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HAZARD MAP

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Following the tug of the audience from complex to simplified hazards maps at Cascade Range volcanoes

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Abstract

Volcano-hazard maps are broadly recognized as important tools for forecasting and managing volcanic crises and for disseminating spatial information to authorities and people at risk. As scientists, we might presume that hazards maps can be developed at the time and with the methods of our discretion, yet the co-production of maps with stakeholder groups, who have programmatic needs of their own, can sway the timing, usability, and acceptance of map products.

We examine two volcano hazard map-making efforts by staff at the U.S. Geological Survey. During the 1990s and early 2000s scientists developed a series of hazard assessments and maps with detailed zonations for volcanoes in Washington and Oregon. In 2009, the National Park Service expressed the need for simplified versions of the existing hazard maps for a high-profile visitor center exhibit. This request created an opportunity for scientists to rethink the objectives, scope, content, and map representations of hazards. The primary focus of this article is a discussion of processes used by scientists to distill the most critical information within the official parent maps into a series of simplified maps using criteria specified. We contextualize this project with information about development of the parent maps, public response to the simplified hazard maps, the value of user engagement in mapmaking, and with reference to the abundance of guidance available to the next generation of hazard-mapmakers.

We argue that simplified versions of maps should be developed in tandem with any hazard maps that contain technical complexities, not as a replacement, but as a mechanism to broaden awareness of hazards. We found that when scientists endeavor to design vivid and easy-to-understand maps, people in many professions find uses for them within their organization's information products, resulting in extensive distribution.

Keywords Cascade Range volcanoes, Geopark, Volcano hazard map, Hazard assessment, Hazard communication, Single Overriding Communication Objective, Volcano museum, Decision support tools

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Introduction

Volcano hazards assessments are broadly acknowledged as important tools for managing volcanic crises, for disseminating information to public officials and people at risk, and for land-use planning aimed at reducing risk (Crandell et al. 1984; Tilling 1989; Haynes et al. 2007; Dransch et al. 2010; Leonard et al. 2014; Thompson et al. 2015, 2017; Ogburn et al. 2023). Critically, maps within a volcano hazards assessment provide spatial context to understand patterns of hazard exposure and identify vulnerabilities (Prosperie 2002). For scientists, developing a hazard assessment can be the ultimate summation of scientific knowledge about a volcano's eruptive history and its potential for disruptive volcanic activity. Producing a hazard assessment and associated maps involves synthesis of interdisciplinary investigations, reasonable scientific consensus, and knowledge about the needs of map users. A hazard assessment that meets user needs can extend the influence of many decades of scientific research.

Volcano hazard assessments are tools used for long-term planning involving public safety. Assessments can have life-saving value, broad audiences, and long lifespans with infrequent revisions. Therefore, authors should seek opportunities to maximize effectiveness of an assessment's textual and visual aspects. Mapmaking skills and an appreciation for the specific needs of users are often acquired through time, both experientially and sequentially, throughout a scientist's career (Fischhoff 1995). This article seeks to accelerate the learning process by sharing more than a decade of insights gained through development and sharing of a series of simplified maps for Cascade Range volcanoes.

Ogburn et al. (2020, 2023) used the term 'parent map' to denote an original map from which derivative maps are made. Parent maps may contain many technical complexities. We use the word 'simplified' for derived maps, where hazard zones have been regrouped to make the map more accessible and understandable for non-specialists, and for ease of placement within products developed by external and observatory users. Simplified maps require accompanying information for context and accurate interpretation and are not intended as standalone map products. We refer to these products as maps, but for many purposes, they are graphics.

The goals of this paper are to document the interagency co-development of simplified maps, to illustrate one volcano observatory's process for simplifying complex parent maps, and to offer recommendations for creating effective hazard maps to the next generation of mapmakers. Chiefly, we focus on creating a series of simplified hazard maps of all 13 noteworthy Cascade Range volcanoes at the request of the National Park Service (NPS) in 2009. The discussion includes background about the evolution of volcano hazard assessments and maps published in the mid-1990s to 2012, key elements of the simplification process, insights gleaned by close work with user groups, prioritizing of communication objectives, and developing maps for multiple audiences. We conclude by pointing to the abundant scientific guidance now available to mapmakers, and to broad recommendations based upon experiences described here. It is our hope that future mapmakers can benefit from these insights and begin their mapmaking journeys where we have paused, rather than retreating to where our mapmaking journey began.

Evolution of volcano hazard maps in the Cascade Range

In the Cascade Range of the United States, the practice of making volcano hazards assessments based largely on a volcano's eruptive history began at Mount Rainier after the discovery of lahar deposits many tens of kilometers from the volcano. The resulting assessment by Crandell and Mullineaux (1967), one of the first such products globally, acknowledged that future populations would be at risk from lahars (stated more broadly as 'debris flows'). Crandell's 1971 report provided new details about past lahars and offered guidance to authorities about lahar-risk mitigation. In 1973, Crandell published a hazard map showing zones of high, moderate, and low risk for both lahar and tephra hazards (Crandell 1973). Assessments with hazard maps soon followed for Mount St. Helens (Crandell and Mullineaux 1978), Mount Baker (Hyde and Crandell 1978), Mount Hood (Crandell 1980), Mount Shasta (Miller 1980), and for volcanoes of California (Miller 1989).

During eruptions at Mount St. Helens in the 1980s, authorities expressed an urgent need for information and utilized U.S. Geological Survey (USGS) hazard maps for designation of evacuation zones, road closures, and rules for access (Miller et al. 1981). Application of information in the Mount St. Helens assessment (Crandell and Mullineaux 1978) that authorities called 'the blue book,' underscored the value of pre-eruption availability of maps. The eruption also demonstrated the importance of scientists engaging in long-term conversations with public officials about volcano hazards regarding preparations pre-crisis (we use the term 'public official' to those with jurisdictional responsibility for public safety, including land-use managers, emergency managers, planners, and responders, and elected officials) (Wright et al. 2023). Events at Mount St. Helens drew attention to potential hazards at other Cascade Range volcanoes and instigated new and in-depth geological studies. As scientists dug into the deposits at these volcanoes and constructed eruption chronologies, they could not anticipate that within a decade, new legislation would further validate the necessity of their geological investigations and prompt them to create a new generation of volcano hazards assessments.

Washington State Growth Management Act spurs the development of a series of hazard assessments

In the early 1990s, Washington State adopted the Growth Management Act (Washington State Legislature 1990; MRSC 2022), a series of state statutes that require comprehensive county land-use plans that give consideration to natural hazards. The USGS Cascades Volcano Observatory (CVO) recognized this legislation as an opportunity to produce a series of Cascade Range-wide assessments for use by public officials. The assessments summarized each volcano's past behavior and the potential for future activity, including likely types and magnitudes of eruptions. Each assessment included one or multiple maps displaying hazard zonations based largely upon the dimensions and timing of past events, but in some situations, upon the results of modeling.

The effort began with Washington's volcanoes and progressed southward through Oregon and California. Between 1995 and 2012, teams of scientists created hazard assessments for twelve of the thirteen major Cascade Range volcanoes (Mount Shasta was excepted due to an existing map from Miller 1980). Each assessment contained one or more large-format paper maps, folded into the back cover of the summary report. Bibliographic information and links are listed in Table 1.

