Communication and Education Strategies to Raise Awareness and Understanding of Volcanic Hazard During Times of Quiescence: A Literature Review

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Abstract. This scoping review examines peer-reviewed research on volcanic hazard communication during periods of quiescence, when immediate crisis pressures are absent but opportunities for long-term preparedness are substantial. While much existing work focuses on communication during eruptions or in specific regions, we examine how volcanic hazards are communicated when a volcano is quiet, a time suited for building awareness, understanding, and sustained public engagement. We reviewed relevant studies and grouped 76 resulting articles into three categories: formal educational materials, informal communication approaches, and informal communication tools. Within the reviewed literature, common themes include clear and accessible language, participatory strategies, and trust built through two-way communication. These themes align with broader science and risk communication research, which emphasizes that effective communication requires more than the delivery of accurate scientific information. Rather, communication during quiescence should be locally relevant, responsive to audience needs, and connected to preparedness actions, while also building familiarity with long-term risk, scientific uncertainty, preparedness actions, and trusted information sources. Few reviewed studies evaluate communication effectiveness, and existing research is geographically uneven, highlighting important gaps in volcano-communication research. This review adds to the literature about how volcanic hazard communication during quiescent periods can support hazard awareness and understanding, and it also highlights the need for more evaluated, participatory, and context-specific strategies that help scientists, educators, communicators, and decision-makers strengthen preparedness before unrest or eruption occurs.

1 Quiescence: A Communication Opportunity

Communication of geohazards requires translating complex, often uncertain, and technical information into messages that help people understand risk, prepare before events occur, and take appropriate action when conditions change. These geohazards include earthquakes, tsunamis, landslides, volcanic eruptions, and related processes, each of which can affect different audiences across different timescales, warning systems, spatial footprints, and social contexts. Because the timing, predictability, uncertainty, and available protective actions vary between hazards, communication strategies cannot be assumed to transfer unchanged from one geohazard setting to another or even within a given geohazard across social and cultural contexts. Natural hazard risk communication research emphasizes that communication should be adapted to the hazard type, audience, decision context, and phase of the risk cycle (Höppner et al., 2010; Doyle & Becker, 2022).

Volcanic hazards represent one specific context within this broader geohazard landscape, and communication needs vary across stages of volcanic activity, including quiescence, unrest, eruption, post-eruption, and recovery (Becker et al., 2024; Das et al., 2025). This variation is partly driven by the contrasting timescales of volcanic systems: volcanoes develop over vast geologic timescales, yet individual eruptions and periods of unrest can unfold abruptly, disrupting landscapes, infrastructure, livelihoods, and communities. Communities may therefore live with volcanic risk for generations without experiencing an eruption, but when unrest begins, decisions may need to be made quickly, and preparedness and planning efforts should already be in place.

Quiescent periods are important because they provide time for communication before the pressures of crisis. During unrest or eruption, communication often must focus on immediate warnings, rapidly changing information, and urgent protective actions (Barclay et al., 2008; Bretton et al., 2018). These circumstances require clear, timely, and action-oriented messages that respond to immediate information needs (Mileti & Sorensen, 1990; Sutton & Kuligowski, 2019). During quiescence, communication can instead support longer-term goals: building baseline awareness of volcanic processes and hazards, developing relationships between scientific institutions and the public, understanding audience needs, strengthening trust in information sources, and helping communities prepare before decisions become time-sensitive. These quieter intervals are critical opportunities for sustained education, engagement, and preparedness, and can contribute to more informed decision-making, enhance public trust, and foster cooperation when future crises arise (Stone et al., 2014; Weichselgartner & Pigeon, 2015).

Broadly, science communication and risk communication research provides an important foundation for understanding volcanic hazard communication during quiescence. While an overview or synthesis of these large bodies of literature is beyond the scope of this paper, there are key elements that can inform the context of volcanic hazard communication. Early approaches to science communication often reflected a deficit model, in which experts assume that the public primarily lacks scientific knowledge and that providing more information will lead to better understanding, acceptance, or action. However, science communication research has increasingly recognized the limitations of this one-way model and focused on approaches that recognize context, audience needs, local expertise, and public participation (Bauer et al., 2007; Brossard & Lewenstein, 2010). Similarly, risk communication has evolved from focusing on producing accurate risk estimates to recognizing that audiences need information that is understandable, decision-relevant, and connected to opportunities for engagement or participation in risk management (Fischhoff, 1995; Bostrom, 2014). These approaches and bodies of literature recognize the role of accurate scientific information; however, they also recognize that information alone is rarely sufficient when people are asked to understand uncertain risks, evaluate preparedness actions, or trust institutions responsible for public safety.

Risk communication literature further emphasizes that effective communication must address what audiences actually care about, not only what experts think they need to know. Public response to risk is shaped by values, prior experience, social context, trust, perceived control, uncertainty, and the credibility of the information source (Frewer, 2004; Kasperson, 2014). These factors influence how people interpret risk information and whether they view it as relevant, credible, and useful for decision-making. Rather than treating uncertainty, public concern, or disagreement as barriers to communication, risk communication research highlights the need to understand how different audiences interpret uncertain information, what concerns they want addressed, and what kinds of information are useful for the decisions they face (Frewer, 2004; Kasperson, 2014). Kasperson (2014) further argues that successful risk communication often requires persistent, long-term effort rather than a small communication push at the end of a technical assessment. These lessons are directly relevant to volcanic hazards, where communication and education efforts seek to raise awareness, explain uncertain future activity, support preparedness, and build trust before crises occur (Mossoux et al., 2016; Urlaub et al., 2013; Bandecchi et al., 2019).

Eruptions are often infrequent, uncertain, and unfamiliar to exposed communities. For low-familiarity hazards, people may have limited direct experience to guide preparedness decisions and may rely more heavily on trust in the agencies, scientists, and communicators providing information (Paton, 2007). This makes quiescent periods especially important. They provide time to build relationships, understand audience needs, develop trust, and support readiness before unrest or eruption increases uncertainty and urgency. Community Engagement Theory similarly suggests that preparedness communication is more likely to support action when it builds outcome expectancy, community participation, collective efficacy, empowerment, and trust, rather than simply delivering information to passive audiences (Paton et al., 2024). Despite this importance, quiescent periods remain less directly examined in volcanic hazard communication syntheses.

Previous syntheses of volcanic hazard communication have largely focused on periods of volcanic crises or on specific geographic regions, leaving quiescent periods underexplored. Similarly, the American Geophysical Union volume *Observing the Volcano World: Volcanic Crisis Communication* compiles many of these case studies and lessons learned from major volcanic events but remains centered on periods of elevated volcanic activity.

Barclay et al. (2008) reviewed risk communication during volcanic crises and emphasized the need to integrate social and physical sciences in volcanic risk communication. They highlight that communication during quiescence differs from warning-focused crisis communication because it must build awareness and motivate risk-reducing behavior before public attention is heightened by unrest or eruption. They also note that, although scientific information has a clear role in disaster risk reduction, less is known about the most effective strategies for communicating volcanic risk during quiet periods.

Subsequent reviews have focused more directly on communication at the hazard-risk interface during periods of volcanic unrest. Bretton et al. (2018) argue that hazard communication should be iterative, structured, and guided by standards that promote contextualization, which they define as "the negotiated product of open and transparent deliberation with stakeholders for the purpose of their risk-related uses" (p. 12). In this framing, effective communication requires meaningful deliberation among scientists, authorities, and the public so that hazard information is relevant to stakeholder needs and decisions.

More recent work has begun to identify research gaps across the full spectrum of volcanic activity. Das et al. (2025) review volcano communication in New Zealand and find that most studies focused on communication during eruptive periods and quiescence while neglecting unrest and post-eruptive stages. They call for more research on how decision-makers use volcano-related information from different periods of activity and for broader documentation of existing practices. In their review, they find that evaluative studies are mostly concentrated on emergency communication, warnings, and response, leaving a need for further examination of how communication during quiescence can support long-term preparedness.

A broader natural hazards synthesis by Graf et al. (2026) further supports the need to distinguish communication strategies by hazard type, temporal context, and communication goal. Their scoping review categorizes risk communication strategies across short-term warnings and long-term adaptation using the goals "Act," "Prepare," and "Aware." They find that strategies vary across hazard groups, that geophysical hazards are commonly addressed through hybrid approaches combining warning and preparedness, and that purely long-term communication strategies are rare despite their importance for resilience. This reinforces the need to examine volcanic quiescence specifically, as quiet periods are when long-term awareness, preparedness, and trust-building must occur.

This study builds on this work by focusing specifically on volcanic hazard communication and education during periods of volcanic quiescence, when immediate crisis pressures are absent but opportunities for long-term preparedness are substantial. We examine how volcanic hazards are communicated when a volcano is quiet, a time suited for building awareness, understanding, and sustained public engagement before unrest or eruption occurs. This scoping review clarifies how volcanic hazard communication during quiescent periods can support hazard awareness and understanding, while also identifying the need for more evaluated, participatory, and context-specific strategies that help scientists, educators, communicators, and decision-makers strengthen preparedness before future volcanic crises.

2 Methods

This study uses a scoping review approach to characterize peer-reviewed literature on volcanic hazard communication during periods of quiescence. Grant and Booth (2009) describe a scoping review as a preliminary assessment of the potential size and scope of an available body of literature, intended to identify the nature and extent of the existing evidence. This approach is

appropriate because communication during volcanic quiescence spans diverse study types, audiences, settings, goals, and products. Munn et al. (2018) note that scoping reviews can be useful for reporting "on the types of evidence that address and inform practice in the field and the way research has been conducted" (p. 2). Our purpose is not to synthesize evidence on the effectiveness of a defined intervention, as in a systematic review, or to critically evaluate the quality of the literature and develop a new conceptual model, as in a critical review. Rather, this review characterizes the peer-reviewed literature with a focus on one dimension of volcano communication literature and identifies areas where further volcano-specific research and evaluation are needed. The review was designed to examine what peer-reviewed literature exists on volcanic hazard communication and education during periods of quiescence; which audiences, geographic settings, and communication goals are represented; what recommendations and limitations recur across the reviewed studies; and the extent to which the strategies suggested have been empirically evaluated. These questions guided the selection of search terms related to communication, engagement, outreach, education, public awareness, audiences, and volcanic settings. This review is not intended to provide an exhaustive assessment of all volcanic hazard communication or broader risk and science communication literature; rather, it maps the quiescence-focused studies captured by our search terms and inclusion criteria. Consequently, relevant strategies discussed primarily in crisis, unrest, warning, or response literature may not be included, and the absence of a topic from the reviewed studies does not indicate it is absent from the broader hazard communication literature.

We conducted the scoping review in consultation with a university research librarian to develop and refine the search strategy. Our search strategy emphasizes terms related to communication, engagement, outreach, education, and public awareness in connection with volcanoes, while excluding studies focused on crisis communication:

[AB (communicat* OR engag* OR outreach OR educat* OR "public awareness") OR TI (communicat* OR engag* OR outreach OR educat* OR "public awareness") OR SU (communicat* OR engag* OR outreach OR educat* OR "public awareness")] AND [AB volcan* OR TI volcan* OR SU volcan*] AND [public OR audience OR resident* OR stakehold* OR communit* OR student* OR indigenous* OR touris* OR curricul* OR tool] NOT crisis (TI)

The primary author searched five databases: GeoRef, Web of Science, ERIC, Academic Search Premier, and the first 100 results from Google Scholar on August 5th, 2024. All references were uploaded to Covidence (Covidence systematic review software, 2024). After deduplication, the search yielded 1,222 results (Figure 1). Following recommendations from Peters et al. (2020), the authors first pilot tested the screening process on 25 articles to ensure that the screening criteria were being interpreted consistently. After confirming consistency in the application of the criteria, two authors independently screened the remaining abstracts and full texts against the inclusion criteria outlined below, resolving disagreements through discussion. After all screening was complete, 76 articles were selected for inclusion in this review.

