REVIEW ARTICLE

VOLCANICA

A systematic review of volcanology learning and teaching in higher education

Jacqueline Dohaney*[α], Alison Jolley[β], Ben Kennedy[γ], and Alex Watson[γ]

[α] Institute for Academic Development, University of Edinburgh, Edinburgh, Scotland, UK.
[β] Te Puna Ako – Centre for Tertiary Teaching & Learning, University of Waikato, Hamilton, Aotearoa New Zealand.
[γ] School of Earth and Environment, University of Canterbury, Christchurch, Aotearoa New Zealand.

Abstract

We present a systematic map of the volcanology higher education literature (1983–2020) consisting of 47 peer-reviewed full texts. The literature describes curricula in varied formats and settings, namely: simulated, in-person, and field-based learning. The phenomena that students are learning about commonly include volcanic processes and landforms, applicable to learning within various geoscience subdisciplines. Frequently published research includes volcano misconceptions and simulated eruptions. However, most texts focus on practitioner wisdom and lack research information, empirical evidence, and/or a research-oriented methodology. A lack of research orientation is a documented phenomenon within the broader field of geoscience education, which is young compared to other discipline-based education research fields. Based on our findings, we recommend future research in conceptual learning of volcanology, instructional strategies, volcanology and society interactions, volcanology education equity and inclusion, volcanology cognition, quantitative learning, affective learning, and institutional change in volcanology.

Résumé

Nous présentons un aperçu systématique de la littérature sur l'enseignement de la volcanologie (1983–2020) composé de 47 textes complets évalués par des pairs. La littérature décrit les programmes d'études dans des formats et des contextes variés, à savoir l'apprentissage simulé, en personne et sur le terrain. Les phénomènes que les élèves étudient comprennent généralement les processus volcaniques et les reliefs, applicables à l'apprentissage dans diverses sous-disciplines géoscientifiques. Les recherches fréquemment publiées incluent des idées fausses sur les volcans et des éruptions simulées. Cependant, la plupart des textes se concentrent sur la sagesse des praticiens et manquent d'informations sur la recherche, de preuves empiriques et / ou d'une méthodologie axée sur la recherche. Le manque d'orientation de la recherche est un phénomène documenté dans le domaine plus large de l'enseignement des géosciences, qui est jeune par rapport aux autres domaines de recherche en éducation axés sur les disciplines. Sur la base de nos résultats, nous recommandons des recherches futures sur l'apprentissage conceptuel de la volcanologie, les stratégies pédagogiques, les interactions entre la volcanologie et la société, l'équité et l'inclusion dans l'enseignement de la volcanologie, la cognition en volcanologie, l'apprentissage quantitatif, l'apprentissage affectif et le changement institutionnel en volcanologie.

Keywords: Higher education; Systematic review; Volcanology; Teaching; Learning.
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1 Introduction

The scholarly research of volcanology education helps our community deliver engaging and effective learning experiences for geoscience students. To know what techniques to use and topics to deliver, it is wise to rely on evidence of 'good' practices in the literature. However, there are no known systematic reviews of volcanology higher education that provide a baseline of insight and findings upon which to improve. Here, we aim to meet this need and investigate the existing literature that describes the learning and teaching of volcanoes from universities and colleges worldwide. Additionally, this piece of work will contribute towards the scholarship of teaching and learning (SoTL) of volcanology helping us to investigate and share our teaching practices, answering the 'what works and why' problem of teaching [McKinney 2013]. Reading and understanding the existing literature in volcanology higher education can provide a powerful foundation upon which to innovate and improve our practices.

Overall, our primary purpose in this research was to document, synthesise, and summarise existing studies in volcanology education research to create a systematic map of the existing literature. Secondarily, it was to characterise the nature of volcanology higher education curricula and research and develop recommendations for future educators and researchers in this field. The intended outcome is to develop a collection of literature that consists of the state of knowledge in volcanology education research identifying current and future innovations in our field. The research questions that guided this work included:

- Primary question: What literature exists where education research is used in learning and teaching of volcanology in higher education?

- What areas of geoscience phenomena, knowledge, and skills is the literature concerned with?

* j.dohaney@ed.ac.uk

- What kind of curricula do they describe, and what is the educational setting and context of these curricula?
- What are the existing educational research findings, and how are they described?

A companion article has been written for volcanology instructors interested in accessing and using the resources available in the literature review [Dohaney et al. 2023].

2 Methodology

The research design we used was informed by existing systematic review methods and embraced a post-positivist research approach (i.e. applying empirical processes guided by the scientific method while valuing all methodologies equally [Guba and Lincoln 2005]). Systematic reviews follow transparent, methodical, and reproducible procedures that might be grouped broadly into two arenas: (1) selecting a collection of appropriate studies that will address the review question from the vast and rapidly increasing knowledge base, and (2) extracting trends, patterns, relationships, and the overall picture from the collected studies [Borrego et al. 2014]. Systematic literature reviews are different in purpose, style, and process from a narrative literature review [e.g. James et al. 2020].

We began by forming a research team consisting of four scholars in education and volcanology, and we defined the purpose of the review, the scope, practical implications, initial research questions, and the intended outcomes (see Introduction). We then selected the appropriate systematic review method aligned with our aims and practical limitations called a **systematic map of the literature** [Grant and Booth 2009]. The key aim of a systematic map is to: "Map out and categorise existing literature from which to commission further reviews and/or primary research by identifying gaps in research literature" [Grant and Booth 2009, p. 94]. Importantly, the purpose of our systematic review is *not* to assess the quality of education or specific interventions (i.e. 'What works?') or to dig into the detail of the findings from individual studies. We aim to answer the question: 'What's out there?' and provide that answer to our readers.

Next, we developed a protocol (see Figure 1) that guided the review process established from validated methods and aligned with best practices defined by the Cochrane Library [Higgins et al. 2019]. The protocol included processes common to all systematic reviews, including the following reproducible steps: Search (i.e. to retrieve studies), Screen and Appraise (a.k.a. selection of pieces; i.e. to apply inclusion and exclusion criteria to the records), Coding (i.e. to describe, characterise, and evaluate the literature), and Analysis (i.e. to analyse and synthesise the results) [Borrego et al. 2014]. We defined literature broadly to include any research articles or other formats, such as book chapters, conference presentations, and reports. The methodology is summarised in two parts:

1. searching, screening, and appraisal of volcanology higher education literature, and
2. coding and analysis of the literature.

For more detailed information required to replicate the systematic review process, please see Appendix A.

2.1 Searching, screening, and appraisal of the literature

The first step was to **search** and compile all of the literature into a database. In **Step 1A**, we developed initial search words and phrases based on the topic and target population, that included terms like volcano, education, learning, university, etc. The aim was to capture all the relevant pieces as was possible, as a systematic literature review on this topic had never been completed before. In **Step 1B**, we identified all the databases (Appendix A2) that hold digital records of the literature relevant to volcanology higher education. In **Step 1C**, we developed initial inclusion and exclusion criteria (Appendix A3) that guided which pieces of literature were included or excluded in the review. The criteria were guided by the research questions and limited to our target population of formal higher education contexts. Importantly, we limited the studies to literature written in English, due to our team's capabilities. In **Step 1D**, we searched the databases using our chosen search terms, collected 3017 initial records, and compiled them into an `Excel` sheet while checking for duplicates (**Step 1E**). The remaining records (2495) were given unique randomised record numbers for tracking purposes.

The next step of the review was to **screen** the records by title and by abstract text. Screening involves reading and assessing the record against the inclusion and exclusion criteria and asking oneself: 'Does this piece of literature belong in our review?'. In **Step 2A**, the title for each record was screened by two researchers, and allocated 'Yes', 'No', or 'Maybe' responses. If the researchers disagreed, the record was further discussed. The title screen resulted in 1852 records rejected, 339 records accepted, 305 maybes and two new records were added as they were recommended by ResearchGate* to the first author when publishing their work during this step (646 records remaining). In **Step 2B**, the abstract for each record was screened by two researchers following the same process in Step 2A and resulted in 369 records rejected, 114 records accepted, 161 maybes (275 records remaining).

The third step of the review was to read and **appraise** the literature pieces in full and apply the inclusion and exclusion criteria. However, of the 275 records remaining, 195 were conference presentations (oral and poster) where the full presentation files were largely unavailable. We removed the 195 records and then later conducted a preliminary analysis on the abstract keywords (n.b. further explored in Appendix C with methods described in Appendix A3).

In **Step 3A**, two researchers appraised each piece of full text literature (80 pieces remaining) resulting in 39 accepted and 41 rejected pieces. In **Step 3B**, we conducted a backward citation search to check for any records that might not have been listed on the databases. We checked the reference list of each accepted piece of literature and located 4 new records. In **Step 3C**, we checked the citations (Forward citation search) of our accepted pieces and added 4 new records. In the final appraisal step, **Step 3D**, we looked for any new pieces published in 2019 and 2020 and found no new pieces. After completing the search, screening, and appraisal steps, there were a total of 47 accepted full texts that moved forward into analysis.

*https://www.researchgate.net/

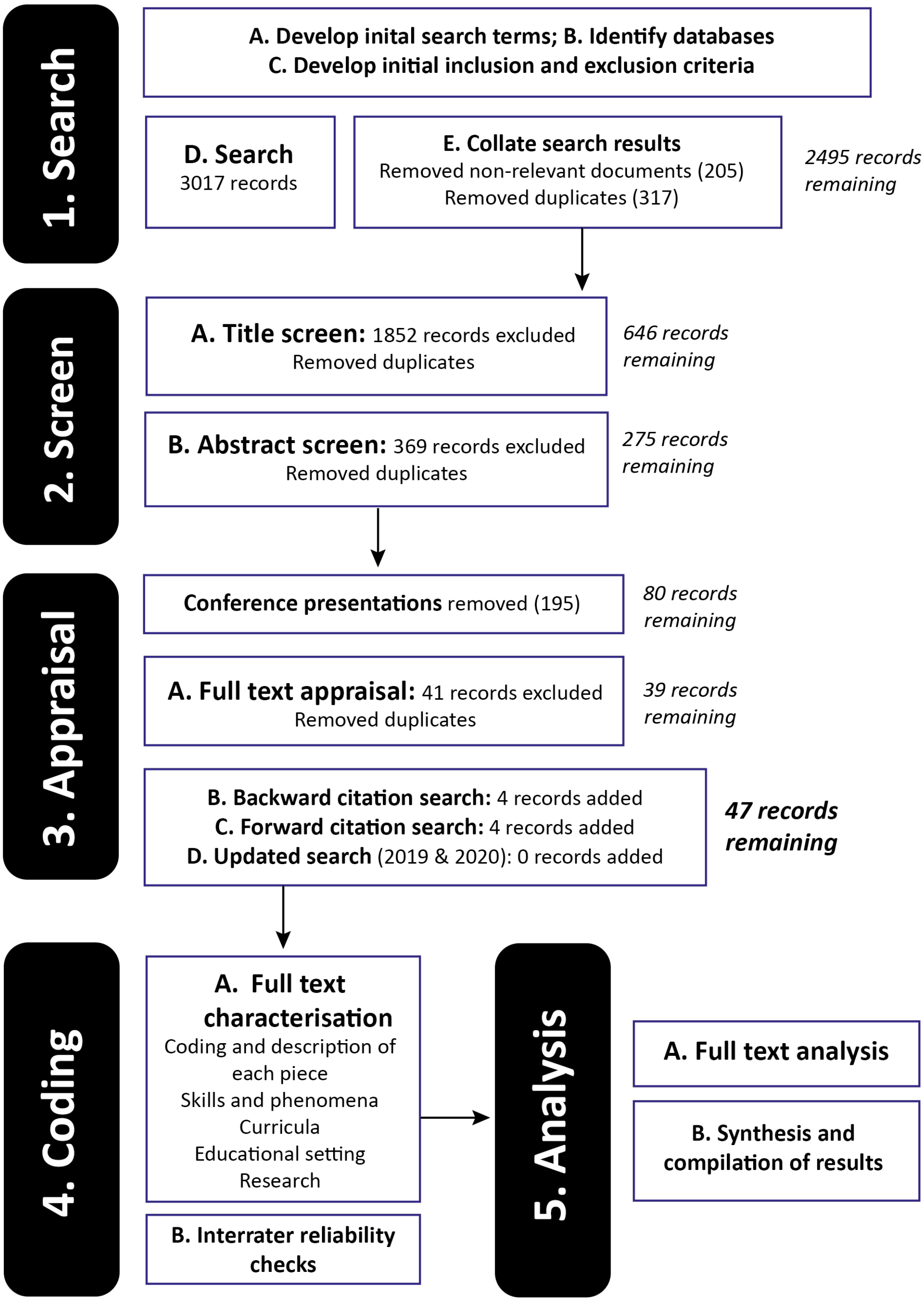

Figure 1: Systematic review method used in this study.

