RESEARCH ARTICLE

VOLCANICA

VolcanoVR: A virtual reality environment for volcanic data visualisation and communication

Kristian Hansen[α, β], Simon J. Barker[α], Finnigan Illsley-Kemp *[α], Craig Anslow[γ], Christof Mueller[δ], and Graham Leonard[δ]

[α] School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand.
[β] Hansen Data Reality Ltd., Christchurch, New Zealand.
[γ] School of Engineering and Computer Science, Victoria University of Wellington, Wellington, New Zealand.
[δ] GNS Science, Avalon Research Centre, Lower Hutt, New Zealand.

Abstract

With the increasing size and complexity of geological datasets relating to volcano monitoring and research, effective visualisation can be challenging. Here, we demonstrate the possibilities of volcanic data visualisation utilising virtual reality (VR) and 3D game engine technology to create a robust and adaptable program called VolcanoVR. VolcanoVR can display multiple complex datasets and has been developed to investigate volcanoes in the Taupō Volcanic Zone, New Zealand. To assess the usability and effectiveness of VolcanoVR a study was conducted, involving 33 participants, ranging in education level and previous experience with volcanic data and VR. Results indicate VolcanoVR is easy to use with high immersion ratings and acceptable system usability and mental demand scores, with minor improvements made following the study. Limited variability across user experience levels indicates the program is useable for a broad range of geoscientists. We have made the source code for VolcanoVR freely available so that it can be easily adapted and applied worldwide to a range of different volcanoes and geological settings.

Keywords: Volcanology; Virtual reality; Data visualisation; Taupo Volcanic Zone.

1 Introduction

Many volcanoes around the world are continuously monitored for any potential signs of unrest and impending eruptions, which creates vast volumes of raw complex data that needs to be analysed for volcanic forecasting [Sparks 2003]. Examples of common volcano monitoring methods include (but is not limited to) gas/water chemistry [e.g. Rouwet et al. 2014], earthquake activity [e.g. McNutt and Roman 2015], and satellite monitoring of ground deformation using interferometry [e.g. Poland and Zebker 2022]. Some monitoring techniques such as gas/water chemistry are only physically collected and are often analysed on a weekly to monthly basis [e.g. Werner et al. 2006], while earthquake activity and satellite GPS interferometry on the other hand can be assessed continuously (i.e. a digital reading every second compared to a manual reading every week or month at the same site). With a range of data types and large volumes of data, visualisation of datasets can be tedious, complex, and difficult to transfer between scientific disciplines, monitoring groups and authorities. Visualisation of technical data can be difficult for non-specialists and the general public to understand [Haynes et al. 2007; Leonard et al. 2014; Thompson et al. 2015]. However, effective communication is crucial in times of volcanic unrest as demonstrated by numerous examples where a gap between scientists and the public has resulted in social anxiety and a disconnect and distrust for official information and requested actions [Bretton et al. 2018; Hill et al. 2018; Newhall and Solidum 2018; Longo 2019].

Intuitive and informative visualisation can be difficult to achieve for data science as the target audiences can vary in background and skill level [Leonard et al. 2014]. If the target audience does not have an effective way of understanding data via visualisation, it holds little value to them. Further, if data is not presented in an immersive and engaging way then the message may be lost [e.g. Haynes et al. 2007; Donalek et al. 2014]. Data visualisation appears in many forms, Azzam et al. [2013] state that in order for a dataset to be considered a proper form of data visualisation, three requirements must be met: (1) it must be based on quantitative and/or qualitative data, (2) it must result in a graphical display that is representative of the data, and (3) it must be readable by viewers and supports exploration, analysis, and communication of the subject data. The field of volcanology is a good example of an area where effective visualisation and mental models are crucial for public understanding of hazards [Thompson et al. 2015].

As more complex and voluminous data is created every day by volcanic monitoring centres and research scientists, new ways of communicating volcanic data are required. This data, while available to the public in some cases (e.g. www.geonet.org.nz in New Zealand), can be challenging to interpret and understand without appropriate education levels and context. Here we have developed a new visualisation program called VolcanoVR, which incorporates volcanic data in a 3D interactive environment and is designed for a broad range of potential applications including volcano research, monitoring, and education. Our study utilised the immersive environment of virtual reality (VR) that involves 3D display, stereoscopic, head-tracked displays with hand/body tracking, and binaural sound [Gigante 1993]. VR technology has been recently utilised in many areas of Earth sciences [e.g. Gerloni et al. 2018; Harknett et al. 2022; Pasquaré Mariotto et al. 2022] as it enables users to visualise complex data spatially and in a way that is more understandable than conventional tech-

* finnigan.illsleykemp@vuw.ac.nz

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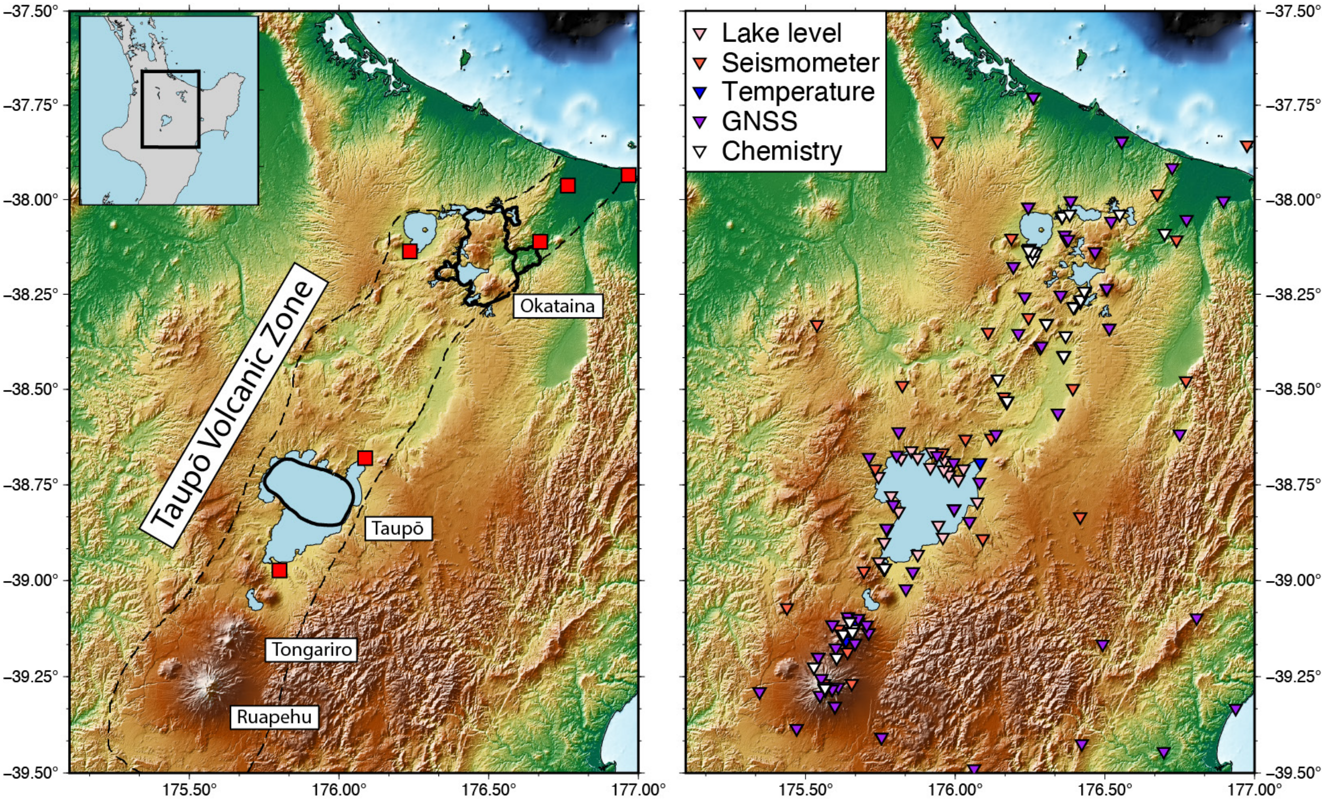

