutions have published research papers on the hazard assessment and map making methodology used to produce operational hazard maps. In general, however, the degree to which research results are included in official and operational hazard maps is variable. The database included such research result maps to show the range of available map-making methodologies that, to date, may not have been utilized in official hazard maps. Similarly, to explore the range in map style and design, the database includes some maps (< 1%) intended for the situational awareness of federal or international governments or aid organizations. These maps are often derived or simplified from other hazard maps and commonly include metrics related to vulnerability.

The intended audience of a map often relates to the intended purpose and may include the general public and the media (14%); tourists or visitors (2%); civil authorities, such as emergency managers, civil protection, first responders (2%); land-use planners such as local or regional government officials and city planners (5%); international aid or relief groups (< 1%); or scientists (22%). The majority of maps (54%) are intended for multiple audiences or have not been specifically tailored to any one audience; however, much like map purpose, the audience can be difficult to discern when not explicitly stated.

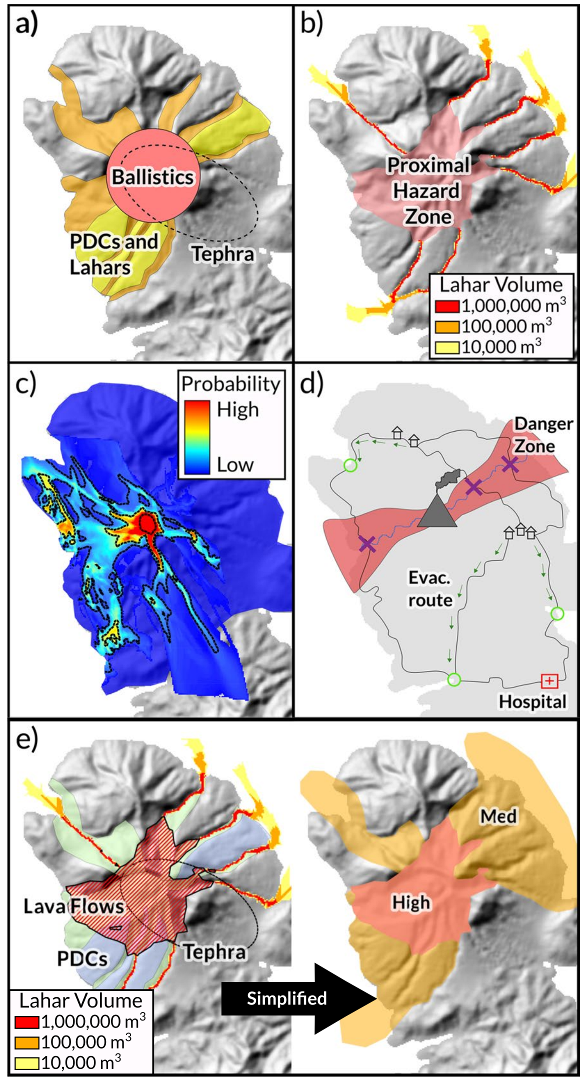



**Fig. 9** Schematic illustrations of hazard zonation methodology types, including **a** geologic history; **b** scenario-based modeling; **c** probabilistic modeling; **d** community participation; and **e** derived or simplified. Note that the final map design may not and need not reflect the map-making methodology as apparently as in these illustrations. The final design of the map should reflect the audience and purpose of the map

## Zonation methodology

Maps can also be classified according to the methodology used to delineate hazard zones (Fig. 9). Hazard zonation commonly incorporates multiple methods or uses different methods for different hazards.

The most common zonation methodology (44% of maps, Fig. 10) is based solely on geologic history (Fig. 9a). Geologic history information includes historical records of eruptive history, field mapping and interpretations of deposits, and information from analog volcanoes. Sometimes, maps based on geologic history also use expert elicitation (Aspinall 2006) or event tree exercises (Newhall et al., 2002, 2015) in order to incorporate broader geologic knowledge and analog information (< 1% of maps in the database).

Scenario-based modeling (Fig. 9b) uses either simple empirical models (e.g., energy cones, Sheridan 1979; LAHARZ, Iverson et al. 1998; Schilling 1998) or geophysical models (e.g., TITAN2DPatra et al. 2005; Pitman et al. 2003) to simulate eruption scenarios of interest. Scenario-based modeling uses a limited number of model runs with input parameters selected to suit particular

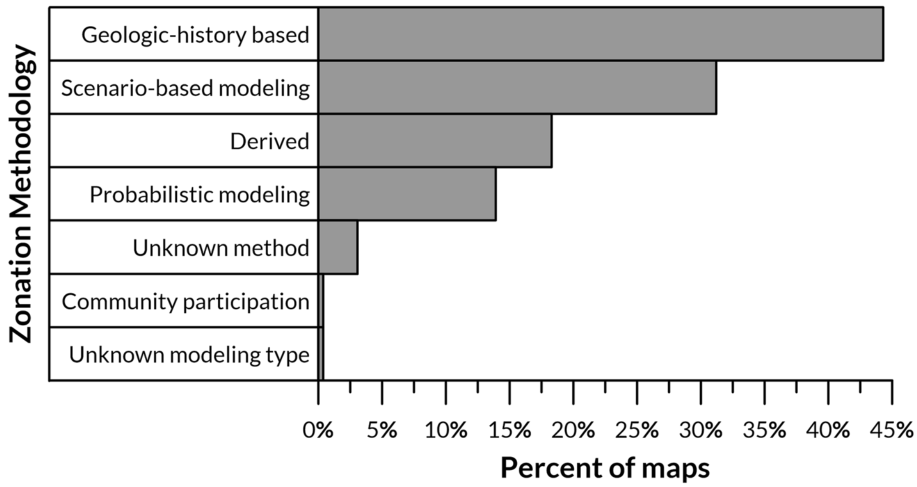



**Fig. 10** Percent of maps in the database using particular zonation methodologies. Note that maps may use multiple zonation methodologies for different zones; this plot prioritizes the most advanced methodology for counting purposes. That is, if one zone uses probabilistic modeling and another zone uses geologic history, the map methodology is counted as probabilistic modeling in order to avoid duplication

scenarios (e.g., most-likely, worst-case, range of eruptive sizes or phenomena volumes). Scenario-based modeling is relatively computationally inexpensive and thus common (31% of maps; Fig. 10).