2.2 Coding and analysis of literature

In this section, we describe how we coded (Step 4) and analysed (Step 5) the literature. Before we began our full text coding and analysis, we conducted a preliminary analysis on the conference presentation abstract GeoRef* keywords to determine initial themes related to our research questions. Categories (of codes) emerged from the keywords including: volcanic phenomena, volcano names, tools and techniques, disciplines, and education topics. These categories helped to guide the coding and analysis of the full texts. A detailed description of the method of analysis is described in Appendix A1 and the results are in Appendix C.

In Step 4A, we coded the 47 full text pieces of literature for key characteristics as defined by our research questions using conventional content analysis. Content analysis is a method for making sense of and deriving meaning from qualitative data [Cohen et al. 2007]. The basic procedure is to view a dataset holistically (in this case, a piece of literature) and assign codes and categories to the data, such as bibliographic infor-

*https://pubs.geoscienceworld.org/georef mation, volcanic phenomena, educational setting, curriculum descriptions, and education research information. The final coding categories are listed in the header of the columns of the database listed in Appendix B1. To increase the reliability of our coding scheme and findings, we assigned two researchers to each paper, and checked for interrater reliability (**Step 4B**), which occurred simultaneously to **Step 4A**. Interrater checking was done by comparing the information the codes provided by two different researchers and checking for agreement and disagreement. The first 26 pieces of literature were checked for interrater reliability until our agreement was 80 % on average. The final coding scheme was applied to the remaining 21 pieces, and the first author read all 47 full tests to ensure coherency as a collection.

In **Step 5A**, all coded data records were compiled into a master `Excel` sheet and prepared for analysis. Then, each category of coded information was assembled, counted, and analysed. Continued categorisation, renaming, and clustering of chunks of information occurred until mutually exclusive categories of information emerged. Once all content analysis and frequency checking was completed, the data was compiled for presentation in tabular and figure format (**Step 5B**).

3 Results

The primary aim of this study was to catalogue and qualitatively code a collection of volcanology higher education research. The results of the study will be organised by our research questions:

- Question 1. What literature exists where education research is used in learning and teaching of volcanology? (Section 3.1; Primary aim of research);
- Question 2. What areas of geoscience phenomena, knowledge, and skills is the literature concerned with? (Section 3.2);
- Question 3. What kind of curricula do they describe, and what is the educational setting of these curricula? (Section 3.3); and
- Question 4. What are the existing educational research findings, and how are they described? (Section 3.4).

The full list of literature that was identified in this search are collated and presented in Appendix B2 as well as a link to the digital catalogue of these literature (Table 5). All of the research that is described in this manuscript is situated before the COVID-19 pandemic.

3.1 Search results

We found and reviewed 47 full pieces of literature (2 % of initial search results). The literature described a range of curricular experiences suited to various disciplines and higher education learning levels and settings. The literature was published in the years 1983–2020, linearly increasing for every decade of research (1980s = 3, 1990s = 8, 2000s = 13, 2010s = 22—strong positive linear relationship; R^2 = .98; very strong positive correlation: Pearson's r = .99).

The vast majority of the literature were journal articles (total 31; 66 %), including *Journal of Geoscience Education* (22; 47 %), *Journal of Applied Volcanology* (2), *Computers & Geosciences* (2), and one article (each) from the following: *Bulletin of Volcanology*, *International Journal of Science Education*, *Journal of College Science Teaching*, *Planet*, *Review of International Geographical Education Online*, *The Science Teacher*, *Statistics in Volcanology*, *Numeracy*, and *Volcanica*. The remaining works include five Geological Society of America (GSA) special papers (from *Analogs for Planetary Exploration*, *Field Geology Education: Historical Perspectives and Modern Approaches*, and *Google Earth and Virtual Visualisation in Geoscience Education and Research*), three conference papers (from *International Conference on Information, Business and Education Technology*, *International Symposium on Visual Computing*, and *Journal of Physics: Conference Series*), a book chapter (*Observing the Volcano World: Volcano Crisis Communication)*, a Masters dissertation, a magazine article (*Eos*), and an Institute of Geological and Nuclear Sciences Limited (GNS) Science scientific report.

3.2 Geoscience skills and phenomena

A secondary aim of this study was to find out the areas of geoscience phenomena and skills described in volcanology higher education research. This section includes 1) the named volcanoes, 2) the named volcanic phenomena, 3) geoscience-specific skills, and 4) transferable skills.

3.2.1 *Volcanic locations*

Thirty seven of the 47 pieces of literature (79 %) reviewed named specific volcanic locations in the text. These volcanic locations were used as case studies for student learning and are mapped in Figure 2. The top ten volcanoes most frequently mentioned (red triangles) have had widely recognisable historical eruptions that caused societal disruption. The volcanoes were predominantly from North, Central, and South America (42; 89 %), followed by Oceania (17; 36 %), Asia (11; 23 %), Europe (8; 17 %), and Africa (3).

3.2.2 *Volcanic phenomena*

During coding, researchers noted all the key social and physical volcanic phenomena mentioned in the main text of the literature. We found 252 unique phenomena with 615 mentions. Each unique volcanic phenomenon is mentioned at least once, but often multiple times (e.g. volcanic eruption is mentioned by 16 different pieces of literature). The most frequently mentioned phenomena including volcanic eruption(s) (16 mentions; 3 %), lava flow(s) (16; 3 %), volcanic hazard(s) (14; 2 %), volcanic gases (12; 2 %), social impacts from volcanoes (10; 2 %), ash (10; 2 %), pyroclastic flow(s) (9; 1 %), ground deformation (9; 1 %), volcanic monitoring (8; 1 %), and volcanic earthquake(s) (8; 1 %). The most frequently mentioned volcanic phenomena are included in Table 1, and all volcanic phenomena in the articles can be searched and viewed in the literature catalogue (Table 5).

These phenomena were thematically organised, clustered, and categorised. We identified five categories organised by scale:

Figure 2: World map illustrating the volcanoes mentioned by authors (black dots), including the top ten most frequently mentioned (red triangles): Top ten volcanoes listed in descending order: 1. Mount St. Helens (8 pieces), 2. Mount Pinatubo (6), 3. Kīlauea (6), 4. Parícutin (4), 5. Mauna Loa (4), 6. Mount Vesuvius (3), 7. Mount Rainier (3), 8. Krakatau (3), 9. Cotopaxi (3), 10. Auckland Volcanic Field (3). Figure made by the first author with QGIS and Google Earth.

- **Volcanic processes** (e.g. volcanic eruptions, volcanic earthquakes, ground deformation, etc.; 92 unique phenomena (37 %) with a total of 215 mentions of phenomena listed in this category (35 %));
- **Landforms and outcrops** (e.g. lava flows, cinder cones, dikes, etc.; 72 phenomena (29 %), 183 mentions (30 %));
- **Sample and microscopic** (e.g. ash, textures, basalt, etc.; 38 phenomena (15 %), 87 mentions (14 %));
- **Societal** (e.g. crisis management, built environment, eruption histories, etc.; 31 phenomena (12 %), 98 mentions (16 %));
- **Global and regional** (e.g. rift volcanism, subduction volcanism, etc.; 19 phenomena (8 %), 32 mentions (5 %)).

Overall, there appears to be a focus on meso- and macro-scale volcanic phenomena published in the literature (e.g. volcanic processes, landforms, outcrops). There is less focus on the global and regional scale, societal elements, and micro-scale volcanic phenomena.

3.2.3 *Geoscience-specific skills*

Fifty-three unique geoscience-specific skills (Table 2) were reported in the reviewed literature with a total of 127 mentions of items in this category. Thirty-five pieces did and 12 pieces did not explicitly describe geoscience skills or techniques. The most frequently mentioned skills include volcano monitoring (13 mentions; 10 %), geologic mapping (9; 7 %), field geology (7; 6 %), volcano hazards mapping (6; 5 %), volcanic forecasting (5; 4 %), satellite image analysis (5; 4 %), volcanic impact analysis (4; 3 %), volcanic crisis management (4; 3 %), radar imaging (4; 3 %), geologic histories (4; 3 %), and aerial photography (4; 3 %).

Table 1: Table of most frequently mentioned uncategorised volcanic phenomena (with ≥3 mentions). Note that plurals were compiled together with singular terms (e.g. gases and gas). *N* = number of mentions.

Phenomena	*N*	Phenomena	*N*	Phenomena	*N*
lava flow(s)	16	eruption mechanisms	5	block(s)	3
volcanic eruption(s)	16	human impact(s)	5	collapse features	3
volcanic hazard(s)	14	magmatic evolution	5	columnar jointing	3
volcanic gas(es)	12	scoria cone(s)	5	debris flow(s)	3
ash	10	shield volcano(es)	5	eruption plumes	3
social impact(s)	10	stratovolcano(es)	5	eruption processes	3
ground deformation	9	crisis management	5	hazard assessment	3
pyroclastic flow(s)	9	hazard mitigation	5	ignimbrites	3
volcanic earthquake(s)	8	weather effects	5	lava tube(s)	3
volcanic monitoring	8	ʻaʻā	4	maar(s)	3
basalt(s)	7	fractional crystallisation	4	magma chamber(s)	3
caldera	7	infrastructure impacts	4	mudflow(s)	3
cinder cone(s)	7	magma composition	4	phreatomagmatism	3
lava dome(s)	7	magma generation	4	pyroclastic airfall	3
texture(s)	7	pāhoehoe	4	rhyolite	3
bomb(s)	6	plate tectonics	4	rift volcanism	3
dike(s)	6	pumice	4	spatter	3
eruption histories	6	volcanic alert levels	4	subduction volcanism	3
eruption style(s)	6	forecasting	4	tephra	3
explosive eruption(s)	6	volcanic rock compositions	4	vent(s)	3
lahar(s)	6	morphology	4	visual surveillance	3
magmatism	6	xenoliths	4	crisis response	3
seismicity	6	andesite	3	volcanic processes	3
viscosity	6	ballistics	3	volcano types	3
volcanic landform(s)	6	block and ash flow(s)	3		

3.2.4 *Transferable skills*

Transferable skills were also commonly reported, defined as skills needed for academic and professional success. There were 82 unique transferable skills (203 mentions of skills in this category) reported in 40 pieces with seven pieces that did not explicitly describe academic or professional skills. The most frequently mentioned transferable skills included observation-making (16 mentions; 8 %), teamwork (14; 7 %), communication (8; 4 %), problem-solving (7; 3 %), quantitative (7; 3 %), decision-making (6; 3 %), communication (oral) (5; 2 %), communication (written) (5; 2 %), critical thinking (5; 2 %), data analysis (5; 2 %), hypothesis-making (5; 2 %), presentation (5; 2 %), research (5; 2 %), and synthesis (5; 2 %).

The transferable skills were thematically organised, clustered, and categorised into seven categories:

- **Research** (e.g. data analysis, interpretation, observation-making, etc.) (23 skills (28 %), 74 mentions in total of this category (36 %));

- **Quantitative** (e.g. computational, data processing, databases) (19 skills (23 %), 38 mentions (19 %));

- **Communication** (e.g. oral, public, written, etc.) (16 skills (20 %), 44 mentions (22 %));

- **Teamwork** (e.g. teamwork, collaboration, decision-making, etc.) (6 unique skills (7 %) with 27 mentions (13 %));

- **Project management** (e.g. financial management, organisation, planning) (6 skills, 8 mentions (4 %));

- **Personal development** (e.g. independent learning, reflection, self-evaluation) (6 skills, 8 mentions (4 %));

- **Social learning** (e.g. community engagement, social interactions, social responsibility) (5 skills (6 %), 5 mentions (2 %)).

