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The diversity of volcanic hazard maps around the world: insights from map makers

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Abstract

The IAVCEI Working Group on Hazard Mapping has been active since 2014 and has facilitated several activities to enable sharing of experiences of how volcanic hazard maps are developed and used around the world. One key activity was a global survey of 90 map makers and practitioners to collect data about official, published volcanic hazard maps and how they were developed. The survey asked questions about map content, design, and input data, as well as about the map development process and key lessons learned. Here we present the results of this global survey, which are then used to quantitatively describe and summarise current practices in volcanic hazard map development.

We received entries related to 89 volcanic hazard maps (78% long-term/background maps and 22% short-term/crisis hazard maps), covering a total of 80 volcanoes across 28 countries. Although most maps captured in the survey are volcano-scale maps of stratovolcanoes that show similar types of content, such as primary hazard footprints or zones, they vary greatly in input data, communication style, format, appearance, scale, content, and visual design. This diversity stems from a range of factors, including differences in map purpose, the methodology used, the level of understanding of past eruptive history, the prevailing scientific and cartographic practice at the time, the state of volcanic activity, and variations in culture, national map standards and legal requirements.

Experiences and lessons shared by our respondents can be divided into six main themes: map design considerations; the process of map development; map audience and map user needs; hazard assessment approach; map availability and accessibility; and external (e.g., political) influences. Insights shared included the importance of: visual design elements, map testing and evaluation, working with stakeholders and end users to improve a map's efficacy and relevance, and considering possible unanticipated uses of hazard maps. These free-form text insights (i.e., responses to open-ended questions) from map makers and practitioners familiar with the maps lend depth and clarity to our results. They provide a rich complement to our more quantitative analysis of design elements and of approaches used to determine and delineate map zones.

Results from our global survey of hazard map makers and practitioners, together with insights from other key initiatives of the Working Group on Hazard Mapping such as the Volcanic Hazard Maps Database (VHMD; https://volcanichazardmaps.org/), provide a snapshot of the wide variety of volcanic hazard maps generated over the past decades, and improve our understanding of the diversity across volcanic hazard mapping practices. These initiatives represent important steps towards fulfilling the aims of the Working Group, namely, to construct a framework for a classification scheme for volcanic hazard maps and to promote harmonized terminology, as well as to identify and categorise good practices and considerations for volcanic hazard mapping.

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Introduction

Volcanic hazard maps are visual, geospatial depictions of the areas that could be impacted by various volcanic phenomena during or subsequent to an eruption. They are developed to communicate a complex array of hazard information to those at risk, or those responsible for managing risk. If they are developed, communicated, and used appropriately for a given volcanic setting and cultural and political context, hazard maps can help guide mitigation measures such as land use and evacuation planning (Crandell et al. 1984; Tilling 2005; Calder et al. 2015).

The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Commission on Volcanic Hazards and Risk established a working group on hazard mapping in 2014. The aim of this initiative was to undertake a comprehensive review of past and current volcanic hazard mapping practices and associated lessons learned through a series of workshops and related initiatives with volcanologists and stakeholders interested in volcanic hazard maps. Towards the beginning of this effort, it became clear that there is extremely rich diversity in volcanic hazard maps and hazard mapping approaches around the world. Our workshops also revealed a wide range in the use and effectiveness of volcanic hazard maps. These observations prompted us to survey map makers who have produced official, operational (or previously operational) published volcanic hazard maps, in order to improve our understanding of the nature and diversity of volcanic hazard mapping practices, as well as the respective philosophies upon which they are based. Here we define official operational maps as those maps produced by (and considered current by) the responsible government agency.

This survey was carried out in parallel to the working group's development of a Volcanic Hazard Maps Database (VHMD) (Ogburn et al. 2023; https://volcanichazardmaps.org), a new database which independently catalogues 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 the map elements. Our survey was designed to capture detailed information about the characterisation of map design and the drivers and principles guiding map development from map makers and contributors, or those closely familiar with the maps. Although the maps summarised here represent a small subset (~5%) of the 1823 volcanic hazard maps currently presented in the database, the detailed results can be used to complement, validate, and assure the quality of the higher-level information collected in the VHMD, particularly regarding implicit or qualitative aspects such as map purpose and audience. Our intention here is thus to provide a snapshot of the wide variety of volcanic hazard maps, build on past volcanic hazard map typologies (e.g., Calder et al. 2015), and extract common approaches and key lessons for good practice in the development and design of maps.

Methods

We developed an online survey that was used to gather information about the development of official volcanic hazard maps. The survey was also available in hard copy paper format and as an interactive digital form. The questions in the survey were developed based on two international workshops of the IAVCEI Working Group on Hazard Mapping. The discussions and outcomes of the first State of the Hazard Map workshop in 2014 in Yogyakarta, Indonesia, resulted in the initial framing of the questions. The survey was then drafted and subsequently piloted with participants of the workshop on Volcanic Hazard Assessments in 2016 in Garut, Indonesia. Participants of the workshops comprised international volcanic hazard researchers and practitioners with experience and interest in volcanic hazard map development. The survey was then refined based on participants' feedback, finalised, and officially launched in mid-2017, following approval from the University of Auckland Human Participant Ethics Committee. The survey remained open for approximately 24 months, until October 2019.

The survey was available in two languages, English and Spanish, and consisted of 30 questions (Additional file 1: Full Survey, English and Spanish versions). Six questions captured general information about the map, including publication date, author(s), and publication format. Three questions captured information about the volcano itself, including how well its eruptive history was understood and how active it was at the time of map creation. Five questions focussed on map purpose and audience, including whether the map had been produced in response to a particular event (e.g., eruption crisis) and whether the map had been formally tested/evaluated after publication. Five questions captured hazard information on the map such as what hazards were depicted and how, what hazard assessment style and input data were used, and the names of the models used, if any. Ten questions captured cartographic and design information, such as map scale, the type of base map used, how hazard zones were depicted and labelled, how uncertainty was depicted on the map, and what accessory, non-hazard information was included on the map. A final, open question invited participants to reflect on the map and its development, and to include any experiences or lessons learned that might be useful for others embarking on a volcanic hazard map-making process.

A purposive sampling approach was used to recruit volunteer participants who were very familiar with official volcanic hazard maps, targeting individuals and agencies who had been involved in developing hazard maps. Invitations to participate were shared on the international Volcano Listserv (Volcano@LISTS.ASU.EDU) and relevant IAVCEI social media accounts, encouraging people who had been involved in generating official volcanic hazard maps to participate. We also distributed the survey to previous workshop participants. We acknowledge potential sampling bias, in that some volcanic hazard map makers may be underrepresented, for example, those not reachable via the channels mentioned above or those not able to fill in the survey in either of the two languages provided. Participants could complete the survey multiple times, one entry per individual map. Where answers were not mutually exclusive, participants were asked to 'tick all that apply.' Participation was voluntary and anonymous in order to encourage open and honest disclosure of opinions and views. Qualtrics® software was used to analyse and present quantitative data. We made the assumption that the participants accurately represented information about the maps in their answers. In order to maintain anonymity, the full raw data set cannot be shared; however, we can supply anonymised subsets of data upon request.

Results

General information

The online survey remained open for approximately 24 months, and entries on 89 volcanic hazard maps covering a total of 80 volcanoes in 28 countries were received (Fig. 1; Table 1). Thus, some maps were of the same volcano (for example, five different maps for Ruapehu were entered; Table 1). All the results reported below are based on respondents' responses in the survey (that is, we did not independently interrogate the maps). Seventy-nine percent (79%) of the maps were reported to be official, operational (or previously operational) volcanic hazard maps and 11% were not, with the remaining 10% unknown/unanswered. All maps were included in the analysis. There was only one discrete map for which two separate entries were received: one entry referring to the poster version of the map, and one referring to the smaller map figure in the accompanying hazard report. As these are two separate versions of the same map, and the participants' responses to the free text questions are different, we chose not to merge the answers in this case but rather treat these as separate entries in the analysis below. Thus, overall, we had 90 individual respondents covering 89 discrete maps.

Publication dates range from 1982 to 'in development,' with over half of the maps published since 2010. In 85%

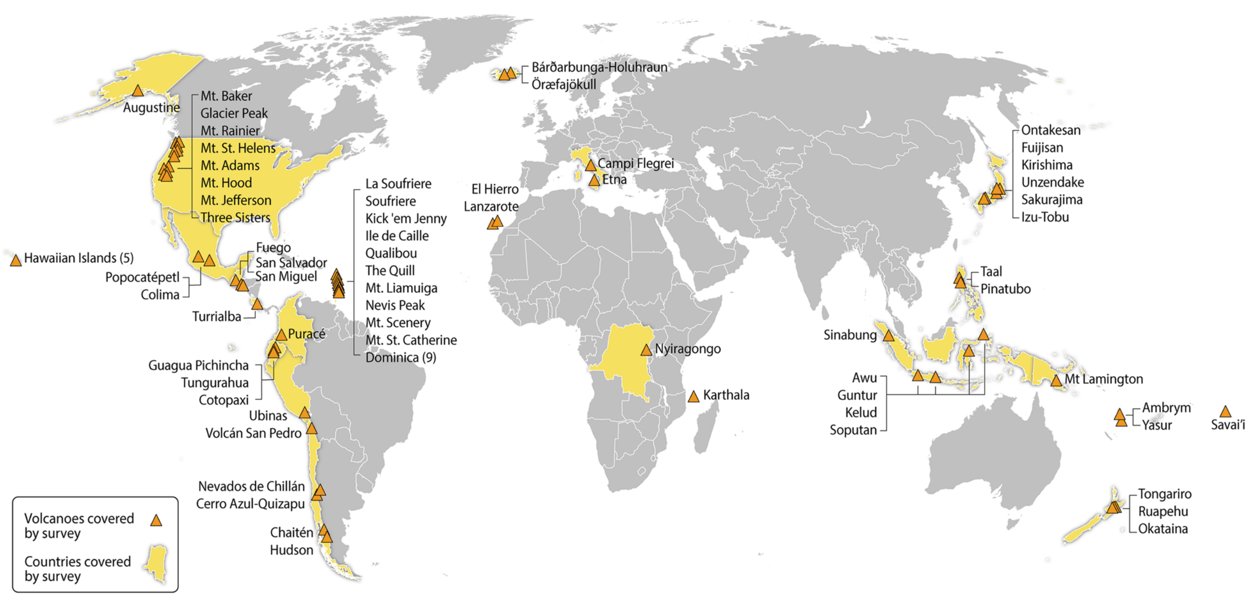


Fig. 1 World map showing location of the volcanoes and countries represented in our survey. Locations from Global Volcanism Program (2013)

Table 1 Volcanoes for which maps were entered in our survey. In most cases one entry was provided for each volcano; for cases where more than one unique map for a given volcano was entered, the number of maps is indicated in parentheses. The Volcano Hazard Maps Database ID is from https://volcanichazardmaps.org/. While not all maps entered in the survey can be found in the database (e.g., no online version available; map never officially published), some survey submissions encompass compilations of maps from the same publication and are therefore linked to more than one map in the database. Volcano name, type and last eruption date were obtained from the Global Volcanism Program (2013)

