RESEARCH ARTICLE

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Design, implementation, and insights from a volcanology Virtual Field Trip to Iceland

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Abstract

Virtual field trips (VFTs) are an effective form of geoscience teaching to support or provide alternatives to in-person field trips. We report on the design and implementation of the Iceland VFT aimed at teaching physical volcanology in a third-year undergraduate course. An evaluation exercise administered following the VFT allowed students to reflect on their learning and provided insights into the student experience. Students found the VFT an interesting and motivating learning experience due to the three-dimensional visualisations, entertaining videos, and being exposed to 'real life' volcanic environments. Students made suggestions on how to improve the VFT, including minimising technical difficulties and completing the VFT at home to allow more time for classroom discussions. These suggestions were implemented in the second iteration of the VFT and informed the development of two massive open online courses and switch to a flipped classroom.

Keywords: Geoscience education; Virtual field trips; Volcanology.

1 Introduction

Field trips are a crucial component of geoscience courses for learning and developing geological skills and integrating concepts [e.g. Lonergan and Andresen 1988; Boyle et al. 2007; Pyle 2009; Petcovic et al. 2014]; providing transformative experiences that nurture scientific identities [e.g. Kastens et al. 2009; Pyle 2009; Mogk and Goodwin 2012; Petcovic et al. 2014]; and developing visual-spatial skills [e.g. Kastens and Ishikawa 2006]. However, field trips are becoming increasingly difficult to implement due to concerns about time, logistics, and finance, as well as health and safety pressures [e.g. Boyle et al. 2007; 2009; Feig 2010; Petcovic et al. 2014; Jolley et al. 2018c]. Therefore, virtual field trips (VFTs) have become a popular supplement or alternative to 'in-person' field trips to overcome such challenges.

VFTs can be defined as a collection of online resources, which can include online video, audio feeds, and activities [Arrowsmith et al. 2005]. VFTs may include elements of virtual reality [Choi et al. 2016]; however, complete immersion in the environment is not the focus of this study. VFTs have benefited from recent advances in technology such as the development of high-quality computer-based learning environments and the increase in broadband access [Mead et al. 2019; Tibaldi et al. 2020]. Furthermore, in light of the COVID-19 pandemic, VFTs can be used to deliver teaching through disruptions or lockdowns [Pennisi 2020].

The Iceland VFT was developed for a third-year volcanology and magmatic systems course at a research university in New Zealand to teach students about physical volcanic features and processes at three locations in Iceland (Reykjanes, Heimaey, and Krafla). The virtual field trip was completed in a traditional lecture-lab course where in-person field trips to the location studied were infeasible under current funding structures in New Zealand.

In this paper, we aim to describe the design and implementation of the first iteration of the Iceland VFT, evaluate the impact of the Iceland VFT on the student experience, and provide some general recommendations for wider VFT design and implementation within geoscience.

2 Literature Review

To contextualise this work, we present current research focused on VFTs within geoscience.

2.1 VFTs in the Geoscience Discipline

VFTs have been used widely within the geosciences for a variety of topics, skills, and education levels [e.g. Stainfield et al. 2000; Arrowsmith et al. 2005; Houghton et al. 2015; Dolphin et al. 2019; Mead et al. 2019]. VFTs have been implemented for the purpose of augmenting traditional fieldwork [Arrowsmith et al. 2005], enhancing basic mapping skills [Houghton et al. 2015], and developing strategies for approaching field work [Dolphin et al. 2019].

2.2 VFT Design

Developing a VFT involves collecting, compiling, and processing visual data from a location of interest to augment or support in-person field work, laboratory exercises, and/or lectures [Dolphin et al. 2019]. The complexity of VFTs can vary from those that provide pictures and text to offer descriptions of an area, to those that are immersive experiences that provide an interactive problem-based approach [e.g. Atchison and Feig 2011]. VFTs can include various types of media such as three-dimensional (3D) visualisations, imagery, and videos [e.g. Hurst 1998; Mead et al. 2019].

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Jolley et al. [2018b] defined four critical design elements for successful VFTs: 1) constructively aligned content, 2) assessment opportunities, 3) student and instructor experience, and 4) connection to place and people. The intended learning outcomes for a VFT need to align with the intended learning outcomes for the course to ensure that they match the course curriculum content and assessment [Jolley et al. 2018b]. Assessment opportunities within a VFT should include a combination of formative and summative assessment, and should be designed to scaffold students from a lower-level of learning to a higher-level of learning [Jolley et al. 2018b]. In addition, students should feel connected to a VFT experience. This can be achieved when the course instructor and/or students are involved in the initial development of a VFT, and when students have opportunities to interact with each other during the VFT [Jolley et al. 2018b]. Furthermore, VFT pedagogy should act to develop a sense of place in students [Jolley et al. 2018b]. Sense of place describes the collection of meanings and attachments that people make in places [e.g. Tuan 1977; Gustafson 2001; Massey 2005] and has been recognised as a significant component within geoscience teaching and learning [e.g. van der Hoeven Kraft et al. 2011; Semken et al. 2017]. Virtual tools such as `Google Maps` and `Google Earth` can be used to help students build their own sense of place by allowing them to explore and interact with the landscape.

2.3 Advantages of VFTs

VFTs offer many advantages to enhance teaching and learning within geoscience. One such advantage is that students have more autonomy over their time as there are fewer time constraints than in the field [Dolphin et al. 2019], which allows students to work at their own pace [Fletcher et al. 2002; Arrowsmith et al. 2005] and revisit VFT locations [Hurst 1998]. VFTs can also mitigate logistical barriers such as poor weather conditions and transportation issues [Dolphin et al. 2019], while avoiding the financial burden of fieldwork to departmental budgets [Jacobson et al. 2009; Litherland and Stott 2012]. Furthermore, increased participation in classroom learning [Litherland and Stott 2012], greater self-reported student learning [Clary and Wandersee 2010], and enhanced student engagement [Dolphin et al. 2019] have been attributed to VFTs.

Recent advances in technology have allowed for the expansion of VFT learning outcomes, particularly in the area of 3D spatial understanding, which is usually an important outcome of in-person field trips [Trinks et al. 2005; Klippel et al. 2019; Bonali et al. 2021; Bond and Cawood 2021]. The implementation of 3D visualisations within geoscience and geography course work is well established in the literature [e.g. Anthamatten and Ziegler 2006; Mountney 2009] and many tools exist in volcanology [Tibaldi et al. 2020]. 3D visualisations allow students to view hard-to-access outcrops in the classroom [Mountney 2009] and permit virtual access to any place on Earth [e.g. Senger et al. 2020]. Studies have found that 3D visualisations have a beneficial impact on student learning and can offer multiple teaching opportunities [McCaffrey et al. 2008; Klippel et al. 2019].

Furthermore, educators are becoming aware of creating more inclusive and accessible field environments [e.g. Carabajal et al. 2017; Whitmeyer et al. 2020], especially in light of the COVID-19 pandemic preventing access to traditional field trips [Sima 2020]. The physical barriers presented by in-person field trips [Stainfield et al. 2000] are significantly reduced by navigation in virtual field environments [Arrowsmith et al. 2005]. VFT activities in a predictable classroom environment can mitigate the anxiety issues that some students feel about field work [Boyle et al. 2007], including for autistic and other neurodivergent students [Kingsbury et al. 2020].

2.4 Disadvantages of VFTs

Although VFTs can offer many advantages to enhance teaching and learning within the geosciences, there are some challenges and limitations associated with VFTs. One such challenge is that participants often do not have the equivalent opportunity to interact with peers in a flexible manner as in the field [Hurst 1998]; therefore, it may be challenging to reproduce the social interactions that would occur in the field [Stumpf et al. 2008]. In addition, VFTs only offer an abstraction of the real thing, which means it may be difficult to communicate the feeling of a spectacular geological landscape [Hurst 1998; Stainfield et al. 2000; Choi et al. 2016]. While VFTs allow for the exploration of sites through data, maps, and digital technologies, these virtual experiences are often not the same socially and experientially as the in-person in field experience [Hurst 1998]. In Arrowsmith et al. [2005], students stated that VFTs did not provide the same experience or opportunity to develop communication and teamwork skills as on in-person field trips.

Some studies have identified that the cognitive demands of virtual learning environments can be too complex for learners [Hedberg et al. 1993; Land 2000]. Cognitive load theory is based on the hypothesis that for effective learning to take place, a person's short-term memory can only process a certain number of elements simultaneously [Chandler and Sweller 1991; Sweller 1994]. The demands in virtual learning environments include keeping track of the concepts covered, the integration of new and prior knowledge, and the generation and refinement of questions and understanding based on new information (meta-cognitive knowledge dilemma) [Lim et al. 2006]. Reducing technical difficulties, off-task information, and providing varying levels of scaffolding (learner support) have been shown to reduce cognitive load [Jaeger et al. 2017]. Furthermore, presenting background information prior to a VFT can reduce cognitive load [Petersen et al. 2020].