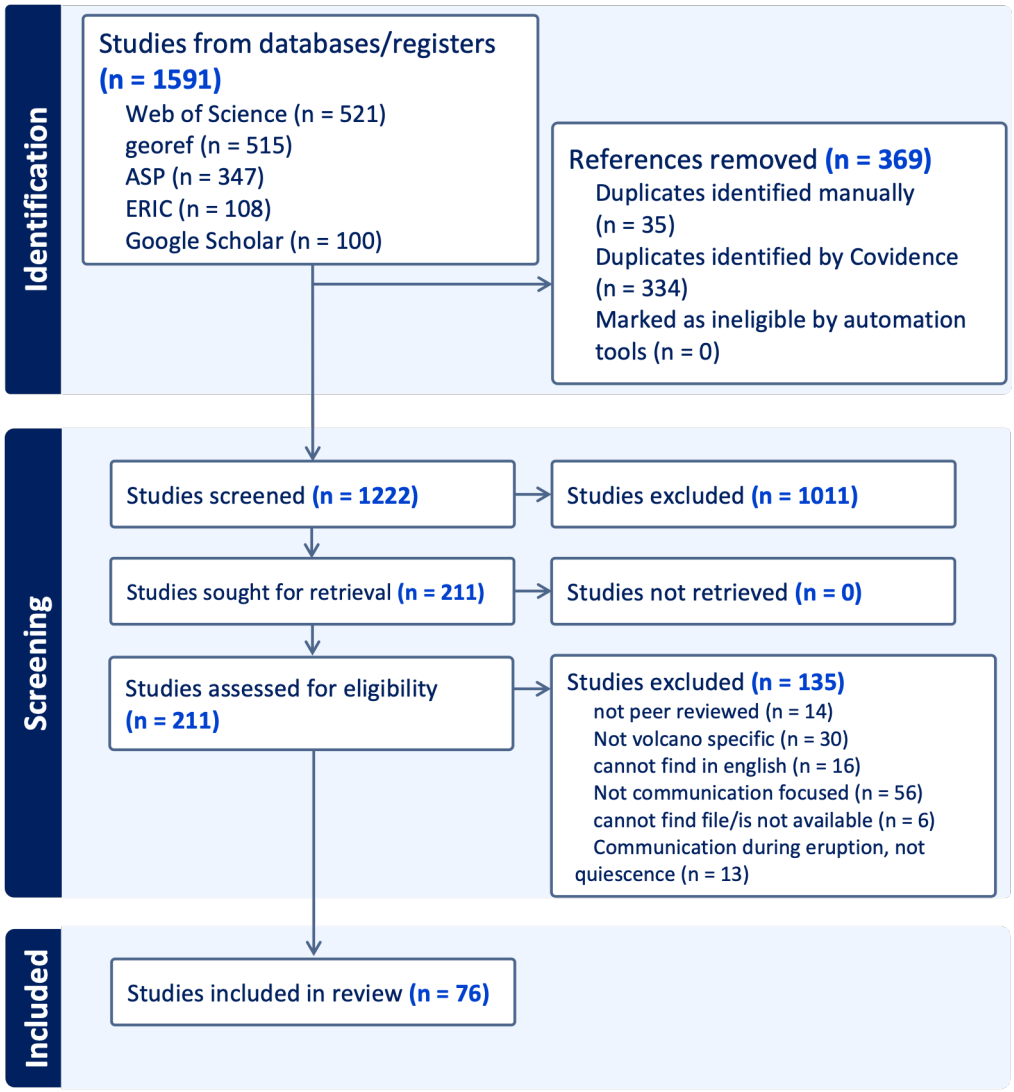

Figure 1. PRISMA diagram of screening process.

We bound the review by specific inclusion and exclusion criteria, filtering for articles that are peer-reviewed, volcano focused, and concerned with communication during quiescence. During screening, we interpreted education and communication broadly, while excluding crisis-specific efforts. For inclusion, the article must be:

1. Published after 1980
2. published in a peer-reviewed academic journal or as a book chapter
3. Describing a tool, approach, or communication system; not another volcanic hazard communication synthesis
4. Communication-focused, and must explain a technique or tool (this can include educational tools or communication tools)
5. Volcano-focused, about communicating volcanic hazards (educational material must have volcano-specific recommendations)
6. Not focused on workforce development (STEM careers)
7. Not a communication approach for crisis situations (unrest and eruption phases)
8. Not a personal perspective piece
9. Not an ashfall, air quality, water quality, or other public health study

For each of the 76 final articles, the first author cataloged key aspects of the study. These include the article's authors, institutional affiliations, volcano or region of focus, study objectives, major findings, and any explicit recommendations.

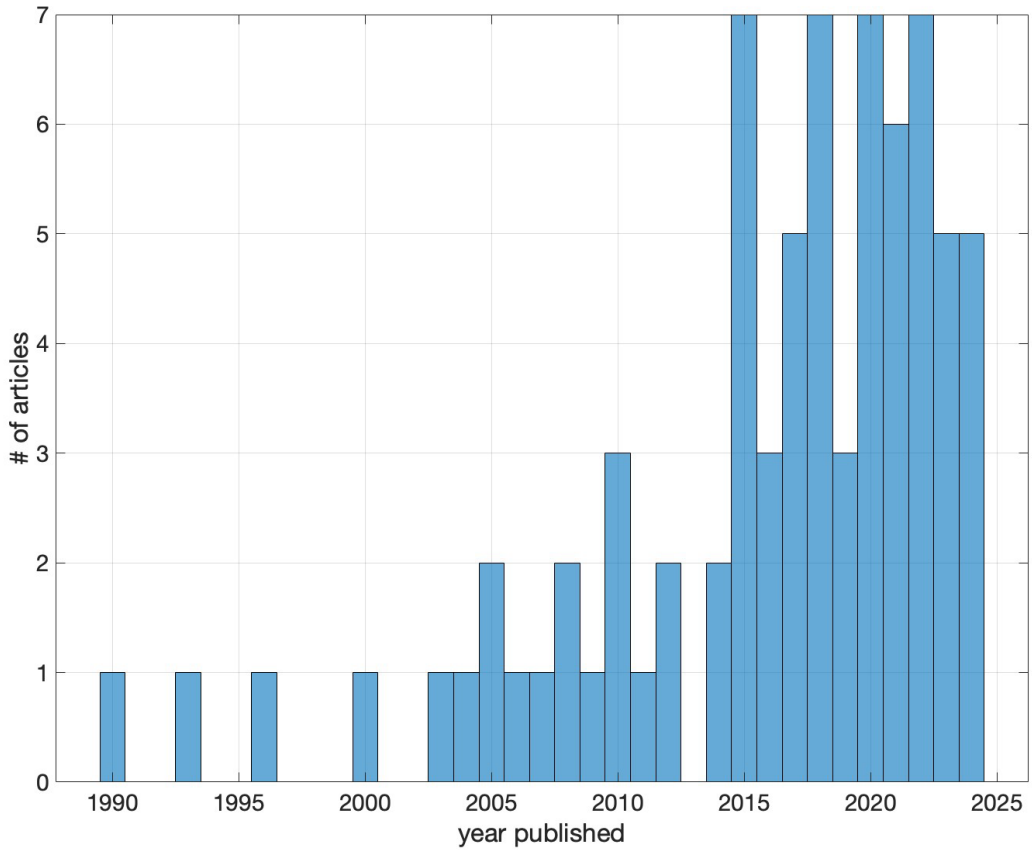

Figure 2. Distribution of publication years for the 76 articles included in this review. Articles published before 1980 were excluded during the database search. The literature search was completed on August 5, 2024.

To organize the reviewed literature, we drew on distinctions between science education and science communication. Researchers have noted areas of overlap and divergence in the two fields' histories, operationalization of key concepts, goals, and approaches (e.g., Baram-Tsabari & Osborne, 2015; Lewenstein, 2015; Kohen & Dori, 2019); Baram-Tsabari and Osborne (2015) describe science education as learning that occurs in formal and informal environments, and science communication as interactions between the scientific community and diverse publics. They note that science education is often oriented toward learning and understanding, while science communication more often emphasizes engagement, interaction, and exchange. Because the reviewed articles included both structured classroom materials and broader public-facing communication efforts, we grouped the studies into three categories: formal educational materials, informal education and communication approaches, and informal education and communication tools.

1. Formal educational material refers to any structured resource or program designed for use in a classroom or other formal learning environment, such as curricula, lesson plans, laboratory exercises, or other materials aligned with educational standards.

2. Approaches to informal education and communication encompass broad, often multifaceted strategies for conveying hazard-related information outside of formal education contexts. These may address particular topics or audiences, and often consider

multiple dimensions of engagement, sometimes drawing on case studies of specific regions or events. They emphasize overarching methods, frameworks, or guidelines rather than the development of a single product.

3. Tools for informal education and communication are specific, tangible products or media, such as hazard maps, interactive games, virtual outcrops, photographs, artistic works, or films. These are accompanied by practical guidance for their creation or implementation and intended to be deployed as discrete components within broader communication efforts.

The first author assigned articles to the category most closely aligned with their main emphasis, though some articles include elements spanning multiple categories. Studies are referenced by number, with a full numbered list provided in the supplementary materials.

3 Results

Here we provide an overview of the reviewed literature, including publication history, geographic focus, and recurring themes, and then present the three thematic categories used to organize the reviewed studies: formal educational materials, informal education and communication approaches, and informal education and communication tools. Our review identified 76 peer-reviewed articles on volcanic hazard communication and education during quiescence. The 76 articles were published between 1990 and 2024 across 41 different publication venues, with a general increase in publication over time, including a sharp rise in the 2010s (Figure 2). This increase suggests communication and education research during quiescent periods has continued to gain more focus as science communication research has evolved. The most frequently represented publication venues are Bulletin of Volcanology (6 articles) and Advances in Volcanology (5). Of the 76 articles, 42 focus on a specific volcano or volcanic area, while the remainder address volcanic communication more broadly (Figure 3).

Most geographically focused studies concentrate on Vesuvius, Etna, Katla, and the Taupo Volcanic Zone, all of which are close to substantial population centers and have long histories of monitoring and research. In contrast, many volcanoes that threaten similarly large or even larger nearby populations, including Mount Nyiragongo near Goma, the Hainan Volcanic Field in China, and Popocatépetl in Mexico, receive little attention in the literature reviewed here. This skewed geographic coverage is significant because communication needs, trusted messengers, cultural relationships to volcanoes, and preparedness priorities can vary widely between volcanic regions.

Across all articles, only 26 empirically evaluate the effectiveness of their tool or approach, making it difficult to determine which strategies work best in practice. This gap highlights the need for more structured evaluation to strengthen research-informed volcanic hazard communication during periods of quiescence. Across the reviewed studies, recurring themes include the importance of audience-specific communication, participatory strategies, and trust-building before periods of unrest or eruption. As we describe results in the following sections, we situate those results within broader hazard and risk communication literature. Reviewed articles are identified with an asterisk (*) throughout the Results, tables, and reference list to distinguish them from references cited in the broader literature.

