Advancing the use of immersive VR in geoscience: Virtual landslide fieldwork for research and education

(地球科学における没入型 VR の活用：ランドスライドのバーチャルフィールドワークによる研究と教育展開)

Abdul Azim Muhammad Zulhilmi
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Division of Environmental Science Development
Graduate School of Environmental Science
Hokkaido University, Japan

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Abdul Azim Muhammad Zulhilmi

76225202

Supervisor:

Dr. Yuichi S. Hayakawa

Date:

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Table of contents

List of Figures

List of Tables

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Abstract

Immersive virtual reality (VR) is an emerging technology that is gaining attention in the geoscientific community. While preliminary research has explored its applications, its effective integration into geoscientific practice remains fairly limited. Therefore, to add towards this developing field this thesis examines the current trend of VR technology in geoscience followed by an investigation how fieldwork and lectures can be adapted and enhanced through VR technology, with the goal of contributing to both scientific methodology and educational innovation.

The first objective (Chapter 2) is a bibliometric analysis of VR-related geoscience publications over the past eight years (2016-2024) was conducted to identify research trends, synthesizing the academic consensus for such technology, and to forecast its future use in VR Geoscience. This review highlights a growing interest in VR applications for visualization, education, and communication within geoscience. Following that in Chapter 3, the objective is a case study to explore traditional geological fieldwork methods emulation in VR. Focusing on a small-scale landslide, the study showcases how VR can support interactive analysis of such geological landform specimen and also contribute towards the literatures pertaining such topic from a VR-based perspective. Finally in Chapter 4, the thesis examines the use of VR as a medium for geoscience education. Through an outreach project involving middle school students at an international school, the study assesses the usability and motivational impact of VR-based lectures, suggesting that immersive environments can enhance engagement and comprehension of geoscience content.

VR geoscience is still growing, and this thesis believes the considerable potential of this technology to drive methodological innovation in research and transform geoscience education. To fully harness the potential of VR technology in our science, future research should prioritize the development of diverse, purpose-built tools and frameworks that can support the widespread and effective integration of VR across both scientific investigation and pedagogical practice.

Keywords: *Immersive Virtual Reality, Geoscience, Education, Fieldwork, Systematic Review*

Chapter 1
General Introduction

1.1 Introduction

The geoscience community constantly engages with a vast array of methods and data to better understand our home planet Earth. These tools are essential for addressing the vast array of today's geoenvironmental challenges, and as service, our findings must ultimately be communicated to the public. Effective communication of scientific knowledge is vital not only for societal progress but also for anticipating and solving future geoscience-related issues.

But what is the point of generating knowledge if it gets lost in a sea of miscommunication, public misunderstandings, dry and inaccessible scientific literature, or poor decisions made by the uninformed stakeholders? Perhaps it is time to embrace emerging technologies that can evolve and enhance how we share and interact with scientific information.

Immersive Virtual Reality (VR), a technology that creates interactive, three-dimensional environments that users can explore and engage with offers an interesting prospect to propel the arsenal of geoscientists in communication and research. By making complex geoscientific concepts more tangible and accessible, VR has the potential to bridge the gap between scientists and the public, transforming the way we communicate, educate, and inspire the future generation.

Literature contextualization

Comprehensive reviews examining the current state of immersive VR technology in geoscience remain relatively scarce. Existing literatures tend to focus on specific subfields, with mining-related applications being the most common (e.g., Suh and Jan-won, 2019; Kamran-Pishhesari et al., 2024; Singh et al., 2024; Strzałkowski et al., 2024). Other than that, reviews have already addressed the use of VR in geohazard studies (Havenith et al., 2019) and training environments (Li et al., 2022). Notably, Özyurt et al. (2021) provides one of the few broader reviews covering both geoscience engineering and education.

Beyond review articles, some individual studies have explored immersive VR applications in specific geoscience contexts. These include VR-based fieldwork and data collection (Antoniou et al., 2020; Tibaldi et al., 2020), structural mapping (Harknett et al., 2022), outcrop interpretation (Seers et al., 2022), visualization of dinosaur footprints (Novotny et al., 2019), and the perception of debris flows for early warning systems (Alene et al., 2023).

Further among these thematic areas, educational applications stand out as the most prevalent. Studies have explored a range of innovative approaches, including role-playing simulations for hydrogeological risk management, virtual electrical resistivity tomography, and analog environment training for Mars exploration (De Lorenzis et al., 2022; Graebling et al., 2024; Paige et al., 2024). Others have focused on interactive educational tools, such as immersive databases (Stella et al., 2023; Horota et al., 2024) and simulated geohazard scenarios (Spero et al., 2022; Alene et al., 2024).

1.2 Rationale & Agenda

The main issue as observed from existing literature is the lack of comprehensive study addressing the fundamental use of VR across the broader field of geoscience. Most existing literatures tend to focus on specific subdisciplines, often examining its application within particular industries (mining being a prominent example). Moreover, immersive VR applications towards physical geoscience remains relatively limited which we believe is largely due to limited availability of accessible tools especially since VR is a recent developed technology not intended primarily for geoscientists. This highlights the need for further research initiatives to explore new and diverse applications of VR in geoscience and to expand the horizons for its potential applicability. Finally, while educational studies are relatively common in the wider scheme of VR research and in the geoscience realm, majority of these studies have not explored traditional techniques that are staple in geoscience educational curriculum such as classroom lectures.

Therefore, the agenda of this research is themed around "exploration" aiming to explore the potential of VR technology in Geoscience while contributing towards expanding the currently limited approaches of VR usage in geoscience. The goal of this research is as follows:

- Examine trends of VR technology use in Geoscience
- Explore and showcase how VR can be used to gather geological data for analysis
- Explore and showcase how VR can enhance teaching geoscience concepts

1.3 Thesis structure & Objectives

The structured objective of each chapter is as follows:

Chapter 2 conducts a systematic literature review of current VR application trends in the subdisciplines of Geoscience from 2016 - 2024. In addition, the exploration of its global usage in the field and provide some suggestions and strategies for future works and initiatives for geoscience research and education.

Chapter 3 showcases a different approach of VR application in geoscience by using it as a tool to conduct virtual fieldwork for data collection, analysis, and interpretation instead of the more visualization-based studies.

Chapter 4 introduces the concept and framework of a "VR Lecture" model. The author developed a fast-paced, automated VR lecture and tested it in a middle school setting to evaluate its usability and its impact on student motivation in geoscience education.

Chapter 5 is the general discussion of the thesis discussing topics such as the emerging role of VR technology in geoscience, impacts and innovations of this thesis towards VR geoscience, and limitations of the thesis.

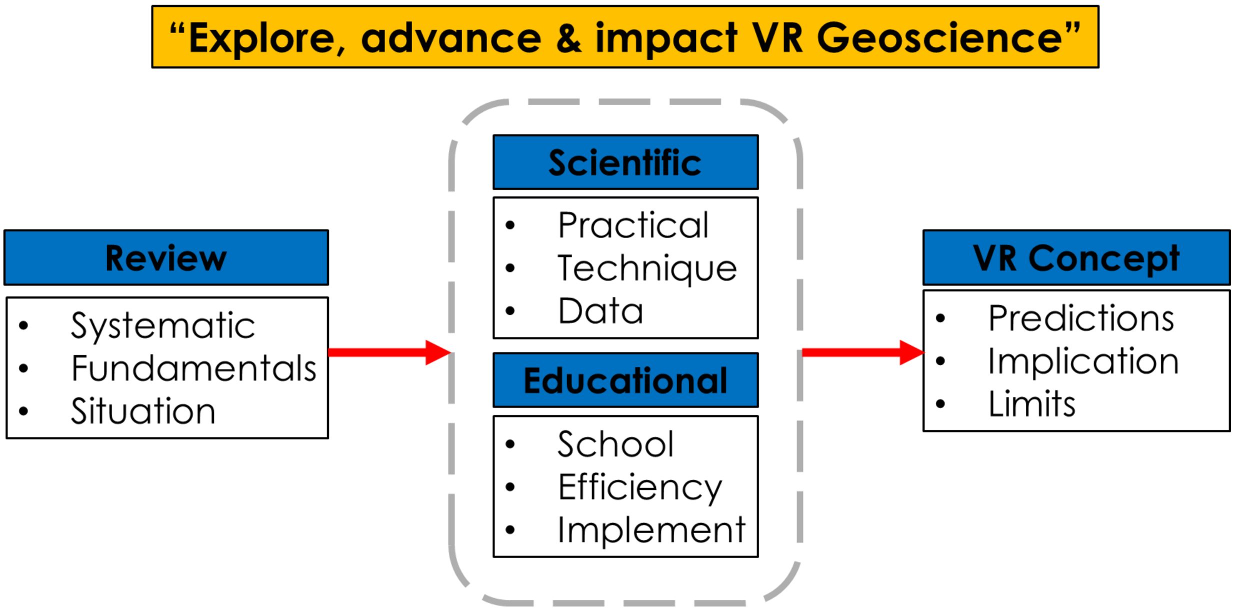

Fig. 1.1 The framework of this thesis

1.4 List of related articles and conferences

1.4.1 Related Articles

- **Zulhilmi, A.**, Hayakawa, Y. S. Immersive Virtual Reality applications trends in the subdisciplines of Geoscience (2016–2024). (Under review at international journal)
- **Zulhilmi, A.**, Hayakawa, Y. S. (2025) Immersive virtual reality fieldwork investigation of a landslide in Hokkaido, Japan. Environmental Earth Sciences, 84, 21. https://doi.org/10.1007/s12665-024-12013-2
- **Zulhilmi, A.**, Hayakawa, Y. S., and Newman, D. R. (2025) Usability and motivational impact of a fast-paced immersive virtual reality lecture on international middle school students in geoscience education, EGUsphere [preprint]. https://doi.org/10.5194/egusphere-2025-129

1.4.2 Related conferences/Meeting activities as the main author

- **Zulhilmi, A.**, Hayakawa, Y.S. and Newman, D. R. (2025.05) Immersive Virtual Reality lecture for Geoscience Education: Usability and Motivational Impact on International Middle School Students. Japan Geoscience Union Meeting 2025, U-15. [2025/05/26-31, JpGU Meeting 2025, Makuhari/Online]
- **Zulhilmi, A.**, Hayakawa, Y.S. (2024) Exploring a Landslide in Hokkaido, Japan: A Virtual Reality Approach. Erasmus+ GeoVT Project Event 2024. [2024/03/05, GeoVT 5th Multiplier Event, Online]
- **Zulhilmi, A.A.M.**, Hayakawa, Y.S. (2024.05) Exploring a co-seismic landslide in Hokkaido, Japan through virtual reality investigation. Japan Geoscience Union Meeting 2024, HGM03-09. [2024/05/26-31, JpGU Meeting 2024, Makuhari/Online]
- **Zulhilmi, A.A.M.**, Hayakawa, Y.S. (2023.10) Exploring Geomorphological Landscapes through Virtual Reality: A Case Study of Landslides in Hokkaido, Japan. Abstract of 2nd International Sustainable Mountain Development and Tourism Conference, 104. [2023/10/06-08, Pokhara, Nepal/Online]

1.4.3 Related conferences/ meeting activities as co-author

- Hayakawa, Y.S., **Zulhilmi, A**., Newman, D. R. (2025) Educational use of VR for physical geography: A trial at an International School. 2025 Spring Meeting of Association of Japanese Geographers, P044. [2025/03/20, AJG Spring Conference 2025]

Chapter 2
Immersive Virtual Reality applications trends in the subdisciplines of Geoscience (2016–2024)

2.1 Introduction

Geosciences have various methods and techniques in their arsenal to visualize and analyze their geoscience data. This ranges from photographs, maps, graphs, field sketches or three-dimensional (3D) models. However, these types of visualization methods have never been able to fully capture the true dimensions of these geological subjects which may lead to misrepresentation or miscommunication of information to those who do not specialize in the field of Geoscience. Immersive Virtual Reality (VR) is such technology that has the capability to solve this problem. VR allows users to enter the virtual space using a head-mounted-display (HMD) and relating controlling input peripherals, which the 3D environment can be interacted with and experienced in an immersive manner. It is part of Extended Reality (XR) which is an umbrella term that comprises VR, Augmented Reality (AR), and Mixed Reality (MR).