Figure 1: Left: The Taupō Volcanic Zone (TVZ) with major volcanic centres shown. Black lines denote the active caldera volcanoes, Taupō and Okataina. The dashed black line denotes the approximate boundary of the TVZ. Red squares denote major population centres in the TVZ. Right: The locations of repeat measurement sites for volcano monitoring in the TVZ, as of 2024. These sites are managed and monitored by GeoNet and GNS Science.

niques of communication such as 2D cross-sections or static diagrams [Bond and Wightman 2012].

VolcanoVR includes a range of data types including earthquake epicentres, GPS and field measurements, and surface topography and geology, but can incorporate many other datasets. We envisage that VolcanoVR could also be used in education, community outreach, and engagement with a variety of stakeholders. The VR aspect of the program is designed to add extra immersion and spatial awareness of the user to explore a particular volcanic region and its accompanying data. The program was initially designed to be applied to the volcanic centres in the Taupō Volcanic Zone, New Zealand, but it can be easily modified to any geographical area as required. To determine the effectiveness of VolcanoVR, a user study was undertaken to obtain feedback on existing features, implementation of new features, and general usability feedback. Here we describe the design of VolcanoVR and present the results of the user study before discussing the improvements and potential applications of the new program that we have made freely available for use and for adaptation and application in other geological settings.

2 Geological setting for VolcanoVR

2.1 Taupō Volcanic Zone (TVZ)

We designed VolcanoVR for investigating volcanic systems in the Taupō Volcanic Zone (TVZ); a region within the Central North Island of New Zealand that is about 300 km long and 60 km wide (Figure 1), as defined by vent locations and caldera structural boundaries [Wilson et al. 1995; Wilson et al. 2009]. The TVZ is a result of subduction of the Pacific plate beneath the Australian plate causing a zone of extension with volcanism and extremely high heat flow, with numerous active geothermal systems [Bibby et al. 1998]. The TVZ is geographically segmented such that the northern and southern parts of the area primarily erupt andesitic compositions and contain stratovolcanoes [e.g. Ruapehu, Tongariro, Whakaari], and the central section primarily erupts rhyolitic magmas from numerous caldera volcanoes including the most recent active regions of Taupō and Okataina [Wilson et al. 2009]. Numerous historic eruptions have occurred from the stratovolcanoes which frequently show signs of volcanic unrest due to their shallow and active magmatic systems [e.g. Kilgour et al. 2021; Leonard et al. 2021]. In contrast, the most recent volcanic eruption from the central TVZ calderas was the 1886 C.E. Tarawera basaltic fissure eruption [Walker et al. 1984; Sable et al. 2006] and previously the 1314 C.E Kaharoa rhyolitic eruption [Hogg et al. 2003; Nairn et al. 2004], both from Okataina caldera. However, the central TVZ calderas have also experienced recent volcanic unrest including in 2008, 2019 and 2022/2023 at Taupō volcano [Barker et al. 2021; Illsley-Kemp et al. 2021]. One of the challenges with monitoring volcanoes in the central TVZ is the large number of faults and geothermal systems where activity may or may not relate to the active volcanic systems [e.g. McGregor et al. 2022; Muirhead et al. 2022].

2.2 Volcanic monitoring in the TVZ

Currently, volcanic centres in New Zealand are monitored continuously by GeoNet and GNS Science using a range of monitoring techniques including seismometers, GNSS/GPS stations, water/gas chemistry, and temperature sensors (Figure 1B). GeoNet employs a ranked system to quantify unrest or eruptive periods for each monitored volcanic region in New Zealand, known as the Volcanic Alert Level system [Potter et al. 2014; 2018]. This system ranges from 0 to 5 (inclusive), where level 0 is considered to be no unrest or activity at a volcano. Levels 1 to 2 are classed as minor and major unrest respectively. Finally, levels 3 to 5 are classed as different degrees of eruptive activity, ranging from minor to major eruption. These levels can change at any given time and will not necessarily be in order. Active volcanic centres in New Zealand are monitored by GeoNet (Figure 1). Specialists use recorded data from these volcanic centres to make decisions on any changes in alert levels for the volcano, and appropriate stakeholders such as Civil Defence and the National Emergency Management Authority (NEMA) are informed of the changes. The public is also informed of any changes via the GeoNet website itself and posts to various social media platforms. Most monitoring data is provided on the GeoNet website either in raw form or presented in a range of common scientific plots. For example, earthquake data is commonly presented as points on a 2D map showing the epicentre of an event. Here, we have taken advantage of the publicly available monitoring data to visualise the different types of data all in one place using `VolcanoVR`.

3 Methods and materials

3.1 Program design: `VolcanoVR`

The team which designed `VolcanoVR` was primarily composed of volcano scientists who have experience in communicating volcano monitoring data to end-users and stakeholders. It was through this experience that the need for a more intuitive data visualisation tool was identified.