Volcano or volcanic system	Volcanic Hazard Maps Database ID	Country	Type	Last known eruption date
Adams	515	USA	Stratovolcano	950
Aira	1573	Japan	Caldera	2022
Ambrym (3)	1159, 1480	Vanuatu	Pyroclastic shield	2022
Augustine	566	USA	Lava dome(s)	2006
Awu	878	Indonesia	Stratovolcano	2004
Baker (2)	419, 1172	USA	Stratovolcano	1880
Bárðarbunga	1364, 1365, 1366, 1367	Iceland	Stratovolcano	2015
Campi Flegrei	1509	Italy	Caldera	1538
Cerro Azul	768	Chile	Stratovolcano	1967
Cerro Hudson	734	Chile	Stratovolcano	2011
Chaitén	729	Chile	Caldera	2011
Colima (3)	963	Mexico	Stratovolcano	2019
Cotopaxi (2)	843,1237, 842, 844	Ecuador	Stratovolcano	2016
Crater Lake	594	USA	Caldera	2850 BCE
Dominica (9 volcanic systems)	629	Dominica	Complex	Unknown
Etna (2)	945, 1223	Italy	Stratovolcano	2022
Fuego (4)	1554, 1555, 1556	Guatemala	Stratovolcano	2022
Fujisan	949	Japan	Stratovolcano	1708
Glacier Peak	430	USA	Stratovolcano	1700
Guagua Pichincha	3359	Ecuador	Stratovolcano	2002
Guntur	895	Indonesia	Complex	1847
Island of Hawaii (5 volcanic systems)	546	USA	Shield	2022
Hierro	3577, 3578, 3579, 3580	Spain (Canary Islands)	Shield	2012
Hood (2)	597, 1104	USA	Stratovolcano	1866
Ile de Caille	625	Grenada	Tuff ring	Unknown
Izu-Tobu	3160	Japan	Pyroclastic cone(s)	1989
Jefferson	433, 626	USA	Stratovolcano	950
Karthala	1516	Comoros	Shield	2007
Kelud	906	Indonesia	Stratovolcano	2014
Kick 'em Jenny	625	Grenada	Submarine	2017
Kirishimayama	3004	Japan	Shield	2018
Lamington		Papua New Guinea	Stratovolcano	1956
Lanzarote	3581, 3582, 3583, 3584	Spain (Canary Islands)	Fissure vent(s)	1824
Lassen Volcanic Center (2)	586	USA	Stratovolcano	1917
Liamuiga	444	Saint Kitts and Nevis	Stratovolcano	160
Medicine Lake	3576	USA	Shield	1060
Nevados de Chillán	753	Chile	Stratovolcano	2022
Nevis Peak	473	Saint Kitts and Nevis	Stratovolcano	Unknown
Nyiragongo & Nyamulagira		DR Congo	Stratovolcano	2022
Okataina		New Zealand	Lava dome (s)	1981
Ontakesan	1566	Japan	Complex	2014
Öræfajökull	1567, 1568, 1569, 1570, 1571, 1572	Iceland	Stratovolcano	1728
Pinatubo	1564	Philippines	Stratovolcano	1993

Table 1 (continued)

Volcano or volcanic system	Volcanic Hazard Maps Database ID	Country	Type	Last known eruption date
Popocatépetl (4)	968, 969, 970, 971, 972, 973, 974, 975	Mexico	Stratovolcano	2022
Puracé	819	Colombia	Stratovolcano	1977
Qualibou	657	St Lucia	Caldera	1766
Rainier	613	USA	Stratovolcano	1450
Ruapehu (5)	485, 512, 639, 3489	New Zealand	Stratovolcano	2007
Saba	640	Saba (Netherlands)	Stratovolcano	1640
San Miguel	855	El Salvador	Stratovolcano	2020
San Pedro-Pellado	771	Chile	Stratovolcano	1960
San Salvador	3348, 3349, 3350, 3351, 3352, 3353, 3354	El Salvador	Stratovolcano	1917
Savai'i	1465	Samoa	Shield	1911
Sinabung	931	Indonesia	Stratovolcano	2021
Soputan	3506	Indonesia	Stratovolcano	2020
Soufriere St. Vincent (2)	505, 653	St. Vincent	Stratovolcano	2021
St. Catherine	658	Grenada	Stratovolcano	Unknown
St. Helens (2)	499, 617, 618, 3499, 3500, 3501	USA	Stratovolcano	2008
Taal	1056	Philippines	Caldera	2021
The Quill	659	Sint Eustatius (Netherlands)	Stratovolcano	250
Three Sisters	601	USA	Complex	440
Tongariro (2)	507, 646	New Zealand	Stratovolcano	2012
Tungurahua	508	Ecuador	Stratovolcano	2016
Turrialba		Costa Rica	Stratovolcano	2022
Ubinas	1016	Peru	Stratovolcano	2019
Unzendake	3005	Japan	Complex	1996
Yasur	1163	Vanuatu	Stratovolcano	2022

of responses, the participants said they were personally involved in making the map. Those who said they were not involved in making the map specified that they were either close users of the map or had contributed to the data contained within the map. The majority of maps (64%; 57 maps) were created by a single type of organisation; of these, 39 maps were generated solely by government institution scientists, 15 maps by university-based scientists, one by a civil defence agency and one by a private consultancy. The remaining 36% (32 maps) were created by authors from more than one type of organisation: 14 maps by a combination of government and university-based scientists, nine by a combination of government scientists and civil authorities, four by a combination of government scientists, civil authorities, and a private company, and five by a combination of government scientists, university-based scientists and civil authorities, one of which also included input from a private consultancy and one from a non-governmental organisation. Overall, 22% of all maps were developed with involvement from civil authorities.

The maps in the survey represent a range of publication formats. Forty-six maps (52%) were published as large posters with an accompanying report, with a further 22 maps (25%) published as large posters without an accompanying book-style report. Around 17 maps (19%) were described as brochure style maps, some as large road signs. The remaining 4 maps (~4%) were published as KMZ or GIS files or as figures in a journal article or book. Most maps were also made available as pdfs/digital images (67%) and on websites (56%). Most maps (~80%) only included one language, with the remaining 20% including two or more languages on the same map. Several maps were available in two different languages.

Only 29 maps (33%) were described as a dynamic map, in the sense that it is underpinned by a geospatial database, designed to be easily modified and updated as new data come to light. Most maps described in this way are stored as GIS files by the authors or lead agency. Only 27% of maps state explicitly when the map should be revised, almost half of which state they should be revised in the case of an eruption. Version numbers are included on only 13% of maps, in some cases as a version number, and in some cases as a year of publication.

Volcano-specific information

Data related to 89 discrete maps were collected in our study, some of which were for the same volcano (for example, five different maps for Ruapehu were entered; Table 1). There were also two maps that covered more than one volcano: the integrated volcanic hazard zonation map for Dominica, and the volcanic hazard map for Hawaii. If we treat the Dominica and Hawaii maps as each covering a single volcanic complex, we can say that our survey captured maps for 68 individual volcanoes. According to the Global Volcanism Program (2013) classifications, these volcanoes can be classified as stratovolcanoes (44), calderas (6), shield volcanoes (6), volcanic complexes (5), lava domes (2), and one each of: tuff ring, submarine volcano, fissure vent, pyroclastic shield, and pyroclastic cone (Table 1). According to survey responses, about a third (33%) of these volcanoes and volcanic systems were moderately well understood at the time of hazard map development, with 30% well understood and 25% very well understood. Just 7% of maps covered volcanoes that were poorly understood at the time of map production, and respondents were not sure about 6% of the maps. In terms of how active the volcano was at the time of map development, the largest proportion of the 89 maps in the survey covered volcanoes at which volcanic activity/unrest was recent or ongoing during hazard map development (27%), followed by frequently active (typically erupts every few years to decades) (25%). Just 3% of the maps were for very frequently active volcanoes (i.e., at least one eruption per year) (Fig. 2).

Map purpose and audience

Most maps in the survey (78%) were classed by respondents as long-term/background maps, i.e., covering a time frame of the next 1- 10,000 years. The remainder (22%) were classified as short term/crisis maps (i.e., covering a timeframe of days, weeks). The time frame is explicitly stated on 65% of maps. Over a quarter of the maps (28%) were noted as being tied to a volcanic alert level or early warning system. This includes the maps from Mt. Ruapehu, New Zealand, which refer to the Eruption Detection System (EDS) on the map in a section called "Warning System," explaining what it is and what to do if sirens are heard (Fig. 3). This also includes several maps that have hazard zones or restricted access zones or evacuation zones that are explicitly linked to alert levels (see Fig. 4 for an example from Japan).

Survey results revealed a wide variety of intended map purposes and audiences. Most maps (83%) had more than one intended purpose, with 24% of maps serving all four purposes and audiences provided as options in the survey (Table 2). The most common map purpose (87% of maps) was reported as crisis management, followed by hazard awareness (72% of maps), land use planning (56% of maps), and impact and/or risk assessment (30% of maps). Most maps (59%) did not explicitly state the audience or purpose of the map on the map face; however, for 70% of these maps, respondents stated that the audience was considered during development. For the 41% of maps that did include audience information, this was usually

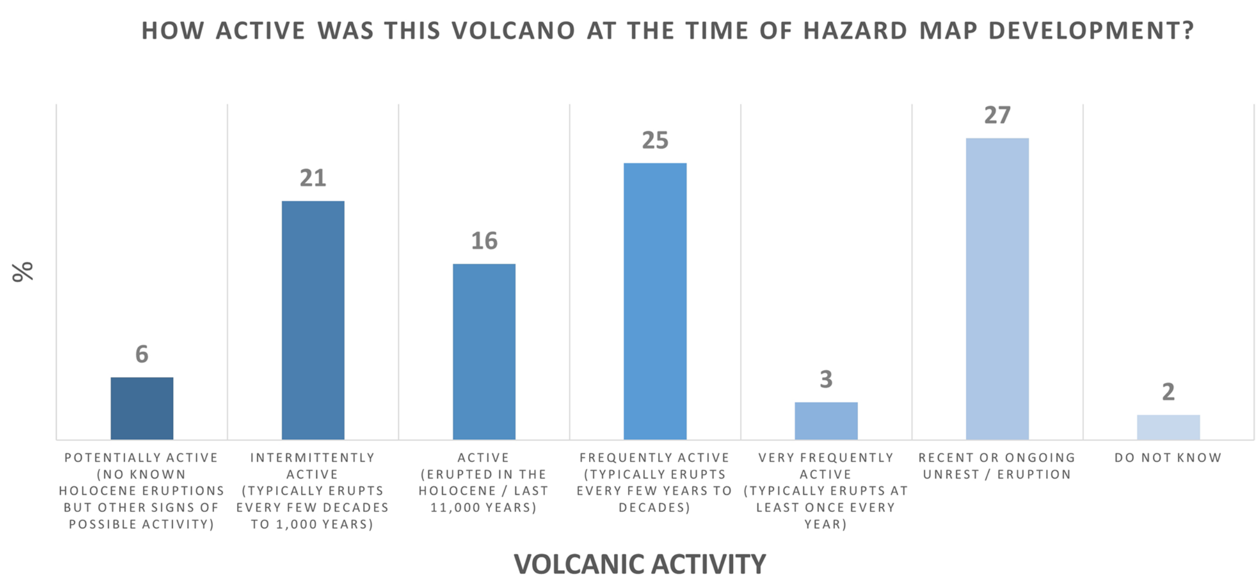


Fig. 2 Proportion of responses to the question: "How active was the volcano at the time of map development?"

