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 study synthesizes 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

10 engagement. We conducted a systematic review of relevant studies and grouped findings into three categories: formal educational materials, informal education approaches, and informal communication tools. Common themes include clear and accessible language, participatory strategies, and trust built through two-way communication. Few studies evaluate communication effectiveness, highlighting an important gap in the literature. This synthesis clarifies how communication during quiescent periods can support disaster risk reduction and strengthen community preparedness over time.

15 1 Quiescence: A Communication Opportunity

Volcanic systems develop over vast geologic timescales, yet individual eruptions are abrupt and destructive events that transform landscapes and disrupt societies. These contrasting tempos create unique challenges for hazard communication. Quiet intervals between eruptions offer strategic opportunities to build public awareness, strengthen preparedness, and foster trust before the urgency of crisis arises.

20 Science education and communication provide valuable frameworks for developing effective approaches to these efforts. Baram-Tsabari & Osborne (2015) define science education as learning that occurs in K-12, higher education, and informal environments, and science communication as interactions between the scientific community and diverse publics. Science education is more focused on raising understanding, while science communication is more concerned with engagement. Broadly, science education and communication share similar goals, seeking "to educate, entertain, and engage the public

25 with and about science" (Baram-Tsabari & Osborne, 2015, p. 135), while emphasizing different aspects. Science education and communication efforts pursue a wide range of goals, from increasing scientific literacy and raising awareness, to sharing the excitement of scientific discovery, influencing attitudes and behaviors, informing policy, and building engagement with diverse communities (Fischhoff, 2013; Nerghes et al., 2022; National Research Council, 2009). In this paper, we focus on science education in formal settings, such as a classroom, and on informal science education, as science communication that

30 happens outside of formal settings.

In the context of geohazards, education and communication efforts have sought to raise awareness of potential risks, explain what may happen during eruption events (including uncertainty), promote preparedness, and build trust (Mossoux et al., 2015; Urlaub et al., 2013; Bandecchi et al., 2019). Previous syntheses of volcanic hazard communication have largely focused on periods of volcanic crises or on specific geographic regions, leaving quiescent periods underexplored. This study addresses that gap by reviewing strategies in peer-reviewed literature for communicating and educating about volcanoes during periods of quiescence. By centering on quiescent periods as strategic opportunities for hazard communication, this review broadens the scope of prior work and provides a foundation for identifying evidence-based strategies to inform practice and future research.

Earlier syntheses emphasized the need to integrate social and physical sciences in volcanic risk communication. Barclay et al., (2008) highlight that effective communication must be tailored to volcanic risk and motivate risk-reducing behavior during quiescence, which differs from issuing warnings during crises when attention is heightened. They note that there is "a lack of insight as to the best strategy for this style of communication, but it should be emphasized that there is a very clear role for scientific information in the communication circuit necessary for disaster risk reduction" (p. 170).

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 is defined as "the negotiated product of open and transparent deliberation with stakeholders for the purpose of their risk-related uses." (p. 12). Thus, it should involve meaningful deliberation between scientists, authorities, and the public. Similarly, the American Geophysical Union volume, Observing the Volcano World: Volcanic Crisis Communication, compiles case studies and lessons learned from major volcanic events, but is centered on times of elevated activity.

More recent work has begun to identify gaps across the full spectrum of volcanic activity. Das et al. (2025) review volcano communication in New Zealand with 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. Although their review classifies the literature into either periods of eruptive activity or of quiescence, evaluative studies remain concentrated on emergency communication, warning, and response.

This study builds on these foundations by focusing specifically on volcanic hazard communication and education during times of volcanic quiescence. We systematically map peer-reviewed literature on these approaches and synthesize common findings across studies. Strengthening understanding of volcanic processes and hazards during quiescence can contribute to more informed decision-making, enhance public trust, and foster cooperation when future crises arise (Stone et al., 2014; Weichselgartner & Pigeon, 2015).