VR technology has increased drastically in popularity, particularly due to the gaming industry driving technological advancements [Cipresso et al. 2018]. `VolcanoVR` was ultimately developed using the `Unity 3D` gaming engine, which provides an environment for constructing 3D scenes and giving functionality by attaching scripts written in the C sharp (`C#`) language to objects in the scene. `Unreal Engine` [Sanders 2016] was also considered as a 3D engine candidate for `VolcanoVR`, but `Unity` was chosen due to easier terrain-based functionality and integration with VR hardware. In addition, the `Unity Engine` (and editor) is free for educational, research, and non-profit uses. There are several VR devices on the market from different companies, of which are varying in price and functionality. `VolcanoVR` was designed with the Oculus Quest 2 and HTC Vive headsets and controllers, which are common and low-cost gaming options. Along with development of the VR version of `VolcanoVR`, a PC version was also developed in tandem to the main VR version. This is to increase accessibility to `VolcanoVR` as not every user will have a VR headset available. During development, newly developed features were transferred from the VR version and adapted to the PC version and keyboard control layout. Note that all screenshots below are taken using the PC version of `VolcanoVR`.

Upon launching `VolcanoVR`, the user is greeted with a main menu which allows the user to select a specific region within the TVZ (defined by latitude/longitude or a predefined region) during a specific time period. This main menu also displays the specific control layout for the host platform the program is running on (Figure 2). Another option for users in the main menu is to load presets with a predefined region and earthquake data for the purposes of examining a certain sequence or unrest period, provided the data is given. The preset menu will load all presets from a folder with the configurations necessary to define the land location and size, along with earthquake data in a CSV table format. Upon selecting a region and time period of data (or selecting a preset), `VolcanoVR` will then load all the data necessary and construct the landscape for examination. There are several steps to this process, where the terrain (at 8 m resolution) and satellite (at 10 m resolution) data are loaded and stitched onto the landscape (Figure 3). Geological data is then loaded using a custom additional `C#` library written for `VolcanoVR` that handles web requests to the GNS servers to request and parse geological data such as earthquakes and field station measurements into a format usable by `VolcanoVR`. Once loaded, the user can navigate the scene by 'flying' around using the VR controllers or keyboard (depending on version) in the direction they are facing. The user can also change map overlays to views other than satellite, which includes elevation/topography data, and the geological map (discussed later).

One of the main features of `VolcanoVR` is to view earthquake data in their true 3D locations in comparison to the map and other earthquake events. These are represented as coloured solid spheres in the exact location of the earthquake event (Figure 4). The spheres are coloured either by magnitude (green to red), or time (yellow to blue), meaning the user can examine earthquake event data through magnitude or time as well as spatially to infer any patterns or structures. Each earthquake can also be interacted with, which shows a window containing the details of the clicked earthquake (time, position, depth, and magnitude). This allows for full data interrogation and detailed exploration. Field data stations (FITS) includes a variety of data types which range from GPS stations to gas/water chemistry measurement stations. Using web requests to GNS FITS web servers, another feature of `VolcanoVR` is the integrated ability to examine data from field stations. The map contains white cylinders with text above them indicating a field station and the name of the site (Figure 3). These cylinders can be interacted with which opens a menu (Figure 5) with options to view/select which data type a station provides, and the time period of which to view data between. Entering no time period will pull all available data for a type from a station. A graph of the data will then appear once a type and timeframe has been entered for examination.

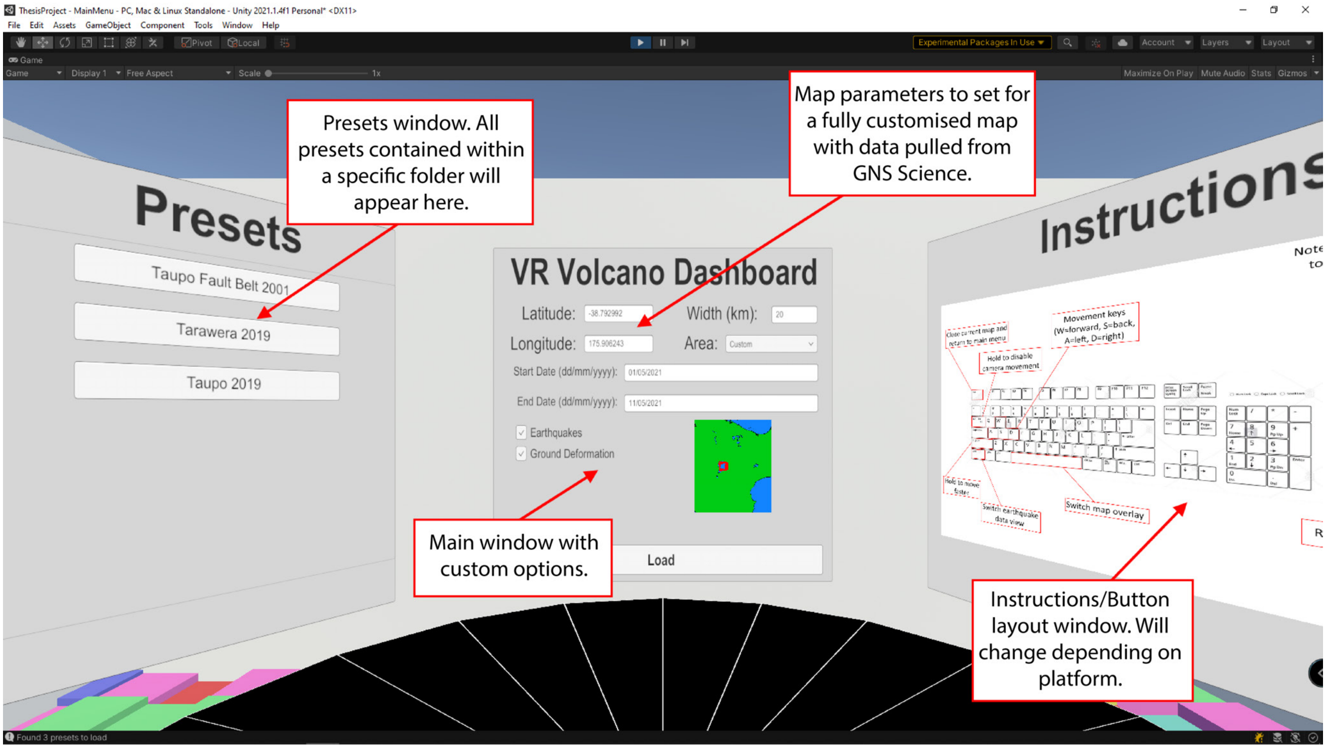

Figure 2: Annotated screenshot of the main window of VolcanoVR that is shown upon launch.

The final major feature of note of VolcanoVR is the ability to view and interact with the geology map of the area. The geology map is accessible by changing the overlay of the landscape to the geology map (Figure 6). VolcanoVR requests the map from the GNS webservers [Rattenbury and Isaac 2012] with a certain bounds reflecting the latitude and longitude of the visible area and downloads this to stitch onto the landscape. What is unique about this overlay is the ability to click any part of the landscape to query the geological (or fault if applicable) information of that point. This data is obtained through another web request to GNS and includes fault data [Langridge et al. 2016] if there is one close to the clicked location. This feature is designed to complement other volcanic data for a more complete picture of the examined region and for research and education purposes.