In light of recent improvements in technology, efforts to reimagine field trips are challenging some of these long-held views about their shortcomings [Cliffe 2017]. Here, we aim to highlight the design and implementation of the Iceland VFT and the associated impacts on the student experience to contribute insights into VFTs within geoscience and volcanology.

2.5 VFTs in a flipped classroom context

The flipped classroom is a hybrid approach, which utilises digital technology to move traditional lecture-based instruction outside of the classroom (i.e. homework or reading), and uses face-to-face classroom time for interactive learning and discussion [Missildine et al. 2013]. This approach sometimes requires the development of digital technologies (e.g. VFTs) that are available for viewing outside of the classroom. The flipped classroom improves peer and instructor interactions, while approaching concepts from different perspectives resulting in deeper understanding [Bergmann and Sams 2012]. Although there is little research on VFTs and flipped classroom models, we suggest the flipped classroom model has implications for both design and implementation of VFTs.

3 The Design of the Iceland VFT

3.1 Educational Setting

The Iceland VFT was implemented as part of a third-year undergraduate volcanology and magmatic systems course, which is primarily for geology majors at a research university where funding was not available for an in-person fieldtrip to active volcanoes. The course is a popular elective in the geology major.

The course was targeted to implement the VFT because it has a strong history of educational transformation, a teaching team with interests in geoscience education, and content that is well-aligned with the achievement standards relating to volcanology [Kennedy et al. 2013]. Fifty-three students were enrolled in the course and forty-nine students agreed to participate in this research study. No demographic data were collected for this research. Ethics approval was awarded by the Human Research Ethics Committee at the research university.

3.2 Structure of the Iceland VFT

The Iceland VFT focused on three volcanic locations in Iceland (Reykjanes, Heimaey, and Krafla), with each location representing a distinct eruption style with different hazards and deposits*. Locating, describing, applying, analysing, synthesizing, evaluating these locations deposits and hazards were all parts of the learning outcomes. The learning outcomes are listed in part in Table 1 and in full in Appendix A. Reykjanes was the first location and focused on pāhoehoe lava flows and their associated features. This location offered vent-to-sea exposures of lava flows and the fissures that fed them. Heimaey was the second location and focused on the historic eruption of ʻaʻā lava flows from a scoria cone and their associated features. This location also focused on the hazards of volcanic eruptions to society. Krafla was the third and final location and focused on volcanic structures and processes that occur at the surface within caldera systems and the varied volcano geomorphology. Krafla also focused on how geophysics can be used to explore and model magma chambers at Krafla and the future possibilities of geothermal energy extraction.

At all locations, geospatial skills were emphasized and assessed as students were asked to locate, describe, apply, analyse, synthesize, and evaluate historical, geomorphological, and textural observations of the volcanic locations and rocks. For example, the Reykjanes location began with a virtual fly-over, which started in New Zealand and finished on the Reykjanes Peninsula. Students then had to locate the fissures and lavas of Reykjanes on a map of Iceland in an interactive map exercise. After students completed the interactive map exercise at each location, technological components (e.g. instructional videos, 360° videos, digital rock samples and digital elevation models) presented the volcanology content within the VFT. Assessment opportunities included fixed response (multi-choice with feedback) and discussion board questions, which assessed student learning following the instructional videos, 360° videos, and digital elevation models (DEMs).

Following the completion of each VFT location, classroom discussions and applied sketching and evaluation exercises were held, which allowed students to reflect upon and apply their learning from each VFT location.

3.3 Constructive Alignment of Intended Learning Outcomes

VFT teaching and assessment should reflect the nature of the student experience and examine whether students have attained the intended learning outcomes and performance expectations set by the teacher [Klemm and Tuthill 2003]. This offers opportunities for students to develop and understand their own competence with the material, thus supporting their intrinsic motivation. Through constructive alignment, teaching and assessment is consistent with pre-determined intended learning outcomes intended for the course [Biggs 1996].

Teaching and assessment within the Iceland VFT were constructively aligned with the intended learning outcomes for the third-year undergraduate volcanology and magmatic systems course (Table 1) covering the range of Bloom's taxonomy [Biggs 1996]. We ensured the VFT questions targeted both recall-style skills (lower-level learning skills), and "applied" complex skills (higher-level learning skills) [Bloom et al. 1956]. We ensured the desired learning outcomes were achieved by students in the VFT as they were not able to progress until they were able to successfully answer the questions within each location of the VFT. This was done through multi-choice questions, with feedback provided to guide students towards correct answers.

The Iceland VFT was initially designed to run partly during laboratory and lecture time (4 hours' worth of lectures and 2.5 hours' worth of lab time), with the expectation that this would be additionally engaged with outside of contact time. Completion of the Iceland VFT comprised 20 % of the course grade.

3.4 Technology-informed Teaching

The technological components that make up the Iceland VFT include digital elevation models, structure from motion (SFM) models, instructional videos, and 360° videos. These components were laid out in a custom-built website interface, designed to be as intuitive as possible. Students were able to use their own devices and a familiar online tool (the internet browser).

3.4.1 *3D Models for students to explore*

A digital elevation models (DEM) is the digital representation of the land surface elevation with respect to any reference datum. DEMs of varied detail are available for most regions of the developed world. Software such as `ArcScene` can display

*Iceland virtual field trip link: https://www.holoceneadventures.com/ivft/

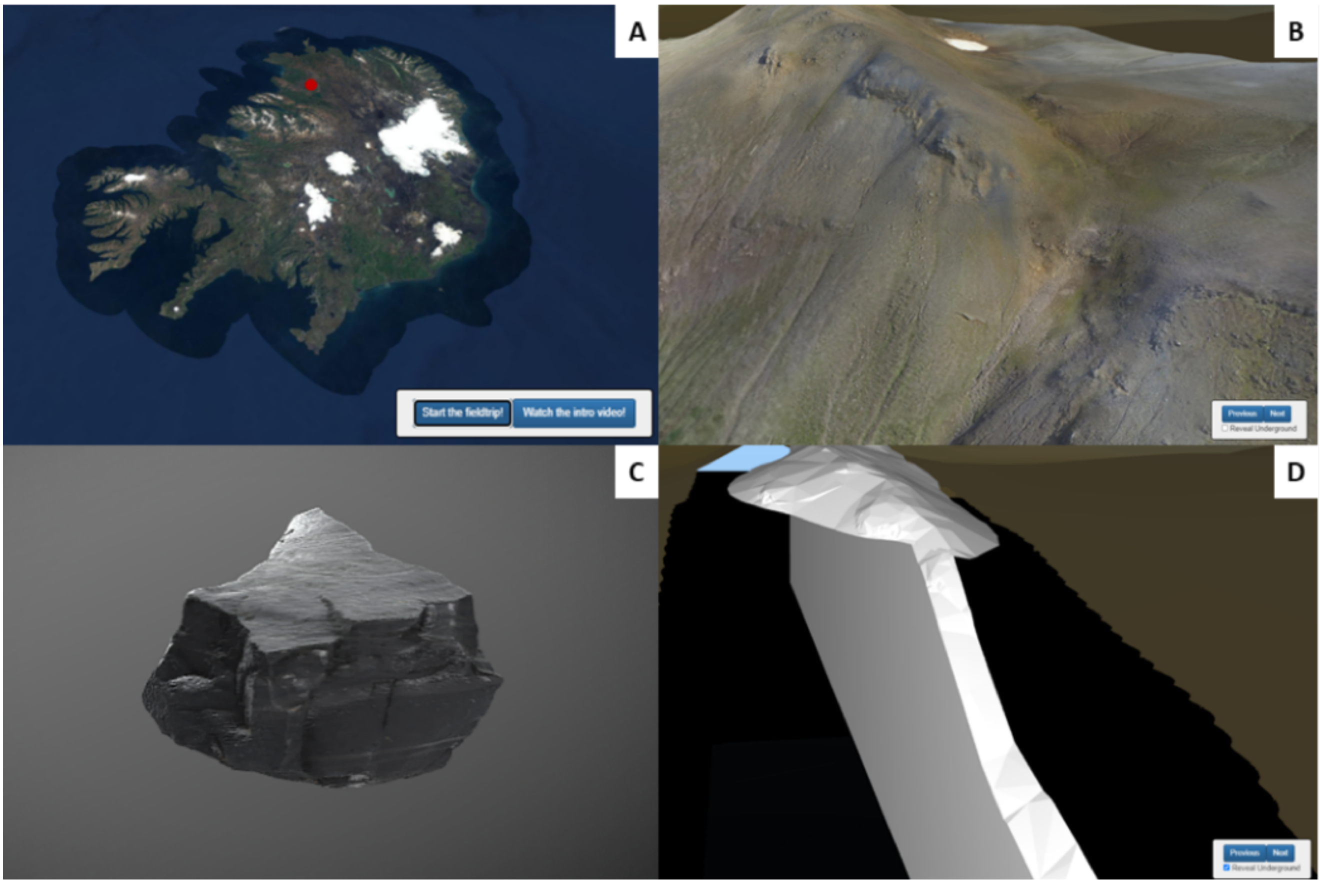

Figure 1: [A] DEM of Iceland (the red circle locates Hrafntinnuhryggur); [B] SfM outcrop model of Hrafntinnuhryggur; [C] SfM rock model of obsidian collected from Hrafntinnuhryggur; [D] 3D conceptual representation of the dyke and surface flow at Hrafntinnuhryggur.