VR is a significant technology for Geoscientists because there was never any method that we could use to efficiently visualize our geoscience data in its true 3D form. Instead, we rely on pseudo-3D, which are 3D elements reprojected into a 2D plane (e.g. computer monitor or paper). Additionally, navigation and interaction using these conventional methods is unintuitive and unnatural especially for geoscience examination and observation. Therefore, when handling geoscience data, it is imperative to emphasize on realistic representation especially for effective interpretation and for communication.

In this chapter, we reviewed the current research trends in the past 8 years of VR in the discipline of Geoscience, now termed as VR Geoscience. In particular, the aim is to achieve these research objectives:

- Analyze VR Geoscience publication trends from 2016 to 2024
- Identify and summarize the contributions of VR applications across different geoscientific subdisciplines
- Characterize and define commonly observed research themes
- Synthesize the key findings and mutual conclusions
- Explore and discuss implementation strategies and practical use cases of VR in geoscience education

2.2 Methodology

2.2.1 Search procedure style

The systematic review procedure was conducted using Google Scholar. We chose the starting point of 2016 as this was the year where the first modern VR HMD was released to consumers (i.e. Oculus Rift CV1). The approach is summarized in (Fig. 2.1).

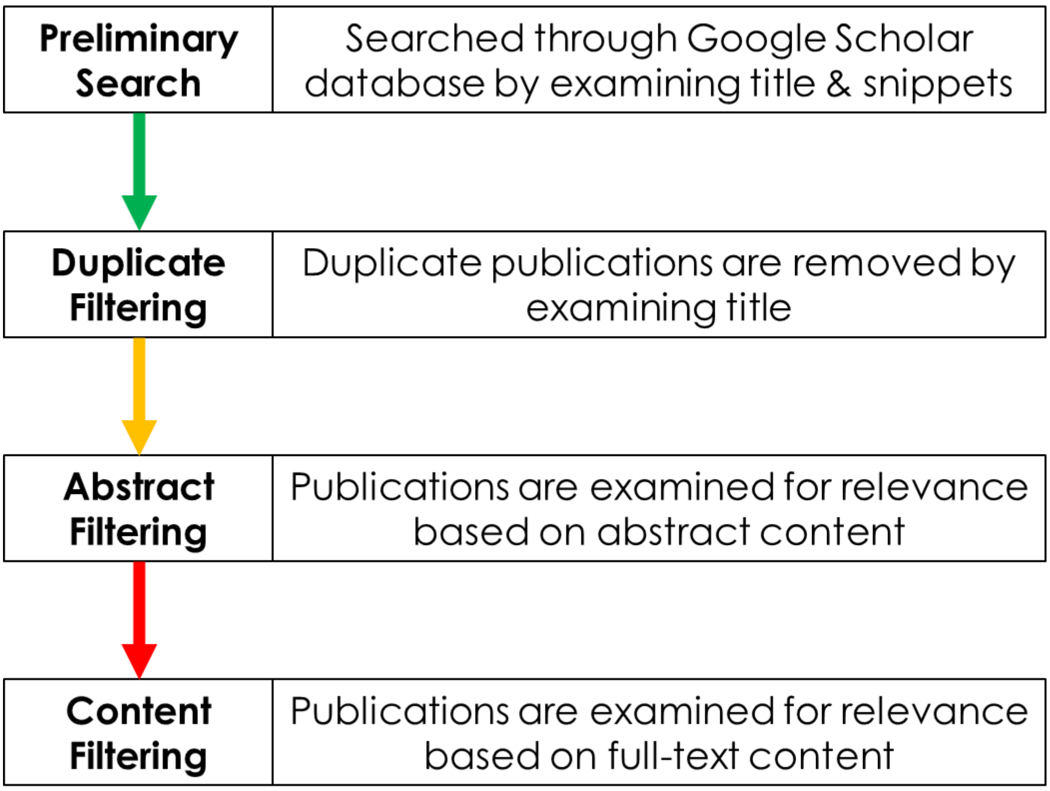

Fig. 2.1 Workflow of this review

We applied the following search string:

(VR OR Immersive Virtual reality) AND BLANK AND (Head mounted display OR HMD)

Where *BLANK* is replaced with the names of Geoscience subdisciplines as stated in (Table 2.1)

The search setting was set to 'sort by relevance' and article type to 'any type'. The time range applied the 'custom range' option and limit the search within each year that we would like to extract articles from (e.g. 2016-2016, 2017-2017, 2024-2024). We conducted the search of the publications on 10th May 2024 for publication the year range 2016-2023 and 16th January 2025 for the year 2024.

The publication types included are: research articles, technical articles, conference articles, review articles, book chapters, abstracts. These publications are focused on immersive VR and excludes AR/MR unless the publication is of hybrid nature.

We categorized the publications based on their subdiscipline following a keyword-based guideline (Table 2.1) informed by common geological course structures, terminologies, and subject divisions typically found in undergraduate curricula. The keywords are followed closely to categorize the publications, but since there are various possible keywords within a given field, the keywords guideline can therefore be associated to or synonymized as long as the meaning of the subdiscipline is approximately maintained.

Table 2.1. Keyword-based guideline for categorization of subdisciplines

Geoscience Subdiscipline	Keywords
Engineering geology	Rock mechanics, construction, tunnelling, planning, equipment, dams, support, schematics

Environmental geology	Geohazard, pollution, sustainability, risk assessment, man-made, natural, remediation, climate change, waste management, hazard management, disaster response
Geomorphology	Landforms, terrestrial features, erosion, weathering
Geophysics	Seismic, subsurface remote sensing, earthquake, well logs, resistivity
Hydrogeology	Groundwater, flow, flood, aquifer
Marine geology	Bathymetry, ocean, submarine landforms
Mineralogy/crystallography	Minerals, crystal, lattice
Mining Geology	Mine, ores, open-pit, underground, mining dust
Palaeontology	Dinosaur, fossil, excavation, fossil site,
Petroleum geology	Petroleum, oil, gas, brine, boundary, industry
Sedimentology/Stratigraphy	Sediment, rock layers, strata, grain size, law of stratigraphy, lithostratigraphy, sedimentary rock
Structural Geology	Faults, tectonics, rock units, deformation history
Volcanology	Volcano, magma, lava, eruption, caldera, ash
Planetary Geology	Planet, moon, mars, extraterrestrial, space

2.2.2 Rationale behind the approach

The rationale for this search procedure is to accommodate the broad scope necessary for synthesizing the current publication activity on Geoscience and VR. However, this broad search may yield a large number of irrelevant results due to the use of broad subdiscipline names as keywords. To mitigate this issue, publication extraction is restricted to the first search results page. This approach is appropriate given that immersive VR applications in Geoscience is relatively recent. Furthermore, it ensures feasibility of the study and promote efficiency allowing for the collection of a substantial number of relevant publications for examination. Additionally, such approach maintains objectivity as a systematic review, supporting the study's repeatability.

2.2.3 Outcome

Using this search procedure, an initial total of 401 publications was collected for filtering. Titles and information snippets were used for a preliminary selection. In the subsequent filtering stage, the removal of duplicates reduced the count to 125 publications. Abstracts were then examined, leading to the exclusion of irrelevant publications, resulting in 100 remaining entries. Finally, a detailed analysis of the full text was conducted, yielding a final selection of 74 publications.

2.3 Results

2.3.1 Publication types

The systematic publication search resulted in a total of 74 publication tally with the identification of 33 journal articles, 17 conference articles, 15 abstracts, 7 review articles, 1 technical note, and 1 book chapter (Fig. 2.2).

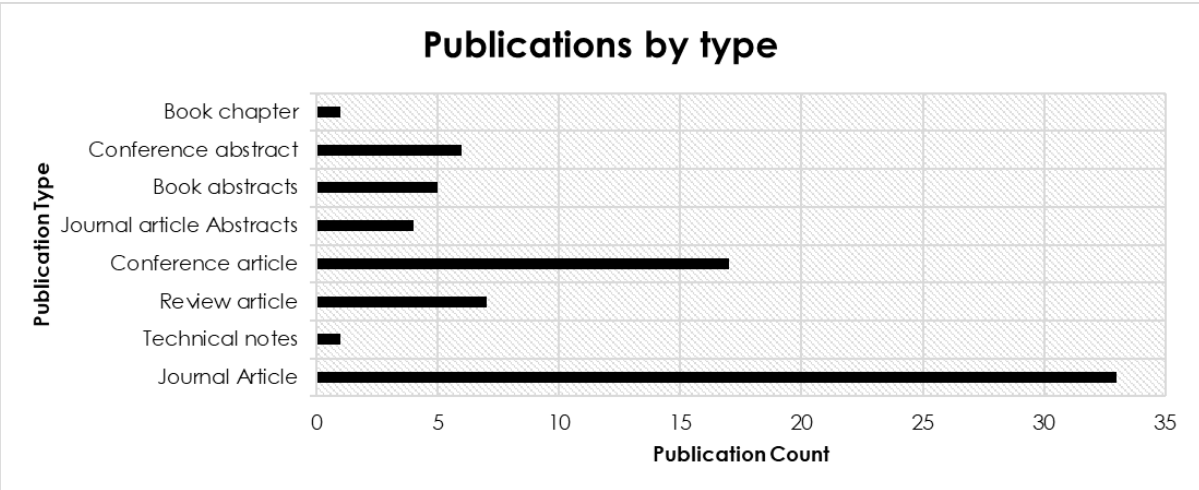

Fig. 2.2 Distribution of publications by type

2.3.2 Publication trends

The distribution of VR Geoscience publications demonstrates an overall upward trend since the introduction of modern consumer VR headsets by Oculus in 2016 (Fig. 2.3). While there are some fluctuations in annual publication (particularly between 2019 and 2021) the limited number of studies makes it difficult to draw strong conclusions about short-term trends.

One possible factor influencing the temporary decline during this period could be the global COVID-19 pandemic, which disrupted research workflows and in-person activities. However, this interpretation remains speculative given the small dataset.

By 2022, publication numbers appear to stabilize, suggesting a return to steady academic interest in the field. Overall, despite remaining a niche area, VR applications in geoscience education and research is gaining gradual momentum.

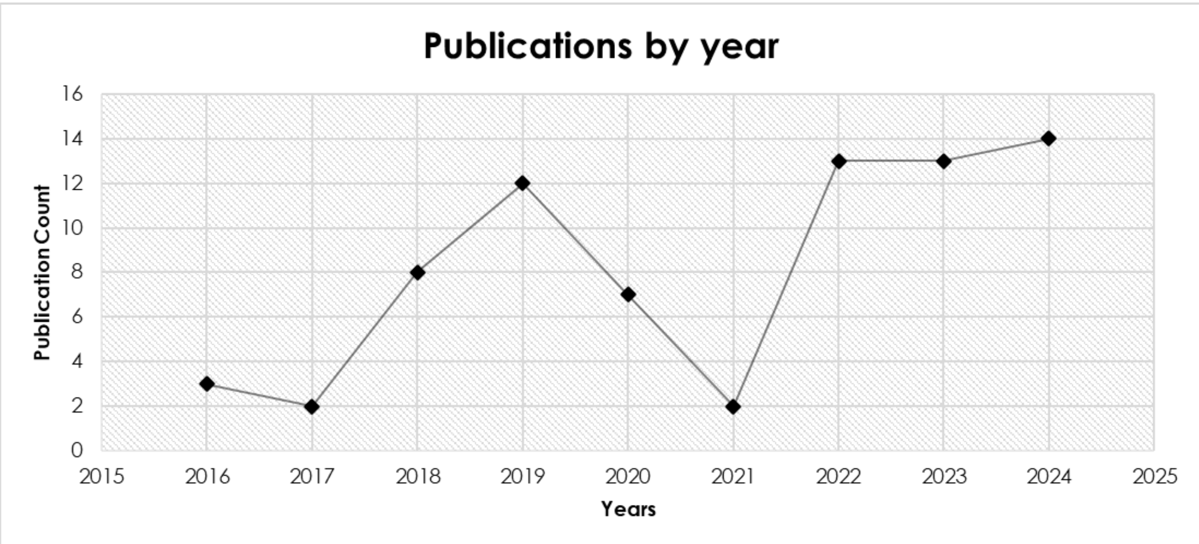

Fig. 2.3 Distribution of VR Geoscience publications by year

2.3.3 Contributions by country

Publications were mainly originating from USA, Italy, England, and China. But in total 23 countries have participated in VR style publications in Geoscience. The classifications are based on each author's affiliation, and they cover Europe, North America, Asia, Oceania and South America (Fig. 2.4).