3.2 User study

The aim of VolcanoVR was to create software which enabled a range of users to investigate volcanic data through a intuitive and immersive experience. In order to evaluate the effectiveness of VolcanoVR, a user study was undertaken, which was used to assess any features that worked well or needs improvement/further suggestions, and inform about the overall usability and task load of VolcanoVR. The study also quantifies user immersion and tutorial effectiveness. Ethics approval for this study was granted by Victoria University of Wellington (application number #0000029559). A total of 33 individual user tests carried out between Victoria University of Wellington and the GNS Science head office in Lower Hutt, Wellington. The tests held at Victoria University were done in a room with access to University VR equipment, and the GNS Science tests were held in the foyer of the building with a portable VR headset and PC. Every test had the same instruction set given to ensure a consistent experience across every participant. Here, the users were asked to load the Taupō unrest sequence of 2019 [Illsley-Kemp et al. 2021] preset and navigate around this scene. The first task was to examine the earthquakes and interact with them. After which, another task was given to examine and explore the FITS data stations, and finally to have a look at the geology map overlay and interact with it. This part took roughly 15 minutes, with the remaining 15 minutes (30 minutes total per test) to fill out the user study.

In the first section of the study, the initial question asked the participant to rate the immersion they feel in the program on a scale from 0 (low immersion) to 5 (high immersion). A follow-up sub-question asked the participant why they gave their score for immersion. The second question asked about tutorial effectiveness, with another follow-up question asking why they gave their answer. The next question asked whether the participant has had any previous VR experience, and if so, how much. The second section was centred around the benefits of the various features of VolcanoVR, or how they could be improved or expanded upon. The next following three questions examined the benefits and disadvantages of seeing earthquakes in a 3D immersive space, viewing FITS data from within the program, and having access to the geological map for cross-comparisons. The final question of this section asked the participant on how much domain knowledge (geology knowledge) they believe a user would need to effectively use VolcanoVR. The third section included the System Usability Scale (SUS) test [Brooke et al. 1996], which asks the participant to rate between 0 and 5 on how much they

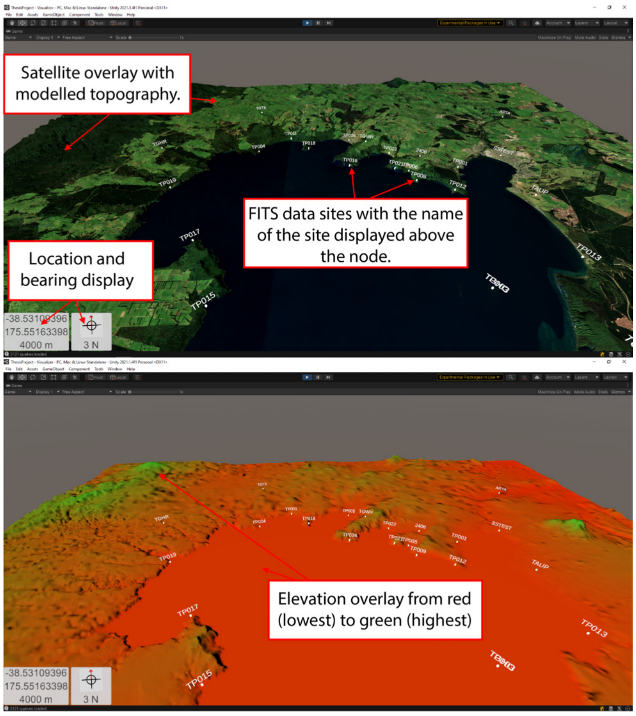

Figure 3: Annotated screenshots of the main view of VolcanoVR, showing the satellite (top) and the elevation overlay (bottom).

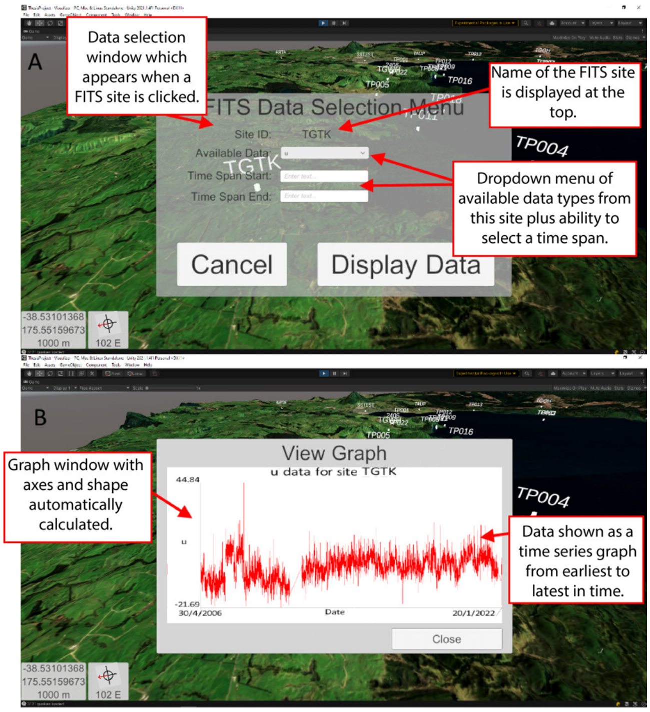

Figure 5: Annotated screenshots of the FITS data selection and data display windows.

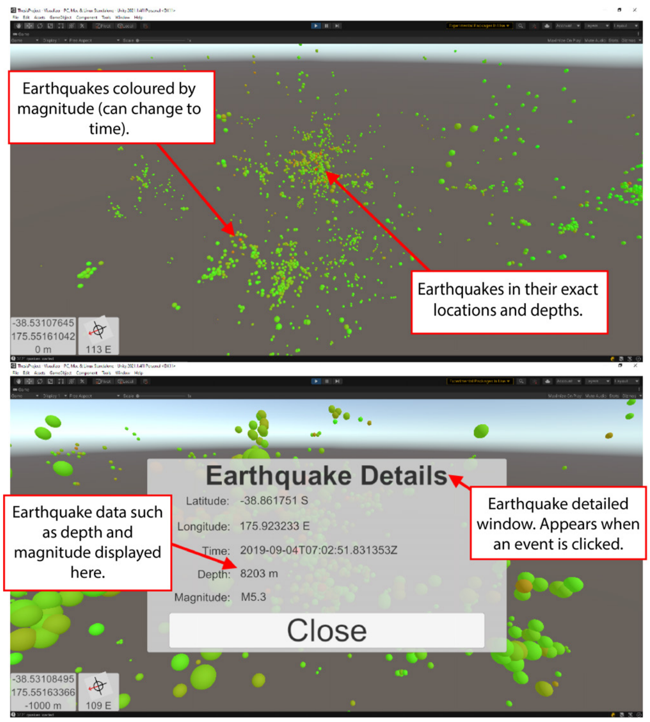

Figure 4: Annotated screenshots showing the earthquakes that can be seen in VolcanoVR and the earthquake details window which appears when an earthquake is clicked.