2 Methods

65 We conducted a scoping review, in consultation with a university research librarian, to examine communication and education strategies during volcanic quiescence. 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* 70 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 Science Premier, and the first 100 results from Google Scholar on August 5th, 2024. All references were uploaded to Covidence systematic review software (Covidence systematic review software, 2024). After deduplication, the search yielded 1,222 results (Figure 1).

Two authors independently screened the abstracts and full texts against the inclusion criteria (outlined below), resolving 75 disagreements through discussion. After all screening, 76 articles were selected for inclusion in this review.
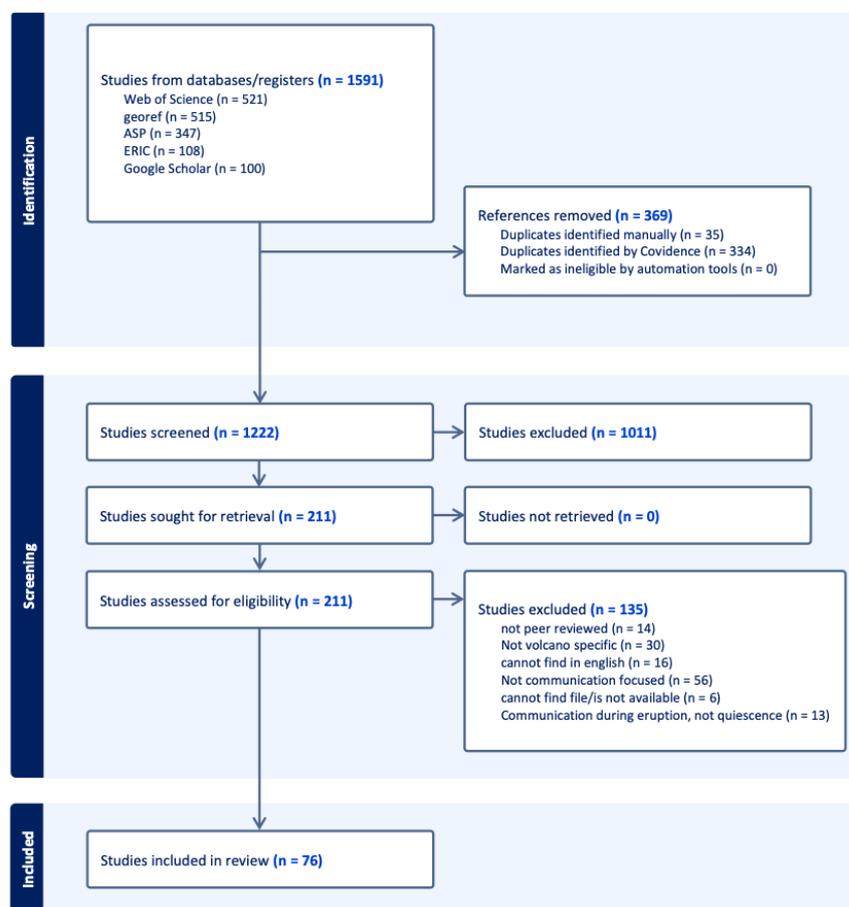

Figure 1. PRISMA diagram of screening process.

We bound the review by specific inclusion and exclusion criteria, filtering for articles that are peer-reviewed, volcano

80 focused, and during quiescence. Reviewers were encouraged to think broadly about education and communication, while excluding crisis-specific efforts. For inclusion, the article must be:

1. Published after 1980

2. A peer reviewed academic journal or book chapter

3. Describing a tool, approach, or communication system; not another volcanic hazard communication synthesis

85 4. Communication focused, 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)