Hazard zones based on probabilistic modeling incorporate numerous model runs (typically many thousands) with a statistical treatment of the input parameters (Fig. 9c). Because the focus of such maps is to convey the differing probability of inundation at different locations, maps using probabilistic modeling commonly illustrate the results for only a single hazard process at a time. Probabilistic modeling is still relatively rare outside of research result maps in academic literature, except for tephra- or gas-dispersal maps (7% of official maps in the database use probabilistic modeling whereas 34% of maps from other sources use probabilistic modeling; 14% of all maps in the database employ probabilistic modeling; Fig. 10).

Participatory, or community-based, hazard maps are designed by and for communities surrounding volcanoes and are commonly hand-drawn or constructed as scale three-dimensional (3D) models from craft supplies (Fig. 9d). Often created during collaborative workshops between NGOs and community members, and sometimes involving scientists, these maps focus heavily on social aspects of a locally useful map, such as evacuation routes, shelters, hospitals, and muster points. The hazard zones on these maps are relatively simple, geologically speaking; they are commonly based on the experience of the community, oral and written histories, cultural beliefs, observed eruptive history, and input from participating scientists. However, the additional information on the maps can be highly detailed in terms of impacts to local infrastructure, such as particular bridges on evacuation routes. Additionally, the maps often incorporate issues of vulnerability and risk; some identify individual households with elderly or pregnant inhabitants, for example. Participatory hazard maps are often focused only on a single community or area around the volcano, but they have been shown to be highly utilized and invested in by the communities that make them (Andreastuti et al. 2017). These maps can be difficult to find outside of the communities that create them, unless images of them are published in reports or academic literature. They are thus relatively rare in the database (< 1% of maps; Fig. 10).

Derived hazard maps (Fig. 9e) are those that are adapted from an existing original or 'parent' hazard map in order to simplify or adapt that map for a different audience or purpose. These include maps that are simplified for educational or warning signage around volcanoes, for public information fact sheets and communication products, and for situational awareness among international aid groups. Derived-hazard maps make up 18% of maps in the database (Fig. 10).

The prevalence of different zonation methods has changed through time as different models and methods have been developed. Figure 11 shows the evolution of zonation methods through time. Early maps (1937–1979) were almost all geology-based or derived from a geology-based map. As empirical models, such as the energy cone model (Sheridan 1979), LAHARZ (Iverson et al. 1998; Schilling 1998), and ASHFALL (Hurst 1994) were developed, a higher percentage of maps (3% 1970–1979; 17% 1980–89; 30% 1990–99) began to employ scenario-based modeling. As more physical models and

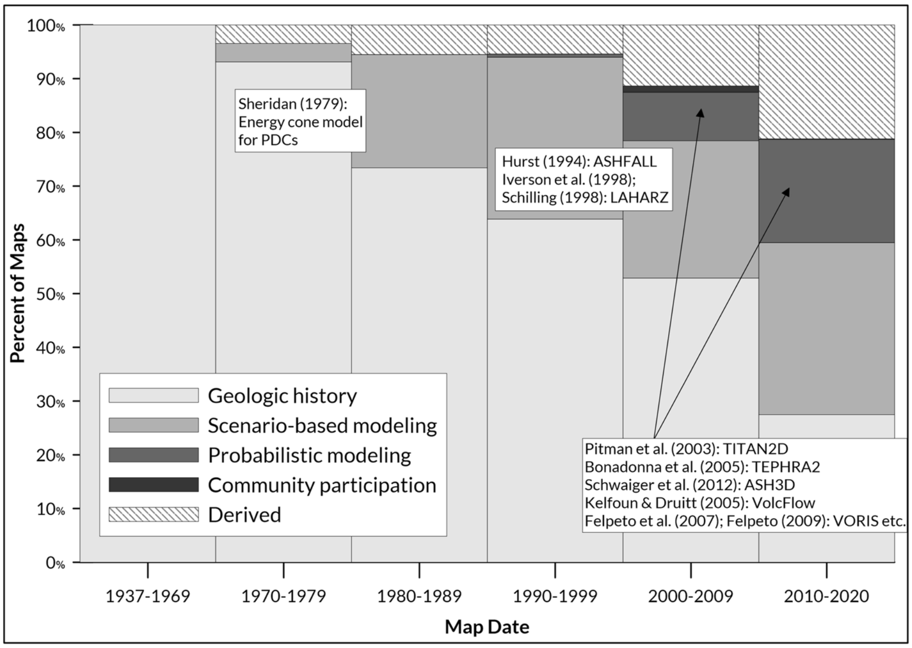



**Fig. 11** The evolution of map zonation methods through time, with notable events in model development noted in boxes

probabilistic methods were developed and computing resources improved, a higher percentage of maps (4% 2000–09; 18% 2010–22) began to use probabilistic methods in the 2000s and 2010s, using models including TITAN2D (Patra et al. 2005; Pitman et al. 2003), TEPHRA2 (Bonadonna 2005), ASH3D (Schwaiger et al. 2012), VolcFlow (Kelfoun & Druitt 2005), and VORIS (Felpeto et al. 2007), among others.