Referencing the classifications by the International Monetary Fund (2023), the majority of these publications originate from countries of advanced economies, with a smaller proportion from developing economies. This distribution suggests that a country's economic background may perhaps have some influence on the publication output.

Examining closely, we identified that USA was the contributing majority with a publication tally of 19, followed by Italy at 10, England at 9, and China at 8. USA focused on engineering, environmental, physics, mining and palaeontology studies. Italy focused on geomorphology, mineralogy/crystallography, structural, and volcanology. England focused on geomorphology, volcanology, and planetary studies. Finally, China focused on engineering, environmental, mining, and sedimentology/stratigraphy studies. This findings were similar to a review by Özyurt et al. (2021) on VR application in mining engineering, which we also observed that USA and China mainly dominated the field of mining, this is because they are the frontiers of the mining industry (Buchholz, 2020). We speculate perhaps, the high publication count by the USA was in large due to being the pioneer in developing the first modern VR HMD.

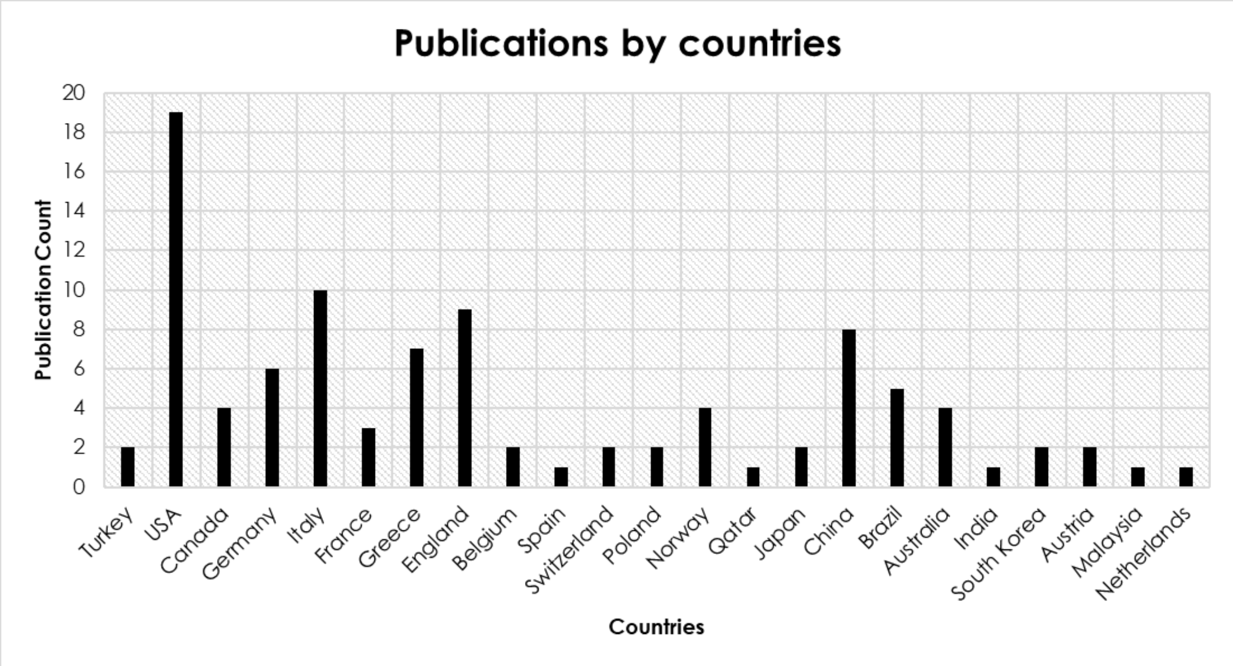

Fig. 2.4 Distribution of VR Geoscience publication by country

2.3.4 Game engine preference

The most preferred game engine was Unity with a count of 33 publications. Unreal engine followed with a total count of 4 publications. Undefined category counted at 38, these are publication types that do not require game engines (e.g., review or abstracts) or those that did not declare their choice in their methodology (Fig. 2.5).

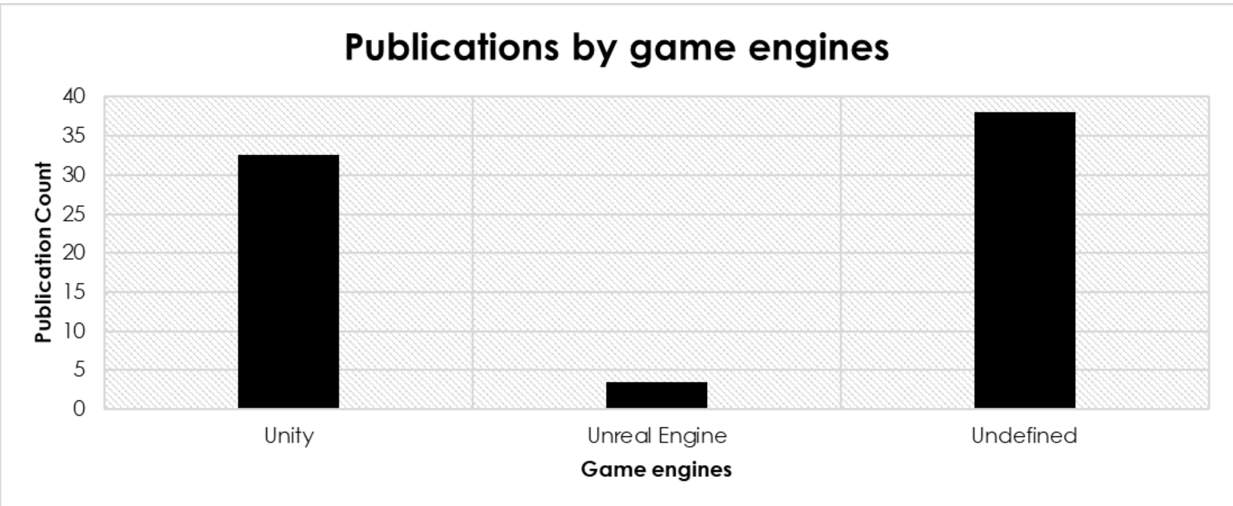

Fig. 2.5 VR Geoscience publication preference on game engines

2.3.5 HMD preference

In terms of VR brand device popularity, Oculus now known as Meta with publication tally of 28 is more popular than HTC at 18. Other niche HMDs from other brands were Pico G3 at 1, Varjo XR3 at 1, Google Cardboard at 2, and Valve Index at 2. However, in terms of the top three preferred HMD type, this was the HTC Vive at 14, followed by Oculus Quest 2/Meta Quest 2 at 9 and Oculus Rift at 13.

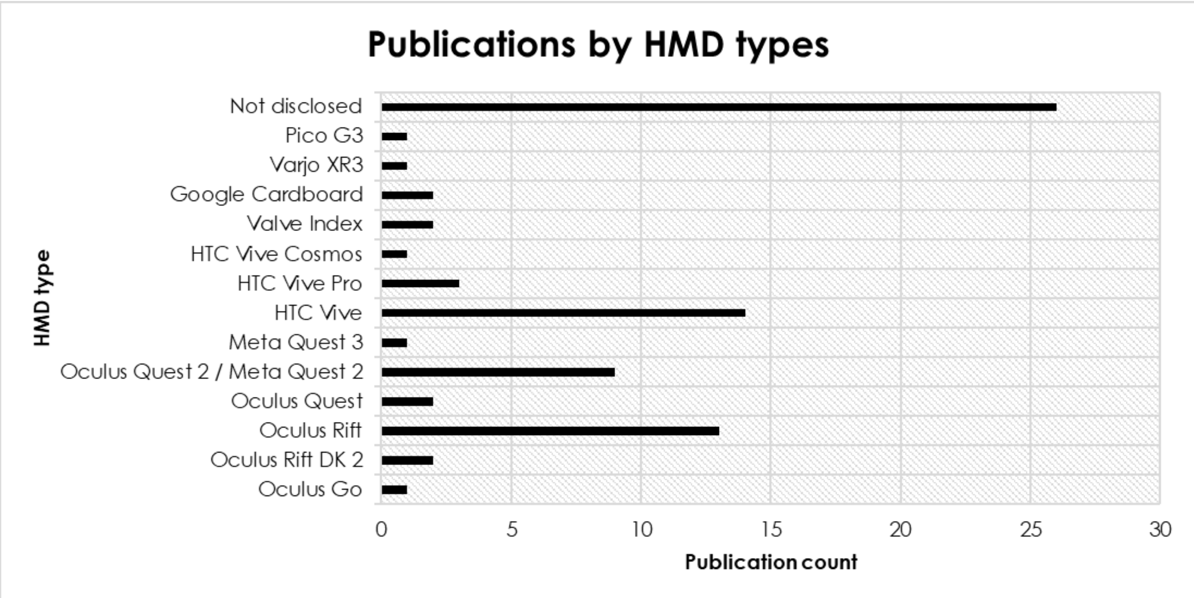

Fig. 2.6 VR Geoscience publication preferences on HMD type

2.3.6 Publication distribution by field

As Geoscience publications are typically of hybrid nature, we have counted approximately 151 subdisciplines from the total publication pool of this review. The Geoscience subdiscipline that have contributed the most is from engineering, environmental, geomorphology, and mining studies. In total there were 14 defined subdisciplines that participated in VR-based publications (Table 2.2).

Table 2.2. *Distribution of publications by field*

Geoscience Subdiscipline	Publication count	Percentage

Engineering geology	24	15.9
Environmental geology	22	14.6
Geomorphology	20	13.2
Geophysics	10	6.6
Hydrogeology	5	3.3
Marine geology	2	1.3
Mineralogy/crystallography	1	0.7
Mining Geology	18	11.9
Palaeontology	6	4.0
Petroleum geology	12	7.9
Planetary Geology	3	2.0
Sedimentology/Stratigraphy	6	4.0
Structural Geology	7	4.6
Volcanology	6	4.0
Undefined	9	6.0

2.3.7 VR's strength and weakness in Geoscience

A comprehensive list of advantages and disadvantages of VR in Geoscience is list in Table 2.3.

Table 2.3. *Advantages of disadvantages for VR*

Advantages	Disadvantages
• Access inaccessible field locations limited by navigational restrictions • Conveys true 3D nature of objects	• VR can be uncomfortable as it can induce motion sickness or can feel cumbersome

• Highly immersive • Enhances interest and engagement • VR objects can be manipulated and interacted • Cost effective solution for geoscience related travel and training • Versatile way to present geoscience content • Spatial freedom and possibility to do things impossible in real life (IRL) • Intuitive and allows human motion • Collaborative tool for geoscientists • Communication capability transcends beyond expertise, language, and culture • Safer alternative to risky fieldwork • Enhances educational approaches • Scalability • Various locomotion capabilities • Multidimensional allows various dimensional data to be integrated into one VR environment • Reduces geoscientist carbon footprint • Portable field experiences	• Expensive hardware to supply large demands, an issue for outreach studies and implementation into industries • Requires a VR-ready computer for more detailed VR experiences • Users require some training before using VR technology • Not currently standardized technology in geoscience • VR experience is dependent on data quality and developer capabilities • Most game engines are not made for geoscientists requiring 3rd party community support • There will always be some realism loss as it is only a simulation • Geoscience data can be large and standalone HMD have issues with their storage • Closed ecosystem of competing companies (e.g. Pico vs Meta)

• Inclusive to handicapped individuals • Develop geoscience skills that cannot be traditionally trained • Simulate geological scenarios unfeasible IRL • Supportive tool for geoscience related management • Bridges communication between different disciplines • Full control of the experience and environment	• Health risk such as long exposure to light, limited external awareness, and physical fatigue • Potential for sensor occlusion and tethered experienced • Tedious VR setup and calibration • VR Geoscience is highly domain dependent • HMD may not fit everyone due to difference in head morphology, inter pupillary distance or age • Privacy concerns such as kinematic fingerprints and data harvesting

2.3.8 VR Geoscience study themes

There are five variation of Geoscience study themes that was observed from the examined publication pool. Below we define them with few examples. We recommend that these terms be standardized to reduce misunderstanding, as this was a factor that posed difficulties when preparing our review and likely for future authors.