Table 1: Iceland VFT questions categorised using Bloom's taxonomy levels [Bloom et al. 1956].

Bloom's taxonomy levels	Objective verbs	Example questions from the Iceland VFT
Knowledge	Define, identify, label, list, locate, match, name, outline, record, reproduce, select, and state.	Locate Reykjanes on the map.
Comprehension	Defend, describe, discuss, estimate, explain, extend, generalise, infer, paraphrase, predict, rewrite, and summarise	Describe the process that creates the cinder cone fed a'a' lava flows.
Application	Change, compute, demonstrate, discover, modify, operate, predict, prepare, produce, relate, show, solve, and use	Sketch what a magma chamber under Krafla looks like.
Analysis	Breakdown, diagram, differentiate, discriminate, identify, illustrate, infer, outline, point out, relate, select, and separate	Provide feedback on the interpretive sketch
Synthesis	Categorise, combine, compile, create, devise, design, generate, integrate, modify, organise, plan, rearrange, and reorganise	Re-arrange the following events into the correct order.
Evaluation	Appraise, compare, conclude, contrast, criticise, debate, justify, interpret, relate, recommend, summarise, support, and weigh	Evaluate the plausibility of converting all of NZ to this form of energy extraction.

DEMs in 3D, which provides an alternative means to present and interpret geological maps and field data [Whitmeyer et al. 2009].

The DEMs in the Iceland VFT were draped with satellite imagery in a similar manner to `Google Earth`. The DEM resolution was dependent on the available data at a specific location. Due to the data being hosted online, dozens of datasets were used in conjunction. These datasets included Shuttle Radar Topography Mission (SRTM) data from NASA (which has a 3 arc second resolution and is available over most of the globe), an 8 metre DEM from LINZ*, and for some locations DEMs were created from drone data using SfM methods (5–20 centimetres).

At the start of each location, students were taken on a 'fly-over' where they were transported to each location using a 3D world built from DEMs and satellite imagery. The users were encouraged to click 'start the field trip' (Figure 1A). This resembled `Google Earth`, which many undergraduate geology students are familiar with. Students could pause and rotate the animation at any point. The fly-over represents the travel to a field location, which often occurs in a van or airplane [Jolley et al. 2018c]. This was used so students could identify and locate where they were, as well as get an idea of the distances and scales involved.

DEMs were used at each location to showcase the varying scales of different landscape features such as tuff cones, caldera margins, and lava flows. These interactive landscapes allowed the students to explore, rotate, and zoom in on geological features and then compare the scales of features. Students were guided to these features in the landscape and were then asked to identify them in fixed-response questions. This allowed students to make their own choices about how they explored a site, outcrop, or sample. This autonomy and authenticity were both critical for developing intrinsic motivation [Jolley et al. 2018a].

SfM models [Westoby et al. 2012; Tavani et al. 2014; Fleming and Pavlis 2018] for the Iceland VFT were generated from drone or handheld photography to create detailed models of outcrops (e.g. Figure 1B). The resolution of these models were 5–20 centimetres. These models allowed students to pan, zoom, and rotate the model to identify volcanic features within the outcrop at a much higher resolution than possible using satellite imagery (i.e. `Google Earth`). Fixed-choice questions accompanied the outcrop models asking students to identify specific features.

SfM models of rock samples from each location allowed students to match a rock with the associated outcrop (Figure 1C). Students were able to rotate and zoom in on the rock sample to identify textural and compositional characteristics. This was similar to techniques used by De Paor [2016]. The models were accompanied by multi-choice questions, which asked students to identify the presence or absence of specific features in the sample.

Furthermore, a SfM model was used to summarise learning at the end of one of the modules to help students understand the 'bigger picture'. To further illustrate the geological relationships in the landscape, the students were able to switch between the SfM model and an interpretative conceptual model of the outcrop they were describing (Figure 1D).

*https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/

3.4.2 *Instructional Videos*

Instructional videos demonstrate a process or explain a concept and are designed to aid understanding and facilitate learning [Giannakos 2013; Yousef et al. 2014]. Instructional videos were utilised throughout the Iceland VFT with commentary from expert volcanologists to convey volcanology concepts. Most instructional videos followed a standard format consisting of learning objectives, content topics, brief text coupled with images (e.g. maps, diagrams, models, and geologic features), and embedded video clips. Most of these instructional videos were filmed on location; however, some were filmed in front of a green screen. The instructional videos were five to seven minutes long to keep students engaged and avoid loss of concentration.

Some studies have found that instructor presence alongside quality course content are essential elements in courses that successfully facilitate online student engagement and learning [e.g. Jolley et al. 2018b; Nortvig et al. 2018]. Online students need to feel connected to the educator, which can be achieved through audio, video, synchronous and asynchronous discussions, and practical activities [Gray and DiLoreto 2016; Nortvig et al. 2018]. Most videos featured the course instructor with whom all of the students were familiar, and the videos were designed to align with the teaching style of the instructor and to build on student-instructor connection.

Some of these were filmed as 360° videos, using omnidirectional cameras that capture a sphere around the camera. Viewers get an immersive experience by freely changing their field of view around the sphere. The 360° videos allowed students to pan around the landscape, and zoom-in and focus on certain features. The 360° videos can also render a virtual reality environment via a head-mounted display, and can be viewed on everyday devices (e.g. laptops, phones) via online video services such as YouTube†.

The 360° videos were between two and seven minutes, and included expert commentary to explain and point out volcanic features and processes at each location. The instructor used voice and physical cue methodologies, as recommended in Lindeman [2018], to highlight the important volcanic features and processes whilst filming.

3.5 Assessment opportunities

3.5.1 *Interactive map exercises*

At the start of each location, interactive map exercises asked students to locate on a map where in Iceland their virtual field work was taking place. The interactive exercises required students to click on the map, which integrated the geology of the area with the geography of Iceland using `Google Maps` (Figure 2A). The map had a tectonic overlay option (Figure 2B), which could be turned on to help students familiarise themselves in the geological context of Iceland. If students correctly answered the question they could progress to the next question, and if they incorrectly answered the question, they

†https://www.youtube.com/

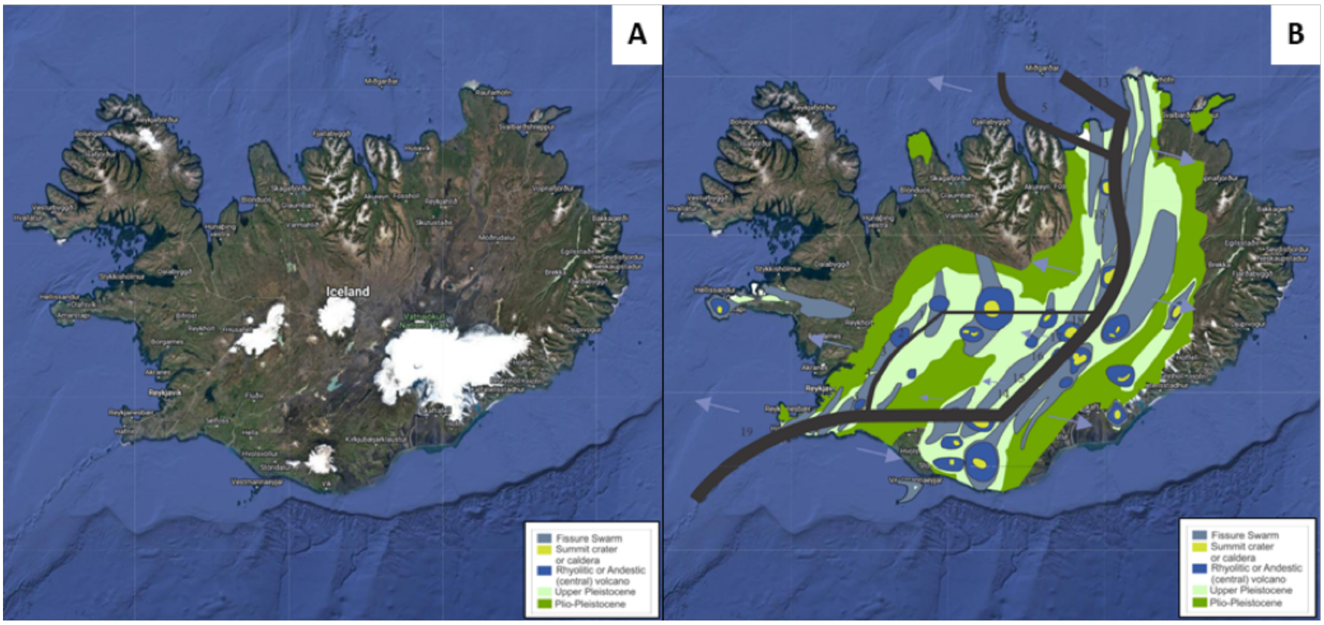

Figure 2: [A] Map of Iceland with volcanic overlay; [B] Map of Iceland with tectonic overlay.

were automatically provided with pre-determined prompts to use the tectonic and volcanic overlay for guidance. Students had to complete the interactive map exercise correctly before the next section was revealed. This section was designed to remind students of the broader geological and geographical context of Iceland, which was in response to research which found that students on roadside-style geology field trips did not have a strong sense of place or connection to field sites due to feeling disoriented and uncertain of the broader picture [Jolley et al. 2018c].