Fig. 3 One of the five maps of Mt Ruapehu, New Zealand, entered in the survey, illustrating how information about a warning system can be shown on a volcanic hazard map (GNS Science, compiler 2008). This map is also an example of how fuzzy boundaries can be used to show uncertainty. This is an example of a "poster style" map. A high-resolution version of this map can be accessed via the Volcanic Hazard Maps Database: VHMD ID 485. Map reproduced with permission from GNS Science

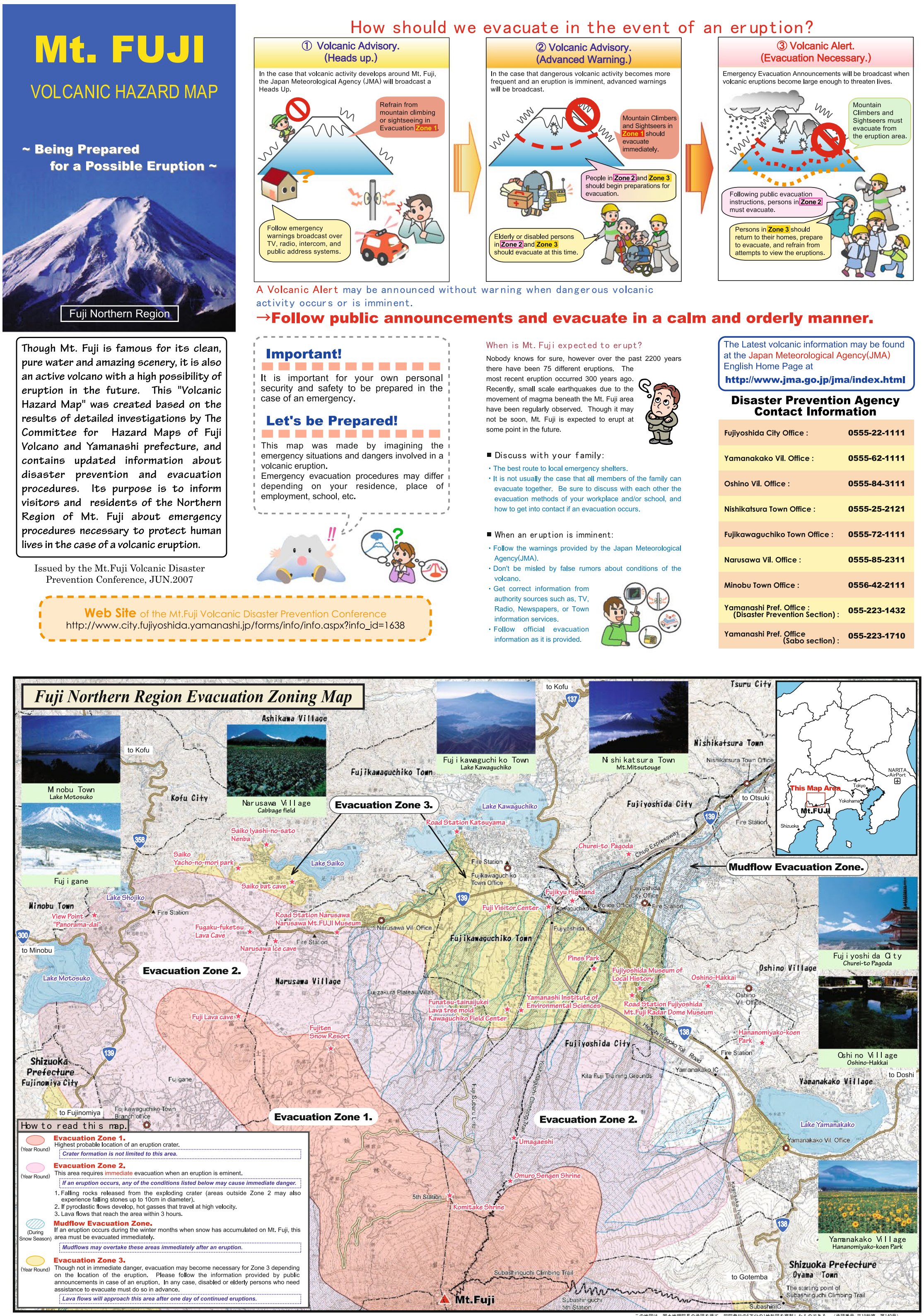


Fig. 4 Volcanic hazards map for Mt Fuji, Japan, illustrating how alert levels (shown in the three boxes at the top) are linked to evacuation zones on the map (Mt. Fuji Volcanic Disaster Prevention Conference 2007). This is an example of a "pamphlet style" map (one that is folded). A high-resolution version of this map can be accessed via the Volcanic Hazard Maps Database: VHMD ID 949. Map reproduced with permission from the Mt. Fuji Disaster Prevention Council

Table 2 Intended map purpose and audience for surveyed maps. Note: numbers and percentages of maps reflect the fact that most maps had more than one stated purpose (in other words, 'tick all that apply' was used for this question)

Map purpose and audience	# of maps	% of maps
Crisis management *(audience primarily emergency managers, civil authorities, aviation authorities)*	77	87%
Hazard awareness *(wide audience, including the public)*	64	72%
Land use planning (e.g., siting a building, network) *(audience primarily land-use planners, authorities)*	50	56%
Impact and/or risk assessment *(audience typically a specific stakeholder)*	27	30%

included in text form, either in the legend on the map or in supporting material.

Most maps were developed in response to a particular event (69%). Of those maps, 64% were created in response to volcanic unrest or an eruption, 21% in response to a stakeholder request, and 14% in response to government legislation. Almost half (45%) of the maps were tested to some degree, with most of the tested maps (70%) being classified as long term (background) maps compared to 30% of tested maps classed as short term (crisis) maps. Given that 78% of maps in the survey are long-term/background maps and 22% short term/crisis maps, this means that a higher proportion (63%) of the short-term/crisis maps was evaluated compared with the proportion of long term/background maps (39%).

About half of the maps that were tested were done so by map content evaluation following an actual eruption, a process in which the actual phenomena that occurred were compared with what was presented on the map. Whilst most respondents did not indicate the outcome of the comparison, a few indicated a good correlation:

> *"Post-eruption map of [pyroclastic density current] PDC extent matches the pre-eruption hazard map pretty well. But we were lucky, since we learned later that what we thought was a worst-case wasn't actually so. The eruption could have been worse and exceeded our PDC hazard zone."*

> *"Since [this volcano] frequently erupts, we overlapped the recent lava flow fields on the maps and [found] they [were] emplaced on [zones with] the highest hazard levels."*

Most of the remaining tested maps were tested during eruption simulation exercises and stakeholder feedback discussions, with the evaluation yielding some insights into how the map could be improved:

> *"[Stakeholders] used [this map] for deciding on when to enter or leave areas near the volcano. No formal, written evaluation, just anecdotes that told us (a) [the map] satisfied their need to know HOW high the risk was, and [that] (b) [the map] would have been too complicated for most to understand, were it not for inclusion of the table of comparable risks. The latter made it easy to understand."*

> *"Red Cross conducted extensive evaluation of the version of the map [in the local language], adding local points of interest/reference and local dialect translations. They did NOT want symbols or photos as all processes have been experienced historically."*

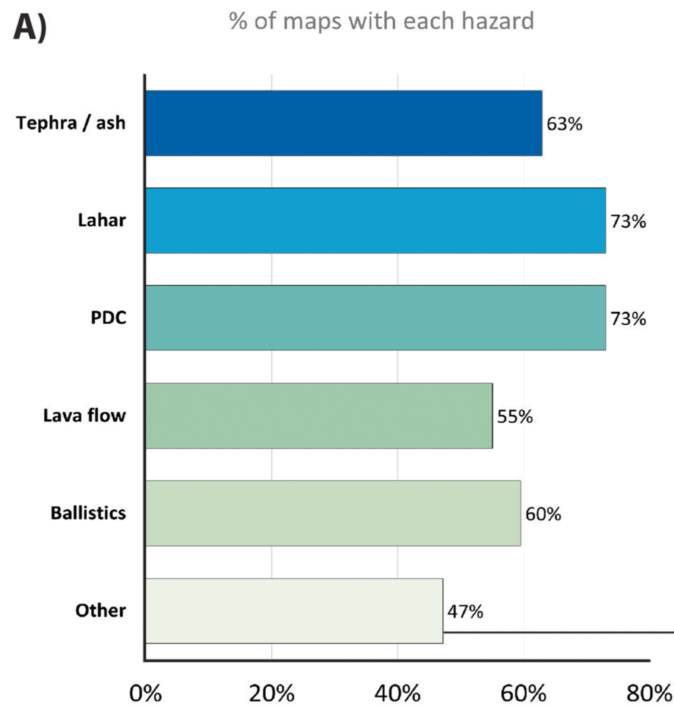
Several maps were tested through a survey of the public in the map area, to investigate awareness of the product and retention of the messaging and content on map. In at least one case this test led to key changes on the map:

> *"Prototypes were tested in a social science study, which is why plan view basemap was used instead of oblique (trekkers and hikers were familiar with basemaps)."*

Hazard information

Hazard maps can be classified according to whether they are hazard-level focused, with different hazard processes integrated into combined hazard level zones, or whether they are hazard-process focused, and thus separated into hazardous phenomena-specific zones or groups (Ogburn et al. 2023). On the maps surveyed here, hazard is most commonly represented through integrated or hazard-level focused zones, for example multiple hazardous phenomena combined into high, medium, and low hazard zones (on 43% of maps), with a lesser proportion of maps showing discrete hazard zones for different phenomena, i.e., zones for individual hazardous processes that may or may not overlap (35% of maps). A mixture of both approaches is present on 22% of maps.

The number of hazard process zones or hazard-level (integrated) zones depicted varies from just one zone (13% of maps) to more than 6 zones (21% of maps). Most maps provide information on four to six hazardous phenomena, with four being the most common number of single hazardous phenomena to appear on the maps (22%). The maximum number of single hazardous phenomena depicted on a map was 7 (three maps). Maps



B)

Other hazards on maps	
Hazard	**Count**
Debris avalanche/edifice collapse	15
Gas	11
Secondary lahar	4
Vent opening	3
Lava Dome building/collapse	3
Debris flow	3
Flooding	2
Thermal anomalies/hydrothermal	2
Water disturbances	2
Directed blast	2
Sedimentation	1
Tsunami	1
Pumice raft	1

Fig. 5 **A** Percentage of maps showing each of the main hazards depicted, and **B** Other hazards depicted on the maps, and number of maps displaying that particular hazard. PDC refers to Pyroclastic Density Current

with information on just one to two hazards typically show flow hazards (lava flow, lahar, PDC).

Regardless of depiction style (hazard-level or hazard-process focussed), pyroclastic density currents (PDCs) and lahars were the most frequently reported hazard processes depicted, with each appearing on 73% of all maps surveyed (Fig. 5a). Other main hazard processes depicted on maps were tephra, ballistics, and lava flows, depicted on 63%, 60% and 55% of all maps surveyed, respectively (Fig. 5a). Almost half (47%) of the maps also showed other processes, including volcanic gases, debris avalanches, tsunami, and vent opening (Fig. 5b). An example of a map that shows several of these other phenomena in addition to the primary hazards is the volcanic hazards map for Augustine Volcano, Alaska (Fig. 6).

Respondents were asked what input data were used for the hazard assessment behind the map, and this was broken down by hazard. The results were fairly consistent across all hazards, with geological information on past activity at the volcano (or at an analogue volcano) being the most common type of input data for assessing hazard. Lahar and tephra hazard assessments tended to include more model inputs, and lava flow hazard assessments tended to include more past geology. Respondents were also asked to identify the modelling tools that they had used to generate input data for their hazard maps. Twenty-five different models were identified (Table 3). The most commonly used models (i.e., more than 4 mentions) were LAHARZ (Iverson et al. 1998; Schilling 1998, 2014) for lahars; the Energy Cone model (Sheridan 1979; Sheridan and Malin 1983) and Titan2D (Pitman et al. 2003; Patra et al. 2005) for PDCs; Tephra2 (Bonadonna et al. 2005, 2010; Connor et al. 2011) and Ash3D (Schwaiger et al. 2012; Mastin et al. 2013) for tephra, and Ballistics (Bertin 2017) and Eject! (Mastin 2001) for ballistic projectiles.