VR fieldwork. Defined as a virtual field investigation using immersive VR that is conducted using a digitized twin of a real geological environment with the intention of gathering and analyzing data. Typically, the data is collected using tools within the VR environment where users can interact and manoeuvre with various form of locomotion. An example paper is by Antoniou et al. (2020) and Tibaldi et al. (2020).

VR fieldtrip. Defined as a virtual viewing session using immersive VR that is conducted in a purposed virtual space or digitized replica of a real geological environment with the intention of visualization. Here the main aim is to connect the viewer with the geoscience content allowing for a virtual environment which promotes curiosity and knowledge development. An example paper is Spero et al. (2022) and Harknett et al. (2022).

VR training. Defined as an immersive VR training simulation to teach individuals the skillsets to tackle real geoscience scenarios. Typically, participants would embody a role designated by the simulation and would also receive adaptive feedback on their performance. An example paper is Graebling et al. (2024) and De Lorenzis et al. (2022).

VR data simulation. These are simulation to imitate earth processes using geoscience data in the immersive VR environment. Typically, their VR environment style is of dynamic nature. The intention is to effectively communicate or to make comparisons of the geoscience models to aid the users to better understanding and make informed decisions. An example paper is Alene et al. (2024b) and Li (2023b).

VR education. Defined as a teaching method to teach classroom geoscience concepts within immersive VR environments. Typically, these would include VR environments with a plethora of factual geoscience information and content intended for knowledge transfer. An example paper is Stella et al. (2023) and Horota et al. (2024).

2.4 Discussion

2.4.1 VR Geology subdisciplines contribution summary

There are various geoscience subdisciplines that have applied and published VR related papers (refer Table 2.2). However, their distribution of research output is not the same. It seems that subdisciplines that are highly observable and physical dominate in more practical study theme compared to theoretical ones. This is because VR highly relies on visualization, and those data that can be easily visualized are easily implemented into the VR environment.

Engineering

VR applications in geoscience engineering are widely explored and integrated across various geoscience subdisciplines, including environmental, structural, sedimentology/stratigraphy, geomorphology, geophysics, hydrogeology, mining, and petroleum studies. Spero et al. (2022) and Cartwright et al. (2022) utilized VR for hydrogeology and reservoir engineering, enhancing data visualization and workflow. Some developed VR tools for mining engineering education (Abdelrazeq et al. 2019) and serious game for safety training regarding geological related hazards, incorporating physics-based failure simulations (Liang et al., 2019). Lyu & Wang, (2024) addressed the challenge of visualizing subsurface geological models in 3D, improving engineers' interpretation of traditionally 2D data. Engineering is an example of a theoretical field, and engineering geologist tend to leverage VR by applying it in engineering education, training, or conducting simulations. Likely its wide subdiscipline collaboration pool allowed it to attain the highest publication count, but its focus is mainly on visualization of engineering concepts.

Environmental

In environmental geoscience, VR applications are closely linked to mining, hydrogeology, geomorphology, engineering, and geophysics studies. VR applications enhance training for mining safety (Isleyen & Duzgun, 2019), quick clay hazard awareness (Alene et al., 2024a), and flood risk communication (Skinner, 2020). Remote or fragile environments, such as peatlands (Kalacska et al., 2021) and sand dune environments (UNESCO Geoparks) (Saito et al., 2022), benefit from VR reconstructions using photogrammetry and Light detection and ranging (LiDAR). Uncrewed aerial systems (UAS) based VR visualization aids mine monitoring (Halik & Smaczyński, 2018). Studies like Havenith et al. (2019) and Li et al. (2022a) emphasize VR's role in disaster simulation but also note the lack of collaborative VR platforms for geoscientist. Gerloni et al. (2018) presents a VR platform (ARGO3D) meant for communicating and assessing geo-hazards environments. The overarching trend is the integration of VR and remote sensing to improve hazard mitigation and assessment, education, data visualization, risk communication and accessibility to complex geological environments. As a broad field, environmental studies integrates various geoscience subdisciplines. Current VR applications primarily focus on geohazard assessment, with comparatively less emphasis on resource management and human-environment interactions.

Geomorphology

VR applications in geomorphology is seen to collaborate with structural, volcanology, mining, and environmental studies. Studies have used UAS, LiDAR, and photogrammetry to reconstruct landscapes in VR, such as peatland microtopography (Kalacska et al., 2021), volcanic features (Antoniou et al., 2020; Bonali et al., 2024; Harknett et al., 2022; Tibaldi et al., 2020), and quick clay landslides (Alene et al., 2024a). VR has also been leveraged for hazard awareness, including flood risk communication using real geomorphology data (Skinner, 2020) and geophysical flow visualization (Alene et al., 2024b). Additionally, Horota et al. (2024) developed a VR tool supporting field-based learning through UAS-derived geomorphic datasets of Svalbard. Trend in geomorphology sees VR application mainly in geomorphic field-based research, education, and public engagement/communication. Given the inherently observational nature of geomorphological data, VR integration (especially when combined with aerial remote sensing) holds significant potential and is expected to become a cornerstone of VR-based geoscience studies.

Mining

VR applications in mining primarily focus on education, safety training, and hazard prevention, with observed collaboration with engineering, environmental, and sedimentology/stratigraphy studies. Educational mining tools like VR-Mine (Abdelrazeq et al., 2019; Suppes et al., 2019) and MINING-VIRTUAL (Gürer et al., 2023) was designed for immersive learning. Studies highlight VR's effectiveness in coal mine disaster prevention (Li et al., 2024c) and equipment training (Wang et al., 2022; Xie et al., 2023). Serious games (Liang et al., 2019) and simulations (Bellanca et al., 2019) enhance safety awareness by modelling hazards like mine ventilation issues and proximity risks. VR offer potential for the future of mining in terms of collaboration and broader application range (Stothard, 2023; Suh, 2019). Reviews (Akbulut & Anani, 2023; Strzałkowski et al., 2024) confirm growing VR adoption, while advancements in LiDAR, drones, and VR (Singh et al., 2024) further integrate VR into mine planning and monitoring. The current VR trend in mining is typically on preparing individuals for mining-related scenarios rather than directly facilitating mineral resource extraction. To advance this subdiscipline, further exploration of VR-driven teleoperation of mining equipment for remote mineral extraction is recommended (see Kamran-Pishhesari et al., 2024).

Petroleum

VR applications in petroleum geoscience are closely linked to engineering, physics, and stratigraphy, with a primary focus on simulations, education, and training. Ramos Mota et al. (2016) developed a VR tool for exploratory well placement, noting PC immersive-VR was preferred for independent work while CAVE systems suited collaboration, though training requirements posed adoption challenges. Lidal et al. (2021) and Hinricher et al. (2023) explored VR for well planning and drilling rig control, respectively. Chan et al. (2023) and Aktar et al. (2022) integrated VR with reservoir analytics, finding it more intuitive than conventional methods. In education, Jiménez et al. (2024) demonstrated VR's benefits for subsurface petroleum geoscience especially in improving comprehension and analysis of seismic and core data signifying an enhanced learning experience, while Gonzaga et al. (2018) enhanced outcrop interpretation with MOSIS, a VR fieldwork tool. De Almeida & Miranda (2019) took VR to the molecular level, simulating petroleum reservoir interfaces for enhanced oil recovery research. Notably, numerous usability studies suggest a concerted effort to integrate VR as a tool for petroleum geoscience workflows. However, despite its advantages, industry adoption remains challenged by usability and training concerns. Emerging cross-reality solutions may help bridge this gap, facilitating progress to implementation.

Geophysics

VR applications in geophysics are primarily used for geophysical hazard simulations, education, and training, with a strong emphasis on visually communicating complex geophysical concepts. Seen collaborative geoscience fields include engineering, environmental, marine, structural, and petroleum studies. Alene et al. (2024b) developed a VR framework for realistic geophysical flow simulations, applicable to hazards like avalanches and landslides. Similarly, Maragkou et al. (2023) created VRQuake, an immersive tool for earthquake preparedness training, while Bagher et al. (2020) studied how VR improves students' spatial ability in understanding earthquake cross-sections. For geophysical experimentation, Graebling et al. (2024) introduced VR-EX, a role-playing serious game that combines field trips to teach about electrical resistivity tomography, particularly in nuclear waste disposal research at Mont Terri. In large-scale data visualization, Wang et al. (2020) developed a VR framework for geophysical big data applied to the Mariana Trench. Applications in seismic interpretation include Sousa Dos Santos et al. (2018), who designed a VR prototype for subsurface volume visualization for the oil and gas industry, and Cerfontaine et al. (2016), who integrated various types of geophysical datasets into VR to improve geophysics related workflow through VR manipulation and visualization. In geophysics, VR enhances hazard perception, facilitates interactive learning, and improves geophysical data interpretation. It serves as a powerful tool for visualization and education, making abstract geophysical processes more accessible and engaging.

Structural

Recent studies have explored VR applications in structural studies, ranging from mapping complex geological terrains to interpreting geological features. This field collaborates closely with volcanology, geomorphology, engineering, and geophysics studies. Harknett et al. (2022) and Bonali et al. (2024) used the GeaVR application for structural mapping and exploration in regions like the Husavik Triple Junction and Mt. Etna. Afuso & Matsubara (2019) developed a VR inspection system utilizing UAS photogrammetry to identify structural geological features, while Seers et al. (2022) used Google Tilt Brush for interpreting structural features from geological DOMs. Educational studies, such as that by Klippel et al. (2019), highlighted the effectiveness of VR-based field trips (VRFTs) compared to traditional actual FTs, with VR students achieving better grades and having a more positive learning experience. These findings highlight VR's potential to enhance both geoscience research and education. Structural studies is particularly well-suited for VR integration, as it enables geoscientists to analyze structural features in their natural dimensions, improving spatial understanding and interpretation.

Volcanology

Studies in volcanology are commonly integrating VR and UAS technologies for fieldwork and education, with seen collaborations with structural, geomorphology, mining, and sedimentology studies. Tibaldi et al. (2020) and Antoniou et al. (2020) used UAS and photogrammetry workflows to generate DOMs for volcanic sites such as Dallol Volcano and the Metaxa mine in Santorini, enhancing fieldwork and educational experiences. Additionally, VR and Geographical Information System techniques were integrated to conduct field analysis of these sites. Li (2023b) further advanced the field by creating a VR-based volcanic eruption simulation, combining geological principles and procedural generation to engage educators and researchers. These studies highlight VR and UAS as valuable tools for creating interactive, immersive experiences in volcanological research and education. By offering engaging and accessible alternatives to traditional fieldwork and data visualization, these technologies enhance learning and improve the analysis of volcanic landforms.

Stratigraphy

In stratigraphy, VR geoscience applications collaborate closely with mining, geomorphology, volcanology, engineering, petroleum, structural, and geophysics studies. Lyu & Wang (2024) developed a VR framework for visualizing and interacting with 3D subsurface models, focusing on complex stratigraphy interpreted from sparse borehole data. Similarly, Chen et al. (2022) created a VR tool to illustrate stratigraphic and seismic data, allowing experts to explore the data intuitively through touch handle interaction, which received positive feedback. Masrur et al. (2017) visualized the Penn State Obelisk, a symbolic geological representation of Pennsylvania's stratigraphy, in VR using photogrammetry. This includes querying information about stone blocks and viewing photospheres of their source locations. Existing studies, though limited, highlight VR's potential for interacting with temporal geoscientific data. VR enhances understanding and engagement with complex subsurface models and stratigraphic history, particularly through virtual field trips (VFT) and immersive visualizations.