Research teams used similar but distinctive approaches that reflected their volcanic region, areas of expertise and professional judgments. Most teams developed hazard assessments based upon decades of previous research (e.g., Mount Rainier) while others conducted first-order, foundational research (e.g., Medicine Lake). Several writing teams included a broad summary of geologic knowledge (e.g., Lassen Volcanic Center), while the majority of the assessments focused upon hazards. Several teams consulted with public officials about practical considerations, including map scale, format dimensions, and availability of the maps as both hard-copy and as digital geospatial data that could be overlaid on existing jurisdictional maps. The earliest maps were assembled on the cusp of the digital map-making age, resulting in development first of paper maps, followed by online digital versions (e.g., Schilling et al. 2008a, b). The result was a series of maps containing many commonalities, but also some substantial differences in content and style.

Uses of hazard maps by public officials elucidated in working groups

During the 1990s and early 2000s, these assessments became conversation starters as scientists introduced themselves and their work to public officials in the Cascade Range. Since then, many conversations have become sustained by establishment of regional 'volcano hazard working groups' in Washington and Oregon, and in

Table 1 1990-2000s Era principal hazard assessments[a]

Volcano(es)	Assessment Name	Authorship
Mount Baker	Potential Volcanic Hazards from Future Activity of Mount Baker, Washington (1995)	C.A. Gardner, K.M. Scott, C.D. Miller, B. Myers, W. Hildreth, and P.T. Pringle
Glacier Peak	Volcanic-Hazard Zonation for Glacier Peak Volcano, Washington (1995)	R.B. Waitt, L.G. Mastin, and J.E. Begét
Mount Rainier	Volcano Hazards from Mount Rainier, Washington, Revised 1998 (orig. 1995)	R.P. Hoblitt, J.S. Walder, C.L. Driedger, K.M. Scott, P.T. Pringle, and J.W. Vallance
Mount St. Helens	Volcanic-Hazard Zonation for Mount St. Helens, Washington, 1995	E.W. Wolfe and T.C. Pierson
Mount Adams	Volcano Hazards in the Mount Adams Region, Washington (1995)	W.E. Scott, R.M. Iverson, J.W. Vallance, and W. Hildreth
Mount Hood	Volcano hazards in the Mount Hood region, Oregon (1997)	W.E. Scott, T.C. Pierson, S.P. Schilling, J.E. Costa, C.A. Gardner, J.W. Vallance, and J.J. Major
Mount Jefferson	Volcano Hazards in the Mount Jefferson Region, Oregon (1999)	J.S. Walder, C.A. Gardner, R.M. Conrey, B.J. Fisher, and S.P. Schilling
Three Sisters	Volcano Hazards in the Three Sisters Region, Oregon (2000)	W.E. Scott, R.M. Iverson, S.P. Schilling, and B.J. Fisher
Newberry	Volcano hazards at Newberry Volcano, Oregon (1997)	D.R. Sherrod, L.G. Mastin, W.E. Scott, and S.P. Schilling
Crater Lake	Volcano and earthquake hazards in the Crater Lake region, Oregon (1997)	C.R. Bacon, L.G. Mastin, K.M. Scott, and M. Nathenson
Medicine Lake	Volcano Hazards Assessment for Medicine Lake Volcano, Northern California (2007)	J.M. Donnelly-Nolan, M. Nathenson, D.E. Champion, D.W. Ramsey, J.B. Lowenstern, and J.W. Ewert
Mount Shasta	*Potential Hazards from Future Eruptions in the Vicinity of Mount Shasta Volcano, Northern California (1980)	C.D. Miller
Lassen Region	Volcano Hazards Assessment for the Lassen Region, Northern California (2012)	M.A. Clynne, J.E. Robinson, M. Nathenson, and L.J.P. Muffler

Table 1 1990-2000s era principal hazard assessments. Most hazard assessments were published as USGS Open-File Reports, but two were published as USGS Scientific Investigations Reports. The maps and corresponding reports were distributed to emergency managers whose jurisdictions included the Cascades Range volcanoes and their hazard zones. Most maps were published in blue on white plates (some color versions were developed later)

[a] No update was required for the 1980 Mount Shasta hazard assessment

a more centralized manner by the California Office of Emergency Services (CalOES). Over the past quarter-century, each working group has written, exercised, and updated emergency coordination plans that are based upon USGS hazard assessments. Working groups aid trust building and mutual understanding of hazards and maintain the 'long-term and ongoing conversations' that Mileti 1999 concluded are essential components of effective risk management. This broad knowledge exchange with working group members has proven useful in eruption responses (Haynes et al. 2007; Driedger et al. 2008, 2020; Wright et al. 2023). The structure, membership, activities, and scope of responsibilities of a working group can be flexible or rigid, but must fulfill its core mission of developing documents that meet legal mandates. Hazard maps have been used within state and federally mandated documents (Homeland Security 2015), including regional volcano emergency coordination and response plans, Comprehensive Emergency Management Plans (CEMP), Threat and Hazard Identification and Risk Assessments (THIRA), and as justification for local land-use requirements (Pierce County 2004; 2020). Volcano hazard working groups sometimes include specialists responsible for water, electrical, medical, and transportation infrastructure. Educators, and safety officers from schools, parks, community organizations, and other groups having communication as a central organizational responsibility often join working groups or function in auxiliary roles, which can expand the distribution of maps and hazard information. Easily understood hazard maps and related decision-support tools are necessary for inclusion in their organizations' information products.

The need arises for simplified maps for non-specialist audiences

As hazard assessment maps became more widely used, a new challenge arose: Hazard maps and reports, designed for policy and decision-makers as decision-support tools, were used increasingly for educating non-specialists, some of whom had difficulty understanding the technical presentation of information. (We use the term non-specialist to refer to everyone, excluding scientists specializing in volcanology or adjacent disciplines.) Working group members made informal requests for derivative, simplified versions of the maps for use within documents and for hazards communication with the public, *not as a replacement, but as complement to the parent hazard map.* Initially, assessment authors decided not to produce derivatives due to concerns about causing confusion as to which map was the official hazard map. In the vacuum created by the absence of official derivative maps, the news media, emergency managers, educators, and some USGS scientists created their own stylized versions perceived as having broader appeal for non-specialist audiences. Ironically, this practice ultimately led the confusion USGS had sought to avoid when a plethora of non-official and differing versions began to appear in newspapers, newsletters, and outreach products. The question was then: How can we create simplified versions of complex maps and maintain a map's original scientific integrity? USGS scientists took initial steps and asked the observatory cartographer/scientific illustrator to create small-format maps with generalized zonations and simplified explanations. These maps were commonly used in USGS presentations, but despite requests, were not distributed externally.

Methodology for the development of simplified hazard maps

A partner agency provides the impetus to develop simplified maps for a broad audience

In 2009, the interpretive media specialists at Mount Rainier National Park asked scientists at the USGS CVO to develop a set of consistently designed maps for all the Cascade Range volcanoes for use in a display within the newly constructed Henry M. Jackson Memorial Visitor Center. The display is part of a broader visitor center geohazards exhibit that fulfills the park's roles within a 1999 inter-agency Mount Rainier Response Plan (now superseded by a revised plan; Pierce County 2020), an internal Geohazards Awareness Campaign described in Driedger et al. 2002, and an NPS internal long-range interpretive plan. The objectives of the exhibit are for visitors to learn about volcano hazards at 13 volcanic regions in the Cascade Range, identify the spatial patterns of ground-based hazards both 'near-volcano' and 'distally,' and to invite comparisons of hazard zones for multiple volcanoes.