We also tried to get a sense of which hazard assessment "style" was used to develop the zones shown on the map. For example, was a scenario shown? Or was probabilistic hazard shown? Or was the hazard map based solely on cumulative geology or cumulative phenomena, with no defined scenario (e.g., based on the footprint of past hazardous phenomena)? This hazard assessment "style" was also broken down by hazard (Fig. 7). The results indicate that the hazard areas shown on most maps surveyed are based on scenarios (single or multiple), rather than a probabilistic hazard assessment, although probabilistic methods are common when tephra hazard was assessed and included on the map (Fig. 7). Cumulative geology was also commonly employed as a hazard assessment style, especially for lava flow hazard (Fig. 7). Where probabilistic hazard was depicted on a map (in 35 instances), respondents were asked to specify the time frame for

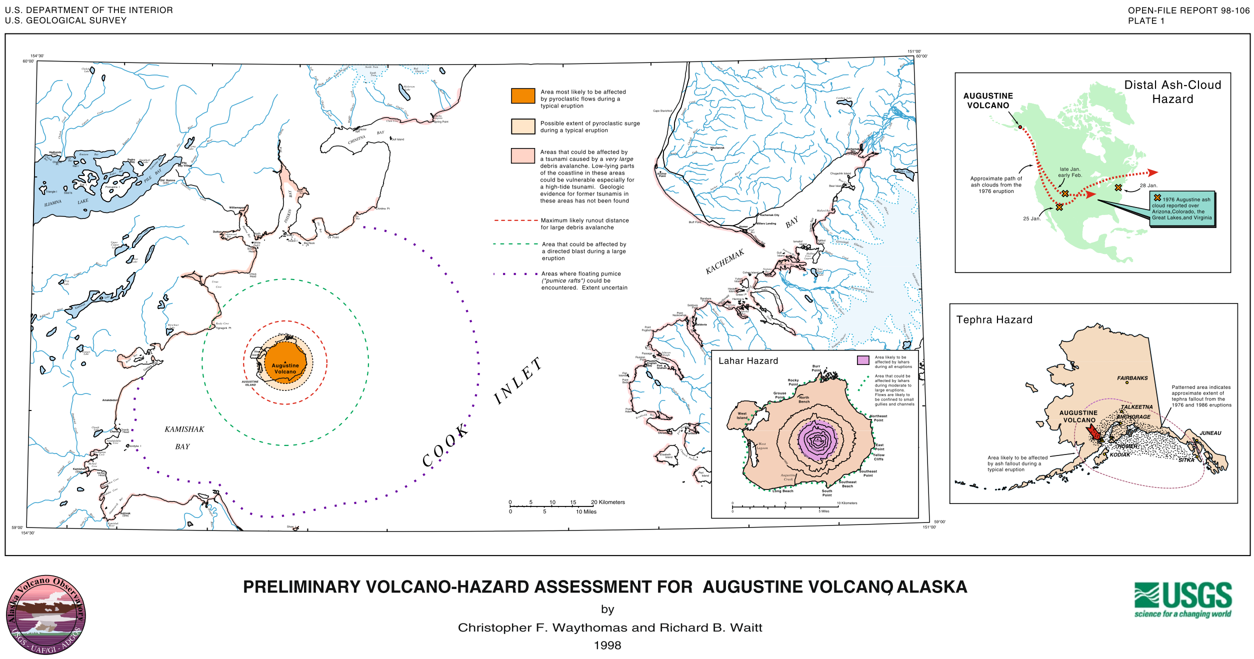


Fig. 6 Volcanic hazards map for Augustine Volcano, Alaska (Waythomas and Waitt 1998), illustrating areas that could be affected by hazards such as tsunami (salmon areas around the coastline), pumice rafts (purple dotted line), directed blasts (green dashed line), and debris avalanches (red dashed line) in addition to the hazards expected during a typical eruption such as pyroclastic flows and surges (orange zones), lahars, and tephra (insets). Overall, seven hazards are depicted on this map, including insets (eight, if pyroclastic surges and flows are counted separately). This is also an example of a map produced as a "large poster with an accompanying report." A high-resolution version of this map can be accessed via the Volcanic Hazard Maps Database: VHMD ID 566. Map reproduced with permission from the U.S. Geological Survey

Table 3 Table summarising the named hazard process models used, and for which hazard, as listed by survey respondents, and the number of maps for which a particular model was used (only models with counts > 2 from all the surveys were listed)

Model	Hazard	Count	Reference
LAHARZ	Lahar	20	Iverson et al. (1998); Schilling (1998; 2014)
Tephra2	Tephra	9	Bonadonna et al. (2005; 2010); Connor et al. (2011)
TITAN2D	Lahar, PDC	9	Pitman et al. (2003); Patra et al. (2005)
Energy Cone	PDC	5	Heim (1932); Sheridan (1979); Sheridan and Malin (1983)
ASH3D	Tephra	4	Schwaiger et al. (2012); Mastin et al. (2013)
Eject!	Ballistics	4	Mastin (2001)
Ballistics	Ballistics	4	Bertin (2017)
VolcFlow	PDC	3	Kelfoun and Druitt (2005)
CALPUFF	Tephra	2	Scire et al. (2000)
FALL3D	Tephra	2	Costa et al. (2006); Folch et al. (2009)
MAGFLOW	Lava	2	Vicari et al. (2007); Del Negro et al. (2008)
Q-LavHA	Lava	2	Mossoux et al. (2016)
VORIS suite	Lava	2	Felpeto et al. (2007); Felpeto (2009)

which the probabilities were determined. The most common time frame selected was 'Conditional on eruption' (37%), meaning the map depicted phenomena likely to occur in the event of an eruption of some specified style or magnitude. This was followed by the time frames: 'Annual' (23%), '10–100 years' (9%) and '1,000 s to 10 s of thousands of years' (9%). Very few maps depicted probabilities on time frames of '100 s to 1000 s years' (6%), 'Hours to days' (3%), '1–10 years' (3%), and 'until the next eruption' (3%).

	Style ranking for each hazard (with % of maps that use that style in brackets)				
Assessment style	Tephra	Lahar	PDC	Lava flows	Ballistics
Single scenario - a certain event or scenario, based on geology and/or conceptual model	1 (31%)	2 (31%)	1 (28%)	3 (19%)	1 (35%)
Multi-scenario (multiple scenarios with no probabilities)	3 (18%)	1 (37%)	3 (26%)	2 (23%)	3 (18%)
Cumulative geology or cumulative phenomena, no defined scenario	4 (16%)	3 (15%)	1 (28%)	1 (32%)	2 (23%)
Probabilistic with quantitative expression of probability (e.g., 25%)	2 (20%)	6 (1%)	5 (4%)	5 (8%)	6 (4%)
Probabilistic with qualitative expression of probability (e.g., likely)	5 (9%)	4 (12%)	4 (9%)	4 (12%)	4 (9%)
Other	6 (6%)	5 (2%)	5 (4%)	6 (5%)	5 (9%)

Fig. 7 Hazard assessment styles / methods used for individual hazards depicted on maps. For example, 20% of all the maps that depict tephra used a probabilistic approach with quantitative expression of probability, and 16% used cumulative geology with no specifically defined scenario. Colours represent the relative occurrence of each assessment style used for depiction of a given hazard, with a ranking of 1 (red) being most common, and a ranking of 6 (pale yellow) least common

Cartographic and design information

Scale and base map

Several aspects of map cartography were collected in our survey, including the spatial scale of the map and the type of base map used. Medium scale maps (volcano ± surrounding region) were most common (71%), followed by small scale maps (global / regional / national / subnational) and large-scale maps (part of a volcano), 17% and 12% of maps, respectively. Digital Elevation Models (or similar, e.g., shaded relief or hillshade) were the most common type of base map used (63%). Base maps showing contours and topographic detail are used in 34% of maps. Other base map types include basic street maps (10%) and aerial photographs, satellite images, and perspective digital terrain models (7%). Some maps showed a combination of base map types.

Presentation of hazard data

Hazard level and hazard process zones are presented on the maps either through the use of colours or patterns. Maps displaying integrated zones show hazards combined by hazard level (e.g., into high, medium, and low hazard zones) or by location (e.g., distal, proximal, regional, summit zones) or by process (e.g., flow hazards); see Fig. 8 for an example of the first two. For these integrated zones, the most common method of depiction is a red to orange to yellow colour scheme, with red representing the highest hazard. Most zone meanings are explained in the legend (74%) rather than directly annotated on the body of the map.

Where discrete hazard zones for different hazardous phenomena were depicted on maps, these were primarily shown using multi-colour or single-colour multi-tone schemes (39% of all single hazard depictions), with the red–orange-yellow colour scheme again the most common.

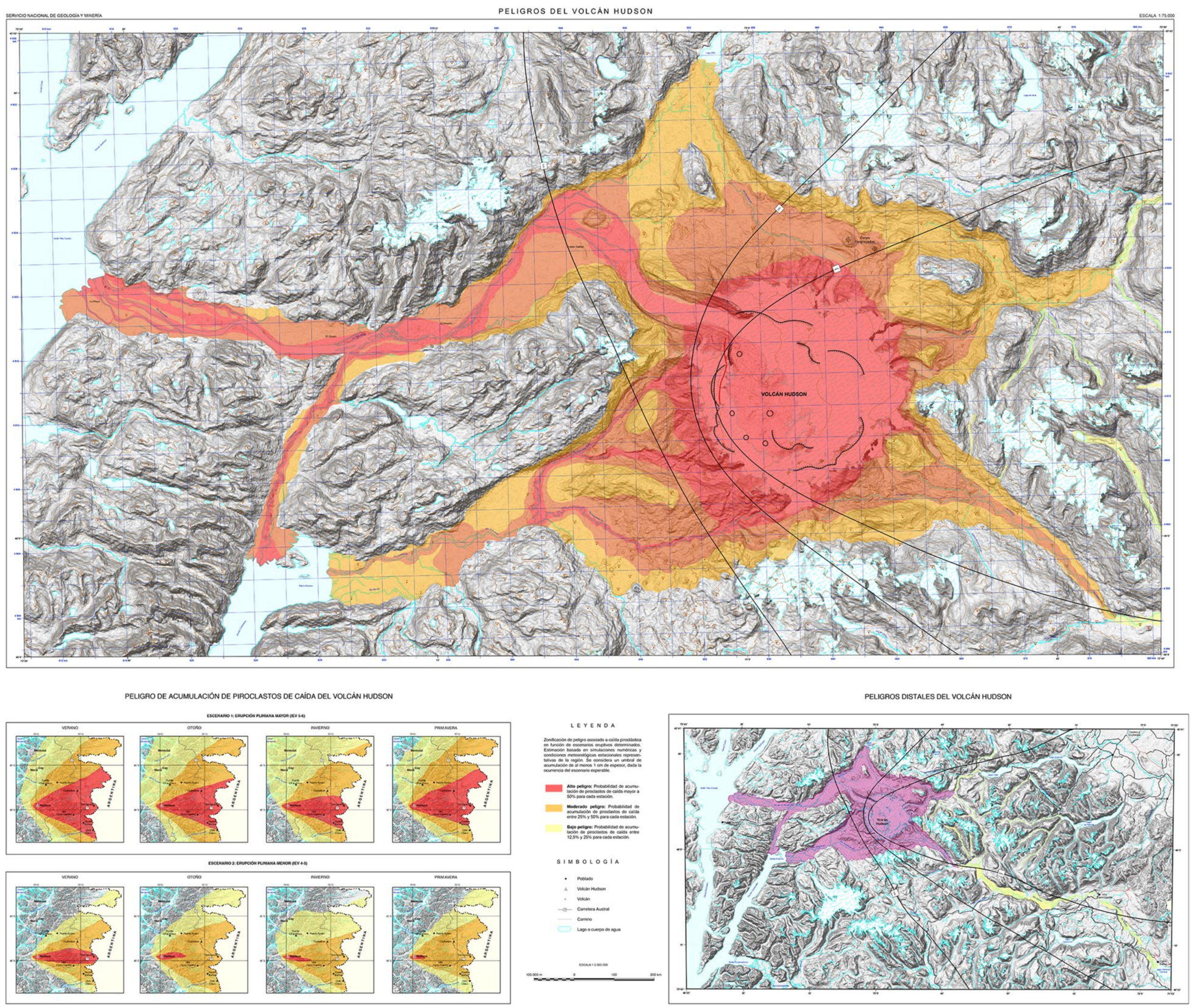


Fig. 8 Volcanic hazards map for Hudson, Chile, illustrating hazards integrated by hazard level using a red–orange-yellow colour scheme in the main map, i.e., very high (red), high (orange), medium (yellow) and low (light yellow) hazard zones (Amigo and Bertin 2014). The lower right panel shows the same volcano with hazards integrated by location, i.e., purple (proximal, corresponding to all the hazard zones on the main map) and light yellow (distal, corresponding to the extension of the main lahar paths beyond the volcano). The lower left panels show tephra hazard for two different scenarios, across four seasons, also using a red–orange-yellow colour scheme. This hazard map is thus also an example of a map that includes additional maps to highlight different aspects of hazard at different scales. It was produced as a "large poster with an accompanying report". A high-resolution version of this map can be accessed via the Volcanic Hazard Maps Database: VHMD ID 734. Map reproduced with permission from SERNAGEOMIN, Chile

Single-colour multi-tone schemes were restricted to depicting varying levels of ash fall and PDC hazard (e.g., Fig. 9F). Discrete hazards were also shown as a single colour (28% of all single hazard depictions) or a pattern (33% of all single hazard depictions), where patterns could be a line (solid or dashed), a patterned area, or symbology (e.g., a text note on the map, arrows, letters, or symbols).