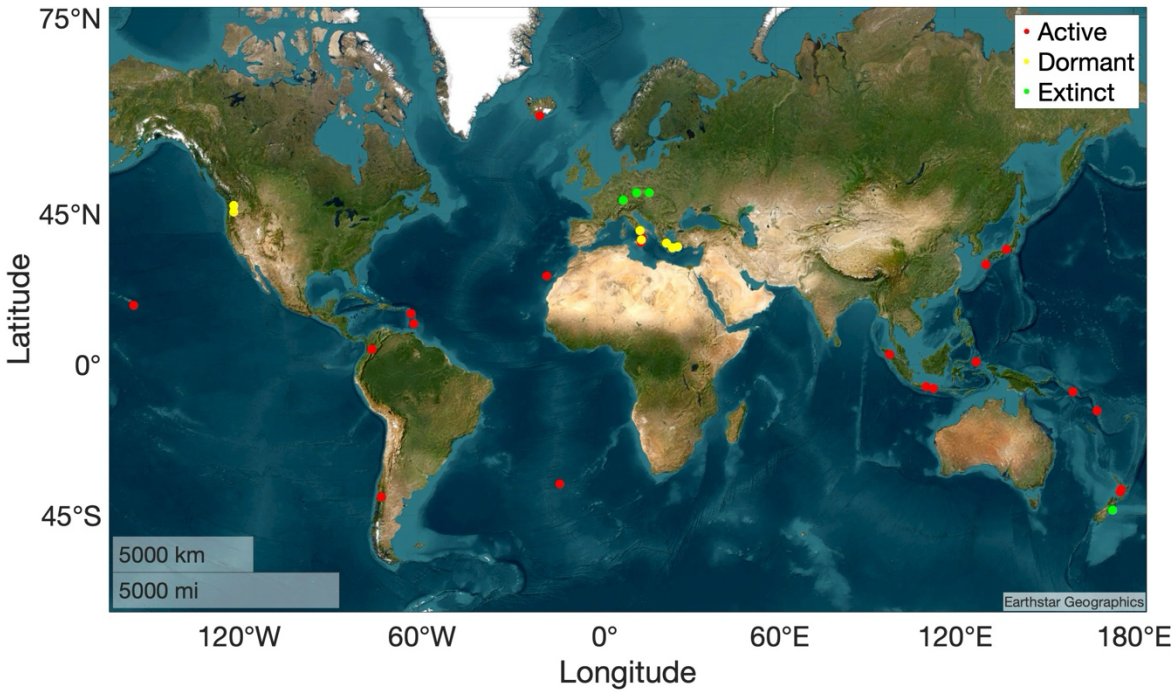

Figure 3. Geographic distribution of volcanoes or volcanic regions examined in the 42 geographically focused studies included in this review. The legend indicates the volcanic activity level at the time each study was published.

3.1 Formal education

Twenty-one articles focus on formal educational activities designed for classroom settings. These studies include lesson plans, curriculum units, hands-on experiments, online activities, games, videos, and other learning tools. Nine articles evaluate their materials in some way, most commonly through pre- and post-tests of student learning or questionnaires assessing student and teacher perceptions of interest, usability, or effectiveness (Table 1). The formal education studies generally emphasize that school-based activities can help sustain awareness of volcanic hazards during long periods between eruptions. Because students may share what they learn with families and communities, classroom education can be used to extend hazard awareness beyond the school setting (Ronan & Johnston, 2001; Shaw et al., 2004; Todesco et al., 2022a).

Citation	Study Area	communication/education tool or approach utilized	Evaluate?	recommendations
Albin, E. F. (1993). Volcanism in the classroom. *Science Activities*, *30* (3), 25–28. https://doi.org/10.1080/00368121.1993.10113101	n/a	educational activity	Just present a tool/approach	use their activities to simulate a lava flow for junior high students
Bachri, S., Rahman Hakiki, A. R., Wibowo, N. A., Sumarmi, Amini, R., Yosritzal, & Nursaribilah, E. (2024). Developing an education support system for disaster management through an ethnoscience-based digital disaster learning module. International Journal of Disaster Risk Reduction, 100, Article 104214. https://doi.org/10.1016/j.ijdrr.2023.104214	Mount Semeru	digital volcano disaster mitigation module	Evaluate data	The Volcano Disaster Mitigation Module should be used to support disaster education in elementary schools, especially in increasing student preparedness knowledge.
Buber, A., & Unal Coban, G. (2020). From modeling to STEM: A predictor activity of volcanic eruption. Science Activities, 57(3), 111–121. https://doi.org/10.1080/00368121.2020.1814193	turkey (schoolteachers there)	Science teaching activity with 3rd grade Science Teachers.	Just present a tool/approach	Support students through trial and error by encouraging questioning, problem-solving, decision-making, and other critical thinking skills during the learning process.
Conway, C. E., Tani, K., Sano, T., Matsumoto, K., & Ishizuka, O. (2023). A kitchen experiment for replicating lava-ice interaction on stratovolcanoes. Frontiers in Earth Science, 11, Article 1116157. https://doi.org/10.3389/feart.2023.1116157	n/a	Educational experiment	Just present a tool/approach	Use this activity in the classroom to engage students in learning about the morphology of volcanoes, natural hazards, and paleoclimate
Erdogan, I. (2005). Controlled volcanism in the classroom: A simulation. Science Activities: Classroom Projects and Curriculum Ideas, 42(1), 21–24. https://doi.org/10.3200/SATS.42.1.21-24	n/a	hands on educational experiment	Just present a tool/approach	Use this activity in a middle school science class
Gates, A. E. (2017). Benefits of a STEAM collaboration in Newark, New Jersey: Volcano simulation through a glass-making experience. Journal of Geoscience Education, 65(1), 4–11. https://doi.org/10.5408/16-188.1	Newark, New Jersey	The Glass Volcano Experience, glass blowing + volcanic processes	Evaluate data	Develop unconventional partnerships to create new educational experiences that can expand and improve geoscience learning.
Jolley, A., & Ayala, G. (2015). "Living with volcanoes": Cross-curricular teaching in the high school classroom. Journal of Geoscience Education, 63(4), 297–309. https://doi.org/10.5408/14-048.1	A-levels in England (11th and 12th grades in the US)	a high school geoarchaeology unit	Evaluate data	To use this unit in the classroom when applicable to the curriculum
Kirstein, K., & Owens, D. (2023). Where are the volcanoes? A socioscientific hunt for volcanoes through the recognition of patterns in Earth science. Science Scope, 46(4), 34–40. https://doi.org/10.1080/08872376.2023.12290908	n/a	Cross-curricular instruction, such as the inclusion of social studies and mathematics in a mapping activity	Just present a tool/approach	To begin class, engage students by asking what they know about volcanoes. Then, capture students interest with the short National Geographic video of volcanoes erupting and the resulting destruction.
Lang, N. P., Lang, K. T., & Camodeca, B. M. (2012). A geology-focused virtual field trip to Tenerife, Spain. In S. J. Whitmeyer, J. E. Bailey, D. G. De Paor, & T. Ormdufff (Eds.), Google Earth and virtual visualizations in geoscience education and research (Geological Society of America Special Paper 492, pp. 323–334). Geological Society of America https://doi.org/10.1130/2012.2492(23)	Tenerife, Spain	Using google earth to create virtual field trips	Evaluate data	Use virtual field trips to teach volcanic landform recognition, support advanced quantitative analyses, compare geologic maps, and create adaptable Google Earth tours for different learning goals.
Lewis, G. M., & Hampton, S. J. (2015). Visualizing volcanic processes in SketchUp: An integrated geo-education tool. Computers & Geosciences, 81, 93–100. https://doi.org/10.1016/j.cageo.2015.05.003	Panama Rock	Sketchup, a geologic teaching tool for educators to use	Just present a tool/approach	Develop 3D geoeducation tools with geologically accurate visuals, while tailoring interpretive text and supporting information to the target audience.
Mattox, S. R. (2000). Teaching the basics about volcanoes to K-16 students. Journal of Geoscience Education, 48(5), 576–577. https://doi.org/10.5408/1089-9995-48.5.576b	n/a	classroom activity	Just present a tool/approach	Begin with guiding questions, then use visuals, demonstrations, hand samples, and slide resources to introduce basic volcano concepts.
Musacchio, G., Piangiamore, G. L., D'Addezio, G., Solarino, S., & Eva, E. (2015). "Scientist as a game": Learning geoscience via competitive activities. Annals of Geophysics, 58(3), S0328. https://doi.org/10.4401/ag-6695	Italy	Scientist as a game: hands-on activity, game-related challenges aimed at school children	Evaluate data	Use simple, affordable hands-on activities and accessible language so teachers can replicate them easily and students remain engaged.
Nasution, L. A., Agustang, A. T. P., & Maulana, J. (2023). Increasing volcanic eruption disaster mitigation through simulation practice with video learning media in Geography Education, University of Khairun. JPG (Jurnal Pendidikan Geografi), 10(2), 108–116. https://doi.org/10.20527/jpg.v10i2.16653	Ternate City	video learning media	Evaluate data	learning media is able to make the learning process more interesting and help students to understand the subject.
Pardo, N., Wilson, H., Procter, J. N., Lattughi, E., & Black, T. (2015). Bridging Māori indigenous knowledge and western geosciences to reduce social vulnerability in active volcanic regions. Journal of Applied Volcanology, 4, Article 5. https://doi.org/10.1186/s13617-014-0019-1	New Zealand	educational tools for indigenous children to learn about volcanic hazards	Just present a tool/approach	Use body language, art, music, and poetry to teach volcanology concepts and bridge traditional knowledge with Western science.
Penatas, D. L., Moll, H. L., & Hariyana, B. A. A. (2024). The effect of augmented reality (AR) based multimedia ATLAS: Volcanic Series volcanism material on learning outcomes of students of SMAN 2 Blitar. Future Space: Studies in Geo-Education, 1(3), 325–335. https://doi.org/10.69877/fssge.v1i3.32	Indonesia	use of Augmented Reality (AR) technology in volcanic hazard education	Evaluate data	Use AR or similar multimedia tools with text, video, and 3D visuals to increase student interest and improve understanding of volcanic structures and eruption types.
Saha, S., Tapuke, S., Kennedy, B., Tapuke, K., Hersey, S., Wright, F., Tolbert, S., Macfarlane, A., Leonard, G., Tupe, R., Ngaropo, P., Milroy, K., & Smith, B. (2022). Use of "Our Supervolcano" virtual field trip to support bicultural classrooms in Aotearoa New Zealand. Science Activities, 59(2), 84–96. https://doi.org/10.1080/00368121.2022.2056115	Aotearoa, New Zealand	virtual field trips (VFTs) to support classrooms	Just present a tool/approach	Use the Our Supervolcano VFT to support Earth science and hazards education while promoting bicultural learning that integrates Mātauranga Māori and Western science.
Schipper, S., & Mattox, S. (2010). Using Google Earth to study the basic characteristics of volcanoes. *Science Scope*, *34* (3), 28–37.	n/a	Using google earth to educate students about volcanoes	Just present a tool/approach	none stated; just to use this tool that they display and explain
Teasdale, R., van der Hoeven Kraft, K., & Poland, M. P. (2015). Using near-real-time monitoring data from Pu'u 'Ō'ō vent at Kilauea Volcano for training and educational purposes. *Journal of Applied Volcanology*, *4* , Article 11. https://doi.org/10.1186/s13617-015-0026-x	Hawaii	use of citizen science or training students to understand online volcano monitoring data	Evaluate data	Use real volcano-monitoring data in guided training activities, paired with role-playing when possible, and allow enough time for non-experts to build confidence without being overwhelmed.
Thompson, S. A., & Thompson, K. S. (1996). Volcanoes in the classroom: An explosive learning experience. Science and Children, 33(6), 16–19, 44. https://www.jstor.org/stable/43170661	n/a	Educational activity for elementary school student	Just present a tool/approach	Use a step-by-step volcano-building activity to help young students observe eruptions and discuss basic volcano processes.
Todesco, M., Ercolani, E., Brasini, F., Modonesi, D., Pessina, V., Nave, R., & Camassi, R. (2022). The imaginary eruption: Volcanic activity through kids' eyes. Geoscience Communication, 5, 205–219. https://doi.org/10.5194/gc-5-205-2022	italy	a workshop for elementary students to write a volcanic eruption story	Evaluate data	Design outreach that explains unrest, false alarms, eruption size and style, evacuation timing, gas hazards, and family decision-making, while encouraging children's problem-solving and building trust through repeated community engagement.
Wighting, M. J., Lucking, R. A., & Christmann, E. P. (2005). Viewing volcanoes. Science Scope, 28(6), 54, 56. https://www.jstor.org/stable/43181589	n/a	educating students about volcanoes, mostly through websites	Just present a tool/approach	Use curated volcano education websites to provide classroom activities on volcanic processes and hazards

Table 1. Articles reviewed placed in the formal education category.