In the exhibit, 13 volcano hazard maps are viewed consecutively on a large visitor-controlled screen-monitor. The NPS had made requests that the maps be vivid, use consistent symbology, and be understandable by park visitors across a broad range of ages, educational backgrounds, regions of residence, and interests. In other words, the maps would need to hold the attention of a 'non-captive audience,' defined as visitors who possess free will to observe closely, or ignore interpretive products (Ham 1992, 2013). The NPS's requirements were based upon their expertise in visual communications and previous interactions with the public. In their plan, adjacent exhibits would describe volcanic processes and rocks. A 1.5-m by 3-m vinyl lahar-hazard map similar to Fig. 1 glued to the floor would allow visitors to walk the valleys at risk from lahars.

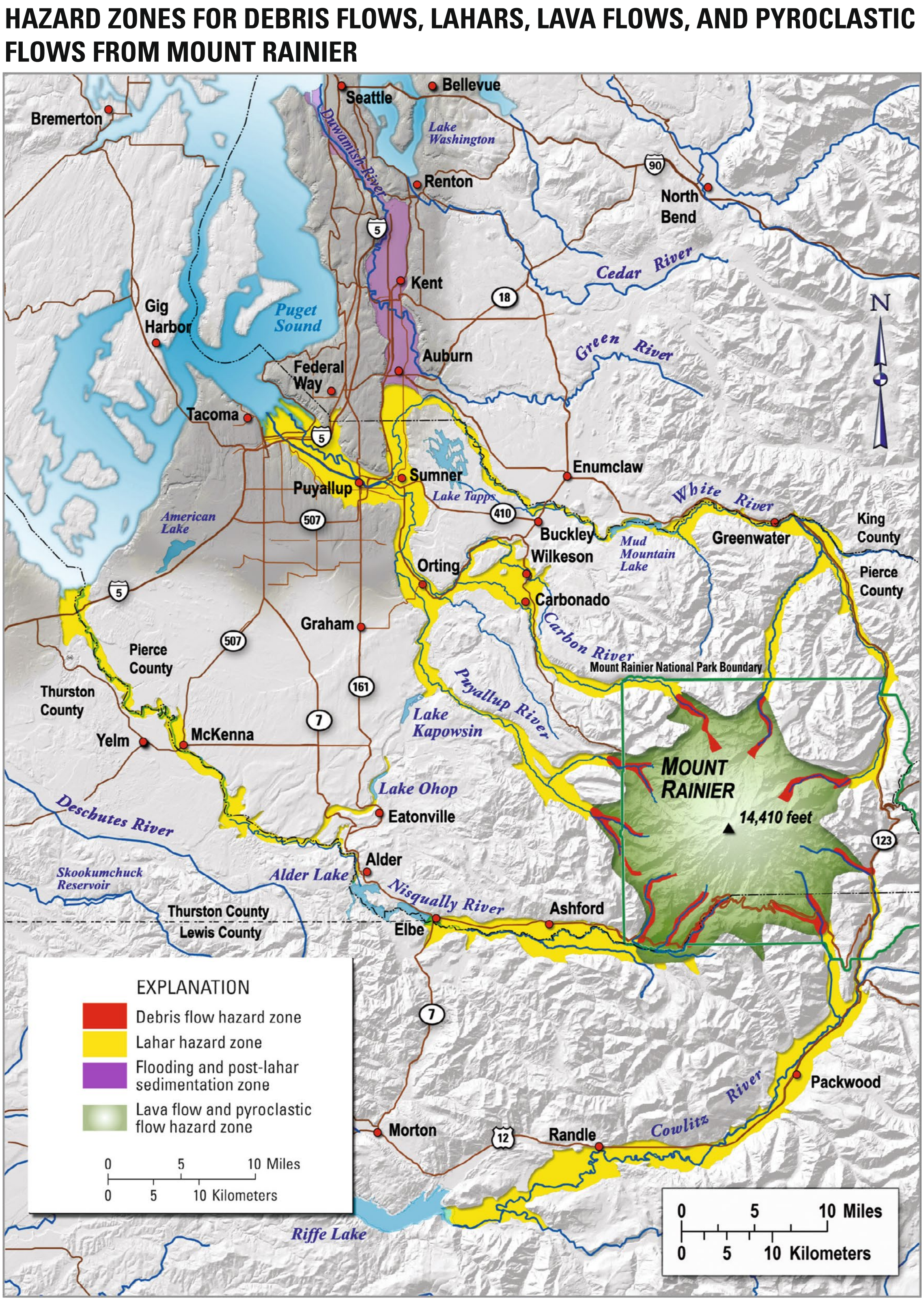

Fig. 1 Map from U.S. Geological Survey Fact Sheet 2008–3062 that was cited by the National Park Service as a model. The map from U.S. Geological Survey Fact Sheet 2008–3062 was cited by the National Park Service as a model for the simplified map series

A prototype inspires additional map development

Inspired by a simplified hazard map in a USGS Mount Rainier Fact Sheet (Driedger and Scott 2008) shown in Fig. 1, NPS requested that the hazard zones in the parent hazard maps be modified to a similar visual treatment within the new series of exhibit-bound simplified maps.

The park interpretive media specialist requested the simplified maps would have the following qualities:

- Single "landscape" layout that could be panned or zoomed interactively,
- Color gradients representing relative potential for inundation when a lahar occurs within lahar hazard zones,
- Hazard zone boundaries represented as distinct color change, without display of quantitative probabilities or regions of uncertainty,
- Hazards classified by area of impacts, being either 'at distance' or 'near' the volcano,
- Full color symbology,
- Shaded relief or orthophoto background without spot altitudes or contour lines,
- Selected, labeled cultural landmarks,
- Hazard zones shown in full rather than truncated by jurisdictional boundaries,
- Ground hazards only,
- Uncluttered appearance,
- Completed maps should be legible on computer monitor and adhere to NPS accessibility standards.

Deliberations and reconsiderations lead to new ways of representing hazards

The Park's request provided an opportunity for the USGS to reconsider holistically how hazard information is presented, and to develop a methodology for maintaining the integrity of the hazard information in simplified version that would meet NPS's requirements. The map's message would drive map appearance.

USGS acknowledged that, if a few key concepts were understood, users could recognize the broad patterns of hazard zonation without needing all known information about the volcano. Parventa et al. 2018 established a methodology for prioritizing objectives and messaging in health science communication. The Single Overriding Communication Objective (SOCO) approach focuses on delivering the single most important message and supportive facts at the expense or total exclusion of other information. A SOCO for most Cascade Range volcanoes evolved organically through conversations between scientists, public official partners, and residents with interest in the process as they developed emergency coordination plans, held exercises, and created outreach products. Among all, there was general recognition that lava flows are commonly overestimated as a threat, while lahars are lesser known yet pose a major threat to communities at risk in the Cascade Range. The SOCO of the simplified maps is: "Lahars are the principal threat to communities. Lahars can be present on valley floors at distance from the volcano; all other ground-based hazards are confined to the vicinity of the volcano." We consider that this SOCO applies to ice and at snow-covered volcanoes and any other volcanoes where lahars are a predominant threat. In later life-safety and preparedness products, emergency managers and scientists augmented the simplified maps with additional text (e.g., Schelling et al. 2014; Ekse et al. 2015).