90 8. Not a personal perspective piece

9. No ashfall, air quality, water quality or other public health studies

For each of the 76 final articles, the first author catalogued 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.
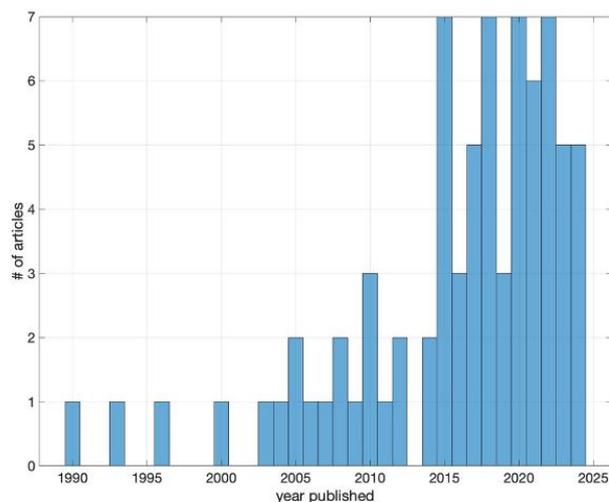
95

Figure 2. Histogram showing range of publication date for final set of articles. The X-axis displays the year the article was published, and the Y-axis shows the number of articles for any given year. Note that articles published before 1980 were filtered out during the database search. The search was completed August 5th, 2024, and as a result no publications past that date were included.

3 Results

Our review identified 76 peer-reviewed articles on volcanic hazard communication and education during quiescence, described here by publication date, geographic focus, and thematic categories. The final set spans 41 different journals, published between 1990 and 2024, with a general increase over time, including a sharp rise in the 2010s (Figure 2). The most frequently represented journals 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). Common themes found are that communication during quiescence is most effective when it is audience-specific, participatory, and grounded in trust. Most studies concentrate on Vesuvius, Etna, Katla, and the Taupo Volcanic Zone, all of which sit 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 in Goma, the Hainan Volcanic Field in China, and Popocatepetl in Mexico, receive little attention and remain poorly studied. There is a need for greater geographic diversity in communication research because effective communication depends strongly on local audiences, and the needs and expectations of communities at each volcano can vary widely. Across all articles, only 26 empirically evaluate the effectiveness of their tool or approach, leaving uncertainty about which strategies work best in practice. This gap highlights the need for more systematic evaluation to strengthen evidence-based communication during periods of quiescence
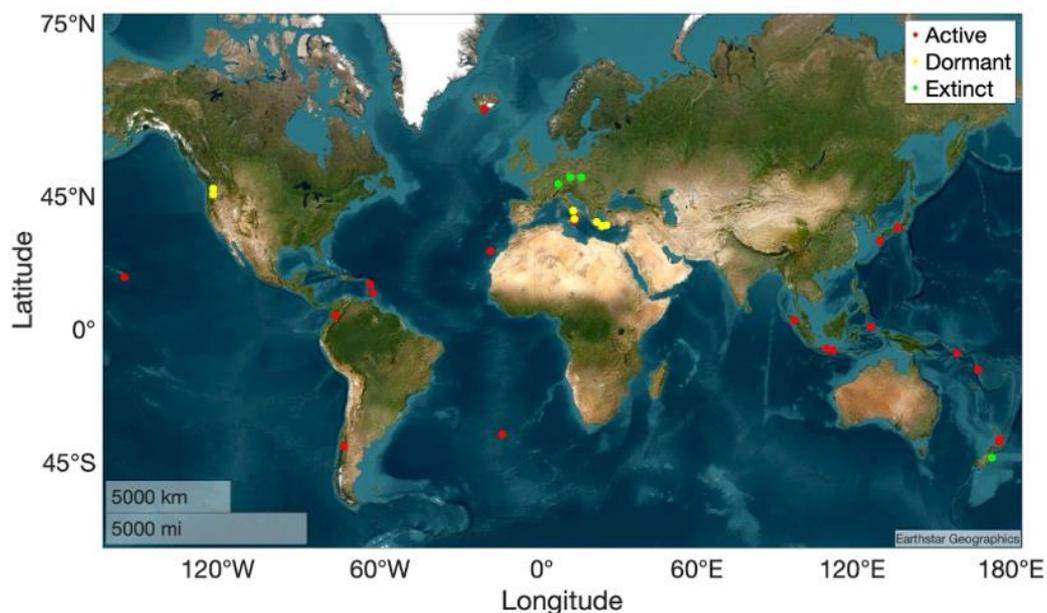

Figure 3. Map view distribution of specific volcanoes or volcanic regions studied in the final set of articles. Legend displays the activity level of the volcano when that article was published.