3.3 Curricula and educational setting

A secondary aim of this study was to describe the curricula and educational setting of the pieces discovered in this literature review. This section includes many types of information, including a description of the student population, institution types, course types, setting and modes of learning, the disciplines relevant to the curriculum, the number and type of curricula, educational topics, and educational resources provided in the literature. This information is critical to replicating the delivery of the curricula or the research. It is important to note that three of the articles were research-only, meaning that the aim of the research was to not design or deliver curriculum

Table 2: Geoscience-specific skills mentioned in the literature. *N* = number of mentions.

Geoscience skills	*N*	Geoscience skills	*N*	Geoscience skills	*N*
volcano monitoring	13	emergency management	2	lithologic descriptions	1
geologic mapping	9	infrared spectroscopy	2	magnetic susceptibility	1
field geology	7	LandSat imagery analysis	2	MATLAB	1
volcano hazards mapping	6	petrography	2	mineral identification	1
image analysis	5	probabilities and probalistic statements	2	orbital/surface visible imagery analysis	1
volcanic forecasting	5	regional geology	2	planetary analogs	1
aerial photography analysis	4	stratigraphy	2	relative age determination	1
geologic histories	4	volcanic alert levels	2	rock identification	1
radar imaging analysis (SAR, TOPSAR)	4	3D visualisations	1	SEM analysis	1
volcanic crisis management	4	altimetry data analysis	1	terrestrial field analogs	1
volcanic impact analysis	4	eruption mechanics	1	titration	1
Google Earth	3	experimental skills	1	unit identification and correlation	1
remote sensing	3	field photography	1	volcanic risk	1
satellite imagery analysis	3	field volcanology methods	1	volcanic textures	1
volcanic tephra mapping and distribution	3	geochemical sampling	1	volcano geomorphology	1
volcano hazards mitigation	3	geologic reasoning	1	water quality measurements	1
2D visualisations	2	GPS (Global Positioning System)	1	world geography	1
cross-sections	2	LiDAR (Light Detection and Ranging)	1		

but to administer surveys or interviews to gather empirical data related to geoscience students and their learning.

3.3.1 *Student population*

There was an inconsistent sharing of information about the target student population in the literature collected. Some areas were relatively well defined (e.g. the major of the students), and others were poorly defined (e.g. the number of students). Additionally, most papers did not distinguish in their description between students participating in the curriculum and students participating in the research. Roughly half of the literature did not explicitly state how many students participated in the learning or research (22 pieces; 47 %). Of those remaining (25; 53 %), nine pieces were set in small class sizes (<20 students; 19 %), seven were medium (21–30 students; 15 %), and 13 were large or greater class sizes (30 or greater students; 28 %).

We searched for higher education only and found 34 pieces (72 %) described activities with undergraduate students, and nine were suited to postgraduate students. Ten did not explicitly mention the level of education of the research participants or curriculum (21 %), but the level was deduced based on the activities described (for the purposes of screening). Several of the works were dually suited to other populations: high school (1), K-12 teachers (1), professionals (1), and academics (2).

The undergraduate literature can be broken down by year level. Eight of 34 undergraduate pieces did not explicitly mention the students' year level. Of the remaining (26; 55 %), there was roughly an even split between first year (6; 13 %; i.e. freshmen), second- (6; 13 %; i.e. sophomore), third- (6; 13 %; junior), and fourth-year (6; 13 % i.e. senior, honours year) levels. Additionally, some pieces described the curricula and research participants as introductory (i.e. lower division; 8; 17 %) or advanced (upper division; 12; 26 %). Overall, the reported curricula and research span from first to final year undergraduate levels.

The next category of information was the major of the students. Within the literature, 11 did not explicitly mention which majors or disciplines the students were studying (23 %). Of the remaining (36; 77 %), the majority of students were geoscience majors (including geology, earth sciences, environmental science, and subdisciplines; 29; 81 %). The literature also reported STEM majors (including engineering, physical and natural sciences, etc.; 13; 36 %) and Non-STEM majors (including fine arts, humanities, social sciences, etc.; 9; 25 %). Five pieces (14 %) reported on curricula or research with non-geoscience majors. However, they did not explicitly describe what kind of majors they were. It is worth noting that several pieces included students from multiple majors.

Very few of the pieces described the demographics of the students participating in the curricula and research (14 mentioned student demographics (30 %), and 33 did not (70 %)). Literature with demographic information included a range of information (in order of most mentioned): gender (7 pieces; 15 %), race and ethnicity (6; 13 %), academic background (e.g.

Table 3: Table of the most commonly mentioned types of learning activities reported on in the literature, listed in order of frequency. *N* = number of mentions.

Learning activity	*N*	Learning activity	*N*	Learning activity	*N*
lecture(s)	10	research planning	2	numerical	1
simulation	10	research proposals	2	offsite visits	1
reading(s)	9	virtual field trip	2	panoramas	1
role-play	7	virtual reality	2	petrography	1
hand sample analysis	5	alert levels	1	photographs	1
imagery	5	analogs	1	plotting	1
computer-aided	4	animations	1	reflection	1
video(s)	4	case studies	1	research	1
experiments	3	coding	1	research cruise	1
field excursions	3	communication	1	resources	1
jigsaw	3	data collection	1	science reports	1
modeling	3	data interpretation	1	seminars	1
research project(s)	3	data management	1	service learning projects	1
websites	3	data processing	1	software	1
data analysis	2	databases	1	stratigraphy	1
demonstrations	2	debrief	1	textbook work	1
field mapping	2	decision matricies	1	Trimble Sketch-up	1
field reconnaissance	2	discussions	1	tutorials	1
field research	2	field presentations	1	virtual laboratories	1
geologic history	2	geochemistry	1	workbooks	1
geologic mapping	2	graphing	1	worksheets	1
Google Earth	2	journaling	1	workshops	1
hazard mapping	2	K-12 teaching	1	world mapping	1
literature review	2	library research	1	writing exercises	1
movies	2	mathematics	1		

prior academic experience; 5; 11 %), age (3; 6 %), nationality and immigration status (3; 6 %), and social class (2; 4 %).

3.3.2 *Educational setting*

A clearly described educational setting is critical for understanding how learning occurs and what social and cultural factors may influence student and staff experiences. The authors more wholly described the educational setting than other categories of information.

Most pieces (44 or 94 %) clearly stated the country where the curricula or research was situated, with only three that did not. The majority (35; 74 %) were situated in the USA, with some studies (6; 13 %) in New Zealand and fewer from other countries and regions: Europe (one in Spain and one in Northern Ireland), three studies occurred in Central and South America (one Mexico, one in the Galapagos Islands, and one in Ecuador), and only one in Asia (from Indonesia). No studies were reported from African countries.

The higher education institution number, type, and name (where appropriate) can also be important for understanding the socio-cultural setting of learning. Most of the literature included the number of institutions (35; 74 %), and 12 did not mention which university or college (26 %) and how many they included in their curriculum or research. The majority were single-institution studies (22; 47 %), with less two-institution studies (8; 17 %) and fewer multi-institution studies (5; 11 %; three institutions (1; 2 %), five institutions (3; 6 %), 15 institutions (1; 2 %)). About half of the pieces published in this collection were written by five groups (i.e. similarly listed authors) of authors (some single, some multi-institutional). Most pieces named the host institution (33; 70 %), with 14 unnamed (30 %). Of those named, most universities are publicly funded institutions (28; 85 %), with fewer pieces coming out of privately funded institutions (8; 25 %, note some pieces included both public and private institutions).

Most of the literature described the topic or name of courses (a.k.a. units or classes) where the curriculum took place (33; 70 %). Fourteen (30 %) did not mention where the curriculum took place. The majority were single-course studies (18; 55 %), followed by studies taking place in two courses (12; 36 %) and fewer studies with multiple courses (three (2; 6 %), and seven (1; 3 %)). Thirty-four of the pieces (72 %) included the topic or name of the course (13 did not mention; 28 %). The key topic/name of courses were introductory geosciences (12; 36 %), volcanology (11; 32 %), hazards (8; 24 %), and petrology (6; 18 %), with fewer topics/names, including planetary science (3; 9 %), physical geology (2; 6 %), environmental sciences (2; 6 %), geomorphology (2; 6 %), science communication (2; 6 %), stratigraphy (1; 3 %), geologic resources (1; 3 %), earth materials (1; 3 %), water management (1; 3 %), and construction (1; 3 %). These course topics overlap significantly with the disciplines that the curriculum fits, described below in Section 3.3.3.

3.3.3 *Curricula descriptions*

Of the 47 pieces of literature, the vast majority (43; 91 %) included a description of the learning environment (i.e. where the curriculum or intervention specifically occurred), often spanning multiple settings (i.e. being both classroom and laboratory-based). More than half of the activities were coded as classroom activities (26 (60 %); a.k.a. lecture-based), with some field (16; 37 %) and laboratory (14; 33 %) settings, and fewer computer-based (3; 7 %) settings. Given these settings, it is unsurprising that the mode of learning was predominantly in person (or face-to-face; 35; 81 %) with fewer online (7; 16 %) and blended modes (1; 2 %). Six studies did not mention specifically what mode of learning took place or where, and three were research-only.

The literature predominantly described one learning activity (32; 82 %), with fewer pieces describing more than one activity (7 (18 %): two activities (1), three activities (1), five activities (3), six activities (1), ten activities (1)). Four pieces did not explicitly include how many learning activities they were describing. Nearly half of the literature did not describe the length or duration of the learning (20; 43 %). For those that did, the duration of the activities varied widely from less than an hour (4; 20 %) to a semester-long course (6; 30 %), including 1–5 hours (5; 25 %), 6 hrs to 1 day (2; 10 %), multi-day (2; 10 %), week (1; 5 %), and multi-week (3; 15 %).

Most literature (42; 89 %) described the specific type(s) of learning activity that they conducted. There were 74 unique learning activities described (with 147 total mentions across the literature), where pieces often described more than one type of learning activity and assessment (e.g. a field trip accompanied by pre-readings and a post-test). Some of the most commonly mentioned curricula types included simulation (15 articles mentioned simulations; 10 % of the 147 total mentions), lectures (12; 8 %), readings (10; 7 %), field trips (9; 6 %), role-play (9; 6 %), modelling (8, 5 %), experiments (7, 5 %), imagery (digital and hardcopy; 6; 4 %), videos (5, 3 %), research project (5, 3 %), and hand sample analysis (5; 3 %). All the most commonly mentioned types of learning activities are displayed in Table 3. When categorised, there are more research-specific activities (23; 31 % mentioned items in this skill category, e.g. data interpretation and research planning) than other activity types. This is followed by discipline-specific (16; 22 %; e.g. hazard mapping and petrography activity) and field-based learning (12; 16 %) activities.

Twenty-seven pieces did not describe the assessment that students undertook as part of the activity (57 %), 18 did describe the assessment (38 %), one explicitly stated they did not assess the learning, and four pieces were research-only and were coded as not-applicable. Of the 18 pieces, there were a broad range of assessments described, with the most mentioned being reports (i.e. field report or research report; 8; 44 %), oral presentations (5; 27 %), writing assignments (i.e. critical reflections, etc. 5), peer evaluations (4; 22 %), self-evaluations (3; 16 %), tests (3; 16 %), and exams (3; 16 %). Assessments with fewer mentions included data collections (2; 11 %), poster presentations (2; 11 %), field maps (2; 11 %), problem sets (1; 6 %), attendance (1; 6 %), group discussions (1; 6 %), hazard assessments (1; 6 %), and field notebooks (1; 6 %).

Regarding student social interaction, we coded the literature for whether the students worked independently (solo) or in groups (of varying sizes). Most of the literature (28; 60 %) described the nature of student interaction during learning, with 17 pieces that did not explicitly mention this aspect (36 %) and four that did not apply. There were equal amounts of studies (14 each; 50 %) that described the learning as solo (or independent) learning activities or group (or team) learning activities.

Lastly, we coded the curricula to specific academic disciplines so that readers could work out what activities might be relevant in their courses and programmes. We built a list of discipline options (adapted from GSA's sections of disciplines). We found that 45 disciplines and subdisciplines could apply the curricula to their areas (Table 4). Disciplines most commonly applicable (>10 pieces) include volcanology (44; 94 %), geology (35; 74 %), disasters (31; 66 %), physical geology (28; 60 %), geochemistry (25; 53 %), geography (20; 43 %), geophysics (16; 34 %), geomorphology (13; 28 %), petrology (13; 28 %), social geology (13; 28 %), geodesy (12; 26 %), geohistory (12; 26 %), computational sciences (11; 23 %), and mineralogy (11; 23 %).