Palaeontology

Several studies have highlighted VR applications in paleontology, primarily for education and site preservation. This field remains relatively isolated, with notable synergies mainly in environmental studies, particularly in conservation efforts. Samuelson et al. (2023) designed a VR/AR-based palaeontology course for biology students, aiming to bridge knowledge gaps in higher education, while Novotny et al. (2019) used VR visualization to analyze dinosaur footprint formation in malleable substrate, promoting students' learning through creativity. Feldman et al. (2016) combined VR with digital techniques to create cinematic content for educational outreach, showcasing the reconstruction of the Dreadnoughtus Schrani dinosaur. In site preservation, Reinoso-Gordo et al. (2020) used UAS photogrammetry to recreate paleontological sites in VR, enabling field visits without damage to remains, while Papadopoulou et al. (2022) mapped geological monuments containing various fossil sites at Lesvos Geopark using different cartographic scales. Additionally, Almeida et al. (2023) employed VR and photogrammetry to allow interaction with fossil specimens in an application called Mosis LAB. VR enhances educational experiences by providing immersive learning environments while also aiding in the preservation and simulation of paleontological sites, ensuring accessibility and long-term study opportunities.

Hydrogeology

Few studies highlight VR applications in hydrogeology, particularly in training, risk management, and public awareness. De Lorenzis et al. (2022) developed a VR training system for first responders, focusing on hydrogeological risk management, with positive results in engagement and attention. Similarly, Alene et al. (2024a) created the "QuickAware" VR tool to raise awareness about quick clay landslides, a geohazard which are influenced by groundwater movement, providing users to observe a simulation of the geohazards and learn about its background through showcase like displays receiving positive feedback from users. Kalacska et al. (2021) visualized the Mer Bleue peatland using UAS LiDAR and photogrammetry in VR, allowing for comparison of their hydrogeological datasets. VR plays a dual role in hydrogeology, which is educating and training users on complex hydrogeological phenomena while enhancing knowledge dissemination through immersive VFTs. These applications improve engagement and accessibility, making hydrogeological concepts more interactive and comprehensible.

Planetary

Surprisingly, only few studies have explored modern VR applications in planetary studies since 2016, with notable use in simulations and VFTs. Ortner et al. (2018) used Pro3D VR to visualize Yellowknife Bay on Mars, enabling users to navigate and measure geological features. On the other hand, Paige et al. (2024) tested VR's operational usefulness by Svalbard geological terrains as a Martian analogue, focusing on scale perception, pattern identification, and geological context, identifying how VR outperformed desktop methods, except for feature identification. In the realm of planetary data analysis, Miles & Jones (2024) developed a VR toolkit that allowed users to measure and annotate data, with participants feeling more inspired and connected to the environment. Current applications primarily enhance geological tasks, data interpretation, and training for planetary geological scenarios. As space travel remains costly and time-intensive, VR in planetary studies is likely to evolve toward more exploratory studies, leveraging remotely sensed space data to simulate extraterrestrial environments and improve research accessibility.

Marine

Marine geoscience related studies has seen limited VR applications, primarily focusing on data simulations and VFTs for exploring submarine landforms. Lütjens et al. (2019) directly applied VR to marine geology, visualizing the Canada fjord Clyde Inlet using Digital Elevation Models and marine bathymetric data, with participants finding the application easy to use. This study highlights VR’s potential in marine geological exploration. While not primarily focused on marine geology, Wang et al. (2020) explored VR in geophysical data visualization, specifically in the Mariana Trench, making it relevant to marine geophysics. VR in marine geoscience is mainly used for visualizing marine environments and interpreting marine geophysical data. Given its parallels with geomorphology, VR has strong potential for enhancing the study of submarine landforms through marine remote sensing techniques. Future research could expand its use in exploratory case studies, improving underwater geoscience investigations.

Mineralogy and Crystallography

Mineralogy and crystallography have seen minimal VR applications, with only one publication focused on education. Stella et al. (2023) developed a VR educational application for crystallography, allowing students to explore crystallographic structures through a 3D library and recorded online lectures. The application received positive feedback regarding its usability, comfort, and engagement, indicating that VR can significantly enhance the learning experience even in fields that are difficult to visualize in 3D like crystallography. By providing an interactive and immersive environment, the tool helps students better visualize complex theoretical structures, potentially improving their understanding compared to traditional methods. These fields are challenging to visualize, as many concepts are only observable at the microscopic level or imagined in theory. Given this inherent limitation, it is unsurprising that VR publications in this area are currently scarce. However, VR has the potential to enhance the teaching of these otherwise invisible concepts more effectively than traditional methods. Future efforts should aim to leverage VR to improve understanding and engagement in mineralogy and crystallography education.

2.4.2 Mutual conclusions between VR Geoscience publications

The use of VR technology in geoscience shows that it is a highly effective tool for education, training, and communication. For education, VR aids users to learn complex 3D geoscience concepts that requires spatial literacy and 3D imagination. It also acts as a medium for knowledge dissemination, specializing on immersive experiential learning that provides users the sense of ownership of their experience which highly motivates learning. Such experience, enhances knowledge recall and data comprehension. Currently, there is a majority preference for the Unity game engine and the Meta HMDs (Fig. 2.5 & Fig. 2.6). Finally, the vast user study conducted tend to result in a positive attitude by participants and excelled when compared to conventional methods. This is indicative of the public's current receptiveness of the VR technology application in geoscience.

2.4.3 Evaluation of current trends in VR Geoscience publications

Current trends in VR Geoscience publications emphasize prototyping applications and tools due to the absence of dedicated, universally accepted software for geoscience applications. As a result, most developments remain fragmented, tailored to specific research objectives. This focus on prototyping suggests that VR Geoscience is still in its early stages, with most researchers falling into the innovators and early adopters category based on Rogers (2023) theory of Diffusion of Innovations. Moving forward, standardizing workflows and increasing public exposure to VR Geoscience could help accelerate its adoption and development.

A common methodology deployed to reconstruct a digital twin of a geological subjects is mainly through photogrammetry. Perhaps this method is preferred, because it is already well engrained methodology in geoscience research, affordable and an accessible dataset which closely replicate the morphology of a geological subject while providing photorealistic textures. Albeit there will be some limitations to have a full one to one replication. There are already some potential alternatives such as Neural Radiance Fields (Mildenhall et al., 2020), NVIDIA Neuralangelo (Li et al., 2023d), and Gaussian Splatting (Kerbl et al., 2023) which are potential avenues for further application in VR Geoscience.

Fieldwork-intensive subdisciplines, such as environmental, mining, geomorphology, volcanology, structural, planetary, sedimentology, marine, paleontology, and hydrogeology, are inherently physical and visual. Their environments can be digitally replicated via photogrammetry or manual generation, as seen in geohazard models like landslides and floods. In contrast, theoretical subdisciplines like engineering, geophysics, geochemistry, and mineralogy focus on training, education, and data simulations, as their abstract nature requires more manual visualization efforts.

Most VR Geoscience publications focus on social studies rather than technical applications due to limited tools for in-depth investigations and VR's primary strength in immersive visualization. Unlike GIS, which has undergone years of development, VR is still emerging and requires further refinement. Currently, Geoscientists use VR mainly for data visualization and public communication, providing opportunities to test prototypes for future applications. Advancing creative visualization techniques and applying VR in inaccessible regions for fieldwork and exploration could enhance its technical potential.

2.4.4 Adoption Barriers

Understanding the potential for the mass adoption of VR in geoscience requires first identifying the barriers that hinder its integration. The most common challenges are outlined below, with a comprehensive list provided in Table 2.3.

Discomfort is among the most frequently reported issues. This includes motion sickness, often referred to as cybersickness or VR sickness, which occurs when the brain experiences a sensory mismatch between visual perception and physical reality. Symptoms such as nausea, dizziness, and general discomfort can create a negative first impression for new users, posing a significant adoption barrier (Alene et al., 2024a; Jiménez et al., 2024; Skinner, 2020; Stella et al., 2023). Additionally, the weight and bulkiness of current VR HMDs contribute to user discomfort, particularly during extended sessions. This is especially problematic for time-intensive applications such as VR-based fieldwork and training. Addressing this challenge remains a major focus in VR development, with ongoing efforts to reduce HMD size and weight.

Reluctance to adoption is another challenge, particularly in geoscience industries where established workflows rely on industry-standard software and methodologies developed over many years for desktop environments. VR technology has not yet achieved the same level of technological maturity, particularly in Geoscience, where its applications remain niche. While some VR tools for geoscience research exist, they are largely in the prototyping stage. The current landscape is fragmented, non-cohesive, and lacks standardization, limiting broader adoption.

Inaccessibility presents further barriers, particularly in terms of cost and required expertise. VR relies on the availability of both VR HMDs and compatible high-performance computers, which can be costly, especially for large-scale implementation across departments. Likely, researchers may face logistical challenges for user-based studies, requiring participants to share HMDs or having to conduct multi-day studies due to limited HMD availability. Additionally, VR Geoscience is an inherently interdisciplinary field, requiring expertise in Geoscience, computer programming, and digital arts. Individuals must either possess skills in all three domains or outsource expertise, introducing potential challenges in cross-disciplinary communication. Effective collaboration between geoscientist, VR developers, and artists is essential to ensure that project objectives align with domain-specific requirements.

Domain dependency further influences VR adoption, as its applicability varies across geoscience subdisciplines. Physical subdisciplines, such as field geology, are well-suited to VR applications in fieldwork and VFTs. In contrast, disciplines such as geochemistry, which lack inherent spatial components, face greater challenges in integrating VR. For these fields, VR applications are often limited to specific themes such as education and training, where manual 3D modelling is required to visualize abstract concepts, necessitating additional expertise.

2.4.5 Strategies for implementation in Geoscience Education

The prevailing consensus in current research is that VR is a valuable tool for geoscience education. As such, the geoscience community should actively integrate VR technology to enhance the communication of geoscience concepts and provide students with broader, more immersive learning experiences. This approach has the potential to contribute to the development of the next generation of geoscientists by expanding access to global geological environments and fostering a deeper understanding of complex geological processes.

We list here some strategies:

- Designate budget for VR technology (consider sharing devices to keep cost low)
- Prioritize implementing standalone VR (once established introduce PC immersive-VR)
- Implement VR for middle school students and above (as HMD large and heavy for children)
- Establish training modules for staff and students to familiarize with the VR technology (early stage implementation is important).
- Repeated exposure to identify and refine the VR implementation in the classroom
- Hybrid format should be firstly implemented where teacher combines traditional teaching methods with VR to discuss difficult 3D concepts
- Systematic VR usage is important especially with clear learning outcomes and intention
- The VR experience should contain clear instructions and guidance
- Design the immersive experience while leveraging content perception and interaction

- Optimize as much as possible to reduce motion sickness and increase immersion
- Collaborate with the art department or teacher to build VR experiences for the students

Use cases:

- Preparation of students before going for field expeditions (e.g. safety, geoscience content, background)
- Training on using geoscience equipment
- Explaining complex geoscience concepts (e.g. plotting stereonets, subsurface data)
- Expose students to global geological environments
- Simulate geological scenarios that teaches students skillsets (e.g. adaptive geohazard scenarios, disaster response)

2.4.6 Suggestion for VR Geoscience

VR in geoscience should primarily focus on education and communication, as current applications remain limited in technical approaches. The lack of standardized tools hinders further advancements, and VR in geoscience is still in its early stages. To address this, geoscientists should actively attempt to integrate VR technology into their workflow, fostering awareness within the scientific community. Additionally, there should be continuous initiatives for prototyping to establish the necessary technical foundations. Future research can explore underrepresented subdisciplines (Table 2.2) by drawing inspiration from more established fields. While non-visual and theoretical geoscience subfields may lean toward social studies, visual and physical subfields should prioritize the development of technical applications.