Recently, two efforts were responsible for the large increase in the number of derived hazard maps in the mid-2010s: one by the USGS to create simplified versions of all Cascades volcanoes for use on park signage (e.g., Mount St. Helens, Wolfe et al. 2014) and one by the Japanese Meteorological Agency (JMA) to create semi-standardized volcanic alert level leaflets, many of which were derived from existing hazard maps (e.g., Asamayama, Japan Meteorological Agency, 2016).

## Scenarios

In addition to the hazard zonation methodology, hazard maps differ based on which scenarios were considered for hazard zonation, such as 'worst-case' scenarios, scenarios based on eruption sizes, or scenarios that consider certain seasons. Many maps may use a combination of different scenario types or may use different scenarios for different zones (e.g., specific volume scenarios for lahars, seasonal tephra dispersal scenarios, worst-case PDC and debris avalanche scenarios); as such, the percentages presented herein add to > 100%. Many maps (48%), especially those that use scenario-based modeling, consider different eruption sizes (VEI) or a range of volumes for different hazard process. Other maps (30%) consider scenarios related to the style of eruption or hazard process, such as effusive, explosive, dome-forming, or phreatic eruptions; rain-triggered versus snowmelt lahars; or dome-collapse or column-collapse PDCs. Others base hazard zones on the most-likely (2%) or worst-case (4%) scenarios, or may consider scenarios related to specific past eruptions, either at the volcano in question (19%) or those of analog volcanoes (4%). Other maps (27%) may consider scenarios related to the possible location or direction of future volcanic activity (e.g., likely vent- or fissure- opening locations; direction of likely lateral blasts); the season or weather conditions during which an eruption might occur (25%; usually for tephra, gas, or lahar hazard zones); the timing or duration of events (5%) (e.g., during or after an eruption); or even the potential composition (3%) of a future eruption (e.g., silicic vs. mafic eruption at a volcanic field). Crisis hazard maps, especially those that serve as forecasts with short time frames, often consider scenarios related to the specific conditions at the time the map was made (2%). Maps which depict access zones often have scenarios related to alert levels (7%). A few maps (< 1%) depict hypothetical hazard zones that are dependent upon future activity; for example, some maps depict the extent of hazard zones that will be established around future lava flows or vents. Many maps have zones that do not consider any specific scenario; rather, they strive to depict all possible outcomes (20% of maps).

### Hazard zone and probability definition

Hazard maps define hazard zones and their probabilities in different ways, often using a combination of definition types for different hazards and giving multiple hazard zone or probability definitions on a single map.

Hazard zone probabilities are commonly defined using qualitative or relative probability (47% of unique maps). These are often categorized as high-medium–low hazard zones, but sometimes they are only numbered or ordered without other descriptive terms. Fewer maps provide numeric (including annual) probabilities for hazard zones (11%) and those maps usually result from probabilistic modeling. Numeric probabilities may be expressed as percentages (e.g., 20%), natural frequencies (e.g., 1 in 5), or as decimals (e.g., 0.2). Numeric probabilities are sometimes given for only one hazard on the map (e.g., tephra fall). Some hazard maps (5%) provide recurrence intervals or rates (e.g., 1 every 10,000 years) instead of probabilities. Some maps give no explicit probability definition, but relative probability can be inferred from the scenario (14%) or the corresponding alert level (7%). Many maps (23%) give no definition of hazard zone probability, even a relative or qualitative one.

Hazard zones themselves may be defined, named, or labelled in different ways. Many maps (37% of maps in the database) label hazard zones using the hazard process names (e.g., lahar hazard zone). Commonly (32%), hazard zones are labelled using qualitative probabilities (e.g., high-medium–low probability). Other maps (23%) define zones based on estimated values or hazard intensity metrics (HIMs), such as tephra thickness or grainsize, loading, or pressure. Some maps (12%) have only simply defined access zones (e.g., exclusion zone, danger zone, daytime entry zone). Scenario names (e.g., VEI 2 hazard zone; $1 \times 10^6$ $m^3$ lahar hazard zone) are used as labels on 12% of maps in the database. Some modeling-based maps (10%), especially those in academic publications, label hazard zones by numeric probability. About 6% of maps label hazard zones by location (e.g., proximal, distal, or regional hazard zones). Occasionally (< 1%), hazard zones are labelled by the recurrence interval (e.g., 100 year flood zone). A few maps (< 1%) have no labels.

### Design and cartographic elements

Volcanic hazard maps that show the same hazard processes, use the same methodology, and serve the same purpose may still be very distinct visually due to the wide range of map design choices and cartographic elements that are included or omitted. Map design plays a huge role in the success of information transfer to map users (Thompson et al. 2015; 2017). A short discussion follows here, but a more detailed discussion of graphic design in volcanic hazard maps is beyond the scope of this paper. The reader is referred to the website for further information and a list of recommended reading (https://volcanichazardmaps.org/map-design/).

#### *Publication format*

Hazard maps are most commonly formatted (Fig. 12) as small-scale figures within hazard assessments (30%); as medium-size map sheets or poster-style maps (26%), which may be published either as pocket-inserts in accompanying hazard assessments (8%); or as standalone map sheets/posters (18%). Maps are also published in scientific journals (21%); on websites (4%); in theses or dissertations (2%); or in conference abstracts or presentations (< 1%).