Mechanics of simplification

Creating a consistent symbology required thorough analysis of all Cascade Range volcano hazard maps for the purpose of identifying commonalities, and to lump, split, and occasionally redefine existing hazard categories. This process entailed discussion among authors with the singular goal of meeting the Park's request. The process proceeded with one or more authors (or representatives for each hazard assessment) assembling in the conference room of CVO for approximately a half dozen meetings. Participants placed Washington and Oregon volcano hazard maps upon a large boardroom-style table for easy visual comparisons (California maps were not included in this process and were handled later with author participation via email and phone). The first task was to identify commonalities and differences in hazard representation at each volcano. A facilitator led a systematic discussion, examining each map element, type of hazard zone, the scientific basis of zones, origins of hazard groupings, symbology, and the most logical way to regroup hazard zones into 'near-volcano' and 'at-distance' zones on the new maps. Next, the inquiry turned to questions about the visual aspects of the maps, including how to achieve consistent content, symbology, explanations, and general appearance while making the fewest departures from the parent maps.

This iterative process produced prodigious and constructive conversations. Spurred forward by an NPS deadline, scientists discussed multiple options for effective graphical visualizations. They reconsidered the necessity and validity of existing hazard zones, and the incorporation of new research findings and modeling results that postdated the parent maps. Authors judged that detailed explanations of each type of pyroclastic density current were of no direct importance to nearly all audiences, and therefore could be lumped into a single near-volcano hazard zone, as had been done on several of the parent maps. Some parent maps contained features that were prominent in the minds of mapmakers during the 1990s, exemplified by inclusion of the Mount St. Helens lateral-blast zone on some maps. Later investigations determined that these zones were unnecessary or misleading, and they were excluded from the simplified maps. Multiple schemas were suggested for inter-map consistency while also maintaining the accuracy contributed by the parent maps.

In the end, all flowage processes (e.g., lava flows, lahars, and pyroclastic flows) and thick tephra fall that could impact people on or immediately adjacent to the volcano were integrated into a near-volcano hazard zone, and zones depicting lahar and post-lahar sedimentation hazards were placed in a 'distal' hazard zone leading away from the volcano. Lahar arrival times on the Mount Hood map were not included because no other volcano contained a time dimension. The most significant scientific discussions led to abandoning probabilistic lahar hazard zones and adopting a red-to-yellow color gradient to indicate relative potential for inundation during a lahar event. Any lines on the parent maps that indicated lahar probability guided the application of color gradient as an approximate indicator of relative potential for inundation. The simplification process is illustrated in Fig. 2 in addition to explanations in the Discussion section. The open-mindedness and willingness of scientists to take a fresh look, to analyze all parent maps, and to develop logic for regrouping, deleting, or reclassifying hazards, were key factors in the efficacy of this simplification process. Multiple meetings were necessary to reach reasonable consensus even in the final stages of map making.

Emergence of a practical framework guides creation of simplified hazard maps

After regrouping of hazards, the process pivoted to applying the agreed upon framework to the construction of each of thirteen simplified maps. Authors and the

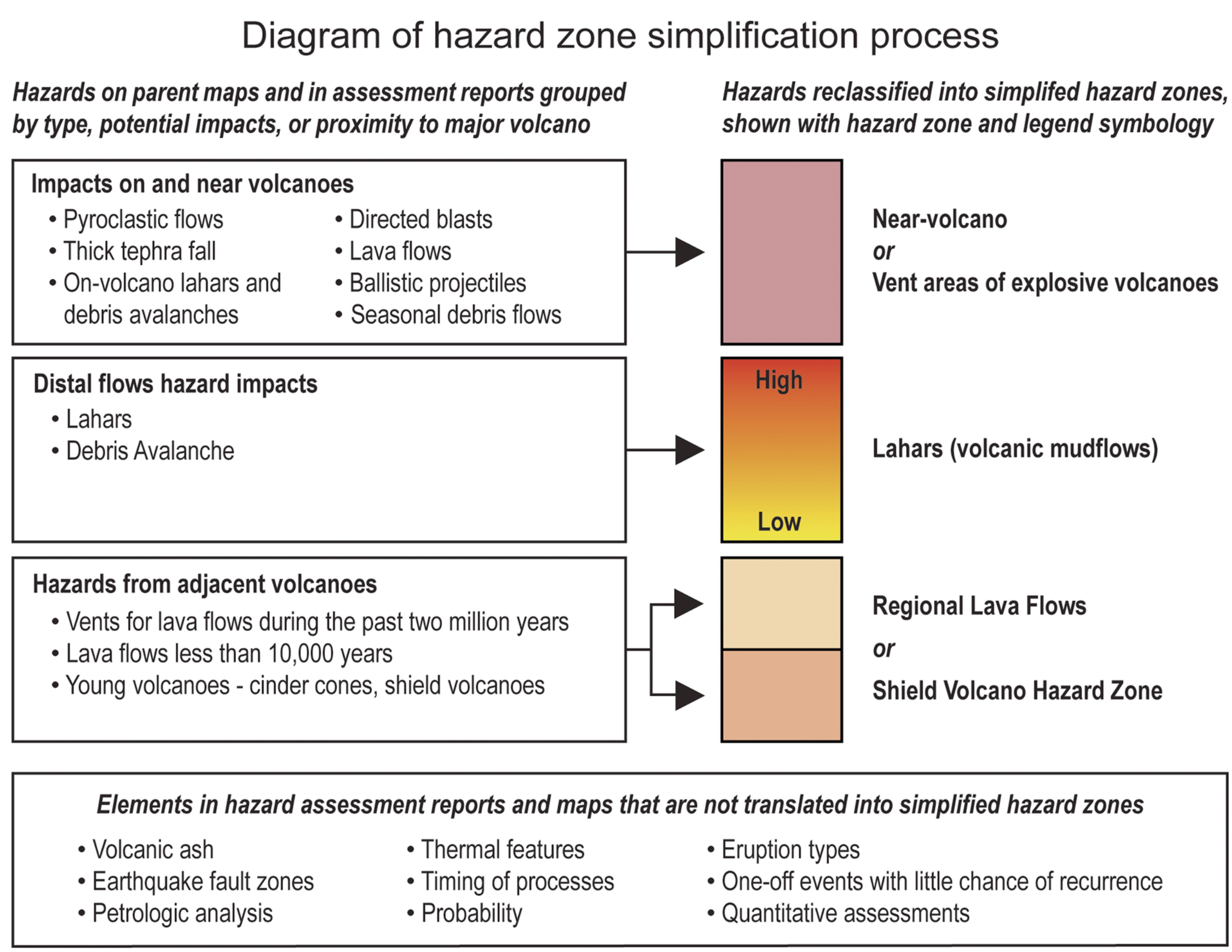

Fig. 2 The diagram provides a visual representation of the simplification process, illustrating how information in parent maps was filtered and regrouped, using the lens of the SOCO, to create simplified hazard maps

cartographer/illustrator followed a five-step process: 1) Examine parent maps to determine how to lump or split hazard zones; 2) identify and discard any zones that did not directly relate to volcano impacts; 3) for lahars, use existing boundaries based on probability or lahar volume along with professional judgment to render zones of relative severity using red to yellow color gradient; 4) follow map symbology criteria set forth by NPS interpretive media specialists; 5) identify landmarks or cultural features that could help to orient the viewer.

Geospatial data layers were exported from ArcGIS into Adobe Illustrator following the NPS's request for static maps for the exhibit. Using Adobe Illustrator, the cartographer/illustrator added separate layers for shaded-relief topography, selected rivers and lakes, key highways and secondary roads, map symbols and the simplified hazard-zone polygons derived from the parent maps. The process required continuous interactions and iterative reviews between the cartographer/illustrator, geospatial specialists, on-site observatory research staff, and authors of the original hazard maps. The process was greatly aided by participation of an experienced volcano observatory cartographer/illustrator who understood both agency requirements and artistic design.