3.5.2 *Multi-choice questions*

Multi-choice questions were the most utilised style of exercise in the Iceland VFT as they provided a way to assess both the lower levels of Bloom's taxonomy (e.g. knowledge and comprehension) and the higher levels of Bloom's taxonomy (e.g. analysis and evaluation). The fixed-response questions incorporated pre-determined feedback which was delivered automatically to students when they submitted an answer.

The intention of feedback for correct answers was to confirm, encourage, and expand upon student understanding of the content. The intention of feedback for incorrect answers was to provide information to target common misconceptions, or to direct students to the relevant content within the VFT. Following feedback, the students were required to re-select an answer until they got the question correct. Only then could they continue on to the next section.

3.5.3 *Discussion board questions*

The discussion board questions were generally open-ended questions which didn't have a specific correct answer and involved any level of Bloom's taxonomy. There was usually an element of reflection in the discussion board questions which allowed students to progress to a higher level of learning. The discussion board questions were presented using the online discussion board application `Padlet`*. Students were encouraged to complete the discussion board questions either before or during the relevant classroom session. Discussion board contributions were not compulsory and did not contribute to the final grade.

Students were encouraged to comment on and rate (either "up vote," "down vote," or "like") their classmates' answers. In this way, students could receive peer feedback as they were completing the exercises together. There is evidence that peer feedback enhances student learning because students actively engage in evolving their understandings of subject matter [Falchikov 2001; Duret et al. 2018]. Peer interaction also helps to facilitate feelings of relatedness, thus contributing to the development of intrinsic motivation [Deci et al. 1991].

4 Implementation of the VFT

The first location was at Reykjanes and was run within a traditional classroom setting, with students sitting row-by-row with the lecturer at the front of the classroom. A team of instructors and teaching assistants guided the students through the VFT material, and students spent the first hour familiarising themselves with the VFT layout and content. Subsequently, all locations within the VFT were made available to students once they had completed the Reykjanes location. After students completed the first online location in the classroom, some students chose to engage with the other locations at home, ahead of the upcoming classroom and laboratory sessions. This allowed these students more time in the in-person classroom sessions to engage in group discussions. These group discussions were modulated by instructors and expanded upon the content that students learned within the VFT. This allowed a natural progression into the flipped classroom [e.g. Bergmann and Sams 2012] model for this part of the class.

*`https://padlet.com`

5 Evaluation approach

Student feedback, teacher feedback, and questionnaires were used to evaluate the effectiveness of VFTs [Arrowsmith et al. 2005; Dolphin et al. 2019; Mead et al. 2019; Bonali et al. 2021]. Student reflection was used as a method to evaluate the impact of the Iceland VFT on the student experience.

A qualitative, open-ended evaluation exercise was used to guide students in the reflection process upon the completion of the VFT. The evaluation exercise was designed to help answer broad research questions associated with student perceptions on how the Iceland VFT was experienced: (1) How was student motivation influenced by the Iceland VFT experience? and (2) What aspects of the Iceland VFT could be improved and how? The evaluation exercise also informed the researcher (Author Watson) on students' perceptions of their learning, while providing constructive feedback to improve future iterations of the virtual field trip. The accompanying evaluation design is best described as a qualitative case study, as it uses open-ended (non-numerical) student responses to answer these research questions while exploring a single context.

The evaluation exercise was part of the course assessment and included as an ungraded part of a final lab with a reflection and applied sketching and interpretation exercise which itself was worth ten percent of the final course grade. As outlined in the ethics this lab was not graded but completion marks were collated, and anonymity maintained to the instructor. The reflection and evaluation components took students thirty minutes to complete during lab time and were collected by a teaching assistant. Anonymisation of the responses of the students who agreed to participate in this study were also maintained to uphold participant confidentiality to the researcher and course instructor. Following this, the exercises were coded and analysed using the process described in the data analysis section below.

6 Data analysis

The student responses to the evaluation exercise were coded using `Microsoft Excel`. Coding is a way of categorising the relevant data into a range of different themes to determine the common themes presented in the research. This can then be used to establish a framework of thematic ideas [Gibbs 2007]. The first pass was predominantly concerned with identifying the common themes within the responses to each question. Following the first round of coding, patterns and themes were detected and the research could begin to be generalised (e.g. by counting the frequencies of codes) [Cohen et al. 2002]. The second pass was concerned with reading back through the data and separating out individual phrases to match with the identified patterns and themes. This was a way to check the identified common themes were present. These were assigned in unique categories generated by the researcher (i.e. parroting phrases exactly from the class dialogue), which followed similar methods used in field education research [Dohaney et al. 2015]. The qualitative results were presented within a quantitative paradigm because it enabled the researcher to make generalisations within the collection of individuals in this study, and it also helped to identify patterns within the research that otherwise may not be as apparent [Maxwell 2010].

7 Results

7.1 Impact of the Iceland VFT on student motivation

Of the forty-nine students who agreed to participate in this research study, all students completed the evaluation exercise and answered Q2:

> "How successful was the Iceland VFT at improving the following (sketching, annotation, motivation and interpretation)? Weight these adding up to 100 percent and explain your reasoning."

Here, we only analyse the student responses regarding how successful the VFT was at improving motivation. The weightings of the other learning outcomes (e.g. sketching, annotation, and interpretation) will be included in a future study. Student responses focussed on motivation across several coding categories. The total raw number of code occurrences was 28, and three students had multiple themes represented in their responses. Table 2 summarises the responses.

Students deemed motivation to be associated with the VFT experience being fun, interactive, and exciting (16 %). One student's response noted that it was both a "unique" and "fun" way to learn, while also being "interactive". Another student commented that "seeing volcanic environments in real life situations" made them excited to learn. Sixteen percent of students found the VFT interesting and indicated that their interest was related to the location and the instructor's sense of humour: "The sense of humour throughout the videos helped me remember and stay interested". Twelve percent of students found the 3D visualisations and instructional videos made them more motivated and that visually having something to look at instead of listening to someone talking made them more "engaged". Another student specifically mentioned that "videos and questions" helped engage their interest and motivate them to complete their work.

7.2 Student recommendations for the Iceland VFT

The last question of the evaluation exercise focused on what could be improved in the Iceland VFT:

> "What aspects of the Iceland VFT could be improved? How could these aspects be improved?"

All forty-nine students who agreed to participate in this research study answered this question. Student responses focussed on recommendations across multiple coding categories. The total raw number of code occurrences was 49, and 14 students had multiple themes represented in their responses. Table 3 summarises the responses.

The most frequent response was that students felt that the discussion board questions could be improved (39 %). Students noted that it would be better to answer the discussion board questions independently before being able to see their peers' answers. Another aspect of the VFT that students thought could be improved were the technical difficul-

Table 2: Themes, example quotes, and frequency count of student answers to the motivation section of Q2 of the evaluation exercise.

Themes	Example representative quote(s)	Frequency (%)
The VFT was fun, interactive and exciting.	"Was a unique fun way to learn, hasn't been done before with it being interactive as well as a singular exercise. Fun and educational." "Seeing volcanic environments in "real life" situations made me appreciate volcanoes more and made me excited to learn about them."	16
The VFT was an interesting experience.	"It stimulated my interest in the area making me more motivated to complete the tasks." "The sense of humour throughout the videos helped me remember and stay interested."	16
The 3D visualisations and instructional videos in the VFT increased students motivation.	"The videos and 3D activities did motivate me to keep working on the correct answers." "Videos and questions helped to engage my interest and motivated me to complete the work."	12
The VFT generally increased student motivation.	"The field trip made me more motivated to do work, than sitting in lectures."	7

ties (20 %). Students found that sometimes there were technical difficulties related to the slow loading of the webpage and instructional videos. Fourteen percent of students mentioned that a save user data option would be useful, as when they exited the webpage their progress was not saved. A similar response was that a login system would be useful to allow answers to be saved (8 %). Twelve percent of student responses stated that allowing time to complete the Iceland VFT at home would be beneficial, and six percent of students stated that "preparation labs/lectures" as background material should be presented prior to the VFT so that students have "prior knowledge of Iceland volcanics".