3.3.4 *Education topics*

For each piece of literature, we recorded any educational terms and topics often used (and searched for). These topics look at what areas of education research have been explored. These terms overlapped with curricula descriptions and educational settings. The literature covered 70 unique educational research topics (with 169 total mentions) that mirrored the curricula described above are shown in Table 5. The topmost commonly mentioned were field-based learning (8; 5 %), simulation-based learning (8; 5 %), active learning (7; 4 %), authentic learning (7; 4 %), computer-based learning (6; 4 %), inquiry-based learning (6; 4 %), interactive learning (6; 4 %), online learning (6; 4 %), research-based learning, co-operative learning (5; 3 %), role-play (5; 3 %), collaborative learning (4; 2 %), and learning through experiments (4; 2 %).

3.3.5 *Educational resources*

Many of the literature included references to additional educational resources that support the delivery of the curricula, like websites, databases, and imagery. We decided to record this data to understand information sharing through these publications.

Most of the pieces included additional resources (28; 60 %), and 19 did not (40 %). From the 28 pieces, 98 resources were described. The majority of additional resources are websites (88; 90 %), followed by material in the appendix of the piece (6; 6 %), within the tables (2; 2 %), supplementary data (1; 1 %), and CD-ROM (1; 1 %). Of the 98 resources, the most commonly included information type was curriculum information (10; 10 %), survey or questionnaire (6; 6 %), general informa-

Table 4: Table showing all of the disciplines that are relevant to the curricula coded within the literature. *N* = number of articles.

Discipline	*N*	Discipline	*N*	Discipline	*N*
volcanology	45	information technology	7	metamorphic geology	3
geology	35	science communication	7	sedimentology	3
disasters	31	seismology	7	geobiology	2
physical geology	28	planetary geology	5	mathematics	2
geochemistry	25	geoarchaeology	4	physics	2
geography	20	geodynamics	4	business	1
geophysics	16	geoinformatics	4	geohealth	1
geomorphology	13	geoscience education	4	geomicrobiology	1
petrology	13	quaternary geology	4	journalism	1
social geology	13	atmospheric science	3	law	1
geodesy	12	economic geology	3	marine geosciences	1
geohistory	12	engineering geology	3	paleomagnetology	1
computational sciences	11	environmental geology	3	politics	1
mineralogy	11	geochronology	3	psychology	1
structural geology	9	hydrogeology	3	sociology	1

Table 5: Table of the uncategorised educational topics coded from the literature. *N* = number of articles.

Educational topics	*N*	Educational topics	*N*	Educational topics	*N*
field-based learning	8	decision-making	2	discipline-based education research	1
simulation-based learning	8	demonstrations	2	formative assessment	1
active learning	7	e-learning	2	graduate education	1
authentic learning	7	experiential learning	2	higher-thinking skills	1
computer-based learning	6	exploration activities	2	innovative learning	1
inquiry-based learning	6	flexible learning	2	interdisciplinary teaching	1
interactive learning	6	instructor perspectives	2	jigsaw activities	1
online learning	6	interactive media	2	learner-centred	1
cooperative learning	5	motivation for learning	2	learning styles	1
role-play	5	place-based learning	2	mathematical modelling	1
collaborative learning	4	problem-based learning	2	modelling	1
learning with experiments	4	research-based learning	2	multimedia	1
Bloom's taxonomy	3	self-efficacy	2	non-traditional techniques	1
critical thinking	3	sources of knowledge	2	open access learning	1
group learning	3	virtual reality	2	peer-to-peer interactions	1
immersive learning	3	misconceptions	1	problem-solving	1
laboratory learning	3	team teaching	1	reinforcement	1
learning by doing	3	analogue learning	1	remote learning	1
undergraduate research	3	audio-visual instruction	1	schema	1
virtual field trips	3	blended learning	1	self-assessment	1
visualisation	3	case studies	1	spatial learning	1
career development	2	cognitive frameworks	1	student-centred learning	1
cognitive load theory	2	conceptual change	1	student perceptions	1
conceptual understanding	2	digital learning	1	visual learning	1

tion (5; 5 %), simulations (4; 4 %), supplementary data (3; 3 %) and maps (3; 3 %). Overall, the resources can be clustered together into categories of curriculum information (18 unique types of resource; 56 %), media (11; 34 %), and research tools (3; 9 %). Of the 88 websites provided in the literature, 36 were "live" (41 %), and 52 were "dead" (59 %). Dead links were more common in the older literature, but some dead links were found in pieces less than five years old.

3.4 Volcanology education research

A secondary aim of this study was to describe the research discovered in this literature review. The key information in this section includes empirical evidence provided (or not provided), the methodology and methods used, and the researchers' claims. This information is critical to replicating the research in other contexts and settings.

3.4.1 *Evidence*

Educational research requires evidence (in many forms) to support the claims made in published materials. Of the 47 pieces, 26 of them (55 %) included evidence that supported the research and 21 (45 %) did not. We defined evidence as any qualitative or quantitative dataset or observation (including empirical instructor reflection or teaching observations), but we excluded post hoc anecdotal information. Of the 47 pieces, 45 of those (96 %) included claims (see Section 3.4.4 below for further information). All of the 21 pieces with no evidence included claims. Additionally, the authors that did provide evidence often made claims within their work that was not supported by the evidence. Thus, much of the literature in this collection may be more accurately described as practitioner wisdom or expert advice rather than research.

3.4.2 *Methodology and methods*

Out of the 47 pieces, only eight (17 %) included a description of the methodology. We defined a research methodology as any clear description of how the research was designed or approached (i.e. theoretical paradigm (e.g. positivism, constructivism, pragmatism), the data collection approach (i.e. qualitative, quantitative, mixed methods), or research strategies (i.e. design, case studies, ethnography, phenomenology, action research) explicitly stated by the author(s). None of the 21 pieces lacking empirical evidence included a methodology. However, of the 26 that did include evidence, only eight of those (30 %) have a clear description of a methodology.

Of the eight pieces that did include a methodology, there were a total of seven different types (total of 18 mentions) with roughly an even split of mentions between qualitative (5 pieces) and quantitative (27 % each) data approaches, three with a mixed methods description (16 %), two design-based (11 %), comparative studies (1; 6 %), experimental (1; 6 %), and quasi-experimental (1; 6 %). Without crucial information on the nature of the study, the quality or strength of the claims made from the data is not easily judged. Using the Geoscience Education Research (GER)-community claims framework for the strength of evidence [St. John et al. 2021, further described and discussed in Section 4.1], the vast majority of articles within the literature review are "Practitioner Wisdom/Expert Opinion" articles, with a lesser number classified as qualitative and quantitative case studies. Only one article could be considered a cohort study [e.g. Parham et al. 2010].

Of the 47 pieces of literature, 29 (62 %) included a description of the methods used. There were 10 unique types of methods, in order of most frequently mentioned (77 total mentions): questionnaires and/or surveys (20 mentions; 26 %), artefacts (e.g. maps, notes, presentations; 9; 12 %), observations (i.e. verbal and visual; 7; 9 %), unstructured feedback (i.e. comments and discussions; 7; 9 %), grades (5; 6 %), quizzes and/or tests (4; 5 %), interviews (structured, semi-structured, and unstructured; 3; 4 %), self- or peer-evaluations (2; 3 %), and polling (1; 1 %). Course evaluations were the most common type of instrument used.

Within the description of methods, we coded for the eight categories of phenomena trying to be measured. They included: student perceptions (i.e. attitudes, feedback, etc.; 24 pieces of literature; 51 %), student behaviours (14; 30 %), student knowledge (11; 23 %), teacher perceptions (6; 13 %), student demographics (5; 11 %), teacher behaviours (2; 4 %), student career paths (1; 2 %), and student attendance (1; 2 %). Note that a description of the research participants is included in Section 3.3 (where learners and research participants were often not differentiated).

3.4.3 *Ethics*

It is worth noting that out of all coded information in this study, we found the least reported information to be human research ethics clearance and/or approval. Only one article (2 %) [Dohaney et al. 2015] had explicitly included receiving approval from an institutional ethics review committee or board. It is highly likely that some of the literature did have approval but did not explicitly mention it. Also, some journal guidelines require researchers to include this information in the cover letter rather than in the text of the article. From the personal experience of the authors of this paper, it appears the standards and guidelines about what kind of research requires review and approval have changed in the past 10–15 years. However, it is essential to note that presently many countries require approval from an institutional research board to meet legal obligations to support transparent research protocols and care for humans.

3.4.4 *Claims*

We recorded and coded each piece of literature for educational claims made by the authors on volcanology higher education. Out of the 47 pieces, 45 included claims (96 %). Two hundred and fifty-one total claims were made, with an average of five claims per piece, a minimum of 0 claims, and a maximum of 17 claims. As noted above, many pieces of literature (21; 45 %) did not include any empirical evidence in their primary text. The claims made in those pieces (66 claims) were omitted in this claim summary.

Additionally, within pieces that did include evidence, some proportion of claims would be backed by data and others were not backed with specific data or evidence. Of the 185 claims remaining, we omitted any specific claim that was coded as "No data". One hundred and twenty claims were supported by data (65 %), and 65 claims (35 %) were not. After coding and assessment, 120 of the total 251 claims (48 %) were included in the aggregate analysis and presented here (Table 6, 7, 8, and 9).

Once coded, the literature was thematically categorised by the phenomena being measured. The categories included claims about: 1) Knowledge and conceptual learning (Table 6), 2) Skills (Table 7), 3) Student engagement and outcomes (Table 8), and 4) Learning design (Table 9). Each claim was also coded and labelled by learning setting (e.g. classroom, lab, field, computer-based) and mode (e.g. face-to-face, online) so that readers can narrow in on learning approaches of interest. Claims were sometimes not mutually exclusive and fitted into multiple categories. References to the literature are also included as their record numbers (accessible in Table 5).

There were 32 claims (26 %) about knowledge and conceptual learning, sorted into four subcategories of pedagogy supports learning of scientific knowledge (9 claims; 28 %), students gained knowledge (6; 19 %), students perceived an improvement in knowledge (3; 9 %), and students scored high or low scores on a measure (14; 44 %). Specific pedagogies repeatedly appear, such as field research, virtual field trips, role-play simulations, and service-learning. One series of cohort studies researched students' knowledge about volcanoes [Parham et al. 2010; 2011], providing a look into demographic influences on volcanic knowledge and the sources of information providing that knowledge. It is worth noting that one journal article by Francek [2013] was rejected at the appraisal step due to not containing 25 % volcanology learning content, despite a fair amount of volcanology misconceptions research included in their work. Readers interested in common volcano misconceptions should look at Francek [2013].

Claims about skill development are presented in Table 7 (26 claims; 22 %). We categorised the skills learning into types of skills: discipline-based (6 claims; 23 %), teamwork (2; 8 %), communication (12; 46 %), research (3; 12 %) and thinking (3; 12 %). Similar pedagogies are mentioned here, as above, with an abundance of research claims about the benefits of role-play simulations on communication and teamwork [Dohaney et al. 2015; 2017] and field-based research on research and thinking skills [Gonzales and Semken 2006; 2009; Stephens et al. 2016].

The third type of claim described student engagement and outcomes after participating in the learning activities (Table 8; 30 claims; 25 % of claims). The subcategories in this section included attitudinal change (4 claims; 13 %), student engagement (7; 23 %), interest (5; 17 %), value (3; 10 %), satisfaction (8; 27 %), and career outcomes (3; 10 %). Interest here is broadly described as students' being interested and enthusiastic about the subject, but interest is a complex concept and is widely and more comprehensively explored in the education literature [e.g. Hidi and Renninger 2006]. In this section, field trips and research-based learning make up most pedagogies reportedly effective at creating positive student engagement and outcomes.

The final category of claims was learning design (Table 9, 17 claims; 14 %). We divided these claims into subcategories of language (i.e. how text and language is used in learning design; 6 claims; 35 %), flexible use (4; 24 %), authenticity (4; 24 %) and other (3; 18 %). Eruption simulations and virtual field trips were commonly reported pedagogies investigated in learning design.

3.5 Results summary

To support clarity for the reader, we have developed a summary list of the results organised by key themes (guided by the research questions):

Literature search results

- Volcanology higher education research is increasingly being published, most commonly in the *Journal of Geoscience Education* and usually from researchers and institutions in the USA. Forty-seven pieces of literature and 202 conference presentations were found.