Results

Application of the framework builds a series of thirteen simplified maps

Unlike the large-format parent maps, the small-format simplified maps can be imported to standard-sized documents. The current versions are posted at multiple locations on the USGS Volcano Science Center website, including multimedia galleries and on individual volcano webpages on U.S. Geological Survey 2022 with a link to the official parent hazard map. Figure 3 provides an example and description of map elements used for the NPS visitor center exhibit. The maps displayed in Fig. 4 illustrate the broad range of features that required attention in the simplification process. The 13 maps use consistent nomenclature and symbology.

Population centers and major transportation lifelines are labeled. Near-volcano hazards are integrated into a single mauve-color zone. Lahar hazard zones use a red-to-yellow color gradient to symbolize relative potential for inundation during a lahar, and zone boundaries are clearly visible, but are not shown with a perceptible boundary line. Tan represents regional lava flow hazards from dispersed events, and gray depicts lahar hazard zones from adjacent volcanoes. Details described in the Fig. 4 caption demonstrate the difficulties with simplification from disparate maps, and how unified zones and symbology are not always possible.

Socialization of maps into user groups elicits feedback

Enthusiastic reception to simplified maps

Soon after initial installation of the Mount Rainier exhibit, the maps went into widespread use in USGS oral presentations, informal exhibits, fact sheets (Dzurisin et al. 2013), a news media guidebook about hazards in Washington (Driedger and Scott 2010), school curricula (Driedger et al. 2005), and as website content. Frequent use and easy availability of these maps resulted in increased demand by external organizations. At this writing, both simplified maps and modified versions of the parent maps have been used in Comprehensive Emergency Management Plans (Washington State Legislature 1990; MRSC 2022), state agency webpages (Washington Geological Survey 2022), trainings, community hazard interpretive signs, and related county websites (Schelling et al. 2014; Ekse et al. 2015). Figure 5 illustrates the maps in use.

Following the tug of the audience by observing map-reading behaviors

In the years since the simplified maps were developed, feedback from map readers, gleaned from numerous informal conversations and more recent directed

(See figure on next page.)

Fig. 3 Visual comparison of an example parent map and simplified map graphic. **a** This figure displays a section of the Mount Hood parent hazard map. The published dimension is 0.83 m by 1.4 m. Advantages for use of the Mount Hood parent map are inclusion of critical distinctions between two proximal zones that correspond to a region of higher threat-probability (area in close proximity to the vent is shown in pink), and a lower-probability zone that is less accessible to the vent (shown in yellow); estimations of lahar travel times; thorough description of volcanic processes and related probabilities; and inclusion of hydrologic and hypsometric features. **b** This figure displays the Mount Hood simplified map with an explanation similar to that developed for the National Park Service exhibit. The simplified hazard map is commonly printed at scale of 0.28 m by 0.36 m. Its Near-volcano hazard zone includes lava flows, pyroclastic flows, thick tephra fall, rock avalanches and rockfall. Relative potential of lahar inundation is indicated as gradient from red to yellow. Tan designates areas subject to lava flows issuing from dispersed vents. Dark gray in valleys near top of map display lahar hazards from other volcanoes that intrude into the space of this map. Advantages of the simplified map include the exclusion of non-essential information including topographic contours and minor hydrographic features, a small format that allows viewers to gain a general sense of the area quickly, ease of viewing of hazard zones information and landmarks, and ease of placement within documents

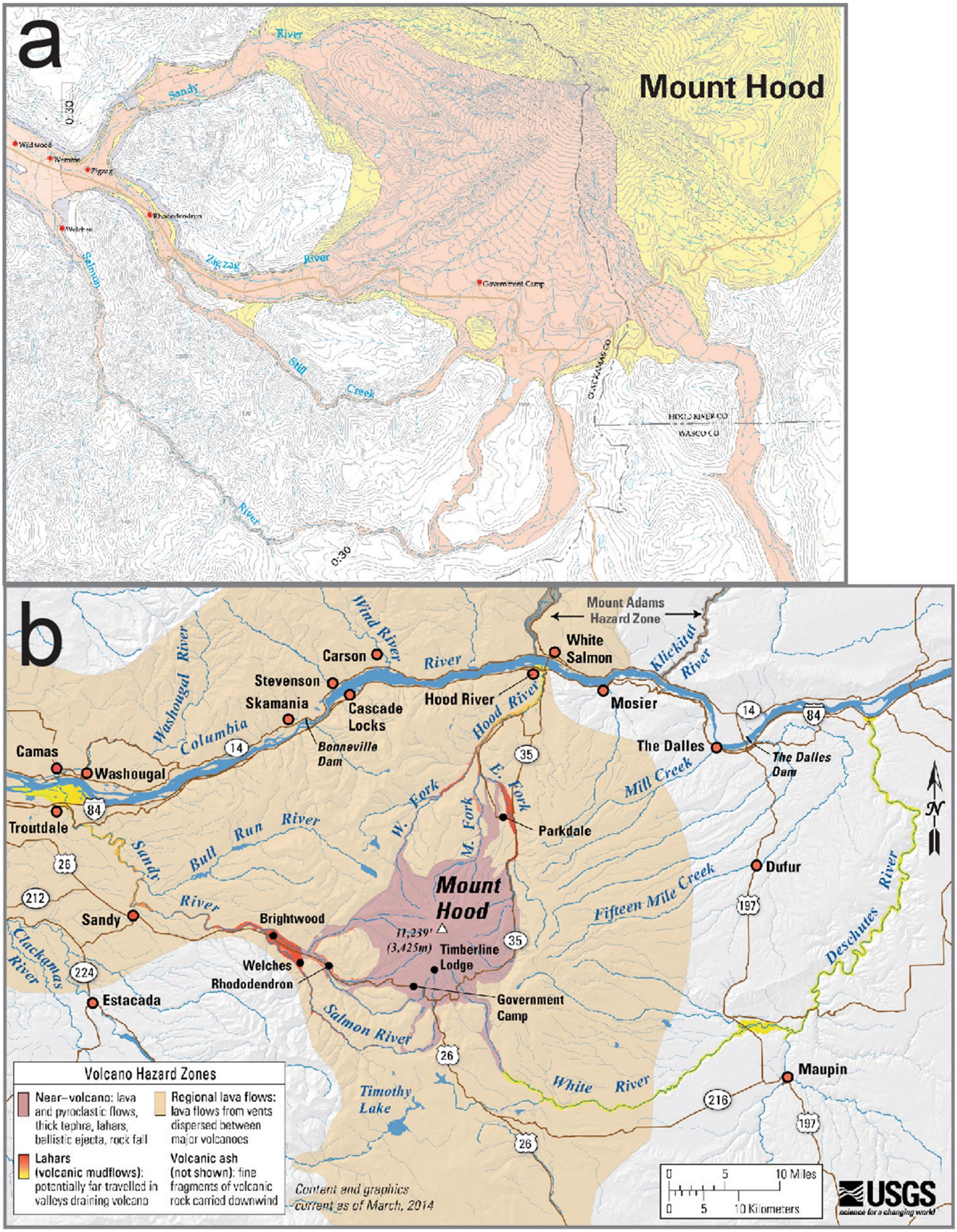

Fig. 3 (See legend on previous page.)