Hazard maps intended for the public are also commonly featured in flyers, brochures, short fact sheets, or infographics (4%). Similarly, some maps (4%) are published as smaller-scale figures in booklets, longer fact sheets, guidebooks, or handbooks. Volcanoes in national parks or with large numbers of visitors may have hazard maps formatted as hiking or trail maps (1%) or as large-scale signs, billboards, or placards (1%), often placed near the volcano or hazard zones themselves. Short-term crisis maps are often published as figures in public information statements (1%; however, a series of information statements over the course of an eruption is only counted once, otherwise there would be many hundreds of hazard maps of this type).

Increasingly, interactive or dynamic web-based hazard maps are being created. Interactive maps allow a user to manipulate the scale, change the view, toggle layers visible on the hazard map, and sometimes to search for particular locations (3%). These maps are commonly underpinned by a geospatial database that can be easily updated as circumstances change. Often, these interactive maps are simplified from another version of the hazard map and are intended for use by the public.

#### *Color scheme*

Three broad types of color schemes are generally used in map design (Brewer 1994): Sequential color schemes, such as dark-to-light schemes, are suited to ordered data (e.g., high-med-low hazard zones). Qualitative or categorical color schemes use differing hues and are suited to non-ordered, categorical data (e.g., lahar hazard zone, PDC hazard zone). Diverging color schemes are suitable for data with a critical central value, such as zero or the mean.

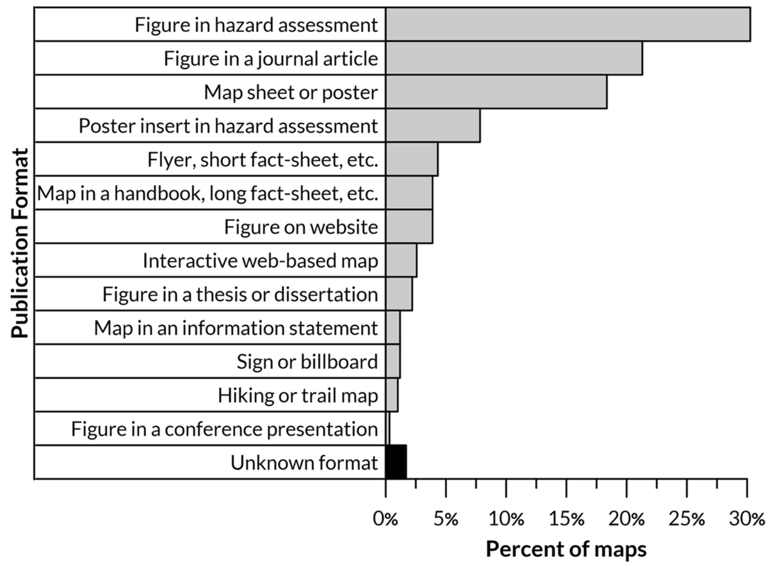



**Fig. 12** Frequency of maps in the database by publication format (shading indicates similar formats). Note that a series of information statements over the course of an eruption is only counted once, otherwise there would be many hundreds of hazard maps of this type

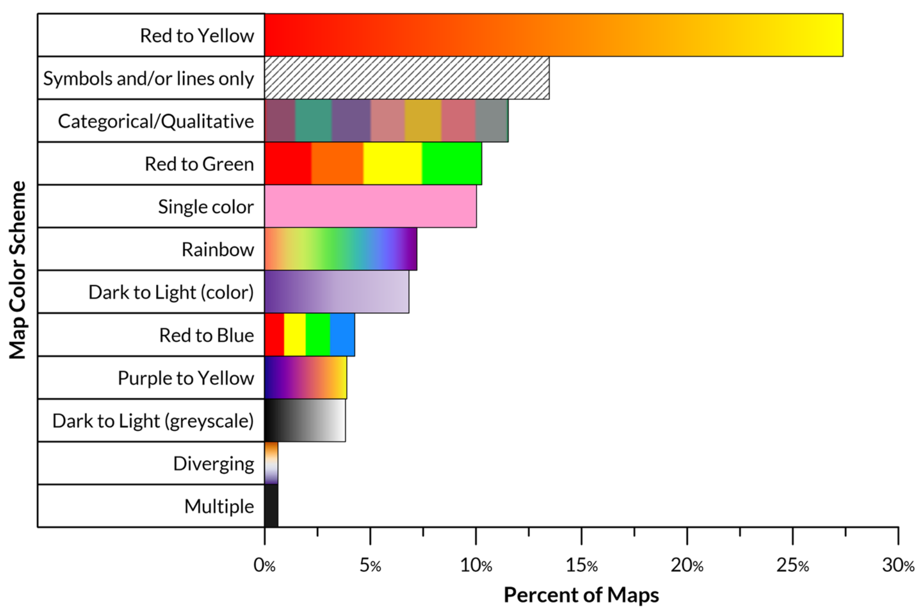



**Fig. 13** Percent of maps in the database using different color-scheme types to differentiate volcanic hazard zones. Bar colors give examples of the color-scheme in question. Note that most of these color schemes might be used as gradients or as discrete colored zones

Volcanic hazard maps use a variety of color schemes to differentiate hazard zones (Fig. 13), with sequential red-to-yellow schemes being the most common (27%). This color scheme is easy to interpret and color-blind safe (Jenny & Kelso 2007; Thompson et al. 2015). Sequential red-to-green color schemes are used on 10% of maps. This color scheme is prone to misinterpretation of green zones as 'safe' (Monmonier 2018) and may be difficult for the color-blind to distinguish low hazard from high hazard zones (Jenny & Kelso 2007). Dark-to-light color schemes that vary the value or saturation of a hue (e.g., grayscale or dark blue to light blue schemes) are used on 11% of maps and are easy to interpret when the darkest or most saturated hue represents high hazard (Bostrom et al. 2008; Brewer 1994; 2006). Additional sequential color scheme variations include purple-to-yellow schemes (4%) and red-to-blue color schemes (4%).