Geoscience phenomena and skills

- The research we found focussed on Americas-centric volcanoes, volcanic processes, landforms, and outcrops, and less on sample, microscopic, societal, global and regional volcanic phenomena.

- The skills documented focussed on (1) technical and social skills from volcanic disaster management, field geology, remote sensing, and (2) research, quantitative, and communication skills. There was less focus on teamwork, project management, personal management, and social learning.

Curricula and educational setting

- Volcano curricula were reported on from a breadth of undergraduate course types and sizes, with broad applicability across the subdisciplines of the geosciences.

- Half of the curricula were classroom activities, followed by field and laboratory and a few computer-based activities. The majority were delivered face-to-face, with fewer online and blended modes with roughly equal amounts of conventional (e.g. lectures, readings) and innovative approaches (e.g. simulation, role-play, experiments).

- Many essential aspects of the educational setting and curricula were inconsistently or under-reported (e.g. student population, length or duration of the activity).

Volcanology educational research

- Almost half of the literature (46 %) did not contain evidence and relied on reporting 'practitioner wisdom'. Additionally, within pieces that did include evidence, some proportion of claims were not backed with specific data or evidence.

- Few pieces (8; 17 %) included a described research methodology, design, or approach with half qualitative and half quantitative studies.

- Human research ethics approval was rarely explicitly reported.

- Two hundred and fifty-one claims were made in 45 pieces of literature with and without empirical evidence; only 120 (48 %) claims were made with empirical evidence and analysed and presented in this literature review.

- Researchers made claims about a wide range of learning phenomena such as student perceptions, behaviours, and knowledge. Commonly reported data-supported claims include:

  – many different volcano curriculum activities foster improved attitudes, engagement, interest, value, and satisfaction [e.g. Bhatia and Corgan 1996; Williams et al. 2011; Palmer 2013; Teasdale et al. 2015];

Table 6: Claims about knowledge and conceptual learning. References to the literature are included as record numbers (e.g. [26], accessible in Appendix B2) All claims were labelled with the educational setting and learning mode: Classroom (C), Laboratory (L), Field (Fi), Computer-based (Co), Face-to-face (Fa), and Online (O). Research-only literature labelled with (R).

Theme	Claims
Pedagogy supports learning of scientific knowledge	• Using real monitoring data improves volcanic monitoring knowledge [26] (Cl, Co, Fa) • Field-based research approach lets students integrate and apply what is learned in lectures and labs [1631] (Fa, Fi, C, L) • The diversity of research activities in the field research projects enhanced students overall knowledge of field petrology [1554] (Fa, Fi, C, L) • Implementation of the virtual field trip showed positive impacts on student learning [1171] (Co, L, Fa, O) • Virtual field trip does not significantly enhance student learning over traditional lectures when teaching about volcanism to an introductory level course [1171] (Co, L, Fa, O) • Students who accessed the virtual field trips for revision were more successful in the course [754] (O, L, Fa) • Role-play simulations may be used to teach participants about volcanic hazards, mitigation and monitoring [1747] (Fa, C, Fi, Co) • Student learning occurred in courses with those not an author of the volcano jigsaw role-play curriculum; therefore, materials can be widely used [2506] (C, Fa) • Volcano computer-based simulation is feasible to be used as a media to improve physics student knowledge of geoscience learning [1947] (Co)
Students gained knowledge (unspecified measure)	• After telepresence-based research experience, students learned science content [2065] (Fi, O, Co, C) • After the field-based research experiences, students enhanced their knowledge of petrology and regional geology [1631] (Fa, Fi, C, L) • Student field research projects enabled students to learn petrology and volcanology [1554] (Fa, Fi, C, L) • Students' insights into how ocean research is conducted appeared to deepen considerably during the fieldwork [2065] (Fi, O, Co, C) • After the volcanic eruption simulation, students improved in their understanding of fundamental scientific concepts [1375] (Fa, C, Co) • Student content knowledge increased due to participation in the volcano jigsaw role-play curriculum [2506] (C, Fa)
Students perceived an improvement in knowledge	• After completing an overseas volcanology field trip, students perceived that they had learned the principles of field geology and volcanology [119] (Fi, Fa) • After completing a K-12 service-learning project, students perceived deepened content knowledge in volcanoes [176] (Fa, Cl, Fi) • After the field-based experiences, students enhanced their knowledge of a geologic locality and sense of place [1631] (Fa, Fi, C, L)

Continued on next page.

– undergraduate students hold many volcano misconceptions [Parham Jr 2009; Parham et al. 2010; 2011],

– students' communication skills can be improved through the use of volcanic role-plays [Dohaney et al. 2015; Fitzgerald et al. 2016; Dohaney et al. 2017],

– undergraduate volcano field research supports professionalisation [Gonzales and Semken 2006; 2009; Williams et al. 2011; Stephens et al. 2016].

4 Discussion

Here, we discuss the findings of the systematic mapping review, explore research gaps and opportunities, and suggestions for improving volcanology higher education research.

4.1 Volcanology and geoscience education research

Overall, the body of volcanology higher education knowledge collected in this study is small and steadily increasing and could be considered in its early stages of development relying significantly upon volcanology teachers' "practitioner wisdom" [St. John et al. 2021]. These findings are mirrored by research done on geoscience education research (GER; i.e. scholarly investigations of geoscience learning and teaching [St. John and McNeal 2017]) with Arthurs [2018] showing that GER publishing is increasing and GER authors often relying on practitioner wisdom rather than conventional education research approaches [St. John and McNeal 2017; St. John et al. 2021]. Notably, a recent review of affective learning in field-

Table 6 [cont.]: Claims about knowledge and conceptual learning. References to the literature are included as record numbers (e.g. [26], accessible in Appendix B2) All claims were labelled with the educational setting and learning mode: Classroom (C), Laboratory (L), Field (Fi), Computer-based (Co), Face-to-face (Fa), and Online (O). Research-only literature labelled with (R).

Theme	Claims
Students scored high or low scores on a measure	• After completing a K-12 service-learning project, students scored higher grades than in other offerings of physical geology [176] (Fa, Cl, Fi) • There was no correlation between academic major and performance in the volcanology course, including the Geodynamics Database [274] (L, Co, Fa) • After participating in the volcano jigsaw role-play curriculum, learning gains occurred in all class types in activities that required application of information as well as in items that required only simple recall [2506] (C, Fa) • 41% of student responses on the Volcanic Concept Survey (VCS) learned about volcanoes from non-traditional sources of knowledge (i.e. movies, films and popular media: TV news, newspapers, magazines) [576] (R; Research-only) • Students with high non-traditional sources of knowledge scored low VCS scores and had a low level of understanding about volcanic systems [209] [576] (R) • Students with high traditional sources of knowledge (i.e. coursework or personal experience) had a higher level of understanding of volcanic systems and plate tectonics [209] [576] (R) • Students hold many volcanic misconceptions (e.g. plate tectonics, volcanism in relation to water, climate, and islands) based on VCS results [209] (R) • Students scored higher on basic content knowledge (i.e. recall) questions than higher thinking questions on the VCS; Generally, students do not demonstrate a deep understanding of volcanic concepts [209] [1792] (R) • Science, technology, engineering, and mathematics (STEM) majors performed significantly better on the VCS than non-STEM majors [209] [1792] (R) • Highly interested (interest and engagement in science) students had higher VCS scores [209] [576] [1792] (R) • Freshmen students scored the lowest on the VCS and knew relatively little about volcanic systems and eruption mechanics [209] (R). Sophomores scored higher VCS scores than juniors and seniors [576] [1792] (R) • Men students had higher VCS scores than women students [209] [576] [1792] (R) • Students from volcanically active regions had higher VCS scores [209] [576] [1792] (R) • Students with a father who had at least a high school diploma had higher VCS scores [576] [1792] (R)

based experiences also found the literature to be dominated by anecdotal evidence [Shinbrot et al. 2022].

Arthurs [2018] found that GER articles were missing methodological information (12 % explicitly stated within their collection; in comparison to our 17 %), lack of studies including marginalised students, and a lack of larger cross-cohort studies (Note: 28 % of the studies included here described data from more than one institutional setting). It is important to note that the lack of studies in our collection including marginalised students may be due to IRB (institutional review board; US-based literature) advice on reducing burden to marginalised groups. When applying the same schema as Arthurs [2018], we find that our collection of literature consists predominantly of instructive and informational articles with the aim of conveying "how-to" and "we-did-this" information (further defined in Arthurs [2018]) (39 articles; 83%). Based on Arthurs [2018] definition (of including an explicit research question statement within the work), none of our articles met the research or hypothesis-driven work with a strong evidence base, though, we assert and acknowledge that many rigorous research approaches do not begin with a set of questions or hypotheses. Teacher reflections and instructive commentaries published alongside curricula activities are useful, but as a community, we can gain much from increasing our evidence-base and our standard of reporting that would allow us to draw larger and more trustworthy conclusions and directions for improvement.

However, in the past two decades GER has shifted towards a more research-oriented approach as evidenced by changing publishing requirements and standards adjusted in the *Journal for Geoscience Education* [Libarkin et al. 2009]. GER researchers advocate for increased numbers and sizes of cohort studies that apply across contexts [St. John et al. 2021; Shinbrot et al. 2022]. To further improve GER, St. John et al. [2021] proposed a framework that helps make sense of GER's past and current research priorities providing future directions. The framework allows researchers to collaborate and build upon existing knowledge bases, support connections between GER and other DBER fields (e.g. physics or biology education), and presents a strength of evidence scheme that describes the im-

Table 7: Claims about measured or perceived skills learning. References to the literature are included as record numbers (accessible in Appendix B2). All claims were labelled with the educational setting and learning mode: Classroom (C), Laboratory (L), Field (Fi), Computer-based (Co), Face-to-face (Fa), and Online (O).

Skill	Claims
Discipline-based	• Using real monitoring data improves self-efficacy in volcanic monitoring methods [26] (Cl, Co, Fa) • Dynamic digital map exercise and research project increased confidence in students' ability to do petrology [389] (C, Co, L) • Virtual field trip (VFT) increased student abilities to construct a geologic map over using a static image [1171] (Co, L, Fa, O) • Volcano simulation significantly influence the eruption prediction skills of physics students [1947] (Co) • After the volcanic eruption simulation, students developed an ability to assess the quality and significance of volcanic data [1375] (Fa, C, Co) • Students' self-efficacy in their ability to accurately identify factors that determine hazards and risks at plate boundaries increased by at least 1 point (on a 5-point scale) following their participation in the volcano jigsaw role-play curriculum [2506] (C, Fa)
Teamwork	• After the volcanic eruption simulation, students developed teamwork skills, delegating and organising responsibilities [1375] (Fa, C, Co) • After the volcanic eruption simulation, students improved in their ability to handle complex management situations [1375] (Fa, C, Co)
Communication	• After the volcanic eruption simulation, Students effectively synthesised information into insightful, logical, and imaginative responses to the crisis [1375] (Fa, C, Co) • After student research presentations, students gained skills and confidence in communication [2065] (Fi, O, Co, C) • Overall, students showed a positive mean change in communication confidence after participating in the volcano role-play simulation; the role-play was effective at improving confidence [1063] [2505] (Fa, Fi, C, Co) • Most students, before participating in the volcano role-play simulation, reported an average level of communication confidence [2505] (Fa, Fi, C, Co) • Students with higher confidence pre-scores achieved the most negative changes after participating in the volcano role-play simulation; becoming less confident communicating due to overestimation of their abilities [2505] (Fa, Fi, C, Co) • Students with lower pre-scores achieve the highest changes in communication confidence after participating in the volcano role-play simulation; therefore, the role-play is effective for those with mild communication apprehension [2505] (Fa, Fi, C, Co) • Students with the greatest positive changes (after participating in the volcano role-play simulation) in communication confidence participated in the public speaking tasks. This may be due to the self-selection effect [1063] [2505] (Fa, Fi, C, Co) • After participating in the volcano role-play simulation, mean changes in confidence for communication to the public and strangers were the highest, aligned with the learning goals of the role-play [2505] (Fa, Fi, C, Co) • There were no significant differences in communication confidence shifts between the field and lecture cohorts. Therefore, the volcano role-play simulation was effective in different learning environments [2505] (Fa, Fi, C, Co) • On average, students had statistically significant positive changes, after participating in the volcano role-play simulation, in perceptions of best practices for science communication, becoming more expert-like [2505] (Fa, Fi, C, Co) • Students with lower pre-scores achieved the highest positive changes in communication perceptions of best practice; therefore, the role-play is most effective for those with the least expert-like perceptions [2505] (Fa, Fi, C, Co) • After participating in the volcano role-play simulation, students described best practices for science communication that focussed on mechanics and strategies of communication (e.g. use of jargon) rather than on how the speaker appears, their behaviour, and the outcomes of the communication [2505] (Fa, Fi, C, Co)

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Table 7 [cont.]: Claims about measured or perceived skills learning. References to the literature are included as record numbers (accessible in Appendix B2). All claims were labelled with the educational setting and learning mode: Classroom (C), Laboratory (L), Field (Fi), Computer-based (Co), Face-to-face (Fa), and Online (O).