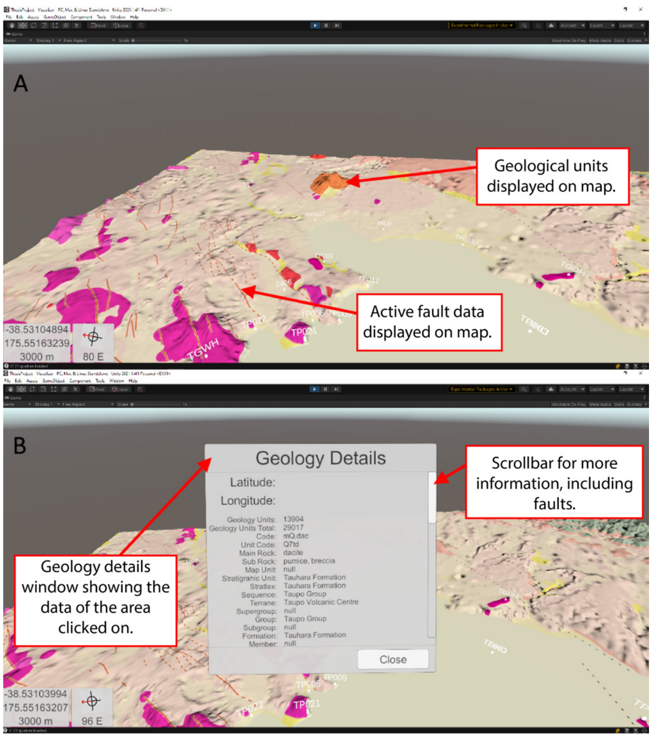

Figure 6: Annotated screenshots of the geology map overlay showing a query of geological information for a particular location. Both geological and fault data are downloaded from the GNS servers [Rattenbury and Isaac 2012; Langridge et al. 2016].

agree or disagree with a series of statements relating to the general usability of the system. The fourth section of questions involved a custom version of the NASA Task Load Index (NASA-TLX) set of questions [Hart and Staveland 1988] which aims to quantify how much effort the user felt in the categories of mental demand, physical demand, time pressure, successfulness, workload, and frustration. The final section involves two questions: one of which is an open-ended question asking for any additional feedback or improvements for VolcanoVR. The final question of this section and of the entire study asked what education level the participant belongs to, out of the options of Undergraduate, Masters, PhD, and Professional/Staff.

4 Results

The education level of the users was split between levels of education and previous experience with VR. From a total of 33 participants, 8 of them were of the Undergraduate education level, 8 were Masters, 7 were PhD, and 10 were Professional/Staff. Education level is an important distinction to assess for any trends and to ensure that VolcanoVR does not rely heavily on user expertise. Of the 33 participants, 12 claimed to have previous experience with VR technologies.

4.1 Immersion

The first question in the study asked participants to quantify immersion felt while in VolcanoVR. Overall, a mean (μ) of 4.09/5.00 and a standard deviation (σ) of 0.78 was scored for immersion (Figure 7A). Immersion scores were split by education level (Figure 7B) and were also split by previous VR experience (Figure 7C). To determine whether there is any statistical significance between immersion ratings and education levels, and whether there is any statistical significance between immersion ratings and previous VR experience, an appropriate statistical test must be carried out. For immersion versus education level, an analysis of variance (ANOVA) test is most appropriate because three or more means need to be tested for significance. The f-statistic obtained from this test was 0.52, which is much lower than the critical value of 2.934 based off the degrees of freedoms and the level of significance of 0.05. Therefore, there is no correlation between immersion rating and education level. For immersion ratings versus previous VR experience, a student's T-test is most appropriate due to having two means to test for significance. From this calculation, a t-value of -0.02 was obtained, which is much lower than the critical value of 2.04 for the same degrees of freedom and level of significance. Therefore, there is no correlation between immersion and previous VR experience. Qualitative feedback for immersion scores varies significantly but is mainly positive. Comments such as "3D perception provides more context" and "easy to navigate and understand" are some of the positive comments given. However, some such as "Quality of the satellite image was poor" and "blurriness and lag made it difficult to be fully immersed" show there is room for improvement to make VolcanoVR more immersive.

4.2 Tutorial

Participants were also asked to rate the tutorial helpfulness (the controller guide in the main menu) and comment on why they gave a particular value. For tutorial ratings, $\mu = 3.36$ and $\sigma = 1.20$ (Figure 7D). This is on average lower than immersion ratings and reflects that there is more room for improvement with the tutorial/guide for VolcanoVR. Tutorial ratings were also split by education level (Figure 7E), and split by previous VR experience (Figure 7F). Like with immersion scores, statistical tests were also done on tutorial ratings to determine whether there is any significance between populations. For tutorial ratings verses education level, another ANOVA test was carried out, resulting in a f-statistic of 0.84, which again is less than the critical value for 2.934 based on the degrees of freedom and level of significance. For tutorial ratings compared with previous VR experience, another T-test was done, resulting in a t-value of 0.19, less than the critical value of 2.04. Both statistical values are less than the critical values, so there is no correlation between tutorial ratings and education level, and no correlation between tutorial ratings and previous VR experience. As with immersion scores, the tutorial ratings also had accompanying comments on what works and what needs improvement. Comments such as "needed to learn with actually using the program" and "might be better to have a more visual explanation" show a simple image showing the controls for the program is not enough, and more information is needed for how to use VolcanoVR. However, some comments showed the tutorial was enough to use the program, for example: "all buttons were put to appropriate actions, very easy" and "very clear, especially for a first-time user". This shows there was a mixed response for the tutorial but that there is room for improvement.