Qualitative or categorical color schemes are used on 12% of maps and are appropriate for displaying non-ordered categorical data, as is the case with maps with separate zones for each hazard process. About 10% of maps in the database use only a single color, often for a single access or danger zone, when only one hazard process is displayed, or when a small island is completely covered by one hazard level.

Diverging color scales (< 1% of maps) are used for data that have a middle value that is special in some way (e.g., elevation data with sea level as the special value (Brewer 1994; 1996)); however, if the middle value is not special then these maps can be misinterpreted (Thompson et al. 2015; 2017).

Many (13%) older maps, created before modern color-printing and before the advent of geographical information systems (GIS), use black-and-white symbology to represent hazard zones.

About 7% of the hazard maps in the database use rainbow color schemes. Rainbow color schemes are commonly used for continuous data, such as numeric probabilities, velocities, thicknesses, tephra loading, etc. Many software packages use a rainbow color map as the default color scheme, perhaps accounting for the prevalence of this color scheme in scientific journal articles. However, rainbow color schemes present several issues with respect to visual perception of color breaks (Eddins 2014; Light & Bartlein 2004). Graphic design campaigns (e.g., Hawkins et al. 2014) have begun to urge editors of scientific journals to disallow rainbow color schemes for figures for these reasons.

Most of these color schemes may be used as continuous gradients where the boundaries between zones are thus also gradational; or, more commonly, discretized with different colors for each hazard zone, producing more visually abrupt boundaries between zones.

### *Basemap*

Volcanic hazard maps are displayed on a variety of basemaps. The choice of basemap depends upon the target audience; some basemaps are more easily understood by the general public, for example, than others (e.g., Haynes et al. 2007). Some maps use several basemap types as overlays on a single map; for example, a hillshade basemap may be overlain with contour lines; thus, the percentages presented in this section sum to more than 100%.

Digital Elevation Models (DEMs) (Fig. 14b), shaded relief or hillshades (Fig. 14c), and Triangulated Irregular Networks (TINs) are all digital representations of topography. Hillshade or shaded relief maps are based on DEMs but simulate shadows to emphasize terrain relief and thus mimic the look of real topography shaded by the sun. Hillshades are the most common type of basemap used for volcanic hazard maps (44% of maps). Studies have shown that hillshade maps are

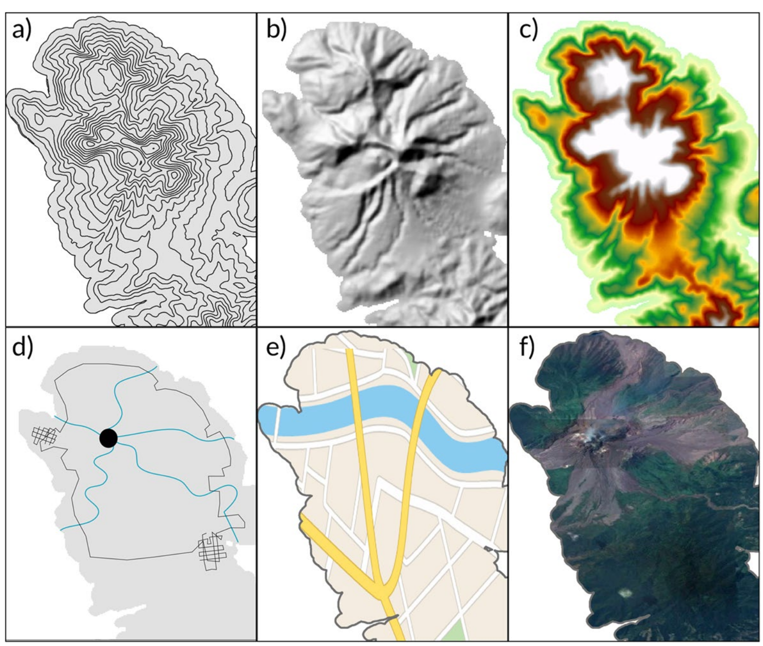



**Fig. 14** Schematic illustrations of different basemap types including **a** a contour or topographic map; **b** a hillshade Digital Elevation Model (DEM); **c** a DEM with no modeled shadows; **d** a simple or sketch map; **e** a street map; and **f** a satellite image

more intuitive for topography interpretation than contour maps (Haugerud & Greenberg 1998; Konnelly 2002). Unshaded DEMs and TINs are used on 2% of maps in the database.

Contour maps, or topographic maps (Fig. 14a), are the second most common type of basemap used for volcanic hazard maps (38% of maps). Contour maps are generally more common on older maps, before the advent of GIS programs that made the use of digital elevation models (DEMs) and hillshade basemaps more prevalent. However, contour maps require specialized training to interpret and are not intuitive for the general public; studies show they may pose a challenge even for those with geoscience knowledge (Clark et al. 2008; Gobert 2005; Rapp et al. 2007).

Simple basemaps (Fig. 14d) are common (18%) on older maps created before GIS systems were available and on regional or distal hazard maps that cannot show fine detail. These maps may show nothing except the outline of an island or municipal boundaries, or they may have symbology portraying major roads, drainages, water features, and other landmarks. They often lack topographical information, other than labeling mountain ranges, hills, or volcanoes.