8 Discussion

8.1 The student experience

Student reflections can provide educators valuable insights into the student experience [Scott et al. 2019]. Student answers in the evaluation exercise indicate that the VFT motivated them to learn because the learning environment was interesting, enjoyable, and fun. Students commented on the motivating nature of seeing volcanic environments in "real-life", and the "sense of humour" of the instructor in the videos. These comments reflect the design methodology around interest in location [Dolphin et al. 2019] and connection to lecturer [Jolley et al. 2018b]. In addition, the VFT aimed to allow students to interpret the volcanic environment using 3D visualisations and videos: the achievement of this aim is reflected in the "real-life" and "motivated to keep working" experience that the students commented on relating to these tools. These aims and responses are in line with self-determination theory [Ryan and Deci 2000; 2002], which propose feelings of relatedness, competence, and autonomy to promote intrinsic motivation to learn. Students found the 3D visualisations and videos made them more motivated to learn and keep working. We interpret that the technology allowed students to independently explore the geological landscapes and rocks in Iceland, which may have helped develop student interest and ownership of their learning. Ownership is an important aspect of motivation in education through the constructs of interest, value, and intrinsic motivation [Komarraju and Nadler 2013]. The importance of ownership suggests that the link between independence and motivation should be incorporated at an appropriate level in these types of learning activities.

8.2 Student recommendations

Students provided feedback on how to improve the discussion board questions in the VFT. Students indicated that it would be better to answer the discussion board questions prior to seeing their fellow students' answers. We took this as a sign of metacognition in students who realised that their learning would benefit from being required to independently engage with the material before sharing and discussing their answers [Ambrose et al. 2010]. In the second iteration of the VFT, when students were satisfied with their answer, they were able to click a button to add their answer to the discussion board and reveal peers' answers.

It is critical to minimise any technical difficulties in a VFT, which has been shown to reduce instructor stress [Jolley et al. 2018b]. In the first iteration of the VFT, students commented on the slow loading website and videos. Video resolution (in particular the 360° videos, which were viewed on student laptops) can be quite large (up to 5.7K), which can present an issue for slow internet connections. As we could not reduce the 360° video resolution without compromising quality, we ensured that the classroom spaces for the second iteration of the VFT had good internet access. In addition, the timeframe for completing the VFT was made more flexible in the second iteration to accommodate students who could not use the campus facilities and had to rely on their home internet connection. Technology and internet access are crucial consider-

Table 3: The themes, relevant quotes, and frequency count of student answers to Q3 of the evaluation exercise.

Themes	Example quote	Frequency (%)
Discussion board questions	"I think the Padlet feature could be improved. It would be better if we answered the question individually, then once answered you could then look at other people's answers. This would help people actually think about the questions rather than just agreeing with someone else's answers."	39
Technical difficulties	"The only problems that I experienced were technical difficulties. Some videos didn't load [the 360° videos] and it took a long time to fix."	20
Save option	"Most recommended: logging in or having your own profile and ability to save answers that you created along the way. This would eliminate the need for PDF submission."	14
Completing the Iceland VFT at home	"It would be better if all the students completed the field trips at home and came into a lecture and/or discussion already knowing what has happened. It runs much more smoothly when completed at home."	12
Login option	"Have a login system, allow multiple attempts, each saved separately: create user accounts."	8
VFT preparation	"Preparation labs/lectures leading up to the field trip so that students have more prior knowledge of Iceland volcanics."	6

ations for ensuring that students have equal VFT experiences [Harris et al. 2020].

Some students mentioned that completing the VFT at home would allow more time for discussion within the classroom (i.e. using a flipped classroom approach). In Kobayashi [2017], utilising the flipped classroom approach for a VFT increased active learning and teamwork, which helped foster student engagement. In the second iteration of the Iceland VFT, the flipped classroom approach was more deliberately embedded in the pedagogy, and this structure was explained to students prior to starting the VFT. Students were expected to complete material at home to allow more time for classroom discussion.

Students also mentioned that including a save option on the website would improve the experience by minimising the chance of lost work and adding flexibility. To remediate this, in the second iteration of the VFT, the web page saved all answers as a cookie on the browser. At the end of each location, students could click a button which summarised all their answers and allowed them to 'submit' their work. An added bonus was that the submitted work got saved to a `Google Sheets` spreadsheet, which allowed the instructor team to review answers in a timely manner, in contrast to the prior method of instructor assessment in the first iteration of the VFT that required students to make print-outs of the online work for course grading.

Students also noted that providing background material prior to the VFT would be beneficial, which can help reduce cognitive load [Petersen et al. 2020]. Relevant sections were taught in the classroom prior to the implementation of the VFT; however, the importance of these sections was not emphasised the first time we ran the VFT. This was rectified in the second iteration and in the subsequent massive open online course (MOOC) versions (see section below).

9 Limitations

One limitation of this research was that data were only collected for the first iteration of the Iceland VFT. The group of students who participated in the first iteration of the VFT had a strong connection with the instructor, while students from different year groups or institutions may not have a strong connection with the same instructor. This problem may be exacerbated by the fact the student data were self-reported and part of the course grade [Brownell et al. 2013].

Students indicated the VFT was a fun, interesting, and motivating experience. Student responses were typically one sentence and often did not justify why the VFT was fun, interesting, or motivating. The ability for students to self-regulate their learning is an expert-level skill, possibly indicating that the lack of depth in student responses may be a result of students not having acquired the expert-level skills required to reflect on their learning. The current version of the MOOC has student reflections embedded at the end of every module, which may help with more focussed in-depth reflection for different year groups and classroom settings. However, more detailed qualitative surveys, interviews, and instructor observations are needed to better understand the overall student experience and the impact the VFT had on student motivation. In particular, the lack of depth in some of the student responses suggests that greater scaffolding in the reflection questions would have been helpful.

Furthermore, a detailed reflection on the progression into the flipped classroom will be interesting to analyse. The teaching team acknowledges that more thought and research is needed to fully inform and maximise learning opportunities associated with flipping the VFT classroom.

10 New directions

The landscape of tertiary education is becoming more flexible and inclusive, while learning platforms are constantly evolving, which can push pedagogies in exciting directions. The skills students need for the workplace are changing, requiring constant re-evaluation of learning goals. This paves the way for new flexible ways of learning such as Massive Open Online Courses (MOOCs) and reimagining the traditional university lecture with more active and reflective learning. However, the applied and transferrable skills aspect of in-person field trips make them essential components of the geology undergraduate experience.

Ongoing work has included the development and implementation of the second iteration of the Iceland VFT (2019), and the development of the Iceland VFT into Part 2 of a Professional Certificate in Volcanology as a MOOC [UCx 2022a] *Volcanic hazards* course*. Both of these iterations have benefitted from the research done on the first iteration of the Iceland VFT. Significant additions have been made focussing on communication skills, authentic assessment tasks, and the importance of cultural inclusion. This is particularly illustrated by the online free course Part 1 of edX Professional Certificate in Volcanology: *Volcanology field science and society* [UCx 2022b]†.

The two MOOC courses are now being used to completely replace lectures in the University of Canterbury's third-year volcanology course, effectively flipping the classroom and following best practices for blended learning environments and maximising feedback and interaction between peers and instructors.

11 Conclusion

This research aimed to describe (1) the design and implementation of the Iceland VFT, (2) the impact the VFT had on the student experience, and (3) determine what aspects of the VFT could be improved and how.

Students found the Iceland VFT a positive learning experience as they perceived their learning in the VFT as being motivating and interesting, due to being exposed to 'real life' volcanic environments, instructor humour, and an interesting volcanic location. Students also found the 3D visualisations and instructional videos made them more motivated.

Based on student responses in the evaluation exercise, the aspects of the Iceland VFT that were improved for the second iteration included the online discussion boards, providing an option to save their progress, minimising technical difficulties, providing context prior to the implementation of the VFT, and allowing time to complete the VFT at home to provide more time for classroom discussions using a flipped classroom model.

Based on students' responses in the evaluation exercise, some recommendations for VFT design and implementation include facilitating the flipped classroom, minimising technical difficulties, implementing appropriate technologies to deliver content, and providing appropriate assessment opportunities that scaffold students from a lower level of learning to a higher level of learning. These suggestions also informed the development of two massive open online courses.

* https://www.edx.org/course/exploring-volcanoes-and-their-hazards-in-iceland?index=product&queryID=cf338f7d9b966828f9e777f93035cf4f&position=1

† https://www.edx.org/course/volcano-field-science-culture-and-communication-new-zealand?index=product&queryID=74c2f5fdd4286269d67ac41512c18842&position=1

Author contributions

The first author led this research, collected and analysed the data with help from all authors. All authors contributed to the writing and editing of the manuscript.

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The Iceland VFT was filmed in conjunction with a primary and secondary school natural hazards VFT, which was a collaboration with LEARNZ, CORE Education, and the research university. LEARNZ is a programme of free online VFTs for teachers and their classes taking them to remote places. CORE Education is a professional learning and development consultancy organisation.

Data availability

All data used in this study are presented in Tables 2 and 3. Iceland VFT link: https://www.holoceneadventures.com/ivft/.

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References

Ambrose, S. A., M. W. Bridges, M. DiPietro, M. C. Lovett, and M. K. Norman (2010). *How learning works: Seven research-based principles for smart teaching*. John Wiley & Sons.

Anthamatten, P. and S. S. Ziegler (2006). "Teaching Geography with 3-D Visualization Technology". *Journal of Geography*

105(6), pages 231–237. ISSN: 1752-6868. DOI: 10.1080/00221340608978692.