A review of existing literature reveals inconsistencies in terminology. The term "virtual reality" is frequently used without specifying whether it refers to immersive, semi-immersive, or non-immersive experiences. We recommend that future studies explicitly state "immersive VR" in their titles when discussing HMD based VR works to enhance clarity. Additionally, as noted by Douglass-Bonner et al. (2024), much of the research has emphasized graphical fidelity and technical applications, often neglecting human-centered design. This presents an opportunity for further research, as user experience is crucial for the foundation.

Future VR applications could try extending beyond static 3D models generated through photogrammetry and LiDAR. Instead, practitioners should leverage various visualization methods, such as 360-degree photospheres (e.g. Barbagallo et al. 2024), spatial audios, panoramas, videos, and interactive media. Another underexplored aspect is VR’s potential for collaboration. Despite being cited as a key strength, few studies have addressed this area. Flatken et al. (2024), Havenith et al. (2019), and Li et al. (2022a) also highlighted the absence of collaborative VR platforms, suggesting this as a promising avenue for further research.

VR-based field trips and fieldwork applications have been well received for educational and communicative purposes (Moysey & Lazar, 2019; Yoon et al., 2022). These implementations could further incorporate creative learning elements, as demonstrated by Hyde et al. (2018), who developed an application allowing live editing. Moreover, platforms like “VROffice” (Rossa et al., 2019) and the Virtual Geology Learning Toolbox (Cho & Clary, 2020) demonstrate how VR enhances geological data visualization, improves fieldwork experiences, and increases student engagement (Bernardes et al., 2018).

Although technical applications are desirable, VR struggles to compete with well-established desktop software that has undergone years of refinement. Additionally, the lack of in-house expertise in application and hardware development forces geoscientists to rely on external expertise. Unless a VR tool emerges with capabilities comparable to established software such as GIS, VR is likely to remain niche within geoscience, primarily serving educational purposes.

However, this should not discourage technical advancements, and research should continue despite the current limitations in tool availability.

2.5 Conclusions

In conclusion, while VR remains a niche subject in Geoscience, publication trends indicate a positive trajectory, with an increasing number of studies emerging each year. Various Geoscience subdisciplines have contributed to VR Geoscience, though their focus is largely domain dependent. At present, research in this field is predominantly oriented toward social and educational applications rather than technical advancements. This trend reflects the early-stage development of VR Geoscience, as evidenced by the prevalence of prototyping studies. However, the widespread focus on social studies suggests that VR has been extensively tested as a communication tool. Moving forward, research should explore strategies for effectively integrating VR into geoscience education to support the development of future geoscientists. Additionally, future studies should address the existing limitations of VR as challenges to overcome while leveraging its demonstrated strengths.

The author strongly believe that VR represents a promising new type of dataset for geoscience, offering significant potential for exploration and communication. However, further development is needed to refine its internal architecture and establish standardized methodologies. VR Geoscience is an interdisciplinary field, blending art, computing, and geosciences, necessitating a hybrid skill set. While technological advancements largely depend on experts from the computing and engineering fields, geoscientists still play a crucial role in shaping its implementation. Importantly, we can explore ways to better equip the next generation of geoscientists, providing them with experiences and insights that were previously inaccessible to prior generations of geoscientists.

Chapter 3
Immersive virtual reality fieldwork investigation of a landslide in Hokkaido, Japan

3.1 Introduction

Landslides are complex three-dimensional (3D) geological phenomena that necessitate a multidisciplinary perspective taking insights from various fields such as geology, hydrology, geography, and engineering. To have a well-rounded understanding of the intricate interplay of the mechanisms that contribute, control, and shape the creation and evolution of landslides requires a comprehensive holistic approach (Lissak et al. 2020). Immersive Virtual Reality (VR) emerges as a transformative tool that may have substantial potential for making significant contributions to geosciences. It stands to become an invaluable new asset in the arsenal of a geologist, offering a unique and immersive perspective that has the capacity to enhance various aspects of geological studies. VR is defined as a computer-generated immersive and interactive environment that simulates a realistic 3D experience that can be accessed by using a VR head-mounted display (HMD) and the respective input peripherals. In the industry, it is part of the broader concept, known as Extended Reality (XR) or spatial computing, alongside Augmented Reality (AR) and Mixed Reality (MR).

Modern VR predominantly serves the entertainment industry, where it originated with the 2011 Oculus Rift prototype by Palmer Luckey. Most VR innovations still arise from the entertainment industry and later extend to fields like healthcare, education, and military. Despite being in its infancy, VR adoption is growing rapidly; Alsop (2023) reported a rise in VR headset shipments from 4.46 million in 2019 to 14.19 million in 2022. Emerging technologies, such as biometric sensors to interact with virtual objects includes brain-computer interfaces (mind-based control), olfactory devices (smell), and biosensing gloves (feel), aim to enhance user immersion (Demolder et al. 2021; Kim et al. 2021; Liu et al. 2023). These advances hint at promising applications in geoscientific disaster research and education.

3.1.1 Literature review

In terms of adoption within academia, there have been academic activities that have already begun using VR as a platform for knowledge dissemination (e.g., 1st International Symposium 2022: The Metaverse and XR Technology – Educational Applications and International Collaboration; VRC Science assembly; 2nd International Mountain Development and Tourism Conference 2023; GeoVT Multiplier Event). These are all stylized in the form of VR oral presentations and poster sessions attended by a diverse group of audiences from all over the world.

Few studies have applied VR in geological disaster contexts. Spero et al. (2022) used VR to simulate the 1976 Teton Dam failure, combining hydrogeologic modeling and VR for flood visualization. Skinner (2020) developed “Flash Flood!” to engage the public using real geomorphology data. De Lorenzis et al. (2022) created a VR Training System for first responders, offering realistic scenarios for hydrogeological risk management.

For earthquake disasters, Feng et al. (2020) used VR with serious games to enhance earthquake response and evacuation preparedness. Takeichi et al. (2020) applied VR for multi-disaster evacuation simulations, aiding nonexpert preparation for events like floods, earthquakes, and fires. Maragkou et al. (2023) developed “VR Quake,” an immersive VR tool for seismology education and disaster preparedness.

Alene et al. (2023) used VR to visualize debris flow landslides, showing road users’ perception of impending landslides varies with viewing angle. This insight supports strategic placement of early warning systems.

As noted above, VR-related research spans a vast variety of topics across different geological disaster fields. However, VR research work in these fields extending beyond social studies remains limited, niche, and experimental, requiring attention from the scientific community to frame its place. For geoscientists, this problem is largely due to the lack of a comprehensive suite of dedicated tools and software for conducting such VR analyses.

3.1.2 Objectives

To further diversify this limited VR research sphere, this chapter explores the use of consumer-grade immersive VR technology for a geoscientific investigation of a landslide, focusing on VR-based measurements, comparisons, observations, and retrodictive interpretations of its development and stabilization. To the author’s knowledge, such VR applications in geoscience have not been previously conducted. It also details the reconstruction of the landslide into VR for those interested in creating their own virtual environments. This study aims to demonstrate VR’s potential in advancing remote landslide research, offering a geoscientific approach distinct from the prevalent social study methodologies, and contributing to the existing knowledge consensus of landslides in the study area.

3.1.3 Overview of study area

The location of the landslide is in Atsuma Town, Hokkaido, Japan (Fig. 3.1). The coordinates are as follows: 42°46’43.5"N 142°00’48.3"E. It is a small (approximately 32 m × 57 m) landslide situated not far from the Apporo Dam towards the northeast. It can be interpreted as a shallow landslide characterized by a high mobility (Varnes 1978; Cruden and Varnes 1996; Osanai et al. 2019). This location is about 120–140 m above sea level. According to Ritonga et al. (2021), the dominant forest cover species are Betula platyphylla, Quercus mongolica, Larix kaempferi, and Abes sachalinensis. The major grass species here is the Sasa kurilensis (a.k.a. Sasa dwarf bamboo grass). Given the volcanic nature of the region’s surface geology, the landslide debris mainly comprises a mixture of the region's vegetation and tephra. The 2018 Hokkaido Eastern Iburi Earthquake (HEIE) (Mw = 6.6) struck on September 6, 2018, triggering 5,625 co-seismic landslides in the Atsuma region and neighboring areas (Yamagishi and Yamazaki 2018; Zhang et al. 2019). These landslides likely occurred due to the halloysite-rich Tarumae-d layer, which retained water from rainfall and was destabilized by seismic waves (Osanai et al. 2019; Wang et al. 2021; Zhang et al. 2019; Zhou et al. 2021). As of 2022, landslide progression continues slowly, influenced by seasonal freeze-thaw cycles on the exposed soil surface (Nakata et al. 2021; Lo et al. 2023).

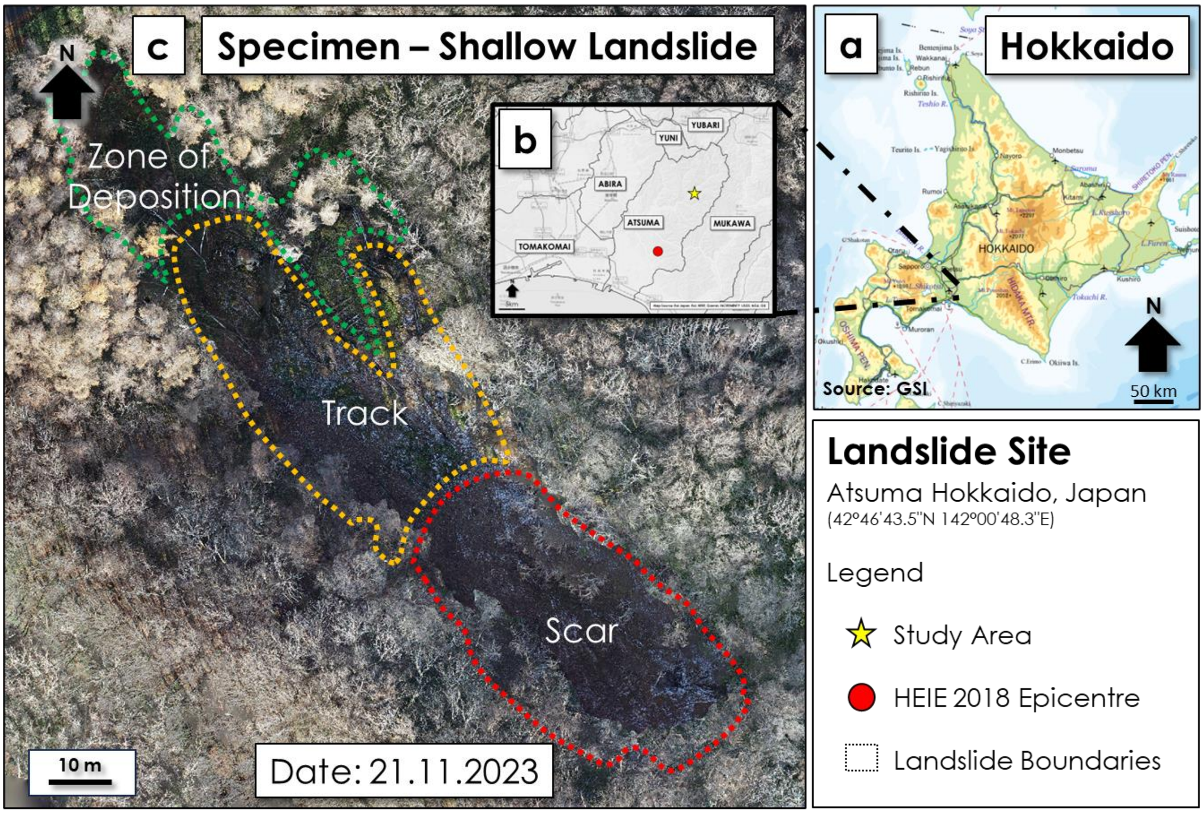

Fig. 3.1 Study site location. (a) Interpretive sketch of the anatomy of the landslide specimen examined in this study. (b) Location of the landslide in Atsuma respective to the earthquake. (c) Map of Hokkaido highlighting Atsuma location near the Hidaka Mountains.

3.2 Methodology

The research workflow comprises two parts: VR and True Reality (TR). In VR, landslide specimens are reconstructed into VR environments, with custom VR tools developed for essential topographical measurements, creating a complete VR fieldwork experience. TR involves conventional fieldwork using standard geological equipment to validate VR-derived measurements. Fig 3.2 summarizes this framework.