4.3 SUS scores

The System Usability Scale (SUS) test [Brooke et al. 1996; Bangor et al. 2008] was included in the user study to quantify how easy and intuitive it is to use VolcanoVR. A SUS score is a value out of 100 that can be compared to other SUS surveys on a distribution curve. A SUS score on its own is meaningless without comparisons [Lewis 2018]. From this survey we calculated $\mu = 72.93$ and $\sigma = 14.05$ (Figure 7G). A SUS score over 70 is considered a good result, as calculated from a distribution curve of many other SUS surveys for different projects [Brooke et al. 1996]. However, one standard deviation below the mean is below this threshold, meaning there is room for improvement with the user interface (UI) of VolcanoVR. Like with immersion and tutorial ratings, SUS scores were grouped by education level (Figure 7H) and grouped by previous VR experience (Figure 7I). Statistical tests were also done on SUS scores, with another ANOVA test for SUS scores versus education level, and a T-test done for SUS scores versus previous VR experience. For SUS scores against education level, the f-statistic returned from the calculation was 0.99. This again is below the critical value of 2.934 so no claim can be made about the relationship between SUS scores and education levels. For SUS scores compared with previous VR experience, the T-test returned a t-value of 0.00, lower than the critical value of 2.04. No claim can be made about the relationship between SUS scores and previous VR experience either.

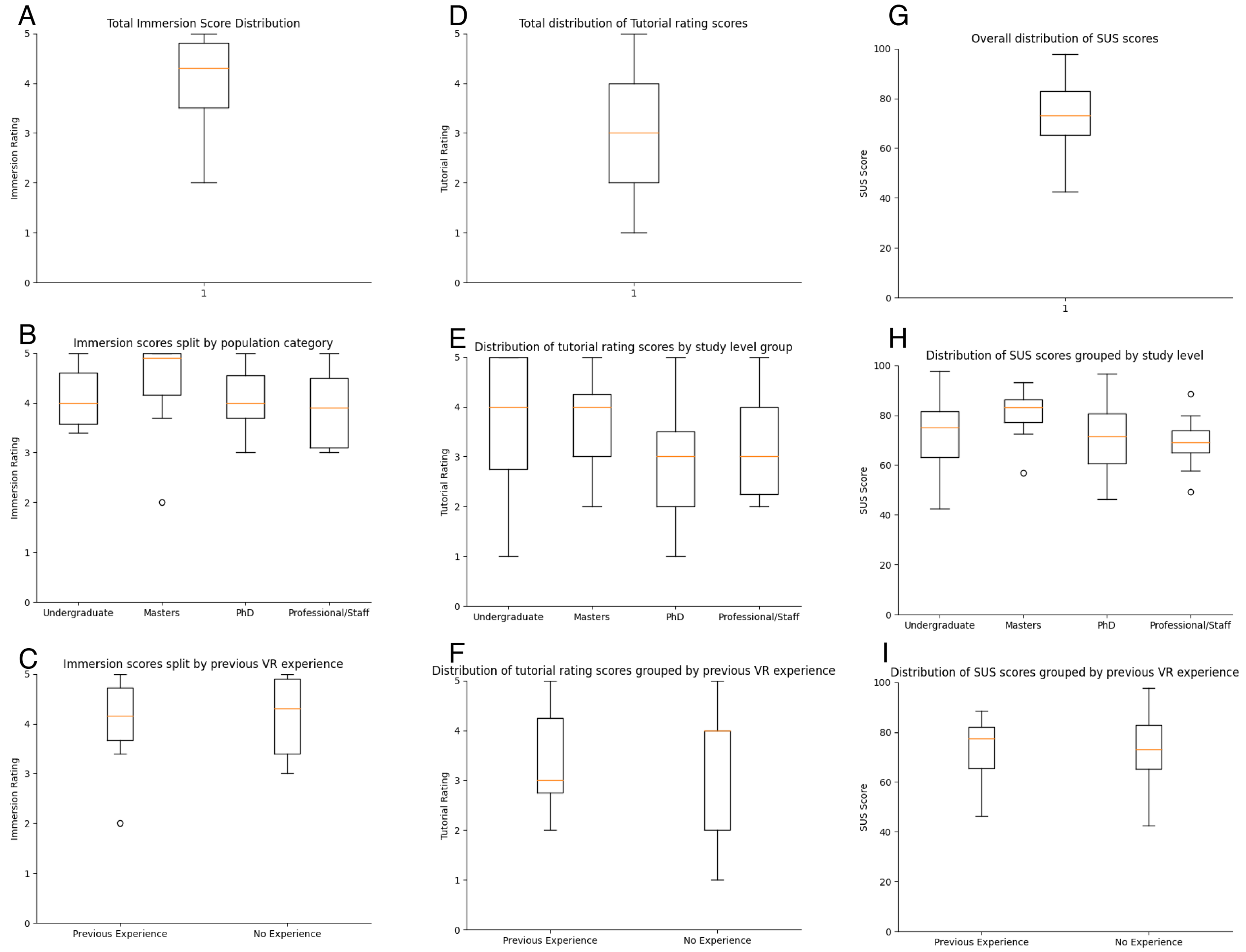

Figure 7: [A]–[C]: Immersion scores by Total, education level, [C]: Previous VR experience. [D]–[F]: Tutorial scores by Total, education level, and Previous VR experience. [G]–[I]: SUS scores by Total, education level, and Previous VR experience.

4.4 NASA-TLX scores

Table 1 lists the means and standard deviations of each category from the NASA-TLX section of the user study. NASA-TLX scores were also split up and compared with education level, as well as being compared with previous VR experience. Statistical tests (ANOVA for education level, T-test for previous VR experience) were computed for each category in the NASA-TLX question set. Table 2 shows the ANOVA tests results from NASA-TLX scores versus education level and whether the null hypothesis (H_0) was accepted, and Table 3 shows the T-test results from NASA-TLX scores versus previous VR experience.

4.5 Qualitative feedback

The bulk of the questions in the user study asked open-ended qualitative questions regarding the different major features currently available in `VolcanoVR`. The study also asked the user to give feedback on how much geology knowledge that would be needed to use the program effectively. Feedback for the earthquake visualisation component of `VolcanoVR` is mainly positive, with helpful comments on how to improve

Table 1: Means and standard deviations of the NASA-TLX results from the `VolcanoVR` user study.

Category	μ	σ
Mental demand	2.08	1.13
Physical demand	1.41	1.19
Time pressure	1.28	1.09
Successfulness	3.37	1.12
Workload	1.27	1.04
Frustration	1.11	1.20

Table 2: ANOVA test results for NASA-TLX results against education level.

Category	f-value	H_0 accepted?
Mental demand	4.26	No
Physical demand	3.10	No
Time pressure	1.63	Yes
Successfulness	1.54	Yes
Workload	1.42	Yes
Frustration	1.25	Yes

Table 3: T-test results for NASA-TLX results against previous VR experience.