Many studies emphasize the importance of active and engaging learning. In classroom settings, students may be present for the activity, but engagement is still needed for hazard information to be understood, remembered, and connected to preparedness (Farley et al., 2013). Hands-on experiments and activities are commonly presented as ways to increase student interest and attention (*Albin, 1993; *Conway et al., 2023; *Erdogan, 2005; *Gates, 2017; *Musacchio et al., 2015), while more developed curriculum units are used to build deeper understanding of volcanic processes, hazards, and impacts across different regions (*Bachri et al., 2024; *Buber & Unal Coban, 2020; *Mattox, 2000; *Thompson & Thompson, 1996; *Wighting et al., 2005). Online activities

have also become increasingly common, including web-based resources, videos, interactive modules, and games (*Lang et al., 2012; *Nasution et al., 2023; *Penatas et al., 2024; *Saha et al., 2022; *Schipper & Mattox, 2010; *Teasdale et al., 2015). Several studies recommend cross-curricular learning (*Bachri et al., 2024; *Jolley & Ayala, 2015; *Kirstein & Owens, 2023; *Pardo et al., 2015; *Saha et al., 2022), allowing students to connect volcanic hazards with broader social, historical, geographic, and community impacts. For example, *Jolley and Ayala (2015) integrate geoscience and archaeology into a single unit, finding that this approach broadens coverage of standardized learning goals, helps students view both disciplines through a new lens, and increases student interest in the material.

Some formal education studies use student responses to identify misconceptions and guide future educational design. *Todesco et al. (2022a) analyzed children's stories about volcanic eruptions and identified common patterns in how students imagined volcanic activity. They found that elementary school students rarely recognized precursory unrest and often underestimated the size and variability of eruptions. The authors suggest that future educational materials should give more attention to periods of volcanic unrest, including how dormant volcanoes may reactivate, how long unrest can last, and how the same volcano can produce different eruptive styles. They recommend interdisciplinary collaboration to develop visual materials that better represent the different eruptive styles volcanoes can display.

Broader disaster education literature supports the value of school-based hazard education while also showing that learning does not automatically translate into preparedness. Johnson et al. (2014a) find that evaluations of children's disaster education programs commonly measure short-term knowledge gains, while fewer studies assess whether education leads to household preparedness, protective behavior, self-efficacy, adaptive capacity, or long-term resilience. Similarly, Ronan et al. (2016) emphasize that child-centered disaster risk reduction should move beyond basic safety messages toward interactive, problem-solving, and skill-building approaches that connect students, households, schools, and communities. This suggests that formal volcanic hazard education during quiescence is valuable because it can sustain awareness when volcanic risk is not immediately visible, but its usefulness depends on whether students are supported in connecting volcanic knowledge to preparedness actions and local decision-making.

Additionally, producing educational materials is only one part of effective disaster education. Johnson et al. (2014b) found that uptake of a voluntary disaster preparedness education resource in New Zealand primary schools depended on teacher awareness, teacher training, school-wide use, curriculum support, and engagement with local emergency management staff. This is especially relevant for volcanic hazards during quiescence, when the absence of recent activity may make disaster education feel less urgent or harder to prioritize. Without sustained implementation support, even well-designed volcanic hazard curricula or classroom activities may have limited reach because effective formal education requires more than just the creation of materials. It also requires integration into school systems, support for teachers, and connections between schools and the agencies or scientists responsible for hazard information.

Formal education must also account for the diversity of students and learning contexts. Ronoh et al. (2017) show that children with disabilities may have substantial hazard knowledge and capacities, but still require accessible language, adapted drills, participatory tools, and opportunities to contribute to disaster planning. This reinforces that school-based volcanic hazard education should not assume a single student audience or a single model of preparedness. Instead, educational materials and activities should be designed so that students with different abilities, experiences, cultural contexts, and local hazard exposures can understand the risk and participate meaningfully in preparedness.

It is critical that these materials be culturally grounded, place-based, and student-centered. Kaiser and Boersen (2020) show that disaster education can be more meaningful when it is developed around local hazards, cultural knowledge, student participation, and community priorities. The materials identified in this review provide a valuable reference for scientists, educators, and communicators seeking classroom resources for volcanic hazard education during quiescence, but they should be adapted and

evaluated for the specific audience and context rather than treated as ready-made solutions. However, the results of this literature search provide limited evidence about whether these classroom activities translate into broader volcanic hazard preparedness beyond the lesson itself. Because many of the reviewed materials are not empirically evaluated, it remains unclear which approaches are most effective, for which student audiences, and under what educational or cultural conditions. Future studies should evaluate whether formal education improves preparedness understanding, accessibility to hazard information, family or community discussion, trust in hazard information, and long-term retention in volcanic settings.

3.2 Approaches

Twenty-seven articles found in this review describe approaches for volcanic hazard communication outside formal education settings (Table 2). These approaches are often audience-specific, with six articles focused on communication with tourists and ten focused on communication with Indigenous populations. Other studies provide general communication frameworks, propose strategies for eruption planning and preparedness exercises, or offer guidance on terminology. Few of these approaches are empirically evaluated, instead offering practices and processes that can be adapted.