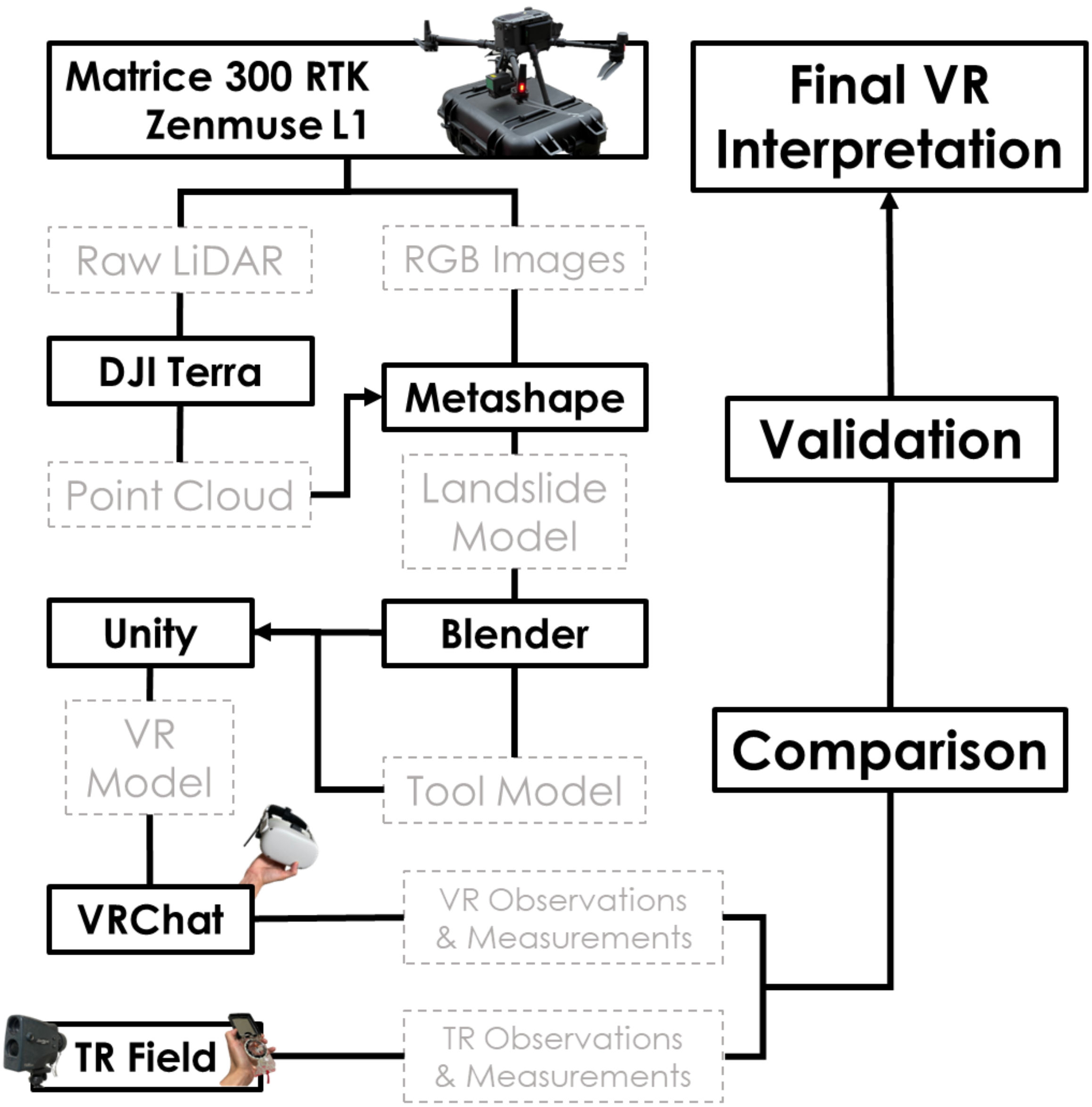

Fig. 3.2 The workflow of this study

3.2.1 Preliminary data compilation and preparation

Data for the study was collected and prepared from data archive of our previous surveys using uncrewed aerial systems (UAS) in the study area. The data used was taken during the autumn season on the 21st November 2023 under partially cloudy conditions with wind speeds of < 2.3 m/s at a temperature ranging between 0.7 and 11.8 °C (Japan Meteorological Agency).

Point cloud data by Light Detection and Ranging (LiDAR) and image data for Structure-from-motion Multi- View-Stereo (SfM-MVS) photogrammetry were taken from the same optical laser sensor Zenmuse L1 (ZL1) payload that was mounted on a DJI Matrice 300 RTK (M300RTK) UAS. The UAS was flown at approximately 80 m (± 20 m) altitude capturing the landslide subject in a single grid route and georeferenced with DJI D-RTK 2 antenna to attain less than 10 cm of positional accuracy. The UAS maintained a consistent altitude relative to the terrain to ensure uniform ground resolution throughout the survey. The workstation used in this research for processing the data was self-built with the specifications listed in Table 3.1.

Table 3.1

Workstation specifications

Component	Model
CPU	AMD Ryzen 5 7600x 5.3 GHz
GPU	NVIDIA RTX 3080 Ti 12GB 1785Mhz
RAM	8GB x 2 5200MT/s DDR5 CL40 XMP 3.0
SSD	WD SN770 M.2 2280 1TB
PSU	Corsair RM850e CP-9020249-JP

Note. Windows 11 Pro (Operating System)

The SfM-MVS dataset in this research comprises 50 georeferenced RGB images captured from the ZL1 sensor with 70–80% overlaps. They are then imported into Agisoft Metashape (Version 1.8.5), bundle adjusted, aligned to create the required tie points, and subsequently generate the dense point clouds. To optimize performance, dense point clouds were manually filtered to remove unnecessary trees and noise, focusing on topography. This, along with View Frustum Culling, reduces computational load by only rendering visible elements, improving

VR rendering efficiency and user experience. The terrain was left intact during filtering. The dense, filtered point clouds were converted into meshes and textured with 8 K resolution textures using RGB photos from the ZL1. Blender 3.6 was also used to perform minor cleanup of stray meshes following the conversion process.

LiDAR datasets are subjected to initial processing using DJI Terra (Version 3.9.3) to extract the point clouds to be used in Agisoft Metashape. Likewise, with SfM-MVS data, they are processed, noise filtered, developed into meshes and texturized with 8 K resolution textures using the images taken from the same ZL1.

Both meshes are then exported from the software with their texture atlas material library file and are then imported into Unity (2019.4.31f1) where VR properties are assigned (e.g. walkability, physics, and interactability) to simulate the VR experience. The virtual models was hosted in a VR social platform known as VRChat (VRC) which runs on the Unity engine, integrated using its legacy Software Development Kit (3.1.13). VRC is a free software with the capability to store virtual worlds for either public or private accessibility. It has not frequently been observed to be used in geoscience-related research but is well used in research works of the past relating to social sciences experiments (Barreda-Ángeles and Hartmann 2022; Maloney et al. 2020; Saffo et al. 2021). This platform is also used for outreaching purposes.

3.2.2 VR tool design

The virtual tool design in this study is inspired by traditional geological fieldwork tools, including a 2-m ranging rod, clinometer, compass, navigational tablet (NavTab), and water bottle (Fig. 3.3). These tools are adapted for VR, considering aspects like size, interactivity, and intuitiveness. Using Blender, 3D models are created and exported with textures to Unity, where VR properties (e.g., wieldability, kinematics, interactability) are assigned for deployment in the virtual space.

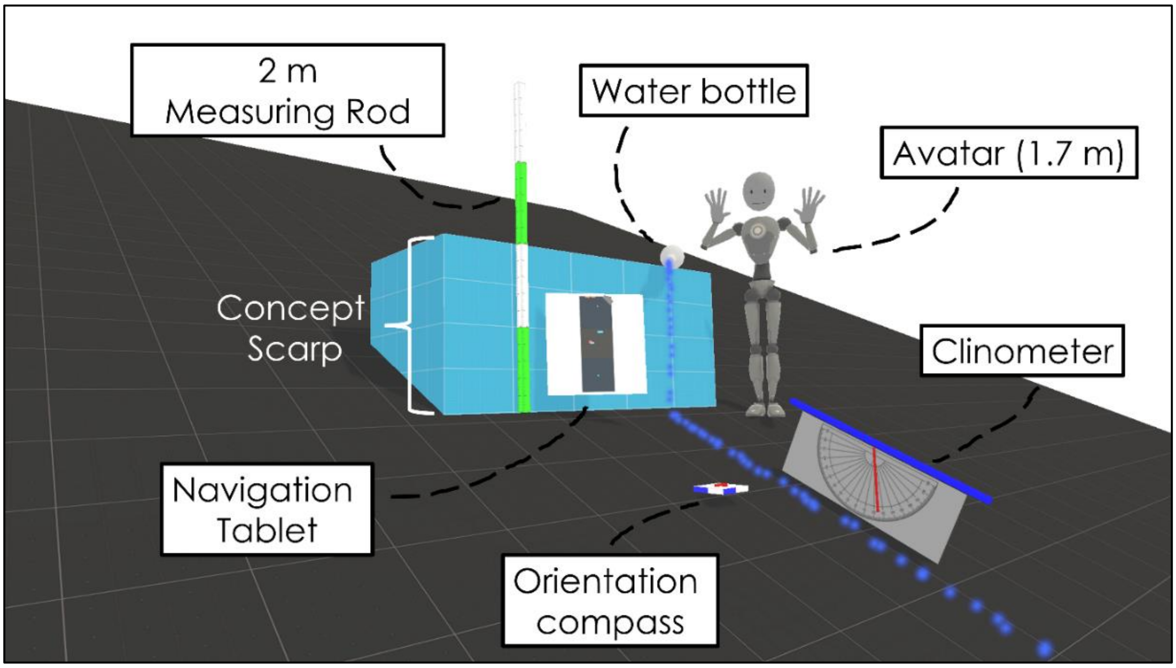

Fig. 3.3 Concept measurement using VR measuring tool created for this study

3.2.3 VR fieldwork

This chapter defines VR geological fieldwork as such only when it possesses these key attributes:

- Inclusion of a virtual environment twin of the geological subject.
- Capability to employ VR tools for interactive measurement and data collection.
- Capacity to facilitate immersive VR observations and locomotion.

The VR fieldwork focuses on tasks which are to make immersive virtual measurements and virtual observations. Initially, an observational study was done on data from 8th November 2022 from data repository of prior drone missions done in the study area (Supplementary; Fig. S4). Then in this study for closer temporal correlation, the data from 2023 was used after taking measurements in the field a few weeks prior so that such time gap influence is reduced.

The time gap concern arises from the approximately one-year interval between the initial VR fieldwork conducted in 2022 and the TR fieldwork in 2023. Over such a period, changes to the landslide site may have occurred, particularly given the Atsuma landslide's is still known to be in an active state, especially due to freeze-thaw cycles during the winter (Nakata et al. 2021; Lo et al. 2023). While the 2022 VR observations are free from the confirmation bias (since they were made prior to revisiting the site) this temporal gap weakens the direct correlation between the VR and TR measurements. Therefore, it was necessary to reconduct the VR fieldwork in November 2023, aligning it more closely with the TR measurements and reducing the impact of time-related changes. Nevertheless, the author recognized that the VR fieldworks conducted in 2022 and 2023 produced similar results.

The Oculus Quest 2 HMD was selected for visualizing the VR landslide due to its affordability, versatility, and popularity, as shown in the 2023 Steam Hardware Survey. Using VR tools, slope angles, directions, and scarp height were measured, with the landslide divided into left and right flanks (Fig. 3.4). Slope characteristics were deduced using a virtual water bottle to measure angle and direction, repeated 10 times (5 per flank). Scarp measurements were taken along a 25-point line at ~ 4 m intervals with a VR measuring rod. These measurements were averaged to enable a straightforward comparison using the available VR data.