Some maps (3%) use more detailed street maps (Fig. 14e) as the main basemap, which may include infrastructure (such as power lines and railroads), street name labels, important buildings or landmarks, bridges, and other municipal information. These maps have enough detail for users to locate themselves or other places of interest relative to hazard zones but lack topographical information. However, many maps (61%) use a street map as an overlay on another basemap style. About 12% of maps portray hiking trails as either the main basemap or as an overlay.

Only a small percentage of maps in the database use satellite images (4%) or photographs (1%) as basemaps (Fig. 14f). Research has shown that true-color satellite images or photographs are particularly easy for the general public to interpret, especially for tasks such as orienting, identifying map features, and comprehending volcanic hazard information (Haynes et al. 2007). However, it may be difficult to layer hazard zone and other information on photographs without the map becoming cluttered or obscuring the photographic base. Interactive maps often allow the user to select a basemap of choice; about 2% of maps use multiple basemaps in this way.

Some maps also display town locations (74%), infrastructure layers (24%), population information layers (1%), land-use zones (< 1%), and flight paths (< 1%).

### *Dimensionality or view type*

Volcanic hazard maps differ in their dimensionality or view type. While the vast majority of maps in the database are presented in a planimetric (Fig. 15a), two-dimensional (2D), or map view (97%), some maps are presented in an oblique (Fig. 15b), 3D, perspective view (2%). A handful of interactive maps (< 1% of maps) allow the user to manipulate the view type. A few maps in the database (< 1%) are presented in cross-sectional view (Fig. 15c) in order to show aerial ballistic hazard zones. Research on the effect of map dimensionality on the comprehension of hazard maps has shown that some tasks are more easily accomplished on planimetric (2D) maps while other tasks are more suited to oblique (3D) maps (Haynes et al. 2007).

### *Layout*

Volcanic hazard maps also vary in the layout of the hazard information. Most maps (77%) consist of just one large main map panel, usually with accompanying text, and sometimes with inset photos or other non-map insets. Other maps (11%) consist of a main map, with a series of insets, along with accompanying text. The main map may show hazard level-focused zones with a series of hazard process-focused insets; or proximal hazards

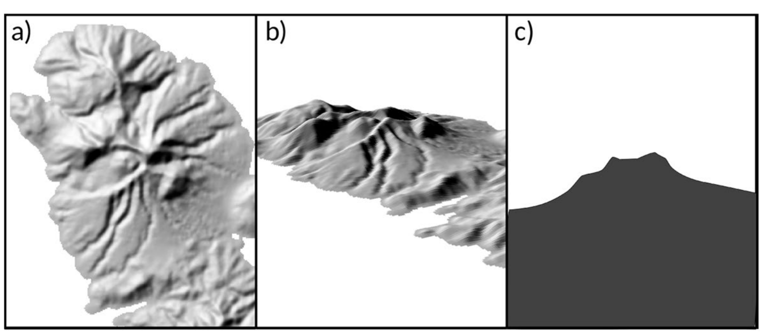



**Fig. 15** Schematic illustrations of map dimensionality, including **a** planimetric, two-dimensional, or map-view; **b** oblique, three-dimensional, or perspective view; and **c** cross-sectional view

may be shown on the main map panel, with distal or regional hazards on the insets; or the most probable hazard processes may be shown on the main map, with less likely hazards processes shown on insets. Some maps (12%) do not have a main map panel, but instead consist of a series of small map panels of roughly the same size. Often, one panel may be devoted to each hazard process, or to a series of different scenarios.

#### *Hazard zone uncertainty*

All hazard zones depicted on hazard maps have associated uncertainty; the degree of hazard does not suddenly fall to zero when crossing the boundary of a hazard zone, and the degree of hazard is not necessarily the same at every location within a hazard zone (MacEachren, 1992). However, uncertainty is notoriously difficult to depict visually on maps without creating confusion (Doyle et al., 2019). Most hazard maps (74%; Fig. 16) do not describe or depict uncertainty about hazard zones in any way, while some hazard maps only describe uncertainty in accompanying text (17%; Fig. 16). Only 9% of maps depict uncertainty visually (Fig. 16). Those that do visually depict uncertainty do so in a variety of ways (Fig. 17), including by using fuzzy boundaries or gradational colors (Fig. 17a; 5%), using symbology (Fig. 17b; 2%), depicting buffer zones (Fig. 17c; < 1%), showing confidence bounds (Fig. 17d; 1%), or depicting different versions of hazard zones that show how uncertainty might evolve through time (Fig. 17e; < 1%).

#### *Other cartographic elements*

A variety of cartographic and other map elements (Table 2), either visually depicted on the map or included in the map text, have been recorded in the database. Many of these elements are search options in the advanced map search. These elements include common cartographic features, such as the north arrows, map scales, coordinates, legends, and area maps. Other map elements recorded in the database include evacuation routes; actions to take; safe zones or shelters; past deposits; eruptive history information; details and definitions of the included hazard processes; impact details and locations; methodology descriptions; references; additional information sources; conditional validity or expiration date; hazards from other volcanoes; and whether hazard process velocity, travel times, or arrival times are labelled on the map or discussed in the map text. For maps that are part of larger works (e.g., hazard assessments, journal articles), we only include those elements that are present on the maps themselves, not those that are only described in the text of the larger work.

## Conclusions

The Volcanic Hazard Maps Database, accessed via the website portal, catalogs the diversity of existing volcanic hazard maps, provides terminology and a classification system for maps, and serves as a community resource for volcanic hazard assessment and mapping. We envision several main uses of the database and website as discussed below.