120 The articles are grouped into 3 categories: formal educational material, approaches to informal education and communication, and tools for informal education and communication.

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.

125 2. Approaches to informal education and communication encompass broad, often multi-faceted 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
130 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. Below, we present the studies within each category and synthesize their findings. Studies are referenced by number, with a full numbered list provided in the supplementary materials.

135 **3.1 Formal education**

Twenty-one articles focus on formal educational activities for a classroom setting. Eight evaluate their materials by either using pre- and post-tests to assess student learning over the course of the activity or using questionnaires to gauge interest and effectiveness from both students and teachers. Most present either interactive activities or online media, such as games, videos, or other learning tools. Volcanic eruptions are often separated by long dormant periods, and engaging schoolchildren
140 helps sustain community hazard awareness. By sharing knowledge with their families, students help maintain understanding and preparedness (Ronan & Johnston, 2001; Shaw et al., 2004; Todesco et al., 2022).

In a classroom setting, you have an audience with required attendance, so while this is useful for ensuring the message is heard, it is important to create an engaging activity to make sure that the message will be remembered (Farley et al., 2013). Hands-on experiments and activities help ensure students are captivated by the activity (#1, 12, 17, 22, 47) while more
145 developed activities and curriculum units may promote a deeper understanding of volcanic hazards and their impact around the world (#6, 10, 40, 68, 76) with specifically online activities becoming increasingly popular (#34, 49, 55, 63, 65, 67). Cross-curricular learning is commonly suggested (#6, 31, 32, 51, 63) to help students receive an overarching view of volcanic disasters and what they mean for a community facing one. For example, Jolley and Ayala (2015; #32), integrate geoscience and archaeology into a single unit, finding that it broadens coverage of standardized learning goals, enables
150 students to view disciplines through a new lens to gain fresh insights, and increases student interest in the material.

Todesco et al., (2022, #72) analyzed stories of volcanic eruptions written by children and used the most common patterns found to identify misconceptions. They find that children rarely recognized precursory unrest and had misconceptions about the size and style of eruptions, they all tended to be very small in the students' stories. They suggest future educational

materials could focus periods of volcanic unrest, helping students understand what it takes, and how long it takes, to
reactivate a dormant volcano. They also suggest interdisciplinary collaboration to devise sketches of volcanic eruptions that
provide a better understanding of the size of big explosive events, and that the same volcano can display very different
eruptive styles.

3.2 Approaches

Twenty-seven articles describe approaches for hazard communication outside of formal education. These approaches are
often audience-specific, with six focused on communication with tourists and ten on communication with Indigenous
populations. Others provide a general communication framework, propose strategies for incorporating eruption planning and
preparedness exercises, or provide guidance on terminology. Few of these approaches are empirically evaluated, instead
offering practices that can be adapted based on audience and topic.

For tourists, recommendations include creating bold and attention seeking efforts to stand out in the crowded sector that is
tourism (#7, 8, 74), including pictures, drawings, and video footage to avoid confusion with scientific terminology (#7, 18).
Presenting hazard information at past eruption sites has greater impact than elsewhere, more easily creating a visual in
people's minds (#42). Learning about an event where it occurred reinforces its significance, especially when paired with
brief, informative titles and high-quality photos on interpretive panels (#42, 43, 74). More broadly, the tourism sector as a
whole must be actively involved in risk reduction strategies (#8, 42). Bird et al., (2020) study this in detail by analyzing risk
communication initiatives in Iceland. They suggest that whole community involvement is necessary, stating that risk
reduction efforts must extend to the dissemination and sharing of risk information by travel agents and tour guides prior to
booking and taking tourists into potentially hazardous environments. Guides must be trained for disasters and have a well-
known protocol in place, and community officials must ensure a long-term and ongoing commitment to risk communication
initiatives. For warnings to be effective, risk communication must be integrated into everyday practices (#7, 8). This means
regularly distributing consistent information through all channels e.g., websites, social media, brochures, signs, and short
films.