Citation	Study Area	communication/education tool or approach utilized	Evaluate?	recommendations
Bird, D. K., Gísladóttir, G., & Dominey-Howes, D. (2010). Volcanic risk and tourism in southern Iceland: Implications for hazard, risk and emergency response education and training. *Journal of Volcanology and Geothermal Research*, *189*(1–2), 33–48. https://doi.org/10.1016/j.jvolgeores.2009.09.020	Iceland	evaluated questionaires about all communication strategies	Evaluate data	Provide tourists and tourism employees with clear hazard and emergency response information through multiple channels, enforce registration systems, promote official real-time updates, and require regular emergency training and evacuation exercises.
Bird, D. K., & Gísladóttir, G. (2020). Enhancing tourists' safety in volcanic areas: An investigation of risk communication initiatives in Iceland. International Journal of Disaster Risk Reduction, 50, Article 101896. https://doi.org/10.1016/j.ijdrr.2020.101896	Iceland	evaluated questionaires about all communication strategies	Evaluate data	Involve the whole tourism sector in ongoing risk communication, train and certify guides and hut wardens, provide clear location-specific safety actions, use consistent terminology and strong visuals, and regularly evaluate materials with tourists.
Cadag, J. R., Driedger, C., Garcia, C., Duncan, M., Gaillard, J. C., Lindsay, J., & Haynes, K. (2018). Fostering participation of local actors in volcanic disaster risk reduction. In C. J. Fearnley, D. K. Bird, K. Haynes, W. J. McGuire, & G. Jolly (Eds.), Observing the volcano world: Volcano crisis communication (Advances in Volcanology, pp. 481–497). Springer. https://doi.org/10.1007/11157_2016_39	Mount Rainier (USA) and Bulusan (Philippines)	Fostering local actor participation through bottom-up and community-based initiatives	Just present a tool/approach	Use participatory CBDRR to build trust, co-develop consistent hazard and response messages, support community-led planning, and establish legal responsibilities before a crisis occurs.
Cronin, S. J., Gaylord, D. R., Charley, D., Alloway, B. V., Wallez, S., & Esau, J. W. (2004). Participatory methods of incorporating scientific with traditional knowledge for volcanic hazard management on Ambae Island, Vanuatu. *Bulletin of Volcanology*, *66*, 652–668. https://doi.org/10.1007/s00445-004-0347-9	Vanuatu	Use of Participatory Rural Appraisal derived volcanic hazard management guidelines	Just present a tool/approach	Use PRA methods to build dialogue and crisis plans with rural communities, keeping visits concise, respecting different belief systems, and using gender-separated exercises when needed to include underrepresented perspectives.
Cronin, S. J., Petterson, M. G., Taylor, P. W., & Biliki, R. (2004). Maximising multi-stakeholder participation in government and community volcanic hazard management programs: A case study from Savo, Solomon Islands. *Natural Hazards*, *33*, 105–136. https://doi.org/10.1023/B:NHAZ.0000035021.09838.27	Solomon Islands	the PRA approach to create a dialogue and volcanic hazard plan with a rural community.	Just present a tool/approach	Hold recurring, inclusive workshops that build on local participation over time, reinforce hazard education, support community-led initiatives, and include continual review to sustain long-term awareness and mitigation capacity.
Cronin, S. J., & Cashman, K. V. (2008). Volcanic oral traditions in hazard assessment and mitigation. In J. Grattan & R. Torrence (Eds.), *Living under the shadow: Cultural impacts of volcanic eruptions* (pp. 175–202). Left Coast Press.	n/a	Use of oral tradition in raising awareness and understanding of volcanic hazards	Just present a tool/approach	Use oral traditions as a culturally relevant tool for communicating volcanic hazards, especially in rural communities and with older generations who preserve disaster memory.
Erfurt-Cooper, P. (2018). Active hydrothermal features as tourist attractions. In C. J. Fearnley, D. K. Bird, K. Haynes, W. J. McGuire, & G. Jolly (Eds.), Observing the volcano world: Volcano crisis communication (Advances in Volcanology, pp. 85–105). Springer. https://doi.org/10.1007/11157_2016_33	n/a	Approach focused on how to communicate to tourists, specifically at hydrothermal features.	Just present a tool/approach	Use clear multilingual and visual hazard communication, real-time alert systems, mobile alerts, apps, and virtual visits to inform tourists, while avoiding excessive warnings that may reduce trust.
Fitzgerald, R. H., Kennedy, B. M., Wilson, T. M., Leonard, G. S., Tsunematsu, K., & Keys, H. (2018). The communication and risk management of volcanic ballistic hazards. In C. J. Fearnley, D. K. Bird, K. Haynes, W. J. McGuire, & G. Jolly (Eds.), Observing the volcano world: Volcano crisis communication (Advances in Volcanology, pp. 121–147). Springer. https://doi.org/10.1007/11157_2016_35	n/a	Just a general approach to communicating about ballistic hazards.	Just present a tool/approach	Assess ballistic hazards using eruption history, deposit mapping, trajectory models, exposure, and vulnerability; communicate results through clear maps, signage, monitoring updates, community partnerships, and transparent, multi-channel messaging.
Gabrielsen, H., Procter, J., Rainforth, H., Black, T., Harmsworth, G., & Pardo, N. (2018). Reflections from an indigenous community on volcanic event management, communications and resilience. In C. J. Fearnley, D. K. Bird, K. Haynes, W. J. McGuire, & G. Jolly (Eds.), Observing the volcano world: Volcano crisis communication (Advances in Volcanology, pp. 463–479). Springer. https://doi.org/10.1007/11157_2016_44	Aotearoa New Zealand	general approach to communicating with indigenous populations	Just present a tool/approach	Incorporate traditional knowledge, Indigenous language, Indigenous researchers, and participatory methods to document past events, support local communities, and encourage preparedness action.
García, C., & Mendez-Fajury, R. (2018). If I understand, I am understood: Experiences of volcanic risk communication in Colombia. In C. J. Fearnley, D. K. Bird, K. Haynes, W. J. McGuire, & G. Jolly (Eds.), Observing the volcano world: Volcano crisis communication (Advances in Volcanology, pp. 335–351). Springer. https://doi.org/10.1007/11157_2016_46	Communities near Nevado del Ruiz Volcano	Empirically-based discussion of the measures undertaken by technical volcanologists in Colombia	Just present a tool/approach	Collaborate with social scientists, local institutions, communities, and media to create respectful, understandable, and redundant communication systems that support timely action.
Graham, O., Edwards, S., & Robertson, R. (2022). More than a warning: Expanding the role of communication in Eastern Caribbean volcano science. *Frontiers in Earth Science*, *10*, Article 907559. https://doi.org/10.3389/feart.2022.907559	Eastern Carribean	Using semi-structured interviews and document review they investigated the impact of strategic communication in a long-term, multi-hazard monitoring program.	Evaluate data	Use quiet periods to prepare authorities and the public, invest in communication and social science expertise, and maintain trust through ongoing two-way outreach.
Harris, A. J. L. (2015). Forecast communication through the newspaper: Part 2: Perceptions of uncertainty. *Bulletin of Volcanology*, *77*, Article 30. https://doi.org/10.1007/s00445-015-0902-6	n/a	how to format language, the focus is on how to convey scientific uncertainty.	Just present a tool/approach	Communicate forecasts with plain language, clearly defined probability terms, and brief explanations of uncertainty; prepare media statements in advance, avoid jargon or exaggerated reassurance, and use consistent, coordinated messaging.
Harris, A. J. L., Belousov, A., Calvari, S., Delgado-Granados, H., Hort, M., Koga, K., Mei, E. T. W., Harijoko, A., Pacheco, J., Privul, J.-M., Solana, C., Þórðarson, Þ., Thouret, J.-C., & van Wyk de Vries, B. (2017). Translations of volcanological terms: Cross-cultural standards for teaching, communication, and reporting. *Bulletin of Volcanology*, *79*, Article 57. https://doi.org/10.1007/s00445-017-1141-9	n/a	Choice of language. They discuss how to translate english terms into other languages to ensure clarity of message.	Just present a tool/approach	Use consistent, carefully vetted translations of volcanology terms that preserve scientific meaning, avoid misleading connotations and acronyms, and pair clear terminology with imagery to support learning.
Hicks, A., Barclay, J., Simmons, P., & Loughlin, S. (2014). An interdisciplinary approach to volcanic risk reduction under conditions of uncertainty: A case study of Tristan da Cunha. *Natural Hazards and Earth System Sciences*, *14*, 1871–1887. https://doi.org/10.5194/nhess-14-1871-2014	Tristan da Cunha	Integrating social and physical sciences with the development of effective, tailored engagement and communication strategies in volcanic risk reduction.	Evaluate data	Use interdisciplinary teams to integrate volcanic hazard knowledge with local social context, co-design tailored engagement strategies with at-risk communities, and use scenario planning to support decision-making under uncertainty.
Holmberg, K. (2023). Merapi and its dynamic "disaster culture." In R. Gertisser, K. Charbonnier, D. A. Nandaka, & A. K. H. Hidayat (Eds.), Merapi Volcano (Active Volcanoes of the World, pp. 67–87). Springer. https://doi.org/10.1007/978-3-031-15040-1_3	Merapi	use of oral traditions to convey hazard information	Just present a tool/approach	Use oral traditions to improve hazard awareness, share early warning signs, and connect residents' existing knowledge of the volcano to preparedness actions.
Horii, M., Yamaoka, K., Kim, H.-Y., Takewaki, S., & Kunitomo, T. (2024). Comparative study of literacy enhancement on volcanic disaster reduction for the residents and visitors in Mt. Ontakesan and other volcanic areas. Journal of Disaster Research, 19(1), 159–172. https://doi.org/10.20965/jdr.2024.p0159	Japan, various volcanoes within	the use of local organizations and facilities to develop the face-to-face relationship between the local community and volcano experts	Evaluate data	Support organizations that combine disaster education, memory transmission, local awareness, and regional development, with particular emphasis on teaching children to carry disaster knowledge forward.
Marín, A., Vergara-Pinto, F., Prado, F., & Farías, C. (2020). Living near volcanoes: Scoping the gaps between the local community and volcanic experts in southern Chile. Journal of Volcanology and Geothermal Research, 398, Article 106903. https://doi.org/10.1016/j.jvolgeores.2020.106903	Lago Ranco commune, in Los Rios region of Chile	Communication with indigenous populations	Evaluate data	Create participatory dialogue spaces that connect local, traditional, and scientific knowledge, build trust with vulnerable groups, and support collaborative decision-making for volcanic risk reduction.
Megerle, H. E. (2020). Geoheritage and geotourism in regions with extinct volcanism in Germany: Case study Southwest Germany with UNESCO Global Geopark Swabian Alb. Geosciences, 10(11), Article 445. https://doi.org/10.3390/geosciences10110445	geoparks in germany	Geotourism as a tool to educate tourists	Just present a tool/approach	Use professional geo-interpretation, cross-sector collaboration, public relations, and marketing to strengthen the geoeducation potential of volcanic landscapes.
Migoń, P., & Pijet-Migoń, E. (2019). Natural disasters, geotourism, and geo-interpretation. Geoheritage, 11, 629–640. https://doi.org/10.1007/s12371-018-0316-x	n/a	"dark Tourism" they look at sites of past natural disasters from the perspective of geotourism	Just present a tool/approach	Use disaster sites, preserved evidence, panels, trails, and interpretive centers to teach not only what happened, but also hazard processes, vulnerability, land-use planning, recovery, and collective memory.
Nasaruddin, Munadi, K., Dirhamsyah, M., & Yuliansyah, D. (2011). A web-based geographic information system for Aceh natural hazards. *TELKOMNIKA*, *9*(1), 89–98.	Aceh Province	an online natural hazards information system to provide hazard maps as the guideline for disaster risk mitigation planning.	Just present a tool/approach	Develop online regional hazard information systems with single- and multi-hazard maps to improve public awareness and support disaster mitigation planning.
Nakamichi, H. (2024). Open-door events of the Sakurajima Volcano Observatory, Kyoto University in the last ten years. Journal of Disaster Research, 19(1), 147–158. https://doi.org/10.20965/jdr.2024.p0147	Sakurajima Volcano Observatory	general engagement techniques from the point of view of a volcano observatory connected to a university	Evaluate data	Use annual open-door events, behind-the-scenes observatory access, and trained boundary workers such as geo-guides to maintain public interest and communication without overburdening researchers.
Petterson, M. G., Tolia, D., Cronin, S. J., & Addison, R. (2008). Communicating geoscience to indigenous people: Examples from the Solomon Islands. In D. G. E. Liverman, C. P. G. Pereira, & B. Marker (Eds.), *Communicating environmental geoscience* (Geological Society, London, Special Publications, Vol. 305, pp. 141–161). Geological Society of London. https://doi.org/10.1144/SP305.13	Solomon Islands	general communication with indigenous populations	Just present a tool/approach	Communicate with Indigenous communities by respecting local culture and governance, involving Indigenous people and all stakeholders throughout the process, using clear face-to-face and visual communication, practical exercises, follow-up evaluation, and sufficient time.
Pierson, T. C., Wood, N. J., & Driedger, C. L. (2014). Reducing risk from lahar hazards: Concepts, case studies, and roles for scientists. Journal of Applied Volcanology, 3, Article 16. https://doi.org/10.1186/s13617-014-0016-4	n/a	lahar hazard communication by scientists	Just present a tool/approach	Engage scientists directly in lahar hazard education by sharing past events and current risks, creating accessible outreach materials, and working through trusted community networks that can spread preparedness information.
Saha, S., Tapuke, S., Kennedy, B., Tolbert, S., Tapuke, K., Macfarlane, A., Hersey, S., Leonard, G., Tupe, R., Ngaropo, P., Milroy, K., & Smith, B. (2023). Aplace-based virtual field trip resource that reflects understandings from multiple knowledge systems for volcano hazard education in Aotearoa NZ: Lessons from collaborations between Māori and non-Māori. Journal of Geoscience Education, 71(3), 388–402. https://doi.org/10.1080/10899995.2022.2109397	Aotearoa, New Zealand	collaboration between Indigenous Maori and non-Maori partners for hazard education	Evaluate data	Build long-term partnerships through repeated engagement, shared project goals, respect for tikanga and cultural safety, fair compensation for Māori partners, and follow-up after project completion.
Stix, J., & Heiken, G. (2022). Communication when it is needed most: The past, present and future of volcano geoheritage. Bulletin of Volcanology, 84, Article 68. https://doi.org/10.1007/s00445-022-01574-4	n/a	a comprehensive system of information collection and dissemination that contains an information web for broad understanding of volcano systems and volcanology	Just present a tool/approach	Create a centralized, institutionally supported volcano information repository with hazard maps and communication resources to support planning, preparedness, and public access.
Todesco, M., De Lucia, M., Bagnato, E., Behncke, B., Bonforte, A., De Astis, G., Giammanco, S., Grassa, F., Neri, M., Scarlato, P., & Neri, A. (2022). Eruptions and social media: Communication and public outreach about volcanoes and volcanic activity in Italy. *Frontiers in Earth Science*, *10*, Article 926155. https://doi.org/10.3389/feart.2022.926155	italy	use of social media to raise awareness	Just present a tool/approach	Maintain a continuous, trusted online presence before and during volcanic unrest, using public attention during crises to share accurate updates, context, and media-friendly explanations.
Vegas, J., Galindo, I., Romero, C., Sánchez, N., Díaz, G. A., Martín-González, E., & Mateo, E. (2019). Geoconservation and geotourism in the Lanzarote and Chinijo Islands UNESCO Global Geopark. In E. Mateo et al. (Eds.), Lanzarote and Chinijo Islands Geopark: From Earth to space (Geoheritage, Geoparks and Geotourism, pp. 99–108). Springer. https://doi.org/10.1007/978-3-030-13130-2_7	Canary Islands	geotourism efforts, specifically, 17 interpretative panels for Lanzarote and La Graciosa Islands, and 5 geo-routes by car in Lanzarote	Just present a tool/approach	Design geotourism materials with engaging titles, concise nontechnical text, clear maps, strong visuals, and self-guided route brochures that connect visitors' observations to one main geological message.

Table 2. Articles reviewed placed in the approaches category.

3.2.1 Tourists

Tourists are a distinct audience for volcanic hazard communication because they may enter hazardous areas with limited local knowledge, limited time to seek information, and varied familiarity with volcanic processes. The studies focused on tourists emphasize that hazard information must be visible, engaging, and easy to interpret within the crowded information environment of tourism. Recommendations include creating bold, attention-seeking materials (*Bird et al., 2010; *Bird & Gísladóttir, 2020; *Vegas et al., 2019) and using pictures, drawings, and video footage to reduce reliance on scientific terminology (*Bird et al.,

2010; *Erfurt-Cooper, 2018). Several studies also emphasize the value of place-based communication. Presenting hazard information at past eruption sites can make the hazard more tangible by helping visitors visualize what occurred there (*Megerle, 2020). Learning about an event where it happened can reinforce its significance, especially when paired with brief, informative titles and high-quality photographs on interpretive panels (*Megerle, 2020; *Migoń & Pijet-Migoń, 2019; *Vegas et al., 2019).

These studies also suggest that tourist communication should not rely only on signs or isolated materials; instead, the tourism sector as a whole must be involved in risk reduction strategies (*Bird & Gísladóttir, 2020; *Megerle, 2020). Tourists are a distinct audience because they are temporary visitors to volcanic landscapes and may differ widely in background knowledge, language, risk perception, and familiarity with local hazards or warning systems. In potentially hazardous volcanic areas, tourists need clear, visible, and accessible safety information, including where to find official updates and what to do if conditions change (*Bird et al., 2020). *Bird et al. (2020) examine risk communication initiatives in Iceland and argue that risk reduction requires whole-community involvement, including the dissemination of risk information by travel agents and tour guides before tourists enter potentially hazardous environments. Guides should be trained for disasters, clear protocols should be in place, and community officials should maintain a long-term commitment to risk communication initiatives. For warnings and preparedness information to be effective, tourist-focused risk communication should be visible, accessible, and integrated into everyday tourism practices through visual materials, interpretive panels, trained guides, travel agents, emergency protocols, and consistent messaging across websites, social media, brochures, signs, short films, and other common visitor channels (*Bird et al., 2010; *Bird & Gísladóttir, 2020; *Erfurt-Cooper, 2018; *Megerle, 2020; *Migoń & Pijet-Migoń, 2019; *Vegas et al., 2019). These findings align with broader risk communication research emphasizing that communication must be designed around audience needs and decision contexts rather than expert assumptions about what information is important (Frewer, 2004; Fischhoff, 1995; Doyle & Becker, 2022).

During quiescence, tourism also provides an opportunity for informal education. When immediate hazard risk is low, visitors may already be interested in the landscape, making place-based interpretation useful for raising awareness of volcanic processes, past eruptions, and long-term hazards (*Megerle, 2020; *Migoń & Pijet-Migoń, 2019; *Vegas et al., 2019). These efforts can improve general volcanic literacy and reduce confusion if visitors later encounter warnings, closures, or future unrest. Future research should evaluate the effectiveness of tourist-focused communication across different visitor groups, including whether materials are noticed, understood, trusted, and connected to appropriate safety actions during changing volcanic conditions.