Skill	Claims
Research	• Dynamic digital map exercise and research project increased student confidence in their ability to do research [389] (C, Co, L) • After telepresence-based research course/unit, students learned science content as well as research tools such as hypothesis testing data collection, analysis, and importantly, and flexibility [2065] (Fi, O, Co, C) • Telepresence provides exposure of students to real-world scientific discourse [2065] (Fi, O, Co, C)
Thinking	• Text-based data presentation format for volcano monitoring data is more effective at building decision-making skills than graphical data presentation [178] • After the field-based research course/unit, students developed a higher order of (critical) thinking; [1631] [1554] (Fa, Fi, C, L) and considered more meaningful questions about the significance and validity of their data and results [1554] (Fa, Fi, C, L)

portance of scholarly work across GER. To improve volcanology higher education, an adapted framework is described in Section 4.2.

4.2 Gaps and opportunities in volcanology higher education research

There is substantial room for geoscientists and GER researchers to explore research-orientated projects in volcanology education. Given that only 55 % of the articles are evidence-based, and referring to the claims provided in Table 6, 7, 8, and 9, the list of topics and pedagogies that were investigated with research methods remains narrow, focussing on simulated eruption processes, simulated volcanic crises, and volcanology learning in field environments (both in-person and virtual). There remains considerable room to explore case studies in a wide range of subject matter, pedagogies, educational topics, and technologies. For example, some notable topic areas for evidence-based investigation include: volcanic sample analysis, historical volcanology, remote sensing and monitoring technologies, global volcanism, and volcanic geochemistry, among other topics in this field.

Here, we draw upon and adapt the thematic research priorities of the GER framework [St. John et al. 2021] and highlight specific broader research themes that volcanologists might investigate:

- student conceptual understanding (i.e. knowledge and facts) of volcanology content
- instructional strategies to improve volcanology learning within different contexts and technologies
- learning and teaching about volcanoes in the context of societal problems
- access and success of marginalised students in volcanology learning
- spatial and temporal cognition in volcanology learning
- quantitative reasoning, problem-solving, and use of models in volcanology learning
- affective learning (i.e. attitudes, beliefs, behaviours) in volcanology
- institutional change and professional development of volcanology higher education

Beyond volcanology and educational topics and themes, there are many potential approaches and methodologies to consider in future research. Firstly, the context and setting of the research documented (including conference presentations) is predominantly US-based, and therefore, there is a need for studies from other regions in the world. Secondly, there is a need for increased investigations with broader populations of students specifically in diversity of age, disability, gender, sexual orientation, race, ethnicity, nationality among other important demographic factors. Of the 14 studies that described demographics, the common descriptors included gender, race, and academic backgrounds. Thirdly, the literature would benefit from increasing the number of studies that have wider application beyond the local context and practitioner wisdom. St. John et al. [2021] recommend qualitative and quantitative case studies across multiple institutions and contexts ultimately moving towards meta-analyses and systematic reviews, with increased strength of evidence and generalisability (see Figure 4 of St. John et al. [2021]). Currently, there are too few studies in our collection to conduct meta-analyses or thematic systematic reviews with any predictive power. Also, the lack of statistical descriptions of significance and effect size in experimental approaches make comparisons of study to study very difficult. Lastly, the lack of curriculum information provided means that the studies reported could not be replicated in a different context and often claims are made without evidence (similar findings were found in Perkins [2004]). Therefore, there is also still a significant need for evidence-rich single-site case studies that are robustly designed and well documented.

4.3 Improving volcanology education research

Beyond future research topics, we have collated three key suggestions that will help our community develop trustworthy

Table 8: Claims about student engagement and outcomes. References to the literature are included as record numbers (accessible in Appendix B2). All claims were labelled with the educational setting and learning mode: Classroom (C), Laboratory (L), Field (Fi), Computer-based (Co), Face-to-face (Fa), and Online (O).

Theme	Claims
Attitudinal change	• Students felt it was useful (on the planetary volcanology field trip) to see how phreatomagmatic constructs and their deposits in the field [349] (Fi, Fa)* • After participating in the volcano jigsaw role-play curriculum, most students agreed that geologic monitoring is likely to be valuable to them and society [2506] (C, Fa) • After the decision-assessment matrix activity, science students are confident that a better understanding of the characteristics of the volcano will contribute significantly to reducing the economic and social effects of eruptions [2498] (Fa, C) • After the decision-assessment matrix activity, students perceived the necessity for their crisis-management strategy to be firmly directed to infrastructural outcomes (mainly saving life and, to a lesser extent, property) but considered that this could be achieved better by investing in monitoring and mapping programmes than in improving existing evacuation regimes and developing management systems [2498] (Fa, C)
Engagement	• Role-play simulations were found to be highly challenging and engaging experiences, and students valued the authenticity, personal experiences, and team dynamics (within and between the teams) varied depending on the students' background, preparedness, and personality [1063] (Fa, Fi, C, Co) • Volcanic eruption simulations create an exciting learning environment/process [1375] • Role-play simulations add higher-level learning challenges for students [1747] (Fa, C, Fi, Co) • In the planetary volcanology field trips, participants interacted with each other, forging collaborations that we hope will persist throughout their careers [1381] • Students engaged in all facets/aspects of the research project {situated within} geologic complexity [1631] (Fa, Fi, C, L) • Students reported that using the digital geographic supplements (Google Street Views, panoramas, topographic maps and terrain views) enhanced student learning, making it feel like a virtual field trip experience; "feels hands-on" [388] (Co, L, O, Fa) • Students said it was good to "get calibrated" with radar data and to understand how different geologic features appear in radar images during the planetary volcanology field trip [349] (Fa, Fi)
Interest	• After completing an overseas volcanology field trip, interacting with students of the other culture was the most memorable aspect of the trip [119] (Fa, Fi) • The volcano jigsaw role-play curriculum and the InTeGrate materials as a whole were successful in increasing student interest in geoscience [2506] (C, Fa) • Dynamic digital map exercise and research project increased student's enthusiasm for petrology/volcanology [389] (C, Co, L) • Student research project work enabled students to {be enthusiastic/have more interest} for research [1631] (Fa, Fi, C, L) • Student field research project enabled students to {be enthusiastic/have more interest} for field research [1554] (Fa, Fi, C, L)

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volcanology education research: receiving academic development support, engaging in ethical research practices, and using systematic reporting strategies.

4.3.1 *Academic development support*

In our collection, we found proportionally higher conference presentations (202) than full texts (47). This means that there are potentially many studies out there that the wider community cannot access or have not been developed further. There is a multitude of reasons for this finding, but one may be that volcanology academics are less aware or confident in publishing in this field [Barnard et al. 2011; Bailey et al. 2021; Jolley et al. 2022]. With such a high time investment required in publishing, scholars want to be assured that their investment will lead to a successful outcome. One way to tackle this challenge is to engage academic development (a.k.a. educational or faculty development) support. There is a range of supports and development opportunities that academic developers can provide to help new education researchers develop a scholarly approach. Namely, they can help make sense of the existing education research available on a particular topic, plan and design a research project, and be supportive co-authors, helping researchers move along the publication pathway [Brogt et al. 2020]. Jolley et al. [2022] found that volcanology instructors

Table 8 [cont.]: Claims about student engagement and outcomes. References to the literature are included as record numbers (accessible in Appendix B2). All claims were labelled with the educational setting and learning mode: Classroom (C), Laboratory (L), Field (Fi), Computer-based (Co), Face-to-face (Fa), and Online (O).

Theme	Claims
Satisfaction	• After completing a K-12 service-learning project, there were overwhelmingly positive reflections on service learning [176] (Fa, Cl, Fi) • Students found that the volcanology course, including the Geodynamics Database, was enjoyable and positive (high level of satisfaction) [274] (L, Co, Fa) • Students responded positively (enjoyable) to learning landforms using a Google Earth exercise and geographic supplements [388] (Co, L, O, Fa) • Large outdoor experiments can convey concepts of volcanic processes to students in an exciting way [1223] (Fa, L) • Most of the physics students stated that the VLP software is a great fit applied in geoscience learning [1947] (Co) • Student feedback indicated the virtual field trips were successful (i.e. student satisfaction) [754] (O, L, Fa) • Students enjoyed the planetary volcanology field trip [349] (Fi, Fa) • Students noted that they enjoyed taking on roles (in the volcanic role-play simulation) that were new to them; this allowed them to explore new topics and gain new perspectives [1063] (Fa, Fi, C, Co)
Career outcomes	• After completing the field-based research course/unit, students perceive increased professional preparation, network-building, conference attendance, and careers prospects [1554] [1631] (Fa, Fi, C, L) • The field-based research increased future undergraduate participation in geoscience research into their future studies [1554] [1631] (Fa, Fi, C, L) • As a result of the field-based research course, students have {positively} impacted the broader scientific community making real contributions [1554] [1631] (Fa, Fi, C, L)

specifically value and take an interest in a variety of educational support from others, but do not seek out that support as much as they valued it, especially for 'educational research colleagues' and 'conducting own research'. Participants in that study specifically noted that the lack of visibility and awareness of educational researchers and their resources might lead to their lack of seeking such support [Jolley et al. 2022]. Additionally, when asked what educational specialists can do to support volcanology instructors, their third most common response was to gain shared knowledge of how to do education research, followed by building connections with education researchers. To echo Jolley et al. [2022], we recommend seeking out the academic development community for support, research, and collaboration opportunities including teaming up with volcanology educators in your wider networks.

4.3.2 *Ethical research practices*

The vast majority of studies in this collection did not explicitly describe their research design and methods, including human research ethics approval. When conducting research with humans, the research design and approach should be peer-reviewed and approved by a regulatory human research ethics committee or institutional research board. These committees will assess the level of risk to the potential participants of your study and ensure that your proposed design minimises any potential harm or burden to people. However, without clearly describing the procedures of collecting data from humans, the readers have no way of knowing whether an ethical approach was used, and that people were not harmed from the research. As a community of researchers, we need to remedy this situation. New researchers can seek assistance with the ethical review process by contacting a representative of your review board. For a full walkthrough of ethical inquiry, we recommend starting with Chapter 2 of Cohen et al. [2007]. As a starting out point, researchers should consider [list adapted from Cohen et al. 2007, p. 51]:

- Gaining informed consent from participants;
- Burden on participants (how much time and energy are you asking of them?);
- Privacy and protection of all data collected and stored;
- Conflicts of interest, reputational risk, coercion, and sponsorship, etc.

4.3.3 *Systematic reporting*

Consistent with findings noted in Arthurs [2018], the majority of research reported in this collection is lacking a descriptive methodology (eight articles mentioned; and few had complete descriptions) and they recommend we collectively improve our research designs. Arthurs wrote, "GER scholars can continue their upward trajectory in improving the rigor in their reporting by attending to the level of connections made to other research and to the level of evidence used to support

Table 9: Claims about learning design. References to the literature are included as record numbers (accessible in Appendix B2). All claims were labelled with the educational setting and learning mode: Classroom (C), Laboratory (L), Field (Fi), Computer-based (Co), Face-to-face (Fa), and Online (O).