For Indigenous populations, studies focus on creating a plan of action for disasters rather than developing a scientific
understanding of the volcano. Many articles emphasize that it is not necessary to reconcile belief systems between local and
scientific viewpoints with respect to the causes and generation of volcanism (#13, 14, 20, 37), which can create
disagreements and distrust. With the goal of disaster risk reduction, the focus should be recognizing precursory signals and
having a plan for when they occur. To help identify these precursory signals and emphasize how catastrophic these eruptions
may be, the use of oral storytelling is suggested by authors (#15, 20, 29, 37, 56). "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" (Cronin and Cashman, 2008, p. 198). Effective communication with Indigenous populations
requires that communicators invest time in understanding the unique social context and dynamics to identify the most
relevant elements of the social system, and in integrating this understanding with knowledge of the volcanic system (#13, 14,
20, 21, 27, 37, 56, 64). To achieve this understanding of culture, customs, values, taboos, and political-governance structures

of the population, there should be involvement of Indigenous people throughout the communication process (#13, 14, 20, 21, 27, 37, 56, 64).

190 Using local actors to convey your message can help develop trust and understanding with your audience (#11). This may be emergency managers, popular local figures, or any other member of the community. Gathering their input and insights while creating your message will increase trust in the message being conveyed, highlighting the importance of a participatory approach.

Two articles discuss the approach to communicating one specific hazard, ballistics and lahars (#19, 58), reviewing research

195 to date and methods of communicating those hazards. For volcanic observatories, articles highlight the importance of outreach during time of quiescence and using this time to educate and establish a relationship within the community (#23, 30, 48, 73). They emphasize the importance of having a strong social media presence and discuss what type of materials observatories should post based on the activity level of the volcano (#73). Two articles suggest the creation of volcanic information databases to provide stakeholders and communicators with a resource for disaster planning (#46, 66).

200 Two articles provide resources for communicating probabilities and translating volcanic terminology into other languages (#24, 25). When translating across languages, Harris et al. (2017, p. 57, #25) emphasize that translations must (1) obey alphabet and accent formats, (2) be lexigraphically accurate, (3) be grammatically correct, and (4) still maintain the intended meaning of the term. Harris (2015, #24) examines how probabilities and uncertainties are communicated, using case studies of newspaper reporting on severe weather systems and volcanoes. In the volcano focused section, they find that the use of

205 terminology is critical in reporting uncertainties and probabilities, and that evocative words with daunting images may prompt unintended interpretations. Table 2, collated from Sink (1995) and earlier work by Doyle et al. (2011), illustrates that scientists and the public often assign different numerical values to the same qualitative probability phrases. These results are based on previous studies of weather probabilities but may apply to other probabilistic scenarios. The variation across audiences demonstrates that interpretation depends strongly on the reader, and that commonly used terms such as unlikely or

210 possible do not convey consistent numerical meanings. Because of these discrepancies, Harris agrees with Gill (2008) that "an effective way to convey uncertainty was to use objective numerical measures (such as probabilities) coupled with plain language that is clearly defined" (page 21). The choice of this plain language is critical, and they provide suggestions in this article.

Recent work by Peters et al. (2025) recommends that communicators use numbers, make numbers more manageable for the

215 audience, make numbers more meaningful, and don't let narrative displace the data. When framing probabilities, they suggest it depend on the audience and goal, stating that "using frequencies rather than probabilities would drive people to imagine the earthquake happening and it would increase emotional reactions and risk perceptions (Slovic et al. 2000). Is the probability or frequency format the correct one? We suggest it depends on the communication goal. If the goal is to convince people to get prepared, the frequency format might better meet this goal."