The classification scheme developed from the IAVCEI CVHR Working Group on Hazard Mapping community workshops and used in this work provides a comprehensive framework of terminology for discussing and naming hazard maps. When browsing maps on the Volcanic Hazard Maps Database website, it is quickly apparent that despite the enormous diversity of map types, many hazard maps have extraordinarily similar titles. In fact, of maps with titles (excluding those with only figure captions, as in academic journals), 36% are titled using some variation of "Hazard Map" or "[Volcano Name] Hazard Map." A further 16% add only the hazard-process name (e.g., [Volcano Name] Lahar Hazard Map). About 8% of titles include version information; 4% include temporal scale; 22% include scenario(s)

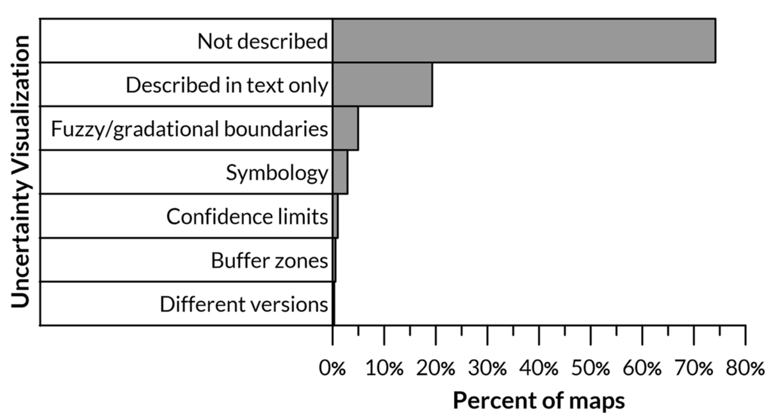



**Fig. 16** Percent of maps in the database which describe or visualize uncertainty in different ways Figure is bar graph

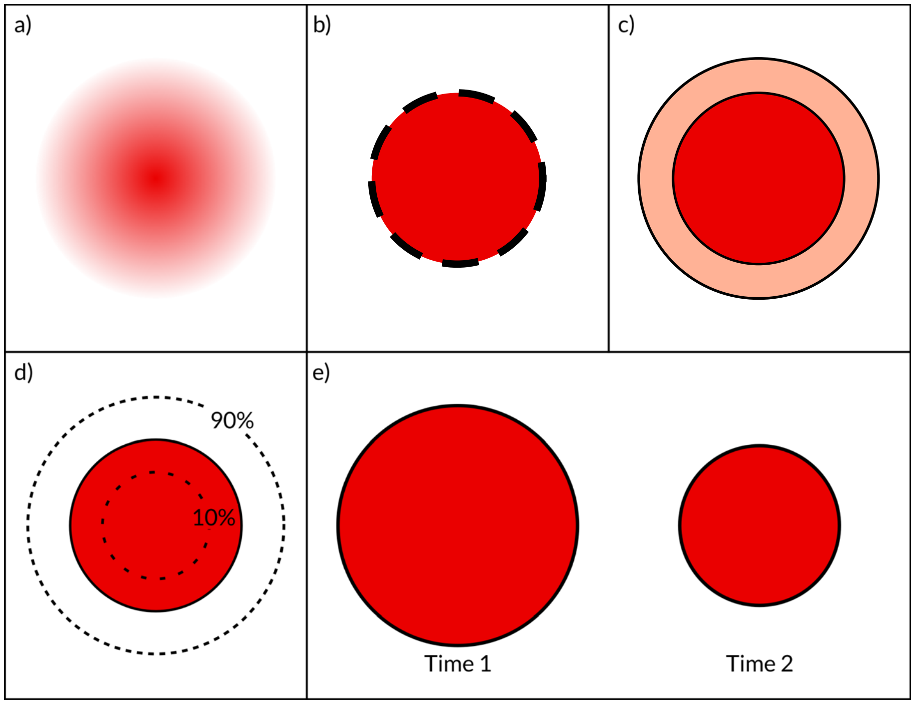



**Fig. 17** Schematic illustrations of different uncertainty visualization methods, including **a** fuzzy boundaries or gradational colors attempt to show uncertainty at outer zone limits or between zones; **b** boundaries of different certainty levels are depicted using different symbology (e.g., dashed or solid lines); **c** a buffer zone depicting uncertainty is placed around the hazard zone; **d** confidence limits, like the 10 and 90% confidence limits shown here, are placed around a hazard zone or shown in different map panels; **e** different versions of the hazard zones are shown on different map insets to show uncertainty, often as the uncertainty is expected to evolve through time (e.g., multiple sizes of a hazard zone around a hypothetical vent location are shown)

considered; and 11% include some reference to purpose or audience. Thus, stakeholders searching for hazard maps for a particular volcano might find dozens of very different hazard maps all having identical names. One use for our classification scheme is to identify relevant category names that could include in volcanic hazard map titles. While this will depend greatly on the particular map, map makers might consider including in the title (where relevant): map temporal scale, version information, purpose or audience, or scenario type.

Hazard mappers often work without the benefit of the experience of workers in other countries; our hope is that the database and website will serve as an information source for hazard mappers, allowing them to draw easily on global experiences. Hazard mappers can use the website to quickly and easily explore the variety of ways that common challenges (e.g., visualizing or describing uncertainty; choosing scenarios; dealing with low probability, high consequence hazards, etc.) have been addressed at different volcanoes, for different hazard processes, and for different audiences. Content pages on the website describe various topics in more depth with discussions about best practices, additional resources and references, and example maps. For example, the page on color-scheme choice (https://volcanichazardmaps.org/map-design/#color) discusses issues such as color-blindness, rainbow color schemes, and tools for color selection. Our intention is to continuously include more map-making considerations, best practices, and case studies from future State of the Hazard Map workshops.