3.2.2 Indigenous Populations

In the reviewed studies focused on Indigenous populations, communication often emphasizes disaster risk reduction and preparedness actions rather than increasing scientific understanding of volcanic processes. Several articles argue that effective communication does not require reconciling all differences between local and scientific explanations of volcanism, because attempting to replace local knowledge systems can create disagreement or distrust (*Cronin et al., 2004a; *Cronin et al., 2004b; *Gabrielsen et al., 2018; *Marín et al., 2020). Instead, the reviewed studies suggest that communication should focus on shared goals, such as recognizing warning signs, understanding potential consequences, and developing locally meaningful plans for what to do if precursory signals occur. Oral storytelling is frequently identified as an important way to communicate past volcanic activity, preserve community memory, and convey the severity of rare but catastrophic eruptions (*Cronin & Cashman, 2008; *Gabrielsen et al., 2018; *Holmberg, 2023; *Marín et al., 2020; *Petterson et al., 2008). As *Cronin and Cashman (2008) note, "The dramatic, but highly sporadic, nature of volcanic activity may promote longevity of these oral traditions for the specific purpose of helping future descendants avoid a similar disaster" (p. 198). Effective communication with Indigenous communities requires time to understand local social context, cultural values, customs, taboos, political and governance structures, and relationships to volcanic landscapes (*Cronin et al., 2004a; *Cronin et al., 2004b; *Gabrielsen et al., 2018; *García & Mendez-

Fajury, 2018; *Hicks et al., 2014; *Marín et al., 2020; *Petterson et al., 2008; *Saha et al., 2023). The Indigenous communities represented in these studies are not a single, uniform audience. Cultural values, knowledge systems, governance structures, relationships to volcanic landscapes, and experiences of past hazards vary substantially, meaning that strategies developed in one setting cannot be assumed to transfer directly to another without locally grounded engagement and adaptation. This requires Indigenous involvement throughout the communication process, so that scientific knowledge of the volcanic system can be integrated with local knowledge, priorities, and decision-making structures (*Cronin et al., 2004a; *Cronin et al., 2004b; *Gabrielsen et al., 2018; *García & Mendez-Fajury, 2018; *Hicks et al., 2014; *Marín et al., 2020; *Petterson et al., 2008; *Saha et al., 2023).

These findings are consistent with broader risk communication literature showing that effective disaster risk reduction communication should treat local and Indigenous knowledge as expertise and create structured opportunities for communities, scientists, and authorities to discuss values, goals, information needs, and actions together (Bidwell, 2009; Doyle & Becker, 2022). However, participation must be carefully designed. Glicken (2000) cautions that poorly planned processes can exclude key groups, treat public input as symbolic, or increase distrust if stakeholders do not see how their knowledge is used. This is especially important when working with Indigenous communities, where different knowledge holders, governance structures, social roles, and community members may shape how risk is understood and how preparedness actions are developed. Communication with Indigenous communities should therefore be approached as a long-term relationship-building and partnership process rather than a one-time translation of scientific information, and quiescence is the best time to establish this relationship. Hicks et al. (2019) note that participatory DRR can range from treating participation itself as a measure of success to using more co-creative approaches, "where both scientists and citizens use and generate different forms of knowledge to integrate new understandings and create a shared agenda" (para. 9). In this context, oral traditions and local histories are not only communication tools; they are knowledge sources that can preserve memory of rare volcanic events, identify locally meaningful warning signs, and connect preparedness actions to community experience. Future volcano-specific research should evaluate how co-developed and culturally grounded communication approaches affect trust, preparedness actions, warning interpretation, and long-term risk awareness within Indigenous communities, while also documenting how these approaches vary across different volcanic, cultural, and governance contexts.

3.2.3 Community Networks

Several reviewed articles address the design of broader communication systems at the community level before unrest occurs. One recurring recommendation is to work with local actors who already have relationships with the intended audience, such as emergency managers, community leaders, popular local figures, educators, or other trusted members of the community (*Cadag et al., 2018). Involving these actors in message design can help communicators understand local concerns, identify appropriate language and channels, and increase trust in the information being shared. This reflects broader risk communication research showing that trust depends not only on message content, but also on the perceived credibility, motives, and relationships of the information source (Frewer, 2004; Paton, 2007; Kasperson, 2014).

Volcanic observatories and scientific institutions also play an important role in building communication capacity during quiescence. The reviewed observatory-focused articles emphasize outreach during quiet periods as a way to educate communities, establish relationships, and maintain visibility before unrest begins (*Graham et al., 2022; *Horii et al., 2024; *Nakamichi, 2024; *Todesco et al., 2022b). This is consistent with Community Engagement Theory, which suggests that preparedness is more likely when communication supports outcome expectancy, empowerment, collective efficacy, and trust, rather than simply delivering information to passive audiences (Paton et al., 2024). For observatories, this means that outreach during quiescence should not be limited to occasional public education products but should help establish durable channels for communication and informal

learning. Feng et al. (2018) argue that informal disaster education can build community resilience by using everyday social networks, local activities, and trusted facilitators to support localized learning and preparedness. Observatories can contribute to these networks by providing consistent scientific information, supporting local communicators, and creating opportunities for ongoing dialogue. Social media, for example, can provide regular contact with audiences and can be adapted to the level of volcanic activity, but it requires sustained management and clear decisions about what information should be posted during periods of quiescence, unrest, and crisis (*Todesco et al., 2022b). Citizen science can extend this role by involving community members in knowledge generation, ranging from data collection to deeper co-production and empowerment, especially when projects provide participant benefits and support long-term engagement (Hicks et al., 2019). However, citizen science efforts are not well documented or evaluated in the articles reviewed here.

Other reviewed articles focus on preparedness resources that can support communication before future activity. Hazard-specific articles synthesize communication needs for particular volcanic hazards, including ballistics and lahars (*Fitzgerald et al., 2018; *Pierson et al., 2014), while database-focused studies propose centralized volcanic information resources for stakeholders and communicators involved in disaster planning (*Nasaruddin et al., 2011; *Stix & Heiken, 2022). These approaches suggest that quiescence is a useful time to prepare communication materials, clarify terminology, organize hazard information, and build shared resources before time-sensitive decisions are required. Future work should evaluate how these communication systems, including local messengers, observatory outreach, social media strategies, hazard-specific guidance, and information databases, affect trust, preparedness, and the ability of different audiences to find and use volcanic hazard information when the level of volcanic activity changes.

3.2.4 Probabilities and Uncertainty

Two articles in the reviewed dataset provide resources for communicating probabilities or translating volcanic terminology across languages. *Harris et al. (2017) focus on terminology translation and emphasize that translations must follow alphabet and accent conventions, be lexicographically accurate, be grammatically correct, and preserve the intended meaning of the original term. This is important for volcanic hazard communication because direct translation may not be sufficient if the translated term changes the meaning, tone, or clarity of the hazard information.

*Harris (2015) examines how probabilities and uncertainties are communicated, using case studies from newspaper reporting on severe weather systems and volcanoes. In the volcano-focused section, Harris argues that terminology is critical when reporting uncertainty and probability because evocative words or dramatic imagery may prompt unintended interpretations. *Harris (2015) illustrates this issue in Table 2 of that article, which was collated from Sink (1995) and earlier work by Doyle et al. (2011) and shows that scientists and members of the public often assign different numerical values to the same qualitative probability phrases. Although these results are not volcano-specific, they illustrate a broader communication challenge that is relevant to volcanic hazards: commonly used terms such as “unlikely” or “possible” may not convey consistent numerical meanings across audiences. Because of these discrepancies, *Harris agrees with Gill (2008) that uncertainty is often best conveyed through objective numerical measures, such as probabilities, paired with clearly defined plain language. The reviewed article therefore emphasizes that both numerical information and word choice require careful design when communicating volcanic uncertainty.

The reviewed studies show that terminology, probability, and uncertainty communication receive limited attention within quiescence-focused volcanic communication research, even though these topics are well developed in broader risk communication and volcanology literature. Risk communication research shows that uncertainty communication is more complicated than simply deciding whether uncertainty should be included or omitted. Effective uncertainty communication depends on the audience, decision context, type of uncertainty, and actions available despite uncertainty (Fischhoff & Davis, 2014; Frewer, 2004; Kasperson, 2014; Bostrom, 2014; Doyle & Becker, 2022). Fischhoff & Davis (2014) provided practical guidance on communicating

uncertainty by focusing on what types of decisions need to be made with the information: "(i) Decisions about action thresholds: Is it time to act? (ii) Decisions with fixed options: Which is best? (iii) Decisions about potential options: What is possible?" (p. 13664). They further note that all three decision-making contexts involve "(i) characterizing uncertainty, by identifying the issues most relevant to the choice; (ii) assessing uncertainty, by summarizing that information in a useful form; and (iii) conveying uncertainty, by creating messages that afford decision makers the detail that their choices warrant" (p. 13664). Dhungana and colleagues (2025) use qualitative interviews in a disaster risk management (DRM) context and highlight how scientists and decision-makers face different pressures and have different perspectives on how uncertainty information can best be communicated, with scientists focusing more on the technical dimensions of uncertainty due to their scientific training, while decision-makers are more concerned with how uncertainty plays out in real-world scenarios. They recommend that uncertainty information be presented in visually engaging formats that have been tested for comprehension. Recent work by Peters et al. (2025) further shows that the most effective numerical framing may depend on the communication goal, with frequency formats potentially increasing emotional salience and preparedness motivation, and probability formats better supporting other forms of risk judgment.

Volcano-specific research has examined uncertainty communication in the context of unrest and crisis decision-making, explaining why these studies were not captured by the quiescence-focused search used here. This literature shows that providing scientifically accurate information is not sufficient if audiences do not interpret it as intended. The framing of probabilities and forecast time windows can influence perceived likelihood, and verbal probability terms may be understood as more ambiguous than equivalent numerical probabilities, leading to different evacuation decisions (Doyle et al., 2014a, 2014b). Similar challenges arise when complex monitoring data and scientific uncertainty are condensed into volcano alert levels or probabilistic hazard maps. These tools can support decision-making, but their meaning is shaped by audience needs, local context, and design choices, and they are most useful when accompanied by dialogue and supplementary communication (Fearnley, 2013; Fearnley & Beaven, 2018; Thompson et al., 2015). Martí (2015) argues that communication should remain ongoing even when a volcano shows no signs of alarm, so that audiences already have some familiarity with volcanic hazards, forecasts, and uncertainty when information must be interpreted more quickly during a crisis.

Uncertainty communication is especially important for volcanic hazards because uncertainty is central to both the science and the communication challenge (Tadini et al., 2025; Mani et al., 2025). Mani and colleagues (2025) note that while significant progress has been made in volcanic risk communication, many challenges remain due to the dynamic nature of crisis events and the multiple potential breakdown points in communication. Volcanoes can remain quiet for long periods before unrest begins, unrest does not always lead to eruption, and the timing, location, size, and style of future activity may remain uncertain even when monitoring data are available. During quiescence, communities may be asked to understand hazards that are possible but not imminent and to prepare for events that may occur beyond everyday planning horizons. In this setting, uncertainty communication is not only about explaining probabilities; it is also about helping audiences understand what is known, what is not known, what changes in activity might mean, and why scientific uncertainty does not make hazard information unreliable. Yet within the quiescence-focused volcanic communication studies captured by this review, probability and uncertainty communication were not central themes. The reviewed studies provide little volcano-specific evidence about how different audiences interpret probabilistic volcanic information, qualitative likelihood terms, long recurrence intervals, changing alert levels, or uncertainty around unrest and eruption forecasts during quiet periods. This is a notable gap because quiescence may be the best time to build familiarity with this language before crisis conditions increase urgency and stress. Future volcano-specific research should therefore evaluate how uncertainty can be communicated during quiescence in ways that support understanding, preparedness, and trust.