220 Communicating uncertainty is particularly challenging for volcanoes, where risk can be large and hazards unfold over long, irregular timescales. Scientists think in terms of decades to centuries, whereas the public often interprets time more

immediately, leading to differing perceptions of future activity. Although other fields have studied how probability language shapes public understanding, little work addresses this specific to volcanic contexts. Targeted research is needed to understand how communities interpret probabilistic volcanic information and how to craft messages that communicate it

225   effectively.

3.3 Tools

Twenty-eight articles present specific tools for hazard communication outside formal settings, including hazard maps, online tools and video games, virtual reality (VR), photos, paintings, film, and tools designed for use in geoparks. Ten of these articles included empirical evaluation, with the majority focused on hazard map assessment (#26, 50, 59) or online media

230   testing (#9, 45, 61, 62, 75).

To create effective hazard maps, authors find that the public tends to prefer arial photographs and 3D maps to best interpret the landscape (#26, 50, 59) whereas scientists and emergency managers tend to prefer contour maps with more detail to interpret (#50). They highlight the importance of a participatory approach, ensuring that the map maker understands the audience's existing knowledge and perspectives, and what information is valued and needed by the community (#50, 52 59,

235   69).

For online media (#3, 4, 5, 38, 61, 62, 71, 75), there are a variety of communication materials that may be used. These articles outline the online communication tool they created and how it may be recreated to formulate your own media. For virtual reality (#9, 39, 41, 53, 70), they similarly outline how they created their tool step-by-step to allow it to be replicated. Both groups encompass things like online museums, virtual outcrops, and geostories that walk the audience through the

240   history of the landscape. They encourage the use of these tools for those unable to travel to a geologic outcrop, like those with disabilities or whole classrooms that cannot attend a large-scale field trip (#9, 38, 39, 53, 61, 70). Two articles highlight the use of serious games (#36, #45) to raise awareness of hazards, showing that even standard video games, when scientifically accurate, can improve understanding of volcanic processes.

Creative media like photos, paintings, and film (#28, 33, 57) are ways to help raise awareness of volcanic hazards in a

245   passive setting. These articles highlight the importance of interdisciplinary collaboration, and the use of this media to more easily elicit an emotional response from viewers to guide thinking and behavior (#33). They emphasize the importance of not using fear-based emotions, because this often results in a fatalist attitude (Sanquini et al., 2016). Instead, showing previous communities recovering and displaying resilience encourages the community to take protective action (#28). In a setting with frequent tourists (#2, 16, 44, 54, 60), articles outline how to create exhibits and trails that are useful for raising

250   awareness of hazards in geoparks, and the best designs and content to enhance understanding.

4 Conclusion

This synthesis highlights a broad range of communication techniques and educational activities tailored to diverse audiences and settings. Peer-reviewed literature on volcanic hazard communication during volcanic quiescence has increased over the past two decades, documenting various approaches to education and engagement with diverse groups. While not exhaustive,

255   this review offers a resource for those seeking activities, approaches, and tools to guide their work.

Consistent with other recent reviews (Das et al., 2025), we find that evaluative research remains limited, and developing accessible tools to assess different communication and educational goals should be a priority. Communication during quiescence differs substantially from crisis communication, yet it remains underexplored. Because quiescence is the longest volcanic period and the most strategic time to raise awareness and understanding of volcanic hazards (Todesco et al., 2022b),

260 empirically tested strategies are especially needed. There is also a strong need for greater geographic diversity in communication research. Communication depends heavily on local context and community needs vary widely across volcanic settings, yet only a few major volcanoes are studied in depth.

Across the articles reviewed, several key tenets emerged: communication should be locally tailored to the audience and region, foster trust through two-way communication and collaboration, and keep language clear and concise. Particularly

265 when conveying scientific probabilities, audiences may vary significantly in their interpretation of probabilistic terms. Specific tools and approaches may vary, but articles underscore the importance of understanding audiences and engaging intentionally during times of quiescence. This study highlights strategies documented in the literature that can guide scientists, educators, and communicators in their work during quiescent periods, while also pointing to the need for further evaluative research to strengthen future communication efforts.

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.

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Author contributions

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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