We looked at several individual hazards to determine whether there were any trends. For example, 15 of the maps in the survey depicted PDCs as discrete hazardous processes. These were depicted in the following ways (illustrated schematically in Fig. 9a-f, respectively): As a dashed outline ($n=1$), a striped area ($n=1$), as a coloured solid line ($n=1$), using a red to yellow colour scheme indicating relative probability of specific scenarios ($n=1$), using two colours within the red to yellow colour scheme to indicate different hazard levels ($n=6$), and as a single colour, in some instances using dark and light tones to differentiate pyroclastic flow and pyroclastic surge and/or a buffer zone ($n=5$).

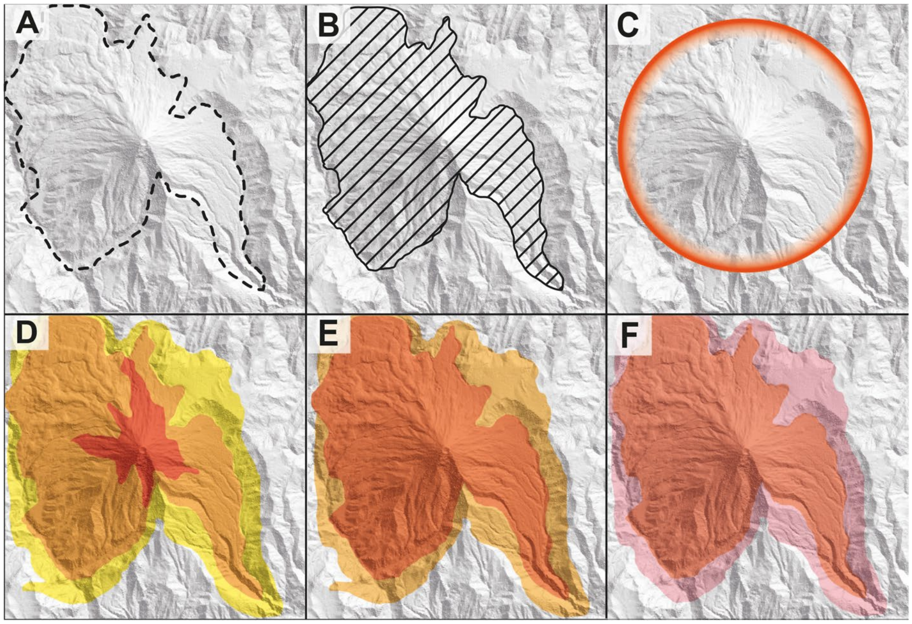


Fig. 9 Schematic illustration of the ways in which PDC hazard is depicted in the maps in the survey (based on all single hazard PDC depictions $n=15$). **A** Dashed outline of maximum PDC extent ($n=1$), **B** Striped area ($n=1$), **C** Coloured solid line ($n=1$), **D** Red to Yellow colour scheme indicating relative probability of specific scenarios ($n=1$), **E** Two colours within the red to yellow colour scheme, e.g., red to orange (shown), or orange to yellow, indicating different hazard levels ($n=6$), **F** Single colour, in some instances using dark to light tones to differentiate pyroclastic flow and pyroclastic surge and/or a buffer zone (shown) ($n=5$)

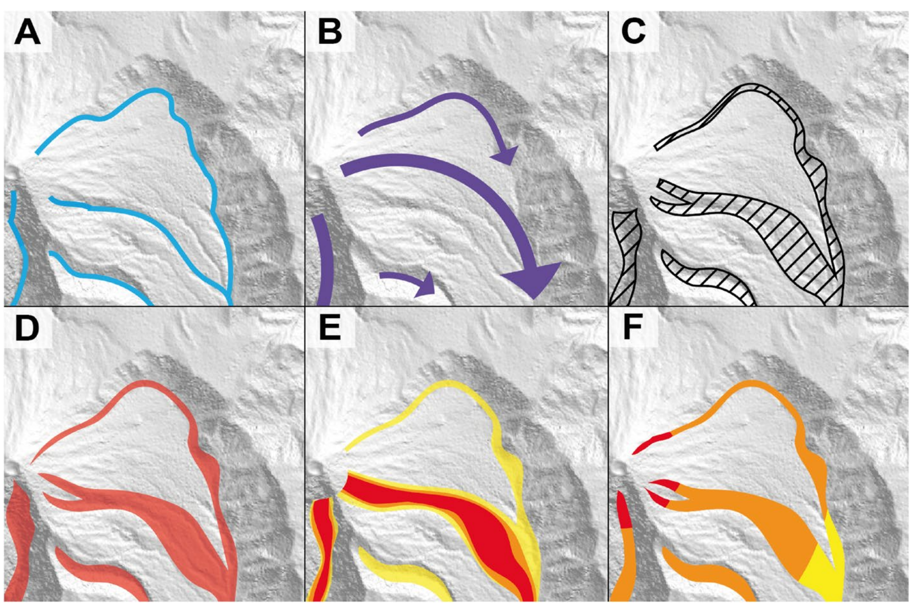


Fig. 10 Schematic illustration of the ways in which lahar hazard is depicted in the maps in the survey (based on all single hazard lahar depictions n = 32). **A** Blue solid line ($n=1$), **B** Purple arrows ($n=1$), **C** patterned area ($n=4$), **D** Single coloured area, most commonly red or grey ($n=17$), **E** Red to yellow colour scheme based on hazard level ($n=8$), **F** Colour scheme reflecting different levels of lahar inundation probability ($n=1$)

In another example, 32 of the maps in the survey depicted lahars as a discrete hazardous process. Lahars were depicted in the following ways (illustrated schematically in Fig. 10a-f, respectively): as a blue solid line ($n=1$), as purple arrows ($n=1$), as a patterned area ($n=4$), as a single-coloured area, most commonly red or grey ($n=17$), using red to yellow colour scheme based on hazard level ($n=8$), and colour scheme reflecting

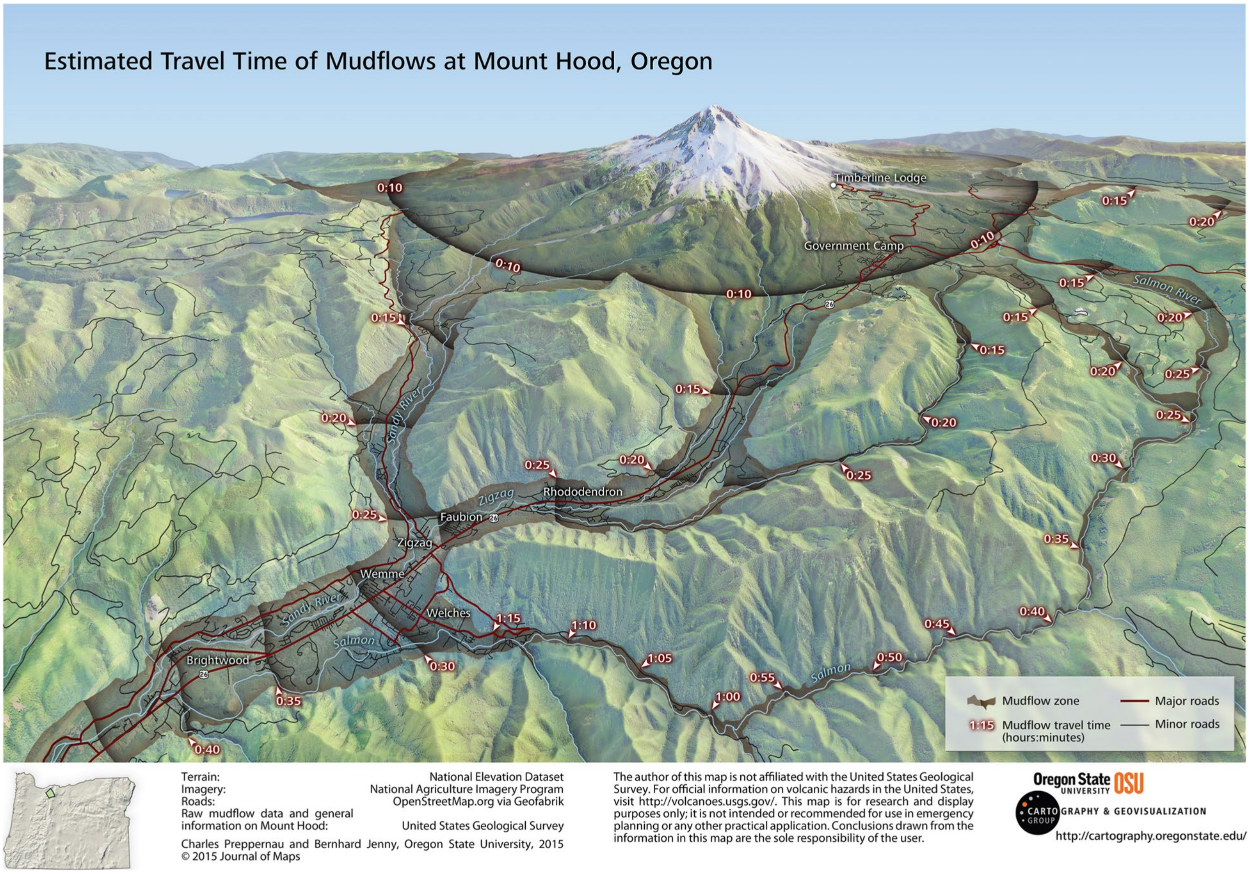


Fig. 11 Volcanic hazards map for Mount Hood, U.S.A, illustrating lahar hazard using a single transparent colour and lahar travel times (red contoured numbers) (Preppernau and Jenny 2016). This is also an example of a map with a 3D perspective view digital terrain model as base map. This map was not produced with anyone affiliated with the U.S Geological Survey (and is therefore one of the few examples entered in the survey that is not an official or operational volcanic hazard map). A high-resolution version of this map can be accessed via the Volcanic Hazard Maps Database: VHMD ID 1104. Map reproduced with permission from Charles Preppernau

different levels of lahar inundation probability ($n=1$). In at least one case, lahar travel times were also shown on the map (see Fig. 11). We also looked at tephra (illustrated schematically in Fig. 12). Twenty five of the maps in the survey depicted tephra fall as a discrete hazardous phenomenon, most often represented by: Black solid lines alongside a quantitative indicator (e.g., thickness, probability of exceedance) ($n=5$), solid and dashed lines ($n=8$), a patterned area ($n=1$), a single coloured area ($n=3$), as well as a multi colour ($n=3$) or a dark to light single colour ($n=3$) scheme to reflect hazard level. Additionally, two maps mentioned in extra text boxes that the entire map area may be exposed to ash fall.