Design variables	Claims
Language	• In an eruption simulation, the framing of the graphic presentation (either positive or negative) and the framing of the hazard scenario (either positive or negative) both influence the way in which students allocate funds (equitably or not equitably) towards key decisions and actions in an eruption crisis [178] (O, Co, Fa) • Students who used the text-based data interface in an eruption simulation were not influenced by the framing of the activity, whereas students who used the graphical data presentation interface were more influenced by the framing of the activity [178] (O, Co, Fa)
Flexible use	• Students who accessed the virtual field trips for revision were more successful in the course [754] (O, L, Fa) • The virtual field trip and associated activities are flexible and can be modified to suit a specific audience, class level and/or learning objectives [1171] (Co, L, Fa, O) • Telepresence is a feasible option for future undergraduate research experiences [2065] (Fi, O, Co, C) • There are a large amount of free open source digital data (e.g. SEMs, radar, and digital line graphs) from the USGS topographic maps available for teaching [434]
Authenticity	• Using real monitoring data improves self-efficacy in volcanic monitoring methods and improves volcanic monitoring knowledge [26] (Cl, Co, Fa) • For an authentic role-play simulation to be successful, the pace of the role-play should be appropriate [1063] (Fa, Fi, C, Co) • For an authentic role-play simulation to be successful, students need to be prepared [1063] (Fa, Fi, C, Co) • For an authentic role-play simulation to be successful, the roles and team structures must be well-defined [1063] (Fa, Fi, C, Co)
Other	• Learners who spent more total time with activities had higher learning gains and self-efficacy in volcanic monitoring methods [26] (Cl, Co, Fa) • Students reported that using the supplements to the exercise enhanced student learning, making it feel like a virtual field trip experience; "feels hands-on" [388] • Research projects linked by a well-defined theme are the most effective for undergraduates when considering student-staff dynamics and logistics [1631] (Fa, Fi, C, L)

their claims." [Arthurs 2018, p. 134]. Like other fields, volcanology education research requires a complete description of the approach, method, results, and claims in order to be understood, judged, expanded upon, or replicated. To improve the quality of our research and allow for more robust and powerful claims to be made about our teaching, scholars in volcanology higher education need to develop comprehensive and systematic reporting methods when writing and presenting research. A detailed list of prompts is included in Table 10 so that researchers new to the field can begin designing and describing their research on good footing. For a more comprehensive approach to planning and describing educational research, we recommend the reader to look at Cohen et al. [2007].

Lastly, researchers and publishers should ensure that research is catalogued and included in the key databases. There were some conference presentations that were unavailable (notably for the Cities on Volcanoes and International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) conferences) because they are not currently searchable within available digital catalogues. Systematic reviews are only as good as the works included within them, and therefore access to the research is crucial.

4.4 Limitations

Like many systematic reviews, the quality of this work relies on the methods and resources available to the researchers to conduct the review. There are potential sources of bias within this study that could be remedied in future research. Importantly, this collection only consists of English works meaning that there is potentially insightful research that has not been included.

To avoid selection bias, we used a rigorous iterative peer review system that ensured key literature was discussed thoroughly when applying our selection (inclusion and exclusion) criteria. We also used an interrater reliability protocol during coding of the texts to ensure consistency of our coding scheme. Several works of the authors were present within the collection, and we made sure that the primary author was not coding their own work or making judgements without a discussion amongst the research team. Lastly, the collection and its findings are only applicable to volcanology and formal

Table 10: Key information needed when designing and reporting on volcanology higher education.

Category	Questions and prompts
Student Population	• How many students/participants are there? (Important note: please indicate the difference between how many students participated in the curriculum, vs. how many consented to participating in the research) • What level of education are they currently undertaking? • What year of study are they current undertaking? • What degree programme or majors are they undertaking? • What key demographic information can you include that helps us understand who they are and how that relates to your research questions/curriculum outcomes? (Gender, age, race, ethnicity, languages, disability, prior academic experience, nationality, immigration status, and/or social class, amongst other factors)
Educational setting	• In what country(ies) did the learning and research take place? • What institution(s) participated in the learning and research? How many were there? • What kind of institution(s)? (Imagine that someone reading doesn't know the difference between types of institutions in your home country) • What course(s) or class(es) did the learning take place in? What topics are being taught in this course?
Curriculum description	• Did the learning take place in the classroom, lecture, laboratory, field, or other type of learning environment? • Was the mode of learning and interaction with students predominantly in person, online, hybrid, or in blended mode? • Is this learning appropriate to other groups of students not described in this research? (e.g. appropriate to all levels of education, etc.) • How many learning activities are you describing? • What is the duration of the learning activities? • What types of learning activities are you describing? • What academic disciplines would this curriculum be appropriate for? • Are the students assessed? Describe the assessment. • What type of student interactions are there? Do they work independently, paired, or in groups? • Where can the wider teaching community access the full curriculum in detail? Are there additional curricular materials that could be provided to the reader to support the learning and teaching process? (Provide a permalink/doi to a source of information, or within an appendix)
Research	• What are your research questions in this study? • What is your approach to the research? • What research methodology and paradigm are you using? • What research method(s) are you using in this study? Describe in detail. • What empirical or anecdotal evidence have you gathered to support your research questions? What kind of evidence and data was gathered? How much evidence/data was collected? • What kind of phenomena are you attempting to measure/characterise? (e.g. student learning, perceptions, attitudes, performance, behaviours…etc) • Describe the recruitment, sampling, and approved ethical human research process of gaining consent for the research • What claims can you make about the data you've collected (results)? How do your claims agree/disagree with the literature in this topic?

higher education as set by our inclusion and exclusion criteria. This is, of course, missing key aspects of the volcanology learning community such as K-12 teaching, museums, geoparks, geoheritage, and public understanding of science (PUS) research that is also a valuable part of the volcano education ecosystem. We recommend colleagues aim to complete similar systematic mapping projects on these key areas.

5 Conclusions

This article described a systematic map of the existing literature in volcanology higher education, the first of its kind in this field. We characterised and described 47 full texts and summarised 202 conference presentation abstracts, dominantly published in US-based outlets, and generally, the publications are increasing by the decade (between 1983–2020). Curricula within the literature described a breadth of undergraduate course types, sizes, and settings applicable to a range of subdisciplines of geology (from the first year to masters-level) with fewer online learning activities than face-to-face. Volcanology topics such as volcanic processes, landforms, and outcrop-scale work were common, with less work describing small-scale (microscopy) and global phenomena. Most pieces focussed on discipline-based, field-based, and communication skills with less focus on project management, personal management and social learning.

Importantly, many aspects of the curriculum were inconsistently and under-reported which would make comparing the effectiveness of these curricula challenging, if not impossible. Nearly half of the literature did not include evidence and few pieces included a methodology, research design, and descriptions of ethical research procedures. Additionally, there were 251 claims made within the collection of research, but only 120 of them were backed by evidence. Our findings are similar to other review research within GER and adjacent DBER fields, with research predominantly characterised as practitioner wisdom lacking a research orientation, evidence, and descriptive methods [Arthurs 2018; Shinbrot et al. 2022]. Practitioner wisdom is important for sharing practices with the wider community, however, without an evidence base and appropriate methods for inquiry, we lack the ability to synthesise and a way to judge the effectiveness or efficacy of the pedagogies and curricula employed. We advocate for improved research design and implementation in volcanology higher education with specific advice to researchers provided in Table 10, to promote systematic reporting.

Holistically, there is distinct interest in publishing work about volcano misconceptions, simulated eruptions, and field-based learning experiences. However, as a young discipline, there remain significant areas of future research for our community, both in subject matter and methodology. Using the GER framework [St. John et al. 2021] we provided distinct areas for focussing our collective efforts; namely in how students learn about volcanology, how students feel about volcanology, who gets to learn about volcanology, and how we improve our teaching individually, programmatically, and globally.

Author Contributions

All four authors wrote and edited the manuscript and completed the systematic literature review analysis together.

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Data Availability

An up-to-date version of the volcanology higher education literature catalogue is published on vHub (https://theghub.org/resources/4963), including new articles that are added since this work was completed.

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Appendix A: Detailed systematic review method

Appendix A1

Full detailed description of each step of the systematic review method applied in this research. Steps are visualised in Figure 1. Please read Section 2.1 and Section 2.2 of the main text before reading the descriptions below.

Table A1: Full detailed description of each step of the systematic review method applied in this research. Steps are visualised in Figure 1.

Steps	Description
Step 1A. Develop initial search terms	We developed a set of search words, phrases, and logical connectors (e.g. AND or OR). The terms were chosen to reflect the topic area, target population, and discipline of concern. Our initial search terms were: volcano, education, learning, teaching, training, university, college, higher education, tertiary education, graduate, post-secondary, undergraduate, and postgraduate, including all derivations of these terms (e.g. volcan* includes volcanology, volcanoes, etc.). The terms and connectors often needed to be modified to suit the database. The final set of search terms and strings is included in Appendix A2.
Step 1B. Identify databases	We identified the databases to search (Appendix A2). A librarian assisted with selecting the databases by outlining which disciplines were suited to physical sciences (volcanology) and social sciences (education) content.
Step 1C. Develop initial inclusion and exclusion criteria	We developed the inclusion and exclusion criteria collaboratively. Six initial exclusion criteria were created, and three exclusion criteria were added during subsequent stages of the review (Appendix A3; Numbered 1–8). The criteria limit and targeted search, aligned with the study's research questions and practical limitations. All peer-reviewed document types as well as conference proceedings were initially included, as we wanted to cast the broadest possible net to capture all volcanology higher education literature. We chose literature written in English as our review team is only proficient in this language. We limited the literature relevant to formal post-secondary education to match our research questions.
Step 1D. Conduct search	We conducted an electronic search of the identified databases using the search strings outlined in Appendix A2. Due to time constraints, a 'hand search' of known journals was not completed. Hand searches involve checking all available titles of articles within a specific journal for suitable inclusion into the study.
Step 1E. Collate search records into an Excel sheet	We compiled all records into an Excel sheet. Before moving to the screening phase, the first author removed 205 records with non-relevant document types (e.g. tv show transcripts) and non-English records. She also checked for completeness of the records and removed 317 duplicates. The first author randomised all remaining records (n=2495) and assigned a unique number (1–2495) to each record. Minor formatting edits were also completed to make reading the titles and abstracts easy for the research team.
Step 2A. Title screening	We screened all the individual records (n=2495) by title. The title of each piece of literature was screened for its inclusion in the study based on our established criteria. In the first round of screening, each team member was allocated 150 records in an Excel sheet and, later, two further rounds of review consisting of 500-600 records each. The researchers asked themselves: 'Based on this title, does this piece of literature belong in our review?' Each of us would respond with No (rejected), Yes (accepted), and Maybe. Each record was reviewed once by two different researchers. This protocol allowed us to check for comparative reliability in applying the exclusion criteria. After each round of screening was completed, we met as a team to discuss Disagreements (i.e. when researchers 1 and 2 had different responses (e.g. one Yes and one No)) and Maybes. Maybes were often assigned to ambiguous titles, and a decision was difficult to ascertain. When the researchers rejected a record, they assigned a specific exclusion criterion (Appendix A3, 1–8). We discussed why specific records either did or did not fit in our review and any biases that emerged during the review process. The first author organised the records for distribution to the research team and collated results after each round of screening.
Step 2B. Abstract screen	The abstract for each piece of literature was screened (by two researchers) for its inclusion in the study based on our established criteria. The exact process described in Step 2A was completed again with each of the 646 records (in batches of 150–200 records), including discussions of disagreements and maybes. Records were randomised again before assigning to the researchers.

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Table A1 [cont.]: Full detailed description of each step of the systematic review method applied in this research. Steps are visualised in Figure 1.