Arrowsmith, C., A. Counihan, and D. McGreevy (2005). "Development of a multi-scaled virtual field trip for the teaching and learning of geospatial science". *International Journal of Education and Development using ICT* 1(3), pages 42–56.

Atchison, C. L. and A. D. Feig (2011). "Theoretical perspectives on constructing experience through alternative field-based learning environments for students with mobility impairments". *Qualitative Inquiry in Geoscience Education Research*. Geological Society of America. DOI: 10.1130/2011.2474(02).

Bergmann, J. and A. Sams (2012). *Flip your classroom: Reach every student in every class every day*. International society for technology in education.

Biggs, J. (1996). "Enhancing teaching through constructive alignment". *Higher Education* 32(3), pages 347–364. ISSN: 1573-174X. DOI: 10.1007/bf00138871.

Bloom, B. S., M. D. Engelhart, E. J. Furst, and W. H. Hill (1956). *Taxonomy of educational objectives: The classification of educational goals*. Volume Handbook I: Cognitive domain. David McKay Company, New York.

Bonali, F. L., E. Russo, F. Vitello, V. Antoniou, F. Marchese, L. Fallati, V. Bracchi, N. Corti, A. Savini, M. Whitworth, K. Drymoni, F. P. Mariotto, P. Nomikou, E. Sciacca, S. Bressan, S. Falsaperla, D. Reitano, B. van Wyk de Vries, M. Krokos, G. Panieri, M. A. Stiller-Reeve, G. Vizzari, U. Becciani, and A. Tibaldi (2021). "How Academics and the Public Experienced Immersive Virtual Reality for Geo-Education". *Geosciences* 12(1), page 9. DOI: 10.3390/geosciences12010009.

Bond, C. E. and A. J. Cawood (2021). "A role for virtual outcrop models in blended learning – improved 3D thinking and positive perceptions of learning". *Geoscience Communication* 4(2), pages 233–244. ISSN: 2569-7110. DOI: 10.5194/gc-4-233-2021.

Boyle, A. P., S. Maguire, A. Martin, C. Milsom, R. Nash, S. Rawlinson, A. Turner, S. Wurthmann, and S. Conchie (2007). "Fieldwork is Good: the Student Perception and the Affective Domain". *Journal of Geography in Higher Education* 31(2), pages 299–317. ISSN: 1466-1845. DOI: 10.1080/03098260601063628.

Boyle, A. P., P. Ryan, and A. Stokes (2009). "External drivers for changing fieldwork practices and provision in the UK and Ireland". *Field Geology Education: Historical Perspectives and Modern Approaches*. Geological Society of America. DOI: 10.1130/2009.2461(24).

Brownell, S. E., M. J. Kloser, T. Fukami, and R. J. Shavelson (2013). "Context Matters: Volunteer Bias, Small Sample Size, and the Value of Comparison Groups in the Assessment of Research-Based Undergraduate Introductory Biology Lab Courses". *Journal of Microbiology & Biology Education* 14(2), pages 176–182. DOI: 10.1128/jmbe.v14i2.609.

Carabajal, I. G., A. M. Marshall, and C. L. Atchison (2017). "A Synthesis of Instructional Strategies in Geoscience Education Literature That Address Barriers to Inclusion for Students With Disabilities". *Journal of Geoscience Education* 65(4), pages 531–541. ISSN: 2158-1428. DOI: 10.5408/16-211.1.

Chandler, P. and J. Sweller (1991). "Cognitive Load Theory and the Format of Instruction". *Cognition and Instruction* 8(4), pages 293–332. DOI: 10.1207/s1532690xci0804_2.

Choi, D. H., A. Dailey-Hebert, and J. S. Estes (2016). *Emerging tools and applications of virtual reality in education*. Information Science Reference Hershey, PA, USA.

Clary, R. M. and J. H. Wandersee (2010). "Virtual field exercises in the online classroom: Practicing science teachers' perceptions of effectiveness, best practices, and implementation". *Journal of College Science Teaching* 39(4), page 50.

Cliffe, A. D. (2017). "A review of the benefits and drawbacks to virtual field guides in today's Geoscience higher education environment". *International Journal of Educational Technology in Higher Education* 14(1). ISSN: 2365-9440. DOI: 10.1186/s41239-017-0066-x.

Cohen, L., L. Manion, and K. Morrison (2002). "Research Methods in Education". DOI: 10.4324/9780203224342.

De Paor, D. G. (2016). "Virtual Rocks". *GSA Today*, pages 4–11. DOI: 10.1130/gsatg257a.1.

Deci, E. L., R. J. Vallerand, L. G. Pelletier, and R. M. Ryan (1991). "Motivation and Education: The Self-Determination Perspective". *Educational Psychologist* 26(3–4), pages 325–346. ISSN: 1532-6985. DOI: 10.1080/00461520.1991.9653137.

Dohaney, J., E. Brogt, and B. Kennedy (2015). "Strategies and Perceptions of Students' Field Note-Taking Skills: Insights From a Geothermal Field Lesson". *Journal of Geoscience Education* 63(3), pages 233–249. ISSN: 2158-1428. DOI: 10.5408/13-026.1.

Dolphin, G., A. Dutchak, B. Karchewski, and J. Cooper (2019). "Virtual field experiences in introductory geology: Addressing a capacity problem, but finding a pedagogical one". *Journal of Geoscience Education* 67(2), pages 114–130. ISSN: 2158-1428. DOI: 10.1080/10899995.2018.1547034.

Duret, D., R. Christley, P. Denny, and A. Senior (2018). "Collaborative learning with PeerWise". *Research in Learning Technology* 26(0). ISSN: 2156-7077. DOI: 10.25304/rlt.v26.1979.

Falchikov, N. (2001). *Learning Together*. Routledge. ISBN: 9780203451496. DOI: 10.4324/9780203451496.

Feig, A. D. (2010). "Technology, Accuracy and Scientific Thought in Field Camp: An Ethnographic Study". *Journal of Geoscience Education* 58(4), pages 241–251. ISSN: 2158-1428. DOI: 10.5408/1.3534863.

Fleming, Z. and T. Pavlis (2018). "An orientation based correction method for SfM-MVS point clouds—Implications for field geology". *Journal of Structural Geology* 113, pages 76–89. DOI: 10.1016/j.jsg.2018.05.014.

Fletcher, S., D. France, K. Moore, and G. Robinson (2002). "Fieldwork Education and Technology: A GEES Perspective". *Planet* 7(1), pages 17–19. ISSN: 1758-3608. DOI: 10.11120/plan.2002.00070017.

Giannakos, M. N. (2013). "Exploring the video-based learning research: A review of the literature". *British Journal of Educational Technology* 44(6). ISSN: 1467-8535. DOI: 10.1111/bjet.12070.

Gibbs, G. R. (2007). "Thematic Coding and Categorizing". *Analyzing Qualitative Data*. SAGE Publications, Ltd, pages 38–55. DOI: 10.4135/9781849208574.n4.

Gray, J. A. and M. DiLoreto (2016). "The effects of student engagement, student satisfaction, and perceived learning in online learning environments." *International Journal of Educational Leadership Preparation* 11(1), n1.

Gustafson, P. (2001). "Meanings of place: Everyday experience and theoretical conceptualizations". *Journal of Environmental Psychology* 21(1), pages 5–16. ISSN: 0272-4944. DOI: 10.1006/jevp.2000.0185.

Harris, B. N., P. C. McCarthy, A. M. Wright, H. Schutz, K. S. Boersma, S. L. Shepherd, L. A. Manning, J. L. Malisch, and R. M. Ellington (2020). "From panic to pedagogy: Using online active learning to promote inclusive instruction in ecology and evolutionary biology courses and beyond". *Ecology and Evolution* 10(22), pages 12581–12612. DOI: 10.1002/ece3.6915.

Hedberg, J. G., B. Harper, and C. Brown (1993). "Reducing cognitive load in multimedia navigation". *Australasian Journal of Educational Technology* 9(2). ISSN: 1449-3098. DOI: 10.14742/ajet.2106.

Houghton, J. J., G. E. Lloyd, A. Robinson, C. E. Gordon, and D. J. Morgan (2015). "TheVirtual Worlds Project: geological mapping and field skills". *Geology Today* 31(6), pages 227–231. ISSN: 0266-6979. DOI: 10.1111/gto.12117.

Hurst, S. D. (1998). "Use of "virtual" field trips in teaching introductory geology". *Computers & Geosciences* 24(7), pages 653–658. DOI: 10.1016/s0098-3004(98)00043-0.

Jacobson, A. R., R. Militello, and P. C. Baveye (2009). "Development of computer-assisted virtual field trips to support multidisciplinary learning". *Computers & Education* 52(3), pages 571–580. ISSN: 0360-1315. DOI: 10.1016/j.compedu.2008.11.007.

Jaeger, A. J., T. F. Shipley, and S. J. Reynolds (2017). "The Roles of Working Memory and Cognitive Load in Geoscience Learning". *Journal of Geoscience Education* 65(4), pages 506–518. ISSN: 2158-1428. DOI: 10.5408/16-209.1.