3.3 Tools

Twenty-eight articles identified in this review present specific tools for volcanic hazard communication outside formal settings, including hazard maps, online tools, video games, virtual reality (VR), photographs, paintings, films, and materials designed for use in geoparks (Table 3). Ten of these articles include empirical evaluation, with most evaluations focused on hazard map assessment (*Haynes et al., 2007; *Nave et al., 2010; *Preppernau & Jenny, 2015) or online media testing (*Bonali et al., 2022; *Mossoux et al., 2016; *Rapprich et al., 2017; *Ravi & Malathy, 2010; *Wang et al., 2022). Together, these studies show that communication tools can support awareness and understanding during quiescence, but their usefulness depends on whether audiences can access, interpret, trust, and apply the information they provide.

Citation	Study Area	communication/education tool or approach utilized	Evaluate?	Recommendations
Haynes, K., Barclay, J., & Pidgeon, N. (2007). Volcanic hazard communication using maps: An evaluation of their effectiveness. *Bulletin of Volcanology*, *70* , 123–138. https://doi.org/10.1007/s00445-007-0124-7	Montserrat	Use of hazard maps to convey volcanic risk.	Evaluate data	Use well-labeled aerial and perspective photographs, and 3D maps when possible, to communicate spatial hazard information more clearly than traditional contour-based hazard maps.
Nave, R., Isaia, R., Vilardo, G., & Barclay, J. (2010). Re-assessing volcanic hazard maps for improving volcanic risk communication: Application to Stromboli Island, Italy. *Journal of Maps*, *2010* , 260–269. https://doi.org/10.4113/jom.2010.1061	Stromboli Island Italy	use of maps to convey hazard information	Evaluate data	Design clear, locally tested hazard maps with simple graphics, accurate topography, hazard zones, and audience-appropriate base maps, using 3D GIS products as educational tools when helpful.
Parra, E., & Cepeda, H. (1990). Volcanic hazard maps of the Nevado del Ruiz volcano, Colombia. *Journal of Volcanology and Geothermal Research*, *42* (1–2), 117–127. https://doi.org/10.1016/0377-0273(90)90071-E	Nevado del Ruiz Colombia	hazard map of Nevado del Ruiz	Just present a tool/approach	Present volcanic risk maps and research findings in formats that are useful to civil authorities, land-use planners, emergency managers, relief organizations, and affected communities.
Preppernau, C. A., & Jenny, B. (2015). Three-dimensional versus conventional volcanic hazard maps. *Natural Hazards*, *78* , 1329–1347. https://doi.org/10.1007/s11069-015-1773-z	Mount Hood Oregon	hazard maps to display lahar hazard	Evaluate data	Use 3D hazard maps, especially with isochrones, to improve terrain interpretation, lahar travel-time communication, and evacuation route planning.
Thompson, M. A., Lindsay, J. M., & Leonard, G. S. (2018). More than meets the eye: Volcanic hazard map design and visual communication. In C. J. Fearnley, D. K. Bird, K. Haynes, W. J. McGuire, & G. Jolly (Eds.), Observing the volcano world: Volcano crisis communication. Springer. https://doi.org/10.1007/11157_2016_47	n/a	Use of hazard maps to convey hazard information	Just present a tool/approach	Design hazard maps around audience needs and existing knowledge, using clear visualizations, accessible color schemes, and audience feedback to reduce confusion and build trust.
Antoniou, V., Raglia, L., Nomikou, P., Bardouli, P., Lampridou, D., Ioannou, T., Kalisperakis, I., & Stentoumis, C. (2018). Creating a story map using geographic information systems to explore geomorphology and history of Methana Peninsula. ISPRS International Journal of Geo-Information, 7(12), Article 484. https://doi.org/10.3390/ijgi7120484	Methana Peninsula	GIS web story	Just present a tool/approach	Use story map applications to present geological, geomorphological, and historical information for geotopes, protected areas, and other sites of educational interest.
Antoniou, V., Nomikou, P., Panousis, D., & Zafeirakopoulou, E. (2021). Nisyros volcanic island: A geosite through a tailored GIS story. Geosciences, 11(3), Article 132. https://doi.org/10.3390/geosciences11030132	Nisyros Volcanic Island	GIS webstory	Just present a tool/approach	Use GIS story maps to communicate the geologic, cultural, and environmental features of volcanic landscapes in an interactive format.
Asgary, A., Bonadonna, C., & Frischknecht, C. (2020). Simulation and visualization of volcanic phenomena using Microsoft Hololens: Case of Vulcano Island (Italy). *IEEE Transactions on Engineering Management*, *67* (3), 545–553. https://doi.org/10.1109/TEM.2019.2932291	Vulcano island italy	VR visualization	Just present a tool/approach	They recommend implementation of this software for communication efforts
Bonali, F. L., Russo, E., Vitello, F., Antoniou, V., Marchese, F., Fallati, L., … Tibaldi, A. (2022). How academics and the public experienced immersive virtual reality for geo-education. *Geosciences*, *12* (1) https://doi.org/10.3390/geosciences12010009	questionnaires taken in italy, greece, and austria	Immersive virtual reality	Evaluate data	Use immersive virtual reality to support geoeducation, public communication, and accessible field experiences, adding scale references to help users understand landscape size and distance.
Mani, L., Cole, P. D., & Stewart, I. (2016). Using video games for volcanic hazard education and communication: An assessment of the method and preliminary results. *Natural Hazards and Earth System Sciences*, *16* , 1673–1689. https://doi.org/10.5194/nhess-16-1673-2016	St. Vincent	developed a video game, St. Vincent's Volcano, for use in volcano education and outreach sessions.	Evaluate data	Use serious games for volcanic hazard education with both students and adults, developing them through iterative testing and revision.
Pasquaré Mariotto, F., Bonali, F. L., & Venturini, C. (2020). Iceland, an open-air museum for geoheritage and Earth science communication purposes. Resources, 9(2), Article 14. https://doi.org/10.3390/resources9020014	Snaefellsnes Peninsula and the Northern Volcanic Zone of iceland	virtual outcrops available online for education	Just present a tool/approach	Use illustrated, well-described virtual geosite tools to improve geoheritage communication, especially for inaccessible sites and younger audiences.
Pasquaré Mariotto, F., Antoniou, V., Drymoni, K., Bonali, F. L., Nomikou, P., Fallati, L., Karatzaferis, O., & Viasopoulos, O. (2021). Virtual geosite communication through a WebGIS platform: A case study from Santorini Island (Greece). Applied Sciences, 11(12), Article 5466. https://doi.org/10.3390/app11125466	Santorini, Greece	Virtual Geosites for remote education	Just present a tool/approach	Use VR-enhanced story maps to promote geotourism and add educational value to online geoscience platforms.
McGowan, E. G., & Scarlett, J. P. (2021). Volcanoes in video games: The portrayal of volcanoes in commercial off-the-shelf (COTS) video games and their learning potential. Geoscience Communication, 4, 11–31. https://doi.org/10.5194/gc-4-11-2021	n/a	Use of role playing video games to learn about geologic hazards through the video game setting.	Just present a tool/approach	Use commercial or VR video games as facilitated learning tools, asking students or public audiences to evaluate volcanic realism and engage more actively with geologic settings.
Mossoux, S., Delcamp, A., Poppe, S., Michellier, C., Canters, F., & Kervyn, M. (2016). Hazagora: Will you survive the next disaster? A serious game to raise awareness about geohazards and disaster risk reduction. *Natural Hazards and Earth System Sciences*, *16* , 135–147. https://doi.org/10.5194/nhess-16-135-2016	n/a	a board game aimed at raising awareness about geohazards and disaster risk reduction strategies.	Evaluate data	Use serious games to teach geohazards and spark discussion, ensuring they are replayable, easy to understand, realistic, visually engaging, and appropriately challenging.
Pasquaré Mariotto, F., & Bonali, F. L. (2021). Virtual geosites as innovative tools for geoheritage popularization: A case study from Eastern Iceland. Geosciences, 11(4), Article 149. https://doi.org/10.3390/geosciences11040149	eastern iceland	immersive and non-immersive virtual reality	Just present a tool/approach	Use virtual geosites to make geoheritage accessible to broad audiences and support Earth science communication beyond physical field sites.
Rapprich, V., Lisec, M., Fferna, P., & Závada, P. (2017). Application of modern technologies in popularization of the Czech volcanic geoheritage. *Geoheritage*, *9* , 413–420. https://doi.org/10.1007/s12371-016-0208-x	Bohemian Massif in Central Europe	The scientific results from each volcanic site were summarized and transformed into images (playscreen) used for the 3D animation.	Evaluate data	Use modern visualization tools, especially 3D animations, to make volcanic processes and scientific findings more understandable and engaging for broader and younger audiences.
Ravi, R., & Malathy, V. A. (2010). Multimedia as an interactive platform in learning volcanoes in social sciences among upper primary students: An experiment. *i-manager's Journal on School Educational Technology*, *6* (2), 42–48	Secondary School at Vellalore Panchayat in Coimbatore city	multimedia for volcano education in students	Evaluate data	multimedia is a very effective tool for teaching and learning purposes and should be used to engage younger populations
Tibaldi, A., Bonali, F. L., Vitello, F., Delage, E., Nomikou, P., Antoniou, V., Becciani, U., van Wyk de Vries, B., Krokos, M., & Whitworth, M. (2020). Real world–based immersive virtual reality for research, teaching and communication in volcanology. Bulletin of Volcanology, 82, Article 38. https://doi.org/10.1007/s00445-020-01376-6	n/a	immersive Virtual Reality (VR)	Just present a tool/approach	Use virtual reality to make remote or inaccessible outcrops available for public engagement and geoscience education, following clear workflows that can be adapted elsewhere.
Todesco, M., Neri, A., Demaria, C., Marmo, C., & Macedonio, G. (2006). È VIVO: Virtual eruptions at Vesuvius; A multimedia tool to illustrate numerical modeling to a general public. *Journal of Volcanology and Geothermal Research*, *155* (3–4), 329–340. https://doi.org/10.1016/j.jvolgeores.2006.03.014	Italy	A multimedia tool (a CD-ROM) to illustrate numerical modeling to a general public	Just present a tool/approach	Use simple multimedia tools with concise text and visuals to explain scientific methods, such as numerical modeling of pyroclastic flows, to general audiences.
Wang, N., Clowdus, Z., Sealander, A., & Stern, R. (2022). Geonews: Timely geoscience educational YouTube videos about recent geologic events. Geoscience Communication, 5, 125–142. https://doi.org/10.5194/gc-5-125-2022	n/a	Use of youtube videos for geoscience education	Evaluate data	Create short, timely videos about recent geologic events to engage public interest, encourage discussion, and reach younger, diverse, and locally affected audiences.
Hicks, A., Armijos, M. T., Barclay, J., Stone, J., Robertson, R., & Cortés, G. P. (2017). Risk communication films: Process, product and potential for improving preparedness and behaviour change. International Journal of Disaster Risk Reduction, 23, 138–151. https://doi.org/10.1016/j.ijdrr.2017.04.015	St Vincent/Columbia	Use of films to raise awareness of hazards	Evaluate data	Integrate risk communication from the start, co-produce films with at-risk communities, tailor screenings to local needs, and use hopeful emotional storytelling to build trust, preparedness, and cross-community communication.
Korinth, B. (2024). Using paintings to teach about the impact of environmental hazards. Environmental Hazards. https://doi.org/10.1080/17477891.2024.2358043	n/a	Use of paintings to convey environmental hazards	Just present a tool/approach	Use figurative painting and disaster photography as visual teaching tools across educational levels to explain volcanic hazards and illustrate their real-world impacts.
Piccione, C. (2012). Memories of the past contribute to prevention: Photography as a direct means for public understanding of science. *Annals of Geophysics*, *55* (3), 427–431. https://doi.org/10.4401/ag-5529	Italy	photography and image communication for hazard education	Just present a tool/approach	Use historical photographs to connect past disasters with present risk awareness and future prevention through clear, memorable visual evidence.
Alessio, G., & De Lucia, M. (2017). Promotion and development of protected volcanic areas through field-based environmental communication activities: The "Gran Cono" tour in the Vesuvius National Park (Italy). *Geoheritage*, *9* (3), 435–442. https://doi.org/10.1007/s12371-017-0242-3	Vesuvius National Park	developing a walking tour	Just present a tool/approach	Build ongoing dialogue with communities during quiet periods so emergency communication is trusted, familiar, and effective when a crisis occurs.
de Vita, S., Di Vito, M. A., Barra, D., Aiello, G., & Gialanella, C. (2021). Disseminating the knowledge on the complex interactions between humans and volcanoes: The geological section of the Villa Arbusto archaeological museum at Lacco Ameno (Ischia, Naples, Italy). *Annals of Geophysics*, *64* (5), VO544. https://doi.org/10.4401/ag-8666	Lacco Ameno, Ischia	Use of museum education	Just present a tool/approach	n/a
Miklín, J., & Lenart, J. (2016). Visualisation of volcanic relief and processes: The Nízký Jesenik upland educational trail, Czech Republic. Journal of Maps, 12(5), 1104–1111. https://doi.org/10.1080/17445647.2015.1127859	Nízký Jeseník Upland	Use of educational trail in a geopark	Just present a tool/approach	Use educational trail panels to help visitors connect the visible landscape with its geologic history and evolution.
Pasquaré Mariotto, F., Bonali, F. L., Tibaldi, A., De Beni, E., Corti, N., Russo, E., Fallati, L., Cantarero, M., & Neri, M. (2022). A new way to explore volcanic areas: QR-code-based virtual geotrail at Mt. Etna volcano, Italy. *Land*, *11* (3), Article 377. https://doi.org/10.3390/land11030377	Mt Etna Italy	QR-Code-Based Virtual Geotrail	Just present a tool/approach	Use modern virtual exploration methods to engage students and general audiences in accessible, interactive volcanology learning.
Punturo, R., Ortolano, G., Visalli, R., Caffo, S., Ferlito, C., & Cirrincione, R. (2019). Geoscience and education: Proposal of a geo-trail at the Etna volcano. Rendiconti Online della Società Geologica Italiana, 49, 55–61. https://doi.org/10.3301/ROL.2019.52	Mt Etna	Geo-trail at Mt Etna	Just present a tool/approach	Use geo-trails to raise local awareness of volcanic geology and help visitors understand landscape evolution in volcanic settings.