Steps	Description
Step 3A. Full-text appraisal	As with the previous steps, the full-text for each piece of literature was appraised (by two researchers) for its inclusion in the study based on our established criteria. We asked the same key question, "Based on the full text provided, does this piece of literature belong in our review?". The appraisal was completed over four rounds in batches of 5–20 pieces of literature where each piece took anywhere from 40–120 minutes to appraise. As a team, we met and discussed our decisions and any new ideas or disagreements that occurred during appraisal. At this step, the decision needed to be accepted or rejected, with no more maybes. At the end of this step, 39 articles were accepted into the study, and 41 were rejected (including six duplicates, and two full texts that could not be located for appraisal).
Step 3B. Backward citation search	Once the collection of full texts was compiled, we discovered that one full text known to us was not found in our database search. We decided to conduct a citation search of the collection to find any remaining literature that was not previously captured. We conducted a backward citation search by looking at the title of each reference list item within each piece of accepted literature. Each new potential record (including conference presentations and full texts) was screened and appraised in the same manner as the other records: title, abstract, full text. Many duplicates were found (where references were already within our collection), and four new full texts met our criteria.
Step 3C. Forward citation search	We also conducted a forward citation search that included checking for the citations of our existing accepted pieces. We checked new pieces using the same screening and appraising process (title, abstract, and full text) and found four new full-text pieces that met our criteria. It is important to note that there were no new pieces found that were previously rejected (in the title or abstract screening steps), providing some support for the effectiveness of that process.
Step 3D. Updated search	Step 3D occurred after characterisation (Step 4A) had already begun and was nearly two years into the research project. The timing allowed us to check if any new publications had been put into the databases in 2019 and 2020 (Note that no 2021 or 2022 articles are included in this study). We revisited the Scopus and GeoRef databases (using the same search strings) as these were the sources of most of our records in the initial search and found 31 records. The majority were rejected, but there were seven new conference presentations (for a new total of 202 records) and four full texts. All four full texts were duplicates found in the previously described forward citation search. After completing the backward citation search, forward citation search, updated database search, and removal of duplicates, there were a total of 47 accepted full texts that moved forward in the next step of review.
Conference presentation preliminary analysis	202 records of conference presentation (oral and posters) abstract text were categorised (year of publication, venues, and locations), analysed, and checked for appropriate statistical relationships such as trends (e.g. correlation of the number of presentations per year). The abstract text was collated into an Excel sheet, and its content was analysed for key themes. Firstly, we completed a word cloud analysis of the abstract text (in bulk) with ATLAS.ti qualitative coding software. However, this analysis did not render meaningful results as many terms used were phrases, like "data analysis" or "science communication". When the words are taken on their own, they have different meanings paired together. Detailed content analysis of 202 abstracts would be very time consuming, so we conducted a content analysis of the GeoRef index terms (likened to keywords) applied to the majority of the records (124 records had GeoRef index terms; 61 %). GeoRef index terms are created by the Scholarly Information Department of the American Geosciences Institute and applied to records within the GeoRef database. Staff scan publications and assign the keywords ("index terms") based on standardized terms in their GeoRef Thesaurus (made of 30,000 standardised terms). GeoRef index terms are incomplete for recent years because cataloguing the vast number of abstracts from major geoscience annual conferences is incredibly resource-intensive. Words were checked for repetition and then counted, clustered, and put into categories.

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Table A1 [cont.]: Full detailed description of each step of the systematic review method applied in this research. Steps are visualised in Figure 1.

Steps	Description
Step 4A. Full text coding	In Step 4A, we coded the 47 full text pieces of literature for key characteristics as defined by our research questions using conventional content analysis. These codes and categories are tabulated. Codes and categories may be counted, and frequencies and descriptive statistics may be reported (where the sample size and distribution are appropriate). Initially, the first author developed a list of categories (i.e. major descriptors) that emerged from our previous steps of screening, appraisal, and preliminary analysis of the conference presentations: bibliographic information, author keywords, student skills, educational setting, student population, curriculum descriptions, and education research methods and approaches. Under each category, specific prompts or a list of options were written to help the researchers' code reliably (See the column headers in the database linked within Appendix B1). We began with two papers per researcher, and we collaboratively iterated our coding categories. We refined the coding scheme (adding subcategories and refinements) over three rounds of coding/discussions. Most coding categories were in vivo codes extracted by taking the exact phrases used by the literature authors. However, some coding categories required thematic coding. For example, when coding for the disciplines that the curriculum/curricula were appropriate, it was rare that the authors of the pieces explicitly included this information like 'this curricula is suited to a geomorphology course'. Therefore, the researchers had to judge the curricula and apply thematic codes based on that decision, e.g. a course with activities suited to geomorphology would be assigned this discipline code. The coding categories where the researchers did not use in vivo codes included: publication type, disciplines, educational topics, sub-themes in curriculum type (e.g. did students work solo or in groups/teams?), sub-themes of educational setting (e.g. is this an online or face-to-face learning activity?), and claims. Claims information was extracted from the text but needed to be numbered and paraphrased by the researchers to increase clarity and brevity. All other coding category data were extracted verbatim from the full text.
Step 4B. Interrater reliability checks	To ensure all researchers were coding in the same way, we applied an interrater reliability protocol to check for the level of agreement amongst the application of the coding scheme and minor refinements of the coding scheme. Co-coding and interrater checking meant that each category was checked and continually refined many times for specific details. Interrater checking was done by comparing the information in the 14 columns of extracted and paraphrased codes provided by two different researchers. If the researchers' information in one of the columns were substantially dissimilar, it would be counted as a disagreement. True disagreements were rare, and often the researchers coded to differing levels of detail. All agreements were added together and divided by the total (14) for a percentage of agreement. Once discussed, both researchers would develop a more comprehensive record for each full text and define any changes to help align their coding approaches. It took three rounds of coding (26 pieces total) and discussion to converge our approaches and establish 80 % agreement between each researcher and the first author. After establishing the 80 % interrater agreement, individual researchers applied the same coding scheme to the 21 remaining pieces. The first author read all 47 full texts to ensure coherency as a collection. It took three rounds of coding (26 pieces total) and discussion to converge our approaches and establish 80 % agreement between each researcher and the first author. After establishing the 80 % interrater agreement, individual researchers applied the same coding scheme to the 21 remaining pieces. The first author read all 47 full texts to ensure coherency as a collection.
Step 5A. Full text analysis	After coding was completed, the full database was checked for formatting, spelling, grammar, and clarity errors. Each category of coded information in the full texts of the literature (47 pieces) was assembled, counted, and analysed. Most categories were broken up into subcategories where like items were grouped. For example, academic skills mentioned in the literature could be grouped into subcategories such as research, communication, and teamwork skills. Continued categorisation, renaming, and clustering of chunks of information occurred until mutually exclusive categories of information emerged. Frequencies were calculated for the number of mentions by specific articles (e.g. How many pieces of literature included an explicit description of the methods used in their research?), and the number of codes within specific categories across the collection (e.g. How many unique volcanic phenomena mentioned in the collection were at outcrop size versus microscopic size?).
Step 5B. Synthesis and compilation	Once all content analysis and frequency checking was completed, the data was compiled for presentation in tabular and figure format.

Appendix A2

Table A2: Databases, search terms, and initial search results

Database	Search string	Records found
SCOPUS	volcan* AND (educat* OR learn* OR teach* OR train*) AND (universit* OR undergrad* OR colleg* OR tertiary OR graduat* OR post-secondary OR postsecondary OR postgrad* OR post-grad*) in Title/Abs/Key	237
Google Scholar	Advanced search (through 'Publish or Perish') allintitle: volcano OR volcanic OR volcanoes AND educate OR education OR learn OR learning OR teach OR teaching OR training	233
Web of Science	TI=(volcan* AND (educat* OR learn* OR teach* OR train*))	69
Informit	volcan* AND educat* OR learn* OR teach* OR train* (in AB {Abstract})	26
ERIC	volcan* in AB	267
EBSCOhost	volcan* AND (educat* OR learn* OR teach* OR train*) AND (universit* OR undergrad* OR colleg* OR tertiary OR graduat* OR post-secondary OR postsecondary OR postgrad* OR post-grad*) in AB	78
ProQuest (including Dissertations)	volcan* AND (educat* OR learn* OR teach* OR train*) AND (universit* OR undergrad* OR colleg* OR tertiary OR graduat* OR post-secondary OR postsecondary OR postgrad* OR post-grad*) in AB	92
APA PsycNet	Abstract: volcan* AND Abstract: educat* OR Abstract: learn* OR Abstract: teach* OR Abstract: train*	45
British Education Index	volcan* AND (educat* OR learn* OR teach* OR train*) AND (universit* OR undergrad* OR colleg* OR tertiary OR graduat* OR post-secondary OR postsecondary OR postgrad* OR post-grad*) in AB	35
Canadian Education Index	volcan* AND educat* OR learn* OR teach* OR train* (in AB)	36
GeoRef	volcan* AND educat* OR learn* OR teach* OR train* (in AB)	1747
ADS Database	volcan* AND (educat* OR learn* OR teach* OR train*) AND (universit* OR undergrad* OR colleg* OR tertiary OR graduat* OR post-secondary OR postsecondary OR postgrad* OR post-grad*) in AB	152

Appendix A3

Table A3: Final inclusion and exclusion criteria. *Italics* indicate criteria added during later systematic review steps.

Inclusion criteria	Exclusion criteria
• All types of volcanology topics included *(including petrology, geothermal, geophysics, tectonics related to volcanism)*	• Pieces without education content (1)
• All lengths, durations, formats, styles of learning activities included	• Pieces without volcanology learning content (2)
• All types of formal higher education (undergraduate, *vocational, postgraduate, professionals*)	• *Pieces with less than 25 % volcanology learning content (2b)*
• All demographic factors (age, race, gender) included	• Pieces that describe informal education learning activities (outreach, museums, *geotourism*, etc.) (3)
• All countries (no geographic limits)	• Pieces that describe K-12 learning *and college prep (GCSE, pre-college)* (only) (4)
• All years (no historic limits)	• Pieces reported in a non-English language (5)
• All relevant databases (Appendix A2)	• Excluded document types: newspaper articles, editorials, magazine articles, book reviews, tv show transcript, wirefeed, geologic maps (6)
• All scholarly publishing formats: Journal articles, government reports, grey literature, books and book chapters, conference proceedings, theses, *published volcanology teaching guides*	• *Pieces that describe K-12 teacher training (only) (7)*
• All methods and approaches (e.g. qualitative, quantitative, different disciplinary approaches)	• *Pieces that have no external peer-review process (e.g. academic websites or commentaries)* (8)

Appendix B: List of full texts analysed in this study

Appendix B1

Full catalogue of reviewed literature provided as a Supplementary Material Excel file.

Appendix B2

List of full texts analysed in this study.

[26 (record number)] Teasdale, R., van der Hoeven Kraft, K., and Poland, M. P. "Using near-real-time monitoring data from Puʻu ʻŌʻō vent at Kīlauea Volcano for training and educational purposes". *Journal of Applied Volcanology* 4(1). ISSN: 2191-5040. DOI: 10.1186/s13617-015-0026-x.

[100] Schimmrich, S. H. and Gore, P. J. W. "Exploring Geology on the World-Wide Web – Volcanoes and Volcanism". *Journal of Geoscience Education* 44(4), pages 448–451. ISSN: 2158-1428. DOI: 10.5408/1089-9995-44.4.448.

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Appendix C: Conference presentation results

We found a total of 202 conference presentations (i.e. conference abstracts that were delivered as oral or poster presentations) out of 2496 initial search results (8 %) that met the inclusion criteria. The presentations were dated from 1996 to 2015, with a maximum number of 17 presentations in 2013 and an average of nine per year. The number of conference presentations increases each year steadily (between 1996-2015; positive linear increase with R2 = .53). Conference presentations were from conferences located predominantly in the United States of America (USA) (197; 96 %): Geological Society of America, Annual Meeting (122; 60 %) and Annual Section Meeting (34; 17 %), American Geophysical Union Fall Meeting (33; 16 %), American Geophysical Union Spring Meeting (3, or 1 %), and only one conference presentation found from the National Conference on Science Education and the Lunar and Planetary Science Conference. International conferences (4 %) included European Geosciences Union General Assembly (5, or 2 %), and one record found (each) from the International Union of Geodesy and Geophysics General Assembly, Cities on Volcanoes, and the International Geological Congress. A preliminary analysis of the 202 conference presentation records indicated that many of the records were incomplete, lacking detail aside from the abstract (e.g. missing keywords or conference venues). Also, the database search did not capture several records (known to us that did meet our search criteria). These results indicated that our collection was unlikely to be a complete representation of the field. However, thematic coding of the GeoRef keywords applied to the presentations revealed a wide variety of curriculum and educational research. The most frequently mentioned keywords included: college-level education (91 abstracts), curricula (42), volcanoes (36), geology (30), volcanism (29), education (27), academic institutions (26), geologic hazards (21), field studies (21), and educational resources (20). Clustering of the keywords revealed categories of (I) Tools and techniques (76), (II) Volcanic phenomena (52), (III) Volcano names (31), (IV) Disciplines (17), and (V) Education (14). These categories helped to guide the coding and analysis of the full texts. A detailed analysis of the 202 conference presentation abstract text was not completed due to time constraints and an incomplete dataset.