Presentation of uncertainty

For 60% of the maps entered in the survey, respondents said that uncertainty was depicted or mentioned in some way. For those maps that depict uncertainty, respondents were asked to describe how uncertainty was expressed. By far the most common method for expressing uncertainty was through the use of written text on the map face. About half of the maps that depicted uncertainty did so in this way; some examples of how respondents described this are given in Table 4. In about 30% of instances uncertainty was described to be depicted in some way in the hazard zones themselves, through for example gradational, fuzzy, or dashed boundaries (Table 4; see Fig. 3 for an example). Uncertainty is also described in the accompanying text. According to respondents, in almost all cases where uncertainty was expressed on the map, either through text or design features, it was done in a qualitative fashion (Table 4).

Additional information

Respondents were asked to briefly list any non-hazard information that was present on the map (e.g., life safety, infrastructure, or landmarks), as well as any hazard

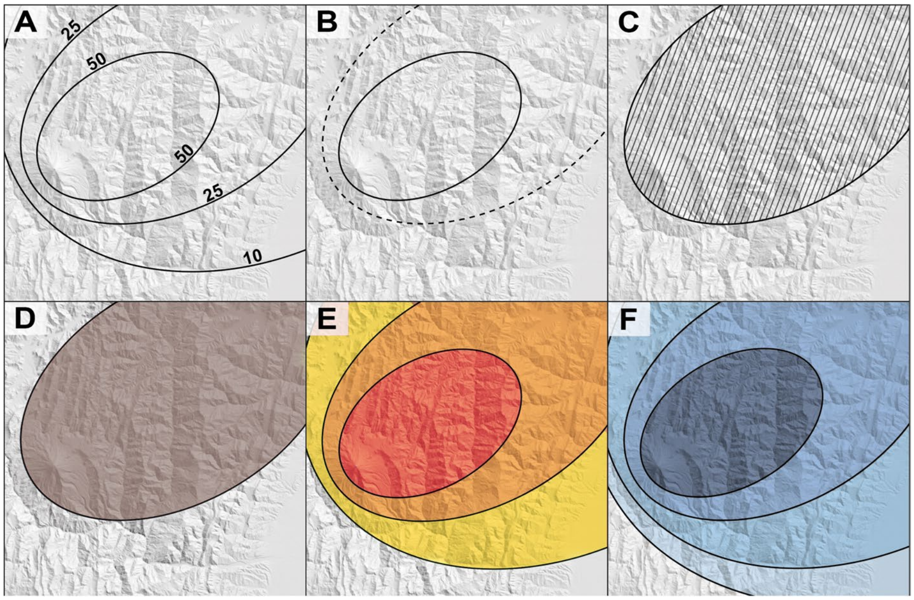


Fig. 12 Schematic illustration of the ways in which tephra hazard is depicted in the maps in the survey (based on all single hazard tephra depictions *n* = 25). **A** Black solid lines with quantitative indicator (*n* = 5), **B** Solid and dashed lines (*n* = 8), **C** Patterned area (*n* = 1), **D** Single coloured area (*n* = 3), **E** Multi-colour scheme based on hazard level (*n* = 3), **F** Dark to light single colour scheme based on hazard level (*n* = 3). Two maps communicated that the entire area displayed on the map may be exposed to ash fall via text boxes (not depicted)

Table 4 Table summarising how respondents described the ways in which uncertainty is expressed on the map, with some bulleted examples

How uncertainty is expressed
As text on the map, in the legend, or header, or on the map face (~ 50% of instances)
• Text stating the limitations of boundaries
• Text stating that zone boundaries do not represent sharp changes
• Text stating that hazard zone boundaries are approximate
• Text stating that hazards may extend offshore
• Text stating that hazards may occur anywhere in the area
• Disclaimer text: hazard may change without notice
• Text stating that tephra zones will depend on vent location
• Conditional validity statement stating that the hazard map applies only when certain criteria are met
• Text indicating possible lahar overflow areas
As zone design features (~ 30% of instances)
• Dashed zone boundaries
• Three lahar hazard zones
• Dashed line for pyroclastic flow zone, which is less certain than lava line which is solid
• Gradational zoning (e.g., from red to yellow, or dark to light orange)
• Fuzzy, fading transparency zone boundaries
• Buffer zones for PDC inundation
As text in accompanying document (~ 20% of instances)
For example, modelling limitations and hazard assessment assumptions presented in:
• Accompanying pamphlet
• Accompanying report
• Informative poster
• Accompanying scientific paper

information that is presented in addition to the main hazard map (e.g., any inset maps). Most respondents noted that their maps contain a range of such additional information to support the main hazard information presented in the maps. A summary of this additional information based on survey responses is presented in Table 5,

Table 5 Additional non-hazard and hazard information present on maps, with an indication of frequency based on mentions made by participants (note: because participants may not have listed all additional elements present, these should be considered minimum percentages)

Category	Detailed element	Frequency (% of maps)
Cartographic elements and landmarks	Water bodies and rivers, including dams and irrigation diversions	29%
	Geographical features, e.g., coastlines, monuments	12%
	Administrative boundaries	12%
	Scale	11%
	Contour lines	8%
	Inset map of wider region	7%
	North arrow	6%
	Legend	4%
Exposure information	Roads (and car parks)	62%
	Population centres (cities, towns, and villages)	52%
	Key buildings (e.g., health facilities)	18%
	Infrastructure (e.g., lifeline systems such as mobile network coverage)	15%
	Other transportation (airports, ports, bus stops, ski lifts, anchorages)	11%
	Railways and stations	6%
	Hiking trails and hiking huts	2%
Life safety information	What to do information (in the event of an eruption; mountain safety)	12%
	Evacuation information (e.g., routes/welfare centres/safe areas/shelters)	9%
Extra hazard information	Wind rose	11%
	Glossary of terms; explanation of hazards and eruptions styles	10%
	Location of observatory and monitoring network; warning systems	9%
	Where to go for more information (e.g., websites/QR codes/phone numbers)	4%
	Description of alert levels or warning systems	3%
	Information about simulations/modelling	2%
	Photographs of volcano(es); aerial photographs of surrounding area	2%

where this additional information has been grouped into four main categories: Cartographic elements and landmarks, exposure information, life safety information, and extra hazard information.

Experiences and lessons learned

Respondents were provided with the opportunity to share their insights based on their hazard mapping experience. Experiences and lessons shared by respondents span a range of topics, from visual design elements to unexpected or unanticipated uses of hazard maps. A qualitative thematic analysis of the responses in this section revealed five main themes (n = the number of times comments aligned with these themes): Map design considerations ($n=42$); the process of map development ($n=22$); map audience and map user needs ($n=20$); hazard assessment approach ($n=14$); map availability and accessibility ($n=9$); and external (e.g., political) influences ($n=3$). These themes are expanded on below. Unless clearly presented as quotations, original responses have been modified or paraphrased for brevity (summarised and in some cases translated into English).

Map design considerations

By far the largest proportion of comments provided by respondents related to map design considerations, with almost half of those comments stressing the importance of keeping maps simple, clear, and easy to understand. Examples of specific considerations provided by participants are listed in Table 6.

An example of a full response is provided below:

> *".. generally the map is too complicated with too many messages...this map may not be the most effective preparedness communication channel for this audience (learnt from surveys).....[we are] moving towards non-map communication approaches...future maps intend to incorporate better probabilistic data behind the zones and a link to tolerable life safety, explicit explanation of the time frame, details including links*

Table 6 Examples of specific map design considerations provided by respondents

Map design considerations
• A few simple hazard zones work better than many different complex zones
• Keep it concise (all on one page)
• Explanation of probabilities and zones should be clear
• Integrated maps were easier to understand
• Consider that the map audience may not be familiar with technical language
• Short summary of geology on map page better than complex extensive additional report
• People did not really understand the gradational nature of the zone boundaries
• Consider using gradual transitions rather than sharp boundaries between zones (and do this visually, rather than trying to explain using text)
• The previous versions of the map were difficult to understand and put into practice due to the highly specialized language, and many maps at different scales
• Consider how your map would be reproduced if photocopied – ours did not copy well
• Showing two volcanoes on a single map was great
• Including features of infrastructures on the map proved to be a good idea
• Augmenting maps with additional simple warning signs is useful for key messaging
• Consider including offshore hazard when creating hazard maps for islands
• Systematic overlay of hazard zones led to confusing zoning in some integrated maps
• Further detail such as locations of roads and other services could be added
• People like 3D style, easier to identify topography this way (compared to contour lines)
• Terrain bending is a useful method in 3D mapping; ideally there should be multiple perspectives of 3D panoramic perspective maps to show all endangered areas
• Consider interactive maps
• Consider including life safety information, explicit explanation of the time frame, details including links to further information, version number, version date, intended audience
• Research to understand map reading behaviour might lead to design improvements to enhance communication of key messages

Table 7 Examples of specific considerations provided by respondents related to the process of map development

The process of map development
• Maps should be revised periodically
• Maps should be tested with communities and map users before finalising, to ensure maps are comprehensible
• This map was tested during an actual unrest episode at the volcano. The small scale used for the map did not match the larger scale used for defining emergency plans. So new maps were created at those larger scales
• Do not forget to create or update a background hazard map after a volcanic crisis ends and the short-term map is no longer valid
• A pre-planned process and checklist for making a crisis hazard map would have been useful
• Our civil protection stakeholders preferred individual scenarios instead of a combined volcanic hazard map, since the individual processes (e.g., lava flows vs. ashfall) require different management approaches
• Stakeholders may prefer qualitative values rather than probabilities, to make the map easier to understand
• Engagement with indigenous partners led to a change in the map title

to further information, version number, version date, intended audience; design improvement to enhance communication of key message ([will involve] new research to understand map reading behaviour)."

The process of map development

The second most frequent comment theme was the process of map development, whereby over half of the responses stressed the importance of co-creating maps with stakeholders. Some specific experiences, lessons, and considerations are listed in Table 7.

Examples of full responses are provided below:

"We gave these maps to the [local Civil Protection agency]. They suggested to us that probabilities associated [with, for example] lava flows should be converted to qualitative values in order to be simple for the map stakeholders."

"Our map's 'eruption phenomena' title [rather than hazards] was a cultural choice based on engagement with indigenous partners / communities."

Table 8 Examples of specific considerations provided by respondents related to map audience and map user needs

Map audience and map user needs
• Not much thought was given to potential audience and their needs
• Identify the map audience right from the start
• Identify end-user needs right from the start
• Several maps as part of a suite of related products may be needed
• Evaluate the best way to disseminate information, based on your intended audience
• Identify the most relevant risk management recommendations
• Linking hazard zones with evacuation zones and alert levels can cause potential problems. For example, areas outside the evacuated area at a given alert level might be wrongly considered safe. There is also a risk that the administration, residents, and climbers may rely too much on alert level information
• Unintended usage: superimposition of 1:100 k scale map onto scales it was not meant for
• The map had unintended consequences, being used to justify decisions by banks and insurance companies
• Our local community wanted an oblique perspective map
• Our map was developed after identifying a local community need for this point-of-interest map
• Some audiences respond better to semi-quantitative risk (rather than hazard) maps as these allow comparison with familiar risks

Map audience and map user needs

Another key theme relates to considering map audience and map user needs in the early stages of developing the map. Several respondents noted, in hindsight, that they should have considered the potential audience much more than they did. Some respondents also commented on unintended uses of their maps, and some noted the value of including risk elements in maps. Specific experiences, lessons and considerations are listed in Table 8.