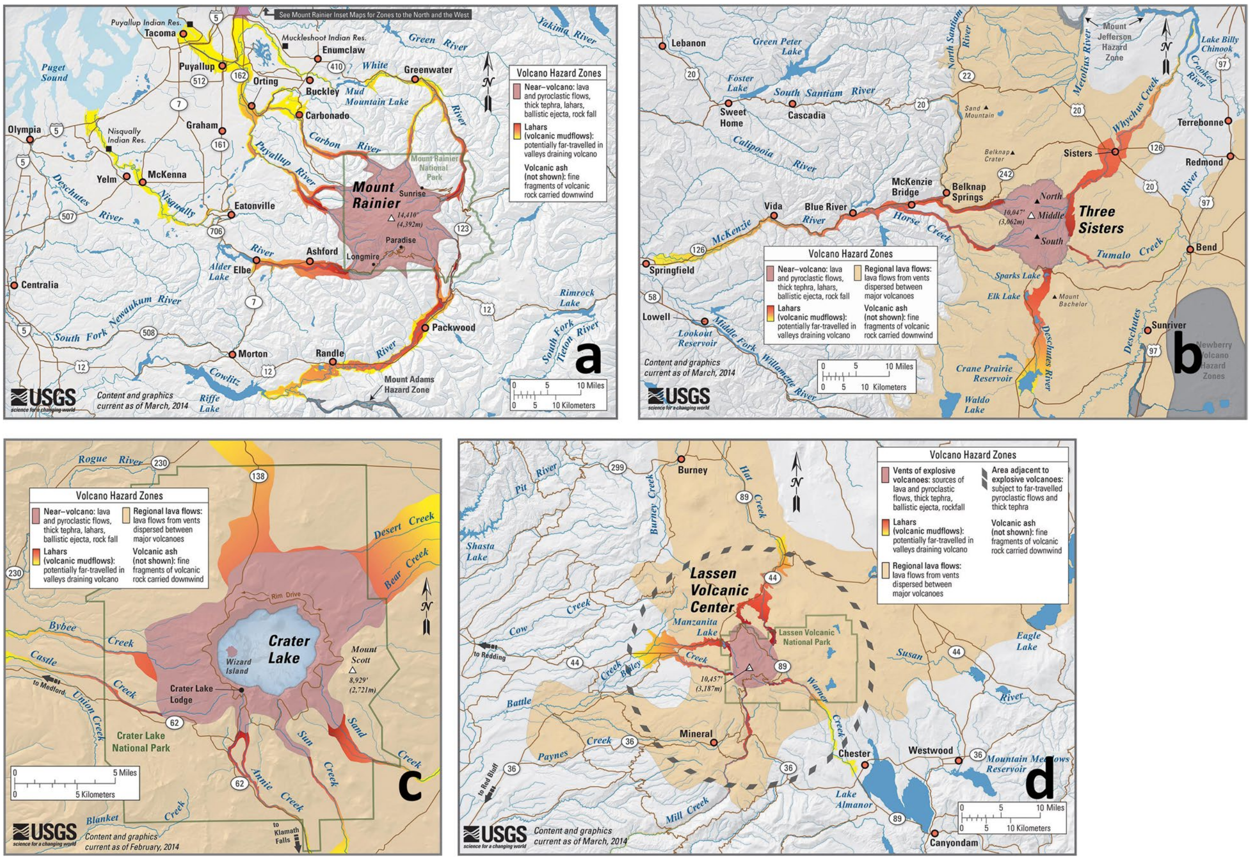

Fig. 4 Examples of simplified maps for four Cascade Range volcanoes show the variability that results after derivations from dissimilar parent maps. High-resolution versions are available at the website (U.S. Geological Survey 2022). Mount Rainier (**a**) shows color gradation of the lahar hazard zones based on detailed studies of lahar deposits. Three Sisters (**b**) displays color gradation of the lahar hazard zones based on LAHARZ-guided inundation modeling (Schilling 1998) and features an extensive regional lava flow hazard zone. Crater Lake hazards (**c**) exist well beyond the borders of both the parent and simplified maps. Reasons for limited areal extent are undocumented. Lassen Volcanic Center's simplified map (**d**) shows slightly modified hazard zonation style as compared to other simplified volcano hazard maps of Cascade Range volcanoes. This is due to greater complexities in this volcanic area that require more complicated representations on the parent map

inquiries, has informed current thinking about user needs for USGS volcano hazard maps.

Inter-agency meetings attended by emergency managers, with simplified maps taped on walls or spread upon tables, have been natural venues for gathering feedback about map usability, and potential modifications for delivery of risk-reduction messages. Additionally, USGS-hosted educator workshops, news media interactions, and public meetings have been rich sources for collecting feedback.

This feedback is mostly anecdotal, but some consistent themes have emerged. Users expressed that simplified maps are appealing because of their simplicity, vivid and uncluttered appearance, familiar landmarks, and consistent hazard representation. When viewed together, the maps are easy to compare. Teachers often ask for digital, interactive versions suitable for classroom teaching. Public audiences commonly request arrows indicating directions of lahar movement, estimated arrival times, and oblique views.

Public officials frequently state the needs for geospatial data. They prefer maximizing the number of cultural landmarks, including tribal lands, towns and communities, key infrastructure, and major roadways, and minimizing hydrologic and hypsographic features such as topographic contours and summit elevations, as exemplified by co-produced product aimed at news media (Driedger and Scott 2010). They request hazard-zone boundaries depicted with discrete lines, and not gradational regions at the margins of hazard zones. On the parent maps, an oft repeated refrain from emergency managers is: "I need a line on the map. You draw a line, or I will draw a line." At best the zonations support a scenario that is based upon events of the past or scientific projections of events that are most severe but reasonably expectable. Map zonation information must

Fig. 5 Demonstrated uses of simplified maps. **a** Maps displayed on a screen monitor engage park visitors at Mount Rainier National Park; (**b**) a vinyl lahar hazard floor map invites visitors to walk the valleys that are at risk from lahars; (**c**) enlarged paper copies facilitate discussion at a USGS-NPS teacher workshop; (**d**) Mount Rainier map is paired with risk mitigation measures on a community park interpretive sign to encourage awareness by residents in areas at risk from lahars; (**e**) map serves as a reference during an exercise of an emergency response plan at Washington Emergency Management Division; (**f**) local residents peruse the map and its implications during a training session in a community down valley from Mount Rainier. Photo (**a**) by P Wold NPS; (**b**),(**c**),(**d**),(**e**),(**f**) are USGS Photos by C Driedger

be scientifically supported for use in officials' legal documents, plans, exercises, and community mitigation efforts.

The red-to-yellow gradient representing the relative intensity of lahar impact provokes two common comments from casual observers who are non-specialists. The first comment: it doesn't matter what the hazard is—representing it with red means most intense and "dangerous." Although Haynes et al. 2007 reported that map readers view the color red to mean lava flows, this has not necessarily been the case with the simplified hazard maps, perhaps because of differences between the hazard context of Haynes' study area, Montserrat, and the Cascade Range volcanoes. A second frequent comment is that all that map users really care about is whether an area on the map is deemed "safe" or "unsafe." Here, we urge mapmakers to carefully consider unintentionally overrepresenting the safety of a particular area. For example, areas outside of lahar hazard zones may not be a refuge from volcanic ash or proximal hazards of unforeseen magnitude, or of hazard types that are beyond the scope of the simplified maps' objectives. The safe/unsafe call depends on a given situation. Thompson Clive et al. 2021 noted a similar desire for map representation of safe areas, and that providing auxiliary text can impart more nuanced information about relative safety.