Hazard mappers can use the website to provide concrete examples of different hazard map styles and map content options to stakeholders. In this way, we envision the website and database serving as a kind of 'menu' that hazard map makers can present to stakeholders for consideration. We are currently developing tools to make this type of 'menu building' even easier, including a tool to build sample, schematic maps with user-selected styles and content to be used during stakeholder engagement activities.

The website and database may also serve an educational role. For example, students participating in the Center for the Study of Active Volcanoes (CSAV) International Training Course (https://hilo.hawaii.edu/csav/international/) have been tasked with making hazard maps as part of modules on modeling tools. Some content on hazard map diversity, map making resources,

**Table 2** Map elements recorded in the database and their frequency

| Map element | Description | % of maps |
|---|---|---|
| action | The map describes what to do during unrest or eruption | 20 |
| alert level scheme | The alert level scheme for the volcano is described | 10 |
| area map | An area map is included that shows the regional context | 22 |
| audience and/or purpose | The intended audience or purpose is described | 10 |
| cartographic legend | A legend is provided for cartographic symbols (e.g., roads, lakes) | 50 |
| color scheme order | Color scheme is in order (e.g., red = high hazard) | 57 |
| conditional validity | The conditions under which the map is valid are described (e.g., VEI < 5, central vent eruptions) | 23 |
| coordinates | Geographic coordinates are shown | 58 |
| eruptive history | The eruptive history of the volcano is described | 19 |
| evacuation route | Evacuation routes are visually depicted on the map | 9 |
| expiration | The conditions that will trigger map revision are described (e.g., summit changes, a time limit, new information) | 6 |
| glossary of terms | Geological terms are defined in a glossary section | 5 |
| hazard details | Hazard processes are defined or described | 17 |
| hazard travel time | Hazard process arrival times or velocities are depicted or described | 12 |
| hazard zone description | Hazard zones have accompanying descriptions beyond labels | 73 |
| hazard zone legend | A legend is provided for the hazard zones | 88 |
| impact details | Impact details (e.g., roof collapse, crop damage) are described | 19 |
| impact locations | Specific towns or drainages are named or listed | 15 |
| insets | Insets containing non-map information are included | 20 |
| methods | Hazard zonation methods are described in the text | 37 |
| more information source | Sources for additional information are given | 16 |
| north arrow | A north arrow is included | 65 |
| oblique image included | Oblique (3D) inset images of the terrain or hazard zones are shown | 4 |
| other volcanos | Hazard zones from nearby volcanos are also shown on the map | 2 |
| past deposits | Deposits from previous eruptions are shown visually | 15 |
| person hours | The amount of time required to make the map is stated | 1 |
| photos | Photos of the volcano, deposits, impacts, etc. are shown | 12 |
| population information | Population information (e.g., numbers of inhabitants in towns or hazard zones) is depicted or described | 8 |
| references | Reference literature is cited | 16 |
| safe areas | Safe areas, including shelters or muster points, are depicted | 12 |
| scale bar | A scale bar is included | 85 |
| version number | Version numbers or a revision history is provided | 10 |
| wind rose diagram | A wind rose diagram of either wind directions or tephra dispersal directions is provided | 1 |

and hazard mapping best practices from early drafts of the database has been presented to these students to assist them with their tasks. The website and database could be incorporated into various training materials, educational resources, and courses in the future.

Our intention is to continually update the database with new maps and to grow the database and website into a valuable community resource for hazard map makers. As such, we welcome feedback from the community and broader users in the form of corrections, updates, map additions, and suggestions, which can be submitted through the website. We intend to solicit more structured feedback and tool development during future CVHR Working Group on Hazard Mapping workshops. Additionally, during previous workshops, a survey was distributed to participants who were involved in the production of hazard maps. This survey targeted official and operational volcanic hazard map makers to gather information and improve the understanding of the nature of mapping practices, as well as the respective philosophies upon which they are based. Future planned work includes a publication concerning the results of this survey and incorporation of the survey results into the database in order to correct database fields that were difficult to extract from the maps themselves (e.g., map purpose and audience).

The Volcanic Hazard Maps Database represents a valuable resource for hazard map makers, hazard practitioners, researchers working on applied aspects of hazard research, and students. The availability and easy comparison of maps in this way, might open the door for new kinds of understanding and studies about hazard maps.

**Abbreviations**

| | |
|---|---|
| CSAV | Center for the Study of Active Volcanoes |
| CVHR | Commission on Volcanic Hazard and Risk |
| DEM | Digital Elevation Model |
| GIS | Geographic Information System |
| IAVCEI | International Association of Volcanology and Chemistry of the Earth's Interior |
| VEI | Volcanic Explosivity Index |
| PDC | Pyroclastic density current |
| DEM | Digital elevation model |

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**Authors' contributions**
SEO: Database development and population; project planning and collaboration; website content creation; manuscript preparation. DC: Database population; project planning and collaboration; website content creation; manuscript contribution. DN: Website development and administration; database administration; manuscript contribution. HW: Project planning and collaboration; manuscript contribution. EC: Project conception, planning, and collaboration; manuscript contribution. JL: Project conception, planning and collaboration; manuscript contribution. JE: Project planning and collaboration; database population; manuscript contribution. ST: Project collaboration; database population; manuscript contribution. YT: Database population; manuscript contribution. The author(s) read and approved the final manuscript.

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**Availability of data and materials**
The database can be accessed at https://volcanichazardmaps.org/.

## Declarations

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

**Consent for publication**
Not applicable.

**Competing interests**
We have no competing interests to declare.

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