Jolley, A., S. J. Hampton, E. Brogt, B. M. Kennedy, L. Fraser, and A. Knox (2018a). "Student field experiences: designing for different instructors and variable weather". *Journal of Geography in Higher Education* 43(1), pages 71–95. DOI: 10.1080/03098265.2018.1554632.

Jolley, A., B. Kennedy, N. Reyna, T. Stahl, S. Hampton, P. Sommerville, T. Wilson, E. Brogt, K. Pedley, J. Davidson, et al. (2018b). *Virtual Field trips in tertiary science.*

Jolley, A., B. M. Kennedy, E. Brogt, S. J. Hampton, and L. Fraser (2018c). "Are we there yet? Sense of place and the student experience on roadside and situated geology field trips". *Geosphere* 14(2), pages 651–667. DOI: 10.1130/ges01484.1.

Kastens, K. A., S. Agrawal, and L. S. Liben (2009). "How Students and Field Geologists Reason in Integrating Spatial Observations from Outcrops to Visualize a 3-D Geological Structure". *International Journal of Science Education* 31(3), pages 365–393. ISSN: 1464-5289. DOI: 10.1080/09500690802595797.

Kastens, K. A. and T. Ishikawa (2006). "Spatial thinking in the geosciences and cognitive sciences: A cross-disciplinary look at the intersection of the two fields". *Earth and Mind: How Geologists Think and Learn about the Earth*. Geological Society of America. DOI: 10.1130/2006.2413(05).

Kennedy, B., E. Brogt, Z. Jordens, A. Jolley, R. Bradshaw, M. Hartnett, B. O'Steen, E. Hartung, A. Soutter, G. Cartwright, et al. (2013). "Transforming tertiary science education: Improving learning during lectures".

Kingsbury, C. G., E. C. Sibert, Z. Killingback, and C. L. Atchison (2020). ""Nothing about us without us:" The perspectives of autistic geoscientists on inclusive instructional practices in geoscience education". *Journal of Geoscience Education* 68(4), pages 302–310. DOI: 10.1080/10899995.2020.1768017.

Klemm, E. B. and G. Tuthill (2003). "Virtual field trips: Best practices". *International Journal of Instructional Media* 30(2), pages 177–193.

Klippel, A., J. Zhao, D. Oprean, J. O. Wallgrün, C. Stubbs, P. La Femina, and K. L. Jackson (2019). "The value of being there: toward a science of immersive virtual field trips". *Virtual Reality* 24(4), pages 753–770. ISSN: 1434-9957. DOI: 10.1007/s10055-019-00418-5.

Kobayashi, K. D. (2017). "Using Flipped Classroom and Virtual Field Trips to Engage Students". *HortTechnology* 27(4), pages 458–460. ISSN: 1943-7714. DOI: 10.21273/horttech03350-17.

Komarraju, M. and D. Nadler (2013). "Self-efficacy and academic achievement: Why do implicit beliefs, goals, and effort regulation matter?" *Learning and Individual Differences* 25, pages 67–72. ISSN: 1041-6080. DOI: 10.1016/j.lindif.2013.01.005.

Land, S. M. (2000). "Cognitive requirements for learning with open-ended learning environments". *Educational Technology Research and Development* 48(3), pages 61–78. ISSN: 1556-6501. DOI: 10.1007/bf02319858.

Lim, C. P., D. Nonis, and J. Hedberg (2006). "Gaming in a 3D multiuser virtual environment: engaging students in Science lessons". *British Journal of Educational Technology* 37(2), pages 211–231. ISSN: 1467-8535. DOI: 10.1111/j.1467-8535.2006.00531.x.

Lindeman, R. (2018). *Tell Me About Antarctica: Guidelines for In Situ Capture and Viewing of 360-degree Video Highlighting Antarctic Science*. http://hdl.handle.net/10092/15836.

Litherland, K. and T. A. Stott (2012). "Virtual Field Sites: losses and gains in authenticity with semantic technologies". *Technology, Pedagogy and Education* 21(2), pages 213–230. ISSN: 1747-5139. DOI: 10.1080/1475939x.2012.697773.

Lonergan, N. and L. W. Andresen (1988). "Field-Based Education: Some Theoretical Considerations". *Higher Education Research & Development* 7(1), pages 63–77. ISSN: 1469-8366. DOI: 10.1080/0729436880070106.

Massey, D. B. (2005). *For space*. Sage, pages 1–232. ISBN: 9781412903622.

Maxwell, J. A. (2010). "Using Numbers in Qualitative Research". *Qualitative Inquiry* 16(6), pages 475–482. ISSN: 1552-7565. DOI: 10.1177/1077800410364740.

McCaffrey, K. J. W., M. Feely, R. Hennessy, and J. Thompson (2008). "Visualization of folding in marble outcrops, Connemara, western Ireland: An application of virtual outcrop technology". *Geosphere* 4(3), page 588. DOI: 10.1130/ges00147.1.

Mead, C., S. Buxner, G. Bruce, W. Taylor, S. Semken, and A. D. Anbar (2019). "Immersive, interactive virtual field trips promote science learning". *Journal of Geoscience Education* 67(2), pages 131–142. ISSN: 2158-1428. DOI: 10.1080/10899995.2019.1565285.

Missildine, K., R. Fountain, L. Summers, and K. Gosselin (2013). "Flipping the Classroom to Improve Student Performance and Satisfaction". *Journal of Nursing Education* 52(10), pages 597–599. ISSN: 1938-2421. DOI: 10.3928/01484834-20130919-03.

Mogk, D. W. and C. Goodwin (2012). "Learning in the field: Synthesis of research on thinking and learning in the geosciences". *Earth and Mind II: A Synthesis of Research on Thinking and Learning in the Geosciences*. Geological Society of America. DOI: 10.1130/2012.2486(24).

Mountney, N. P. (2009). "Improving student understanding of complex spatial-temporal relationships in Earth Sciences using computer animation and visualization". *Planet* 22(1), pages 72–77. ISSN: 1758-3608. DOI: 10.11120/plan.2009.00220072.

Nortvig, A.-M., A. K. Petersen, and S. H. Balle (2018). "A Literature Review of the Factors Influencing E-Learning and Blended Learning in Relation to Learning Outcome, Student Satisfaction and Engagement". *Electronic Journal of E-learning* 16(1), pp46–55.

Pennisi, E. (2020). "During the pandemic, students do field and lab work without leaving home". *Science*. DOI: 10.1126/science.abd8385.

Petcovic, H., A. Stokes, and J. Caulkins (2014). "Geoscientists' perceptions of the value of undergraduate field education". *GSA Today* 24(7), pages 4–10. DOI: 10.1130/gsatg196a.1.

Petersen, G. B., S. Klingenberg, R. E. Mayer, and G. Makransky (2020). "The virtual field trip: Investigating how to optimize immersive virtual learning in climate change education". *British Journal of Educational Technology* 51(6), pages 2099–2115. ISSN: 1467-8535. DOI: 10.1111/bjet.12991.

Pyle, E. J. (2009). "The evaluation of field course experiences: A framework for development, improvement, and reporting". *Field Geology Education: Historical Perspectives and Modern Approaches*. Geological Society of America. DOI: 10.1130/2009.2461(26).

Ryan, R. M. and E. L. Deci (2002). "Overview of self-determination theory: An organismic dialectical perspective". *Handbook of self-determination research* 2, pages 3–33.

– (2000). "Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being." *American Psychologist* 55(1), pages 68–78. ISSN: 0003-066X. DOI: 10.1037/0003-066x.55.1.68.

Scott, G. W., S. Humphries, and D. C. Henri (2019). "Expectation, motivation, engagement and ownership: using student reflections in the conative and affective domains to enhance residential field courses". *Journal of Geography in Higher Education* 43(3), pages 280–298. ISSN: 1466-1845. DOI: 10.1080/03098265.2019.1608516.

Semken, S., E. G. Ward, S. Moosavi, and P. W. U. Chinn (2017). "Place-Based Education in Geoscience: Theory, Research, Practice, and Assessment". *Journal of Geoscience Education* 65(4), pages 542–562. ISSN: 2158-1428. DOI: 10.5408/17-276.1.

Senger, K., P. Betlem, T. Birchall, S. J. Buckley, B. Coakley, C. H. Eide, P. P. Flaig, M. Forien, O. Galland, L. Gonzaga, M. Jensen, T. Kurz, I. Lecomte, K. Mair, R. H. Malm, M. Mulrooney, N. Naumann, I. Nordmo, N. Nolde, K. Ogata, O. Rabbel, N. W. Schaaf, and A. Smyrak-Sikora (2020). "Using digital outcrops to make the high Arctic more accessible through the Svalbox database". *Journal of Geoscience Education* 69(2), pages 123–137. DOI: 10.1080/10899995.2020.1813865.

Sima, R. (2020). "Accessibility and Fieldwork in the Time of Coronavirus". *Eos* 101. DOI: 10.1029/2020eo147056.

Stainfield, J., P. Fisher, B. Ford, and M. Solem (2000). "International Virtual Field Trips: A new direction?" *Journal of Geography in Higher Education* 24(2), pages 255–262. ISSN: 1466-1845. DOI: 10.1080/713677387.