Examples of full responses are provided below:

> *"The map had what I thought were unintended consequences in that the Banking + insurance sectors used the map to determine their risk and denied access to loans and insurance to [certain hazard zones]. As a result, politicians came up with... the government will provide insurance to development in [these] zones. In my opinion land use planning regulations should be codified to restrict housing development in these zones."*

> *"Our local community wanted [an] oblique perspective map, but data processing workflows and 3D projection proved too difficult /time consuming."*

> *"This map [of a tourist village on a volcano] was based on results of a one-off survey on communication needs; local community voiced a need for detailed point-of-interest maps of at-risk areas downstream of lahar."*

> *"Some audiences respond better to semi-quantitative risk maps. They want us to quantify and integrate risk from all volcanic causes, in a way that allows them to compare to more familiar risks. Bluntly put, people don't care if they get killed by a PDC or a ballistic or a lahar. The end result is the same. They just want to know their chance of being killed by anything from the volcano........I've made more conventional hazard maps in my career.... but I've never seen light bulbs click on in a user's eyes like they do with these risk maps."*

Hazard assessment approach

Several comments related to the approach taken to assess the hazard. Specific experiences, lessons, considerations, and challenges are listed in Table 9.

Examples of full responses are provided below:

> *"Another decision we had to make was whether to depict on the map the initial stages of a volcanic eruption (which might show a single valley given the current configuration of the summit), or the "cumulative" hazard expected over the course of the eruption (which would cover a wider area as all valleys could be affected over the course of the eruption). We went for the latter. We believed this was the most accurate way to approach the hazard map, given our knowledge at the time, despite it not being very precise."*

> *"A pretty good hazard reconnaissance map can be made in a very short period of time [~1 week], using air photo interpretation and field spot checks. However, if using aerial photographs beware that alluvial fans on large stratovolcanoes can cover distal parts of large PDC deposits."*

Map availability and accessibility

Another thematic area relates to the accessibility of maps. All responses related to the desire for maps to be made easily available and accessible to either the map user (through open access, or websites) or to future

Table 9 Examples of specific considerations provided by respondents related to hazard assessment approach

Hazard assessment approach
• It is important to consider as many eruption events as possible including worst case scenario
• Consider all possible hazards (some were missing on the map, e.g., tephra fall)
• Hazard during summer and winter seasons is very different, so having different maps available is useful
• Consider incorporating lava flow arrival times
• Travel time of lahars included in map automatically indicates speed without extra explanation of the phenomenon
• We were unsure what scenario to include: most likely vs. worst case
• Volcanic Complexes: What volcano to choose for hazard map?
• Exceedance probability contours (and zones) are hard to interpret and explain to the users
• Our models had limitations—especially when modelling eruptions with recurrence on a 100 s to 1000 s-year time scale. These are not well represented in the geological record. Large and small eruptions are better constrained: Large infrequent eruptions are preserved in the geological record and small frequent ones have been witnessed historically
• We stress the importance of a conceptual model and probabilistic event tree in deciding what to portray in the map
• For monogenetic fields, consider using high seismicity area for the map
• Consider whether to depict on the map just the initial stages of the eruption, or the 'cumulative' hazard expected over the course of the eruption
• A pretty good hazard reconnaissance map can be made in a very short period of time [~ 1 week], using air photo interpretation and field spot checks
• Assessing hazards on the basis of petrology is probably an evolutionary dead end

map makers (by providing access to metadata and shape files) in order to facilitate map updates.

Example response:

> *"Creating an accessible and editable format gives us the flexibility of customizing the level and type of information to suit respective end users."*

External (e.g., political) influences

Three of our respondents pointed to outside influences on either the map development process or the dissemination of the map. In one case, political pressure led to a particular hazard zone being reduced in size slightly to allow economic activity to continue. In another case, the volcanic hazard zones terminated at state boundaries for legislative reasons. The third comment related to maps not being disseminated for political reasons, despite being socialised among civil authorities.

Discussion

In contrast to global reviews of hazard maps carried out for other perils, such as flood (e.g., Mudashiru et al. 2021) and landslide (e.g., Bichler et al. 2004), which typically include an external assessment of the scientific methodologies used to develop maps, here, we present an end-to-end review of different hazard map approaches based on knowledge and insights contributed by the map makers and those familiar with the development process. In addition to providing a review of the scientific methodologies used to develop maps around the world, the findings of this work help capture the stories associated with volcanic hazard maps by revealing the processes behind their development and the tacit knowledge, motivations, relationships, and constraints that underpin their design and application. Collectively, they represent a vast body of collaboration, innovation, and coordination between different types of knowledge and different needs of stakeholders. The qualitative insights contributed by map makers and practitioners familiar with the maps lend depth and clarity to our results, and complement our more quantitative analysis of design elements and of approaches used to determine and delineate map zones. Here, we consider the breadth of map diversity, the role of people and human experience in map making, comparisons to the volcanic hazard maps database, and reflect on implications for future map practice.

Map diversity

Our results reveal how the variety in volcanic hazard maps is rooted in a complex combination of approaches (e.g., probabilistic vs. deterministic), author preference, assessment methods, timelines, volcanic status, and driving influences. Although most maps captured in the survey are medium-scale maps of stratovolcanoes that show similar types of content, such as primary hazard footprints or zones, they vary greatly in input data, communication style, format, appearance, scale, content, and visual design. This diversity stems from a range of factors, including differences in map purpose, the methodology used, the level of understanding of past eruptive history, the prevailing scientific and cartographic practice at the time, the state of volcanic activity, and variations in culture, national map regulations and legal requirements.

Previous work has emphasised the need for a context-specific approach to hazard mapping, rather than a one-size-fits-all framework (e.g., Calder et al. 2015; Thompson et al. 2015; Clive et al. 2021). Our results confirm observations about the diversity of approaches used globally (e.g., Calder et al. 2015; Charlton 2018) and reveal how this is nuanced by the map audience and prior experience in addition to methodologies used. For example, a "lesson learned" by one map maker was that gradational boundaries were misunderstood and should be avoided, while a "lesson learned" by another was that gradational boundaries should be used to reduce misinterpretation of sharp changes between hazard areas. Although these lessons appear explicitly contradictory, they both suggest that map makers should consider and test visual representation of uncertain boundaries between hazard zones with their target audience in their target location, as this could affect interpretation of the hazard and potential audience/user behaviour. They also highlight how the experience of map contributors may inform and guide the development of future map design in different ways. The effort to accurately represent hazard boundary data in a meaningful way for audiences based on prior experience illustrates the reflexive and creative nature of map production as a process that relies on an interplay between both objective technical aims and social constructs and experience (Kitchin and Dodge 2007).

"Hazard awareness" was reported as the underpinning purpose for 72% of maps in the survey, and audience needs were reported as being considered in 70% of maps. Together with the reflective emphasis on clear, understandable map design and reducing risk, this indicates a widespread norm of developing products to support relevant communities and reduce harm. Different communities will have different levels of awareness and different cultural contexts for engaging with volcanic hazard information, which leads to many different potential pathways for representing hazard data, even if it was developed using similar assessment and analytical techniques. While the diversity in map design is fundamentally linked to the variety of scientific hazard assessment approaches reported, participants described how the map products were also enhanced, supplemented, and formatted in a variety of different ways to make them accessible to the audience and fit for their technical literacy. Some of these nuances can be ascribed in a general way to different cultural practice. Although we didn't specifically ask a question on this, some clear associations can be inferred from the maps. For example, many Japanese hazard maps are extremely detailed with lots of additional non-hazard information (e.g., packing lists) and often incorporate cartoons (e.g., Fig. 4). In another example from Aotearoa New Zealand, the map makers noted that the 'eruption phenomena' title (rather than 'hazards') was a cultural choice based on engagement with Māori partners (Leonard et al. 2014). The influence of culture on hazard mapping practices would be a very interesting topic for future study.

Despite the diversity discussed above, global similarities across mapping practice also emerged. For example, representing hazard with integrated zones (e.g., low, medium, high hazard) was the most common approach used on maps in this study and the majority of maps in the study were long-term or background hazard maps. Previous work has shown that integrated zones can be an effective choice for capturing attention and engaging audiences in assessing high-level hazards outside of an evolving eruption crisis (Clive et al. 2021), suggesting the practice of using integrated hazard zones aligns well with the hazard awareness goals. Participants from multiple regions around the world reflected on the value of having maps accompanied by a suite or collection of multiple hazard assessment communication products, which aligns with the best practice guidelines summarised by Pallister et al. (2019) and enables multiple ways of communicating information for different audience needs. Several respondents noted the importance of testing and evaluating maps, mentioning a range of triggers (e.g., following an eruption, upon the completion of the map, new information coming to hand) and approaches (e.g., eruption simulation exercises, public surveys, stakeholder discussions). This range, and the fact that less than half (45%) of all maps in the survey were in fact tested to some degree, suggests that perhaps a map testing and evaluation step should be incorporated into any map development cycle. The form this takes will differ depending on the purpose of the map and the activity of the volcano (among other things) and so will need to be agreed upon by the map development group. If a time frame and/or trigger is established upon map development (say, every two years, or if there is an eruption), this might increase the likelihood that the map is indeed evaluated and updated to ensure it remains fit-for-purpose.

It is useful here to comment on the intersection between hazard and risk on maps. In our survey we specifically focussed on hazard maps, in part because comprehensive risk maps (that fully integrate exposure, vulnerability and hazard to create risk zones) are quite rare. Much more common is for hazard, exposure, and vulnerability elements to be depicted separately on maps (or in the accompanying text), enabling the map user to infer relative risk. For example, maps might include societal exposure and vulnerability information (such as infrastructure, towns, population numbers within certain zones, household access to transportation) overlain by hazard zones, which in turn may or may not be depicted in terms of a hazard intensity metric (such as ash loading, dynamic pressure, or arrival time). Alternatively, some maps show summit (or other) exclusion or danger zones (e.g., the Yasur Safety Map in our survey; Vanuatu Meteorology and Geo-Hazards Department 2016). Rather than actual risk maps, these maps could be considered hazard maps that include "what to do" information (e.g., in this case, stay out of the high-hazard zone). Almost all the maps in our survey that were co-created with three or more different groups including civil authorities (e.g., the maps shown in Figs. 3 and 4) included such "what to do" information.

We note that in other disciplines (such as meteorology) there is a move towards impact-based forecasts and warnings (e.g., Potter et al. 2018), which could lead to the emergence of more impact- and even risk-based maps, including in volcanology. It would be an interesting future study to explore how impact- and risk-based maps could be developed in volcanology.

People behind the maps

Volcanic hazard maps are inherently geology-based tools, informed and guided by the deposits of previous eruptions and modelling of potential future events. However, our results shed light on the important influence of people, the human experience, and social dynamics in the development of these products. Ultimately, difficult decisions have to be made along the development pathway, and teams often rely on the insights of prior experience and best practice at the time to help guide these decisions. While our results outline how volcanic hazard map contributors endeavour to create the most accurate and useful representation of the hazard, a final map is but one of many possible representations of the hazard for the audience (Monmonier 2018). The lessons learned include descriptions of navigating scientific challenges (e.g., data scarcity) but also challenges rooted in social and political spaces (e.g., legislative boundaries on hazards, competing views, and risk communication needs).

Each map carries a unique thumbprint, capturing the circumstances, environment, science, resources, and people affecting its development at the time (e.g., Wright 1942, Kitchin and Dodge 2007). For example, participants noted how short crisis timelines affected hazard assessment, how access to numerical models affected analysis, how previous experience influenced methodology, and how risk management and legislation affected design choices. Human experience was also consulted as a key source of data for multiple maps, where interviews of people who witnessed previous eruption impacts helped inform the hazard extent. Reaching agreement on a conceptual model among scientists and testing different modelling tools also required cooperative negotiation, consideration and validation among scientists. Acknowledging that these maps were reflective of a particular point in time of the history of the volcano and scientific understanding, many participants recommended reviewing, updating, and evaluating the maps they described in the survey at some point in the future.