Table 3. Articles reviewed placed in the tools category.

3.3.1 Hazard Maps

Several reviewed articles focus on hazard maps as tools for communicating volcanic risk. These studies show that map design needs vary by audience. Public audiences often prefer aerial photographs and 3D maps because these formats make it easier to interpret the landscape, while scientists and emergency managers may prefer contour maps that provide greater technical detail (*Haynes et al., 2007; *Nave et al., 2010; *Preppernau & Jenny, 2015). The reviewed studies also emphasize that hazard maps should be developed with attention to audience knowledge, perspectives, and information needs. Participatory approaches can help mapmakers understand what information communities value, how they interpret spatial risk, and what map formats are most useful for preparedness and decision-making (*Nave et al., 2010; *Parra & Cepeda, 1990; *Preppernau & Jenny, 2015; *Thompson et al., 2018).

Broader participatory mapping and stakeholder engagement literature reinforces that maps are not just technical products; they can also function as tools for dialogue, knowledge integration, and planning. Cadag and Gaillard (2012) show that participatory mapping can help connect scientific and local knowledge, make risk more tangible, and support disaster risk reduction actions when communities are actively involved in the mapping process. Glicken (2000) similarly emphasizes that stakeholder participation must be purposeful and carefully designed so that the right people are included, the right questions are asked, and the resulting information is useful for decision-making. Volcanic hazard maps should therefore be adapted to the intended audience, tested with intended users, and, where possible, developed through participatory processes that clarify what information different users need, how they interpret spatial hazard information, and which map formats best support preparedness, decision-making, trust, understanding, and use of hazard information.

3.3.2 Online Media

Several reviewed articles present online media and digital tools for volcanic hazard communication (*Antoniou et al., 2018; *Antoniou et al., 2021; *Asgary et al., 2020; *Pasquaré Mariotto et al., 2020; *Rapprich et al., 2017; *Ravi & Malathy, 2010; *Todesco et al., 2006; *Wang et al., 2022). These studies describe the design of online communication resources, including online museums, virtual outcrops, geostories, and other interactive materials that guide users through volcanic landscapes, histories, and hazards. Articles focused on VR tools similarly describe their development process in detail, often providing step-by-step guidance so that similar tools can be recreated or adapted elsewhere (*Bonali et al., 2022; *Pasquaré Mariotto et al., 2021; *McGowan & Scarlett, 2021; *Pasquaré Mariotto & Bonali, 2021; *Tibaldi et al., 2020). Many of these digital tools are presented as ways to expand access to volcanic landscapes for audiences who cannot travel to a field site, including students, people with disabilities, or large classroom groups unable to participate in field trips (*Bonali et al., 2022; *Pasquaré Mariotto et al., 2020; *Pasquaré Mariotto et al., 2021; *Pasquaré Mariotto & Bonali, 2021; *Rapprich et al., 2017; *Tibaldi et al., 2020). Two articles also examine serious games as tools for raising hazard awareness (*Mani et al., 2016; *Mossoux et al., 2016), showing that scientifically accurate games can support understanding of volcanic processes while engaging users through interactive learning.

These digital tools are valuable for expanding access to volcanic landscapes and hazard information. Ronoh et al. (2017) emphasize that disaster education must account for diverse access and support needs, including for children with disabilities, and that participatory, adapted tools can help make DRR education more inclusive. In this context, online media, VR, virtual outcrops, and serious games may help reach audiences who cannot physically visit volcanic sites, including students, people with disabilities, distant communities, or classrooms without the resources to conduct a field trip. However, the existence of a digital tool does not guarantee that it will be used, understood, or connected to preparedness. For volcanic hazard communication during quiescence, future research should therefore evaluate not only whether online tools are engaging, but whether different volcano-focused

audiences can access them, interpret them accurately, trust the information provided, and connect what they learn to preparedness before unrest or eruption occurs.

3.3.3 Creative and Place-Based Media

Creative media like photos, paintings, and film (*Hicks et al., 2017; *Korinth, 2024; *Piccione, 2012) are ways to help raise awareness of volcanic hazards in a passive setting. These studies emphasize the value of interdisciplinary collaboration between scientists, artists, filmmakers, educators, and communicators. Creative media can make volcanic hazards more emotionally resonant and accessible, helping audiences connect with risk information in ways that technical products alone may not (*Korinth, 2024). While studies caution against fear-based messaging because it can produce fatalism rather than preparedness (Sanquini et al., 2016), communication that shows how previous communities recovered, adapted, or demonstrated resilience may instead encourage protective action (*Hicks et al., 2017). Similarly, place-based tools in geoparks, including exhibits, trails, and interpretive materials, can make volcanic hazards more tangible and personally meaningful by connecting hazard information to visible landscapes, past eruptions, and visitor experience (*Alessio & De Lucia, 2017; *de Vita et al., 2021; *Miklín & Lenart, 2016; *Pasquaré Mariotto et al., 2022; *Punturo et al., 2019).

Overall, the tools identified in this review provide a useful baseline for scientists, educators, and communicators developing volcanic hazard communication materials during quiescence. Many of the reviewed articles document the design process in enough detail that the tools could be recreated, adapted, or used as models for future efforts. The usefulness of these tools depends on audience needs, decision context, trust in the information source, and accessibility, and should be assessed through evaluation. Their adaptability is one of their strengths, provided they are intentionally tailored rather than applied unchanged across settings. Ideally, tool development should include participation from the intended audience to ensure that the format, language, content, and delivery method are appropriate for the specific volcanic context and communication goal.

4 Conclusion

This scoping review maps peer-reviewed literature on volcanic hazard communication during periods of quiescence, when immediate crisis pressures are absent but opportunities for long-term preparedness are substantial. This study has several limitations. Its narrow focus on quiescence and volcano-specific communication limits the representation of studies from the broader bodies of literature on geohazard risk communication and science communication. In addition, data were charted only by the first author, and the review was limited to peer-reviewed literature identified through specific databases, excluding grey literature. It therefore does not provide a comprehensive assessment of volcanic hazard communication during quiescence. Despite these limitations, the 76 articles reviewed here document a broad range of formal educational materials, informal education and communication approaches, and informal education and communication tools designed to raise awareness and understanding of volcanic hazards before unrest or eruption occurs. The reviewed literature has grown over the past two decades, showing increasing attention to communication outside crisis settings. Future work should examine grey literature and communication efforts outside the peer-reviewed literature to provide a more complete picture. This scoping review provides insight into research-informed strategies and identifies priorities for future volcano-specific communication research during periods of quiescence.

Across the reviewed articles, several recurring themes emerged. Communication during quiescence should be locally relevant, audience-specific, accessible, and connected to preparedness rather than limited to general awareness or information delivery. Formal educational materials, informal approaches, and informal tools each provide useful models for future work, including classroom activities, participatory engagement, observatory outreach, community networks, hazard maps, digital resources, creative media, and place-based interpretation. However, these strategies should not be treated as ready-made solutions that can

be transferred unchanged across settings. As noted throughout this paper, their usefulness depends on audience needs, accessibility, trust in the source, decision context, and cultural and geographic setting, and should be assessed through evaluation.

The reviewed volcano-specific studies are consistent with broader science communication and DRR literature showing that effective communication is context-specific, participatory, and connected to decisions and actions. However, communication during volcanic quiescence poses distinct challenges compared to other geohazards: volcanoes may remain quiet for generations, unrest may or may not lead to eruption, and future activity can involve substantial uncertainty in timing, location, style, and impact. Our results highlight that empirical evaluation during quiescence remains limited. Only 26 of the 76 articles evaluate the effectiveness of their tool or approach, and many evaluations focus on interest, usability, or knowledge rather than preparedness, behavior, trust, long-term retention, or decision-making. Geographic coverage is also uneven, with several well-studied volcanoes represented repeatedly while many volcanic regions with large, exposed populations receive little attention in the quiescence-focused communication literature. This matters because communication needs, trusted information sources, cultural relationships to volcanoes, educational systems, and preparedness priorities vary widely between volcanic settings. More volcano-specific research is therefore needed to evaluate how different audiences interpret, trust, and use hazard information across volcanic settings and activity phases.

For educators, the reviewed studies recommend active, place-based, and inclusive classroom materials that connect volcanic hazard education to preparedness actions beyond short-term knowledge gains. Scientists and observatories can support communication during quiescence by maintaining trusted information channels, developing accessible hazard resources, supporting local communicators, and creating opportunities for dialogue before unrest begins. Communicators or scientists working with tourists, residents, or Indigenous communities should adapt messages to the audience's context, using visual, multilingual, place-based, and participatory approaches rather than assuming that technical information will transfer unchanged across settings. Emergency managers and decision-makers can use quiescent periods to coordinate with schools, tourism networks, community leaders, observatories, and other trusted actors so that preparedness messages, terminology, protocols, and information pathways are already established before activity changes. Across these groups, the reviewed literature suggests that communication is strongest when audiences are treated not merely as recipients of information but as active participants in shaping, translating, sharing, and evaluating volcanic hazard communication.

Quiescence is not a gap between meaningful communication moments, but a period when awareness can be built, relationships can be established, uncertainty can be explained, and preparedness can become part of everyday community knowledge. To fully use this opportunity, volcanic hazard communication needs participatory and context-specific strategies that are rigorously evaluated and that help different audiences understand volcanic hazards and prepare before the pressures of unrest or eruption begin.

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Competing interests

The authors declare that they have no conflict of interest.

Data availability

The literature reviewed in this manuscript can be reproduced using the search terms, databases, inclusion criteria, and screening procedures described in the Methods section, for publications from 1990 through August 5, 2024. The reviewed articles and extracted study information are listed in the manuscript tables and supplementary materials.

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Author contributions

RH, HS and EH worked together to conceptualize the project. RH, HS, and LG performed paper screening to obtain final dataset; RH performed grouping of articles and information extraction; RH and HS wrote the manuscript draft; and EH reviewed and edited the manuscript.

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