Category	t-value	H_0 accepted?
Mental demand	0.12	Yes
Physical demand	−0.37	Yes
Time pressure	−0.35	Yes
Successfulness	0.73	Yes
Workload	−0.27	Yes
Frustration	−0.79	Yes

the features. Some of this feedback includes comments such as "helps understand the 3D relationship with earthquakes" and "much easier to see the earthquakes through space and time". Some suggestions for improvement of this feature includes having the earthquakes appear through time in an animation for further data exploration and understanding, as well as including reference to other structures like faults and the subducting Hikurangi plate to complement earthquake locations. The geology map overlay of `VolcanoVR` was received well, however users pointed out that this feature would be more useful for outreach purposes and to better understand the spatial relationship between geology and fault structures to topography. Users stated that this feature helps to further understand the spatial relationship of the terrain and topographical features in 3D, and "to make geological patterns more recognisable". Feedback for improvements to this feature included suggestions about the possibility for more information to be included on the geological map.

FITS data stations and visualisation was the final major feature of `VolcanoVR` that was included in the user study for feedback. From the feedback, this feature is the one that could use the most improvement and refining to make it more useful and effective at conveying volcanic data, but in general it was received well. Participants pointed out that this feature enables "the ability to get details of a location at the click of a button" and "helps to link data together," showing the FITS data view feature has use. However, some participants have pointed out that "it would be better to make comparisons with other graphs" and "you do not need a fancy program to display a graph, `VolcanoVR` is better at viewing structure instead" showing that the FITS data view feature needs more refining to make it more useful for the average user.

Users have shown from the study that the amount of domain knowledge (geology knowledge) needed to use `VolcanoVR` effectively is minimal, meaning that the program is accessible even to beginners. `VolcanoVR` was said to "provide a multi-level user experience," though some comments suggested "people unfamiliar with VR need time to learn the controls". The user study shows `VolcanoVR` is intuitive for users of all levels of geological experience, however those that are unfamiliar with VR or gaming controllers may take a little longer to adapt.

5 Discussion

5.1 Usability of `VolcanoVR`

Throughout all the statistical tests done with numerical data from the user study, there is no statistical significance between these datasets split between education level and split between previous VR experience. The only exception to this is the mental and physical demand from the NASA-TLX survey split by education level, where a claim can be made that the data is statistically significant between education levels. Here, participants in the Professional/Staff education level rated physical and mental demand higher than any of the other study groups. A possible cause for this is people in the Professional/Staff category tend to be older in age than undergraduate or postgraduate education level members and thus more susceptible to mental and physical fatigue [Egerton et al. 2016] and causing them to rate mental and physical demand higher than usual. This is not a surprising result and is a natural outcome of physically demanding activities.

Common themes and topics stand out from the qualitative feedback provided by the participants during the user study. With the immersion section of the study, the main topics that were mentioned were the program provides sufficient user immersion, but some improvements need to be made to further increase immersion. The positive feedback on immersion is promising, as several studies have shown that an immersive virtual reality environment promotes greater user engagement and understanding of the data [Bayyari and Tudoreanu 2006; Johnston et al. 2018]. However this has limits, and some studies have found that interfaces which incorporate body movements can reduce effectiveness [Andersen et al. 2019].

For the tutorial ratings, the main feedback themes provided were that the button layout proved to be confusing at times, and the instructions could be clearer with an option to review them while viewing a map instead of solely in the main menu of `VolcanoVR`. A future improvement to `VolcanoVR` could be create a more interactive tutorial, such as those that are commonly used in video games [Charsky 2010]. From the study feedback, it is apparent that not much geology knowledge is needed to use the program and benefit from its use, however some is needed to make interpretations and deeply understand the processes at work beneath a volcano. This shows that `VolcanoVR` is suitable for all audiences with at least undergraduate knowledge of geology and can be used for a range of purposes including geological data interpretation for more advanced users, or education for beginners as `VolcanoVR` provides good visualisation of geological data for a given region. In our study we tested against VR experience and education level, but we note that future developments may want to investigate whether the user experience varies by other attributes, such as gender and age.

5.2 Potential uses of `VolcanoVR`

5.2.1 *Monitoring and volcano research*

One of the goals of `VolcanoVR` is to assist with the current existing system used by GNS to examine and interpret volcanic data in the TVZ, which is used to guide decisions on Volcanic Alert Levels that are made by a team of specialists at weekly meetings. The current system used by GNS that is visible and usable by the public is a series of graphs and maps displayed on their website*. VolcanoVR is designed to improve upon this service by providing a 3D perspective of presented data compared with other datasets available online such as earthquakes (Figure 8). In Figure 8, VolcanoVR is contrasted against a current method of visualising earthquakes, showing the 2D cross-section from multiple views and the 3D perspective visualisation of the same earthquake sequence [Illsley-Kemp et al. 2021]. With a 2D cross-section of earthquake locations, it can be harder to determine any spatial patterns or shapes due to the limited angles of 2D cross-sections, compared with the ability to rotate and zoom around a 3D representation of the earthquake locations, thus VolcanoVR improves how data can be interpreted to aid volcano monitoring and research. It is important to note that VolcanoVR accesses the same database as the existing GNS system (the FITS database). However, currently VolcanoVR also displays FITS data as graphs, much like the current GNS system, but from within a virtual world. This means that FITS data between VolcanoVR and the existing system is not displayed any differently, but VolcanoVR provides more locational context and relates the FITS data to other datasets in the program. Further development will be able to change the options for how this data is displayed depending on user needs. We also envisage that VolcanoVR could be enhanced to include three-dimensional geological, geophysical, and conceptual models. This could also include volcanic hazard maps which are frequently produced for multiple stakeholders [e.g. Leonard et al. 2014].

5.2.2 *Education and outreach*

VolcanoVR has already been shown to assist with visualisation of volcanic data for geoscientists, but its potential for outreach and education to the public requires further investigation. VolcanoVR also has the potential to be used in classrooms and university learning environments for further educational and outreach purposes. In particular, the PC version of VolcanoVR has the ability to rapidly provide datasets to students who could use the program and explore volcanic systems. The results of our user study show that VolcanoVR is effective with both undergraduate and postgraduate geoscience students. However, a new round of user tests targeting lower education levels and the general public would be ideal. The potential use of VolcanoVR for virtual field trips is also possible, especially during the height of a global pandemic (i.e. COVID-19) where field trips are limited and restricted. It may also make fieldtrips more accessible for people with physical or financial barriers to participation [McGowan and Alcott 2022]. VolcanoVR provides an overview of the landscape along with geological datasets and the introduction of 360° photos/videos of the area and therefore can be used for an introductory overview of a region which aligns with the purpose of a particular field trip. Several studies have shown that immersive technology can increase student engagement and learning outcomes [Schindler et al. 2017; Nkomo et al. 2021; Yu et al. 2021]. We suggest that VolcanoVR, and software similar to this, could be an effective tool for Earth science education.