In 2021, CVO partnered with the University of Tennessee User eXperience Laboratory to take a more directed approach to studying comprehension of some Cascade Range simplified maps for agency-internal guidance. Overall, the study found participants understand the map portrayal of the hazards, but simple changes to the legend and color palette could improve map readability. Importantly and within our expectations, the study found that full comprehension of the maps requires adjacent descriptions of the volcano hazards and impacts. For fullest comprehension, the simplified hazard maps do not stand alone well and require annotation and auxiliary information to provide context. (Volentine 2021).

Discussion

This article has focused attention on simplified maps made by distilling essential information from parent maps. Here, we discuss some key considerations for hazard mapmakers.

Simplified maps serve as conversation starters

The simplified maps have proved a valuable tool for promoting conversations between observatory staff and map users and served as an entry to discussions about volcano hazards in the Cascade Range. Notably, in teacher workshops and regular meetings with public officials where informal feedback was obtained, almost all participants said that the maps are valuable to their profession. In many jurisdictions, public officials are accustomed to working in close partnership with scientists while developing and exercising Volcano Coordination Plans, co-producing outreach products, and jointly participating in community outreach events. By extension, they view themselves as deserving a voice in product development rather than simply as recipients of USGS information. We note that ongoing conversations with agency partners about their map and graphics needs are strengthening our commitments to working together for development of successful mitigation efforts.

As community conversation starters, simplified hazard-maps have been installed as central points of attraction in park and community interpretive signs, exhibits, brochures, videos, and in presentations, as seen in Fig. 5. Maps can be understood more fully with the aid of companion images, graphics, videos, and text (Dallo et al. 2020, 2022), especially those that are aimed at a carefully identified target user groups (Opach and Rød 2022). Providing the map user with information context, and with a search task such as 'Find your location' or 'Find the path to safety' directs reader attention and reduces cognitive load (Thompson Clive et al. 2021). For the purpose of informing visitors about hazards and zones to safety, the Japan Meteorological Agency (2016) noted in Ogburn (2023), recently created a semi-standardized series of simplified hazard maps for use in visitor safety leaflets. Figures within Lindsey et al. (2023) demonstrate various geospatial depictions of hazards developed for geopark visitors. Regional institutions create simplified maps and graphics germane to their own populations, although these products may gain minimal international attention, as exemplified in Martinez-Villegas (2013).

Intentional map messaging and sharing of worldviews

A mapmaker should explore the elements required for map clarity and user purpose and provide intended users with a grasp of the relevant science necessary for informed decision making. In an overview of the roles of maps through previous centuries, Freundschuh (2009) noted that the mapmaker seeks to communicate a purposeful message, and that success results in the map reader sharing the 'worldview' of the mapmaker. We assert that hazard maps should be developed based upon a well-considered message, which in our simplified maps emphasizes distal travel by lahars, and collective representation of near-volcano, ground-based hazards.

Development of a map message requires information culling in support of the over-arching message. This approach is common in communication professions. Park interpreters identify 'The Big Idea' (Serrell 2015) and develop text and graphics based upon a theme, which captures and delivers a single whole idea textually and visually (Ham 1992, 2013). Educators identify Core Ideas and Crosscutting Concepts in US Next Generation Science Standards (The National Academies 2013). Emergency communicators require information about threat characteristics, timing, and impacts, which they can pair with preparedness information and for development of Whole Community Strategic Themes (Homeland Security 2011); the traditional news media requires distilled information that is new, meaningful and relevant (Driedger and Westby 2020). While the SOCO methodology was conceived for addressing the needs of the news media (Parventa et al. 2018), its concepts provide a novel and intentional methodology useful for volcano hazard map cartography.

The case for a diverse portfolio of maps to meet user needs

Simplified maps provided scientists with an opportunity to make spatial volcano hazards information approachable to non-specialist audiences. However, there are compromises with this approach and mapmakers should be keenly aware of their audiences' needs and contexts when deciding whether compromises are warranted. Some communication opportunities afforded by simplified maps are: presenting information with reduced complexity to deliver a general sense of the hazard zones and to draw the attention of casual viewers (e.g., a park visitor); maps can be designed to emphasize hazards of importance to any distinct user group (e.g., a populace at high risk); users do not need to understand complex terminology to comprehend basic map objectives; when viewed together, hazard zonations at multiple volcanoes can be visually compared; maps are easily integrated into products that offer additional context.

Parent maps containing additional complexity and explanations tell a fuller story. As noted on Fig. 3a, the last two eruptive periods at Mount Hood chiefly affected only the higher probability zone and two principal river valleys, as is likely during future eruptions. Elimination of probability zones removes this critical detail that remains important for some specialized audiences. Public officials' legal documents require direct references to scientific documents that describe justifications for zonations; large-format maps containing topography, hydrology, structures, intricate hazard boundaries, and zones of equal probability can provide informed viewers with broad knowledge of direct and indirect impacts and event likelihood; secondary inset maps and graphics may display estimates of hazard timing and probabilities, and information about previous eruption deposits, and hazards from airborne ash and distal ashfall. Terms, definitions, and in-depth scientific explanations may be available in an adjacent text report or added to the larger maps.

We contend that a near-simultaneous development of parent maps, simplified maps, and potentially other specialty products in a portfolio of products can capitalize on this broad gradient of user needs and can accommodate specialists and non-specialists at multiple stages of their understanding, from gaining general senses about the hazards, through decision-making in a crisis. Thompson Clive et al. 2021 concluded that maps with integrated-hazard areas can capture early attention and encourage deliberate thought processing in casual users who have limited familiarity with rare natural events. The integration reduces reliance on working memory capacity. Integrated maps can be useful during pre-crisis and early crisis stages, but as a hazardous event progresses, maps with discrete zones for individual hazards might be more effective in raising comprehension about the timing, character, and uncertainties associated with each process.

Building a foundation for user engagement in mapmaking

Mapmakers' initial efforts can benefit from identification of as many potential user groups with common purposes and communication needs as possible and by seeking input iteratively, from the beginning and throughout the mapmaking, and potentially from the onset of research project design (Fischhoff 2013). They can be guided by tenants of Participatory Science (Nowotny 2003; U.S. Geological Survey 2021) with a range of engagement options, from consultations with stakeholders to co-production of materials. Mapmakers should acknowledge the breadth of professional cultures, mindsets, and technical languages of users (Newhall 2017; Slotterback and Lauria 2019).

In practical terms, input is obtainable through informal conversations, semi-structured interviews, emergency response exercises, and study frameworks based upon map objectives, as exemplified by Thompson et al. 2015; Haynes et al. 2007; Dransch 2010, and many others. Use of SOCO principles (Parventa et al. 2018), and user-experience design tools such as personas and journey maps can outline the demographic and journey of the user's experience (Howard 2014). Throughout the mapmaking process, reviews are possible through iterative testing and usability studies as exemplified by the Agile User X Design process (Gothelf and Seiden 2016; Volentine 2021). Collaborative approaches might involve social scientists, a skilled cartographer with knowledge of artistic design, volcano specialists, and representatives of user communities. We assert that a hazard map can be developed mutually by scientists and users and hold its scientific integrity. To this end, Grant 2021 recommends that every creative group build a 'challenge network' of trusted associates to point out blind spots, and present critical feedback during a design process. All mapmakers should be mindful of findings of Fischhoff 1995, who identified common stages of scientist-user interactions and advocated for direct contact with users at project initiation.