The role and level of co-production was also a common thread among lessons learnt and reflections on the process. Working together with key stakeholders and communities can help ensure the final product is the most relevant representation for the map audience and purpose. Among the 33 maps that were created by multiple agencies, participants noted that working together with partners was "critical" to developing a successful hazard map product. However, more than half of maps reported on (62%, $n=57$) were created by a single organisation and many participants also reflected on the fact that more engagement with end users and stakeholders could have improved the maps' efficacy or relevancy. Community relationships and stakeholder partnerships are increasingly recognised as playing a key role in developing effective and relevant maps and the participants emphasised the importance of consultation and collaboration throughout their comments.

Comparison with data from the volcanic hazard maps database

The maps in our survey cover a wide range of volcano types and hazard map styles and scales, which aligns with trends recorded by the Volcanic Hazard Maps Database. The purpose of the database and its accompanying website (https://volcanichazardmaps.org/) is to serve as a resource for hazard mappers to explore how common aspects of hazard map development and design have been addressed in different countries, for different hazards, and for different intended purposes and audiences (Ogburn et al. 2023). All the maps in our study that are publicly available are included in the database (the few maps that are not in the database are not publicly available). Because the information on the hazard maps in our study was submitted by map makers and/or practitioners familiar with the making of the map, it provides a useful check for the more subjective information in the Volcanic Hazard Maps Database (i.e., information that cannot be easily extracted by looking at the map), such as map purpose and audience, map makers (including involvement of stakeholders) and the motivation for the map. In the discussion below, we begin by exploring the high-level results of our survey in the context of the Volcanic Hazard Maps Database, and then provide a comparison of specific data from a sub-set of maps in both data sets.

High-level comparison

Our survey includes 89 individual hazard maps covering 69 individual volcanoes or volcanic complexes in 28 different countries. This represents only a small subset of those in the Volcanic Hazard Maps Database, which at the time of writing includes 1823 individual hazard maps covering 634 individual volcanoes or volcanic complexes in 53 different countries. To evaluate how representative a sample our subset of maps is, we carried out a high-level comparison between similar types of data collected in our survey and explored in the analysis presented in Ogburn et al. (2023). All figures below are rounded to the nearest percent. There is a good correlation between the percentage of official volcanic hazard maps in each sample: 79% In our study compared to 78% in the database. Furthermore, when comparing the survey results to maps from the database recorded as "official," many of the results are similar across our two analyses; for example, the most popular hazards depicted on maps are similar in both cases, namely PDCs, tephra, and lahar, with a somewhat lesser proportion depicting lava and ballistic projectiles. Hazard is most commonly represented through integrated or hazard-level focused zones in both cases, and the percentages of maps that depict hazard-process focussed zones (i.e., maps showing discrete hazard zones for different hazardous phenomena) were similar in both cases (our study 35%; database 41%). The most common spatial scale of the map ("volcano and surrounding area") was unsurprisingly the same in both data sets; somewhat more surprising was that exactly 71% of maps in both samples were of this scale.

Some differences were also observed, particularly in map purpose and audience. One of the ways in which Ogburn et al. (2023) classified hazard maps in the Volcanic Hazard Maps Database was according to their primary intended purpose, although it was clearly noted that it was 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 (57% of the maps in the database) (Ogburn et al. 2023). Crisis management maps (including very short-term forecast-type maps) make up 19% of the database, land-use planning maps 12%, and maps intended for hazard awareness just 7% of the database. In comparison, in our study 83% had more than one intended purpose, with 24% of maps being considered by map makers to be multi-purpose, i.e., serving all four stated purposes (Table 2). Interestingly, considering all the purposes noted by participants for each map, the most common map purpose (87% of maps) was crisis management, followed by hazard awareness (72% of maps), land use planning (56% of maps), and impact and/or risk assessment (30% of maps). The differences in these percentages between our survey and the database likely relates to the difficulty in elucidating the original purpose and audience of the map just by looking at/reading it, unless such information is explicitly stated (Ogburn et al. 2023). Thus, many more maps in our study were purported by map makers to have a crisis management purpose (87%) than inferred for the database maps (19%). This reflects the fact that many map makers intended their long-term/background maps to be multi-purpose, including for crisis management, despite the fact that the design of these maps would not explicitly indicate crisis management as a purpose. Relevant to this is that several survey participants noted that they did not give a lot of thought to the intended audience or purpose, and so in those cases "multi-purpose" can perhaps be considered a default answer. An interesting inference here is that a large proportion of long-term/ background volcanic hazard maps in existence may have been intended by the map makers to be used for crisis management, yet they may be ill-suited to that use if purpose and audience were not considered during the production of the map.

One final interesting difference is that in our survey, 60% of our respondents indicated that uncertainty was communicated in some way on the map (including through written text on the map face); this compares to just 28% of the maps in the database. It is unclear whether this just reflects differences in the way "uncertainty" is interpreted in both cases, or whether this might be hinting at the fact that map makers might believe uncertainty is depicted on the map, but this might not be completely obvious when someone not involved in the map making process reviews the map. This could of course also just be a function of our small sample size in comparison with the much larger database.

Map-specific comparison of trends

We randomly chose eight different maps (~10% of the maps surveyed) to compare and cross check specific results from our survey with equivalent entries within the database in order to explore in more detail the differences between specific entries across both data sets where comparable questions were asked, and to provide some nuance to the high-level comparisons above. For the most part direct comparisons with the database are difficult because of the different ways the data have been captured and analysed in both cases; however, 10 questions were deemed similar enough for results to be directly compared (Table 10).

As expected, aspects of the map that are easy for someone to discern simply by looking at the map (for example: timescale, scale, base map, version and how hazard is depicted) showed good agreement between the two databases. However, more subjective aspects that are more difficult to discern simply by looking at the map showed some discrepancies. For example, differences were seen in map audience (with 5 of the maps yielding different answers) and map purpose, which differed in

Table 10 Comparison between some of the survey results and the database entries. X—indicates a difference in classification between the database entry for that map (compiled by Ogburn et al. 2023) and our data set as determined by the map maker

Map title	**Pinatubo Volcano Preliminary Hazard Map**	**Volcanic Hazard Map for Ambrym Island (Vanuatu)**	**Mapa de Amenaza Volcánica del Volcán Puracé Actual**	**Lahar hazards at Soputan volcano**	**Izu-Tobu Volcanoes Volcanic Alert Levels**	**Lava flow hazard map of Mt Etna volcano**	**Mt. Fuji Volcanic Hazard Map**	**Volcanic Hazards at Whakapapa Mt. Ruapehu**
Country	**Philippines**	**Vanuatu**	**Colombia**	**Indonesia**	**Japan**	**Italy**	**Japan**	**New Zealand**
Database map ID	**1564**	**1480**	**819**	**3506**	**3160**	**945**	**949**	**512**
Audience of the map				X	X	X	X	X
Purpose of the map	X			X		X		
Timescale of the map					X			
Scale of the map								
Type of base map								
Version included?	X							
Tied to alert level?	X		X					X
Uncertainty included?	X				X			X
How uncertainty is represented	X	X	X		X	X	X	X
How hazard is depicted								

three out of the eight maps. Differences were also seen in whether and to what extent uncertainty was depicted (in 3 and 7 maps, respectively), which corroborates what was noticed above during the high-level comparison. In a few cases, participants said that uncertainty was not depicted, yet the database entry suggests it was, and on re-inspection of the map we confirmed that there was indeed some portrayal of uncertainty on those maps. This supports the suggestion that people may interpret uncertainty depiction differently.

Another interesting aspect that varied in three out of the eight sample maps was whether the map was tied specifically to any volcanic alert levels. In these three cases, the map makers that completed our survey indicated that the map is linked to alert levels; however, this was not picked up during entry of information about these maps into the database. In at least one case this is because of differences in how 'tied to alert level' was interpreted, i.e., the warning system information on the Mt. Ruapehu map (Fig. 3) was not classed as being strictly 'tied to alert level' in the database. However, in the other cases, this discrepancy could mean that the link with alert level may not be completely clear on the map itself. Where both volcanic alert levels and hazard maps are used as communication tools, we suggest it should be made as clear as possible if there is any connection between the two mechanisms.

Overall, for most of the compared fields there was thus good correlation between the database and survey data for the same map, which provides a useful, independent endorsement of the data entries in the Volcanic Hazard Maps Database. Any differences outlined above in information recorded for a single map highlight not only the large diversity in volcanic hazard map style and complexity in content, but also diversity in the terminology used to describe volcanic hazard maps (Ogburn et al. 2023). One of the drivers for the development of the Volcanic Hazard Maps Database and indeed the Working Group on Hazard Mapping itself was to work towards a framework for a classification scheme for hazard maps and to promote harmonization of terminology. There is currently a wide variety of terminology used to describe volcanic hazard maps. Through initiatives such as the Volcanic Hazard Maps Database and its accompanying descriptive text on the website we can, as a community, move towards a common terminology, which will help reduce misinterpretations when trying to describe hazard maps. We encourage the reader to consult the database (https://volcanichazardmaps.org/) and the companion paper (Ogburn et al. 2023) for recommended volcanic hazard map terminology.

Concluding comments

Our study provides a review of past and current volcanic hazard mapping practices, and associated lessons learned, and can be viewed as a snapshot of the wide variety of volcanic hazard maps that have been developed since the 1980s. We surveyed individuals representing 89 'self-selected' volcanic hazard maps out of the thousands that have been developed and were able to capture valuable insights from the map makers themselves, which differs from approaches used by other hazard map compilations. These insights highlight the range of factors that lead to the wide diversity in volcanic hazard maps, and the importance of considering the influence of people behind the development of the maps as well as those who are the intended audience of the maps.

The Working Group on Hazard Mapping of the IAVCEI Commission on Volcanic Hazard and Risk was established in 2014 because it was recognised that the volcanological community has a limited understanding of the nature and diversity of volcanic hazard mapping practices, as well as the respective philosophies upon which these practices are based. This study sheds some light on that diversity at this moment in time. Our contribution complements the Volcanic Hazard Map Database (https://volcanichazardmaps.org/) also developed by the Working Group, and which includes a framework for a classification scheme for hazard maps and promotes harmonization of terminology (Ogburn et al. 2023). The results of our study, together with insights from the Database and the series of State of the Hazard Map workshops that we have hosted since 2014, are now being consolidated into an IAVCEI Sourcebook on volcanic hazard mapping, in which we identify and categorise a suite of good practices and considerations for volcanic hazard mapping. Looking to the future, for individuals or groups tasked with the development of new volcanic hazards maps, we hope that our combined efforts will provide some clarity and documented consensus on good practice for the development process, content, design, and format of maps. Finally, we hope that our study highlights the value of sharing volcanic hazard mapping practice and the thought process behind map development, and we encourage map makers to share their stories, for example, through publication outlets tailored to present hazard mapping approaches.

Supplementary Information

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Additional file 1a and 1b. Full Survey, English and Spanish versions.

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Authors' contributions

J.M.L., E.S.C., M.A.T.C., H.W., S.O. and J.E. conceived the project. D.B. carried out spanish translations. D.C. and M.A.T.C. led the quantitative data analysis. B.S. obtained copyright permissions. J.M.L. managed the project and lead the writing; all authors prepared figures and reviewed the manuscript.

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Availability of data and materials

Data is available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate

This study was approved by the University of Auckland Human Participant Ethics Committee [Ref. 014529, Ref. 014853].

Competing interests

The authors declare no competing interests..

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