*www.geonet.org.nz

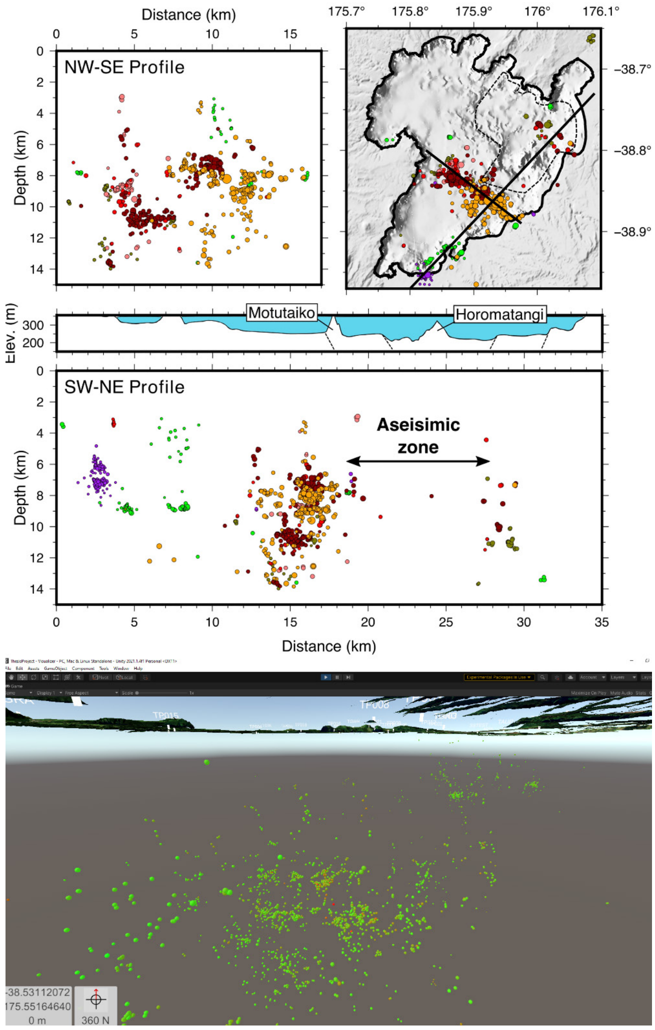

Figure 8: Comparison between the 2019 Taupō earthquake sequence from Illsley-Kemp et al. [2021] (top) and the same sequence viewed in VolcanoVR (bottom).

6 Implementation of VolcanoVR

VolcanoVR was designed for a specific use-case in a particular part of New Zealand. However our hope is that it can serve as a template for similar tools which can be applied to a variety of Earth science challenges worldwide. VolcanoVR was developed to be accessible, utilising free software and relatively cheap, widely available hardware. The main challenge, as with much software, will be ongoing upkeep and support for users.

6.1 Hardware requirements

Implementation of VolcanoVR requires a few steps to get the program running. Firstly, the correct equipment will need to be available for running VolcanoVR. For the VR version, VR headsets are required along with a computer to run the program. The computer which VolcanoVR was developed on has an Intel Core i5 processor 2.9 Ghz, 16 Gb of DDR4 RAM, and a NVIDIA GeForce GTX 1650 graphics processing unit. A PC with these levels of hardware (or equivalent thereof) will run the program smoothly and efficiently. The VR headsets the program was developed on was the Oculus Quest 2 and the HTC Vive. A Steam account is required to access SteamVR and run the program on a VR headset. For the HTC Vive, this is automatically integrated with SteamVR. For the Oculus Quest 2, Oculus AirLink was used to cast the program from the computer to the Oculus headset and to integrate SteamVR features into the Oculus environment. The program was developed and tested using Windows 10 64 bit, compatibility with other operating systems theoretically should work due to the cross-platform nature of `Unity` applications, but have not been tested. `VolcanoVR` has also not been tested with differing levels and brands of computer hardware, and so the minimum requirements for a PC to run this program are unknown. To execute this program, providing all hardware requirements are met, is as simple as launching the executable provided with the program files (an executable file is a file with the .exe extension which is the entry point for a program). The program will start SteamVR and run from VR hardware, providing the VR hardware is set up and configured correctly.

6.2 Adaptation to other volcanic areas

`VolcanoVR` has the potential to be adapted to other volcanic areas around the world, given easy access and availability of volcanic data and a modification of the underlying base program to read and display such datasets. The current TVZ data is accessed using a separate library of functions that use GeoNet's web request tool to retrieve relevant data based on a regional selection. Therefore, it is possible to reprogram and adapt `VolcanoVR` to use a different region (along with satellite and topographical data) and obtain volcanic data from appropriate sources. This expands the potential and relevance of `VolcanoVR` to any volcanic region of the world. However, some work on the program code has to be done to configure `VolcanoVR` to a different area. We have made the source code for `VolcanoVR` freely available*.

7 Conclusion

`VolcanoVR` has proved to be an effective tool for visualisation of volcanic data for a case study in the TVZ, New Zealand. From the results of the user study, immersion ratings scored highly (4.09) and the SUS scored 72.93: an acceptable and usable interface for the program. The qualitative feedback from the user study has also been insightful and helpful to guide the future development of `VolcanoVR`; for example, an improved tutorial. The user study shows that neither previous VR experience or a particular education level are required for `VolcanoVR` to be effective. `VolcanoVR` provides a single immersive environment that contains a broad range of geological data that can be rapidly displayed and compared spatially. `VolcanoVR` has also shown to be useful for university students, postgraduates and geoscience professionals to visualise volcano data, but there is also further potential for outreach and education for non-specialists. `VolcanoVR` can, in principle, be adapted to any location in the world and expanded with any set of data. With further development and adoption, `VolcanoVR` may prove to be highly effective for gaining a better understanding of volcanic systems worldwide and for better communication of volcanic data in general.

*https://gitlab.com/kris91268/volcanovr

Author Contributions

KH led development and design of `VolcanoVR`, performed the user study, interpretation of the data and writing of the manuscript. SJB, FIK and CA assisted with conceptualisation and supervision, advised on the design of the program and user study, analysis of the study results and contributed to writing and editing the manuscript. GL assisted with program design and feedback. CM assisted with data access and software.

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Data Availability

The source code for `VolcanoVR` is publically available at https://gitlab.com/kris91268/volcanovr. `VolcanoVR` uses freely available data from GeoNet at https://www.geonet.org.nz. The earthquake data from Illsley-Kemp et al. [2021] shown in Figures 4 and 8 is available at https://doi.org/10.5281/zenodo.4595831.

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