One challenge to building a foundation for user engagement in mapmaking is the top-down approach that ignores local knowledge and needs. This awareness has encouraged formalization of community-based methodologies termed broadly as Participatory Mapmaking. Organizers engage with inhabitants to create a map with meaningful visual associations of their landscape (Gaillard and Dibben 2008; Thompson et al. 2015, Cadag et al. 2017; and Thompson Clive 2021). Resulting maps contain information that is important and relevant because it can assign spatial attributes that formal mapping and planning might not identify, as recognized by Cronin et al. 2004; Cadag et al. 2017; Andreastuti et al. 2017. The participatory process can produce critical reflections about risk-related solutions (IFAD 2009; Pappalardo 2017). Similarly, the U.S. Homeland Security Whole Community Approach (Homeland Security 2011) embraces the collective experience approach in development of strategies for community risk mitigation. Participatory mapmaking, accomplished at multiple scales and with various audiences, might be the lever that moves mapmakers from accepting simple nods of user approval, to creating maps designed with intention that effectively address users' expressed criteria for information needs.

An abundance of guidance awaits future mapmakers

Our simplified map project relied upon guidance from the NPS professional interpretive product specialists and our knowledge of their statutory requirements and best practices (Tilden 1957; Ham 1992, 2013; Serrell 2015). Since then, we have observed a plethora of research contributions that offer guidance for creation of both simplified and more in-depth volcano hazard maps. Volcano hazard map source books exemplified by Crandell et al. 1984, and the massive assemblage of hazard maps in the IAVCEI hazard map data base (IAVCEI 2018; Ogburn et al. 2020) can suggest ideas. Contributions by previous researchers (e.g., Haynes et al. 2007; Thompson et al. 2015; Thompson Clive et al. 2021; Lindsay et al. 2023; Ogburn et al. 2023) offer general principles and recommendations for map representation. In broad studies about the use of color gradation, red is recognized as indicative of danger, orange warning, yellow caution, and green is safe (Hupka et al. 1997). Olson and Brewer 1997 offered guidance for adjusting colors to aid users with color vision deficiency. Bostrom et al. (2008) demonstrated that the most effective color representation occurs with light-to-dark hues representing low-to-high values. Color is broadly acknowledged as making a map more vivid and understandable (Haynes et al. 2007; Severtson and Vatovic 2012); Thompson Clive et al. 2021). Color imbues a map with psychological meaning as noted by Severtson and Vatovic (2012). Use of color and the display of protective structures can change how viewers characterize a hazard (Lahr and Kooistra 2010). Preppernau and Jenny 2015, 2016 showed the merits of three-dimensional map views and the representation of hazard arrival times as point markers and isochrones. Pederson et al. 2005 observed in classrooms that, while most new maps are now consumed online, paper maps facilitate observations of map features, offer a tactile experience, and increase potential for group interaction. Fabrikant et al. 2012 explained the emotional impact of map design aesthetics. Gardiner 2015 and Charlton 2018 illustrated how inclusion of political borders on maps can influence risk perception.

Social scientists and natural scientists share common goals for improved communication, and working together can continue to improve risk reduction products (Barclay et al. 2008; Fischhoff 2013). We encourage volcano observatories and academic institutions to publish articles about their mapping experiences as exemplified by Nave et al. 2010; Leonard et al. 2014; Charlton 2018.

Broad insights about creating usable hazard maps

Mapmaking organizations face a mounting compendium of volcano information coupled with ever-increasing data complexity. Growing use of probabilistic and statistical information challenges the map users' capabilities at new levels. This trend toward increased complexity of available scientific data illustrates the need for careful deliberation and restraint when developing the scope of information to be presented. It requires identification of key map messages through use of a SOCO or similar methodology, and inclusion of map features that address stated user needs. In our situation, creating a sequence of simplified maps of similar appearance was a challenge owing to the many individuals involved over nearly two decades of work, using similar but differing approaches.

We acknowledge that differences in map-reading abilities and user needs make it difficult to find a perfect scheme for representing volcano hazards. Some misinterpretation is inevitable because map reading is a skill that is informed by each reader's context and experience. Akella 2009 found that even trained emergency responders could not come to consensus on the meaning of some map symbols. Regardless of scale, users require maps that are intuitive, functional, and meaningful to their lives. Users must have the ability to decode mapped information and to identify, interpret, and understand the volcano information presented (Haynes et al. 2007) with sufficient context to reduce the possibilities for misinterpretation (Thompson et al. 2015).

Divergent views from scientists and stakeholders highlight the persistent tension between complex and less-complex versions of maps. Therefore, mapmakers should anticipate that for each relevant user group, an iterative process will be required to answer questions like "How much information should be on the map?" and "What is the right information to have on the map?" In all situations, maps must be clear, illustrative, and geared to the concerns of the intended users. A portfolio of one or more derived maps and Geographic Information System (GIS) map layers with visually comparable elements might be the ultimate solution to providing users with the ability to create their own need-specific maps.

Additionally, we recommend organizations be proactive in releasing and socializing geospatial map layers from hazard investigations and model outputs to ensure data are easily accessible for other mapmakers. Recall the lesson learned when USGS chose initially not to make an official derivative hazard map. The void was filled by some competing unofficial maps.

Conclusions

This article offers two clear examples—1990s-2000 parent maps and 2009-era simplified maps—of user groups driving aspects of the mapmaking process. While mapmakers can spend years in discussion about optimal input and map representations, quickly expressed requests from stakeholders, legislative mandates, and the progression of natural events quickly can drive the timing, content, and appearance of hazard maps.

Conscientious forethought can improve scientists' readiness for rapid mapmaking. We advise mapmakers in all hazard disciplines to analyze and hone messaging using SOCO principles during mapmaking. Employ the concepts of User-centered Design (Gothelf and Seiden 2016) in map development. Conduct interviews and assemble a list of products where the maps will be used. Examine maps in the repository established by the IAVCEI Commission on Hazards and Risk (Calder et al. 2015; IAVCEI 2018; Ogburn et al. 2020; Lindsay et al. 2023). Hazard maps are most usable when they are contextualized as the central piece within an ensemble of graphics, pictograms, text, and invitation for the reader to engage in a map-reading task. Simplified maps do not replace parent maps but support the common purpose of reaching multiple audiences in the cause of promoting risk awareness.

We end this discussion with distilled comments that can serve as broad guidelines. Scientists and mapmakers do not need to 'guess' what users want and need; they can work closely and employ existing methodologies for translating user needs into map design. Examine the experiences of other mapmakers; prioritize map content; involve map users in the map-making process; and become familiar with best practices for map readability. Finally, no one volcano hazard map can meet the needs of all users; sometimes scientists must reexamine their highly technical maps and distill the abundant detail into versions that are guided by a single communication objective to present the most essential hazard information clearly and simply.

Abbreviations

CalOES	California Office of Emergency Services
CVO	Cascades Volcano Observatory
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior
MRSC	Municipal Research and Services Center
SOCO	Single Overriding Communication Objective
USGS	U.S. Geological Survey
NPS	National Park Service

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Authors' contributions

Carolyn Driedger, David Ramsey, and Joseph Bard wrote the manuscript text and created figures and tables. William Scott was a principal participant in the development of some parent maps, the map-simplification process, and he had oversight of map production. He provided valuable insights for this article. Cartographer/Illustrator Lisa Faust used professional judgment in creating map vividness and readability in the rendering of these maps. Patti Wold from the National Park Service is the Interpretive Media Specialist who originated the map request. All authors reviewed the manuscript.

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Declarations

Competing interests

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