Stumpf, R. J., J. Douglass, and R. I. Dorn (2008). "Learning Desert Geomorphology Virtually versus in the Field". *Journal of Geography in Higher Education* 32(3), pages 387–399. ISSN: 1466-1845. DOI: 10.1080/03098260802221140.

Sweller, J. (1994). "Cognitive load theory, learning difficulty, and instructional design". *Learning and Instruction* 4(4), pages 295–312. DOI: 10.1016/0959-4752(94)90003-5.

Tavani, S., P. Granado, A. Corradetti, M. Girundo, A. Iannace, P. Arbués, J. Muñoz, and S. Mazzoli (2014). "Building a virtual outcrop, extracting geological information from it, and sharing the results in Google Earth via OpenPlot and Photoscan: An example from the Khaviz Anticline (Iran)". *Computers & Geosciences* 63, pages 44–53. ISSN: 0098-3004. DOI: 10.1016/j.cageo.2013.10.013.

Tibaldi, A., F. L. Bonali, F. Vitello, E. Delage, P. Nomikou, V. Antoniou, U. Becciani, B. V. W. de Vries, M. Krokos, and M. Whitworth (2020). "Real world–based immersive Virtual Reality for research, teaching and communication in volcanology". *Bulletin of Volcanology* 82(5). ISSN: 1432-0819. DOI: 10.1007/s00445-020-01376-6.

Trinks, I., P. Clegg, K. McCaffrey, R. Jones, R. Hobbs, B. Holdsworth, N. Holliman, J. Imber, S. Waggott, and R. Wilson (2005). "Mapping and analysing virtual outcrops". *Visual Geosciences* 10(1), pages 13–19. DOI: 10.1007/s10069-005-0026-9.

Tuan, Y.-F. (1977). *Space and place: The perspective of experience*. U of Minnesota Press.

University of Canterbury (UCx) (2022a). *Volcanic hazards* [MOOC]. URL: https://www.edx.org/course/exploring-volcanoes-and-their-hazards-in-iceland?index=product%5C&queryID=cf338f7d9b966828f9e777f93035cf4f%5C&position=1 (visited on 11/16/2022).

University of Canterbury (UCx) (2022b). *Volcanology field science and society* [MOOC]. URL: https://www.edx.org/course/volcano-field-science-culture-and-communication-new-zealand?index=product%5C&queryID=74c2f5fdd4286269d67ac41512c18842%5C&position=1 (visited on 11/16/2022).

van der Hoeven Kraft, K. J., L. Srogi, J. Husman, S. Semken, and M. Fuhrman (2011). "Engaging Students to Learn Through the Affective Domain: A new Framework for Teaching in the Geosciences". *Journal of Geoscience Education* 59(2), pages 71–84. DOI: 10.5408/1.3543934a.

Westoby, M., J. Brasington, N. Glasser, M. Hambrey, and J. Reynolds (2012). "'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications". *Geomorphology* 179, pages 300–314. ISSN: 0169-555X. DOI: 10.1016/j.geomorph.2012.08.021.

Whitmeyer, S., C. Atchison, and T. Collins (2020). "Using Mobile Technologies to Enhance Accessibility and Inclusion in Field-Based Learning". *GSA Today* 30(9), pages 4–10. DOI: 10.1130/gsatg462a.1.

Whitmeyer, S., M. Feely, D. D. Paor, R. Hennessy, S. Whitmeyer, J. Nicoletti, B. Santangelo, J. Daniels, and M. Rivera (2009). "Visualization techniques in field geology education: A case study from western Ireland". *Field Geology Education: Historical Perspectives and Modern Approaches*. Geological Society of America. DOI: 10.1130/2009.2461(10).

Yousef, A. M. F., M. A. Chatti, and U. Schroeder (2014). "Video-based learning: A critical analysis of the research published in 2003-2013 and future visions". *eLmL 2014, The Sixth International Conference on Mobile, Hybrid, and On-line Learning*, pages 112–119.

Appendix A

Table A1: Alignment of the VTF Reykjanes intended learning outcomes, the intended learning outcomes from the third-year undergraduate volcanology and magmatic systems course, and the associated Bloom's taxonomy level.

Reykjanes Intended Learning Outcomes	GEOL336 Intended Learning Outcomes	GEOL336 Iceland Virtual Fieldtrip Questions	Bloom's Taxonomy Level for GEOL336 Iceland Virtual Fieldtrip Questions
Locate Reykjanes in the context of the fissure-fed volcanism and rifting tectonism of spreading ridges	NA	Can you find the Reykjanes fissure zone on the map?	Comprehension
Record systematic and detailed observations of an outcrop and a rock of a typical fissure fed eruption of a pāhoehoe flow.	• Discuss physical volcanological processes with relevance to magma properties. • Identify and classify igneous rocks and their geological environments.	• What is the average thickness of each of the pāhoehoe sheets? • Estimate the number of pāhoehoe lava sheets in the outcrop above.	Knowledge/ Comprehension
Record detailed observations of the map- scale geology and geomorphology of a fissure-fed eruption (etc. toes).	Discuss physical volcanological processes with relevance to magma properties.	Use the 3D viewer below to explore different features, then select the descriptions for features.	Knowledge
Combine your observations with the eruption history to explain the typical morphology of an pāhoehoe flow.	Discuss physical volcanological processes with relevance to magma properties.	What are the structures and textures that are characteristic from front view, side view and map view of a pāhoehoe lava flow?	Synthesis
Explain outcrop observations that allow you to identify submarine versus subaerial basaltic volcanism.	• Discuss physical volcanological processes with relevance to magma properties. • Identify and classify igneous rocks and their geological environments.	What is not characteristic of subaqueous eruptions?	Comprehension/ Comprehension

Table A2: Alignment of the VTF Heimaey intended learning outcomes, the intended learning outcomes from the third-year undergraduate volcanology and magmatic systems course, and the associated Bloom's taxonomy level.

Heimaey Intended Learning Outcomes	GEOL336 Intended Learning Outcomes	GEOL336 Iceland Virtual Fieldtrip Questions	Bloom's Taxonomy Level for GEOL336 Iceland Virtual Fieldtrip Questions
Locate Heimaey in the context of the volcanism and tectonism of Iceland.	NA	Can you find Heimaey on the map?	Knowledge
Record systematic and detailed observations of an outcrop, rock of a typical cone fed ʻaʻā flow.	• Discuss physical volcanological processes with relevance to magma properties. • Identify and classify igneous rocks and their geological environments.	• Which of the following best describes a cinder cone? • What is the typical thickness, height and width of an ʻaʻā lava flow.	Knowledge/ Comprehension
Record detailed observations of the map- scale geology and geomorphology of a cinder cone volcano.	Discuss physical volcanological processes with relevance to magma properties.	• What are cinder cones made of? • Describe the process that creates the cinder-cone fed ʻaʻā lava flows.	Knowledge/ Comprehension
Record your observations with the eruption history to explain the typical behaviour of an ʻaʻā flow (and the formation of spiky protrusions).	• Discuss physical volcanological processes with relevance to magma properties. • Identify and classify igneous rocks and their geological environments.	• What is a typical thickness, width, and length of an ʻaʻā flow? • What causes the >1 m spiky protrusions on the surface of an lava flow?	Knowledge/ Comprehension

Table A3: Alignment of the VTF Krafla intended learning outcomes, the intended learning outcomes from the third-year undergraduate volcanology and magmatic systems course, and the associated Bloom's taxonomy level.

Krafla Intended Learning Outcomes	GEOL336 Intended Learning Outcomes	GEOL336 Iceland Virtual Fieldtrip Questions	Bloom's Taxonomy Level for GEOL336 Iceland Virtual Fieldtrip Questions
Record systematic and detailed observations of an outcrop, rock and thin section of a typical obsidian flow and fine- grained rhyolite at Krafla caldera.	• Use geochemical data, thin sections, and maps to reconstruct the magmatic and volcanological histories. • Discuss physical volcanological processes with relevance to magma properties. • Identify and classify igneous rocks and their geological environments.	• Make observations of structural features to inform the orientation of the rhyolite (main rock type in image). • What textural features can you see in the rock above?	Knowledge/ Comprehension
Record and compare systematic and detailed observations of the map-scale geology and geomorphology of tuff cones and caldera volcanoes.	Discuss physical volcanological processes with relevance to magma properties.	Use the 3D viewer below to explore distinctive features, then select the descriptions for features.	Knowledge/ Comprehension
Integrate your knowledge on intrusions in caldera settings to judge conceptual models of the magma beneath Krafla.	NA	• Which of the following statements best describes shallow intrusions at Krafla from borehole geology? • What are the possible models at Krafla?	Synthesis
Compare the implications of different geophysical datasets to illustrate the uncertainty associated with the magma chamber size and shape.	NA	What geological techniques are most useful when studying magma bodies?	Evaluation
Debate the potential eruptions scenarios and the implications for Krafla geothermal power plant and Iceland as a whole.	Realize the importance of igneous rocks in geology and to society.	Summarise the benefits that drilling into a magma chamber may provide to society.	Evaluation