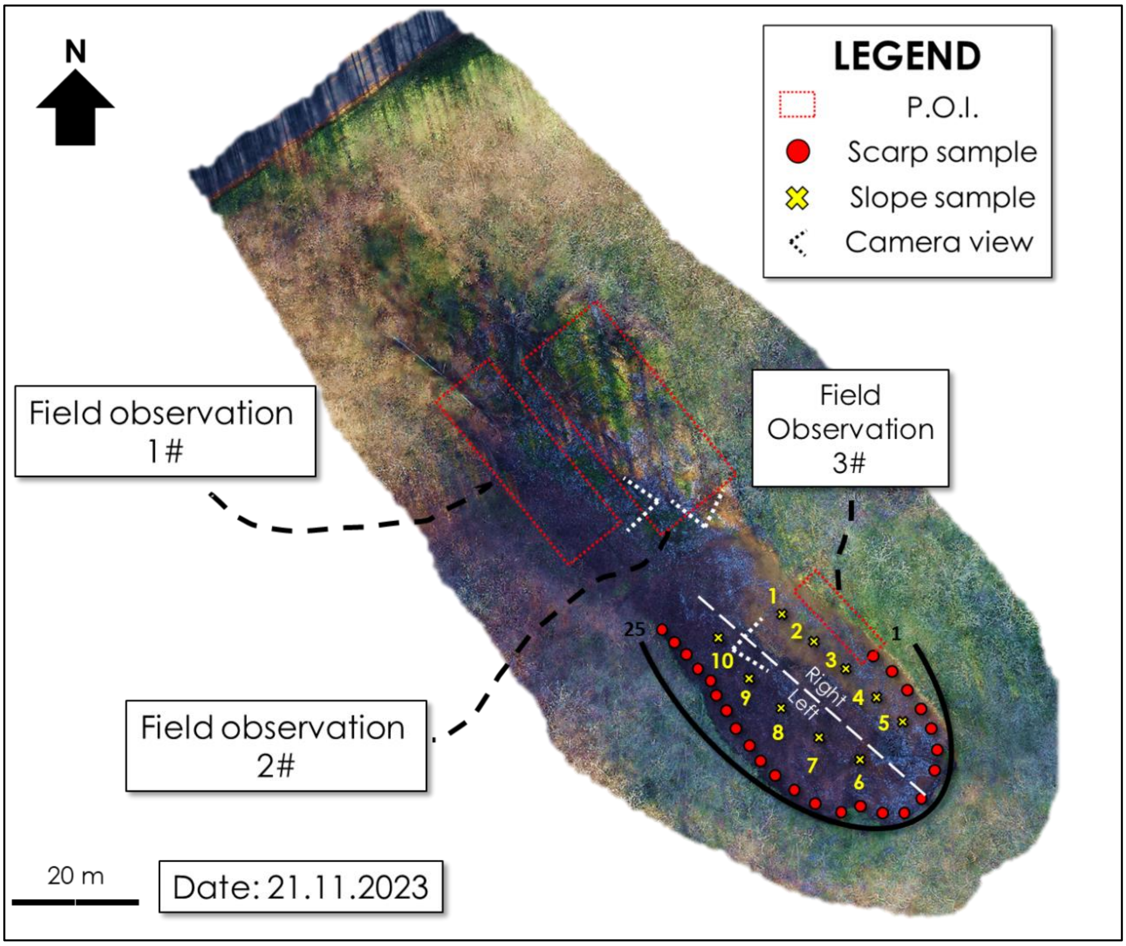

Fig. 3.4 This image shows the measured sample location on the landslide, camera view of POI, and the partitions of the left/right flank

In virtual observations, the author leverage the mobility afforded by VR to explore the landslide subjects from diverse angles and perspectives. This includes walking, sprinting, jumping, levitation, and phasing. The author logged observations, took virtual field pictures using a VR camera system, and made notes of several points of interest (POI) at the study site. For positioning-related concerns, the author relied on the NavTab which feeds live information of the user's location on the map.

3.2.4 TR fieldwork

For the case of TR fieldwork, the aim was to validate the observations and measurement results that were collected in VR. Similarly to the VR workflow, there are two parts in TR fieldwork which consist of 'boots on the ground' measurements and observations. The fieldwork was conducted on 31st October 2023 from 10:30 − 3:00 pm (~ 5-hour duration) under cloudy conditions at ambient temperatures of 15–17 °C.

In TR, measurement was done on the landslide slope angle, directions, and scarp height replicating as it was conducted in VR. For slope-related measurements, a geological field compass, SUUNTO MC-2 G Mirror Compass (plastic needle version) was used and calibrated with a magnetic declination of 9° west derived based on the World Magnetic Model 2020 (Chulliat et al. 2020). For scarp measurements, the TRUPULSE ® 360° B Rangefinder was used to gather approximate measurements at a safe distance, with similar sample counts taken in VR of the scarp from the ground until the base of the grass cover.

The logged POIs identified during VR observations were confirmed to exist based on prior observations conducted in TR. Field photographs were captured using an iPhone 12 Pro and a RICOH Theta X.

3.2.5 Validation and interpretation

The measurement results taken from VR are then compiled and compared to the accumulated TR field measurement results. The purpose is to simply establish reliability, thereby enabling this research to proceed with the VR field investigation style of its methods (not to be mistaken for a comprehensive accuracy study). The author took the mean average results of the slope and scarp measurements of each flank and use these values to compare, and the results are considered as the validated results. Lastly, field notes and photographs from both TR and VR observations are utilized to form an initial interpretation of the field site. These observations are then integrated with the validated measurement results to construct a comprehensive VR-style interpretation of the landslide subject.

3.3 Results

3.3.1 Virtual field observations

Several key observations related to the landslide are listed in Figure 3.5, which illustrates the observations from both VR and TR perspectives:

- Incomplete scarp development (right flank).
- Oriented tree deposits.
- Deviation in the flow path of the landslide.

The first observation reveals an incomplete scarp, that resides on the right flank of the landslide which appears to have initiated midway, as depicted in Figs. 3.5a and b, alongside the presence of a scarp mound that lies next to it (Fig. 3.5j). The second observation is the tree deposits that are oriented in the area indicating the landslide direction oriented towards the northwest, as shown in Figs. 3.5d and 3.5e. Furthermore, the third observation is that there is a noticeable deviation in the landslide's flow path, gradually shifting from the northwest to a direction closer to the north, as evidenced in Figs. 3.5g and 3.5h. Observations in TR is as shown in Figs. 3.5c, 3.5f, and 3.5i.

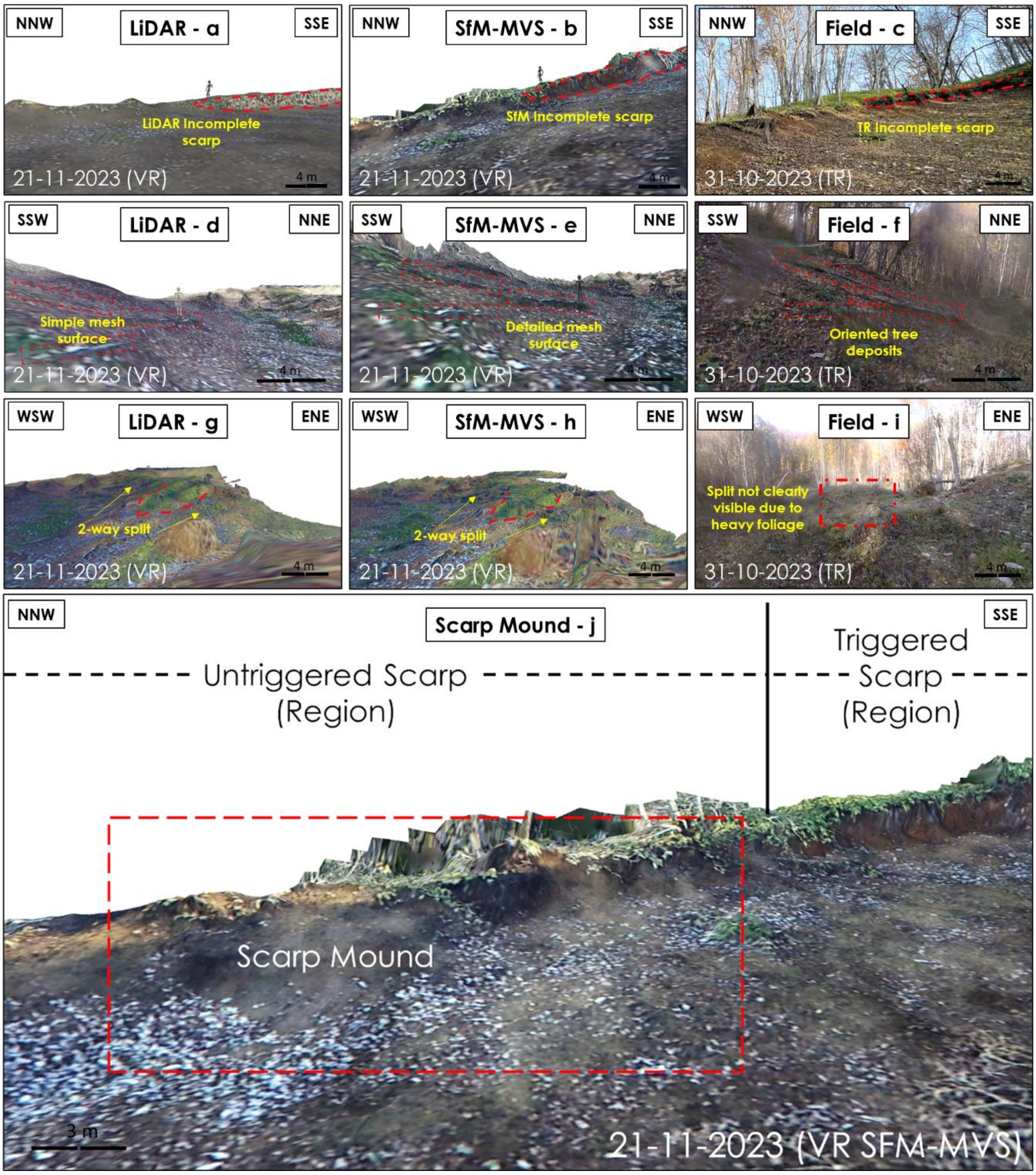

Fig. 3.5 Observed POIs as seen in VR LiDAR, VR SfM-MVS and field

3.3.2 Interpretation of the landslide

Based on the VR-based measurement results, observation and current knowledge of the landslide event, a preliminary interpretation of the landslides was performed. In interpreting the data, it is proposed that the process of the landslide occurred through six simultaneous and rapid steps. (Fig. 3.6a-f):

1. Initiation of scarp failure– The landslide was initiated as a simultaneous cohesive event, with the first half of the right scarp remaining inactive (Fig. 3.6a).
2. Shallow landslide – The landslide exhibited high fluidity due to seismic waves and halloysite-induced liquefaction (Wang et al. 2021; Zhang et al. 2019). The main flow originated from the steep, unobstructed left flank, while the right scarp lagged due to obstruction by the inactive landslide section (Fig. 3.6b).
3. Overflow and abrasion – As debris moves northwest, the unactivated region is abraded at two angles by the main flow and right flank subflow, generating material at the contact point. Combined with north- and west-facing slopes, this excess material surpasses the flow path's capacity, creating a chokepoint that ejects debris northward into the non-landslide area (Fig. 3.6c).
4. 1st deposition and momentum loss – This brief and instantaneous phase suggests overflow material encountering obstructing trees in this non-landslide area, resulting in their collapse and immediate deposition (Fig. 3.6d).
5. 2nd deposition and momentum loss – Haphazardly deposited trees in the overflow region impede the main flow, reducing momentum. This effect, common in tree-rich areas (Ritonga et al. 2021), combined with gentler terrain and lower elevation, initiates the second deposition phase at the landslide lobe (Fig. 3.6e).
6. Final deposition – The final deposition sees the trailing trees at the tail of the landslide being deposited preserving the orientation of the original flow. Furthermore, the obstruction from the inactivated scarp is fully reduced into a scarp mound as seen in the virtual field (Fig. 3.6f).

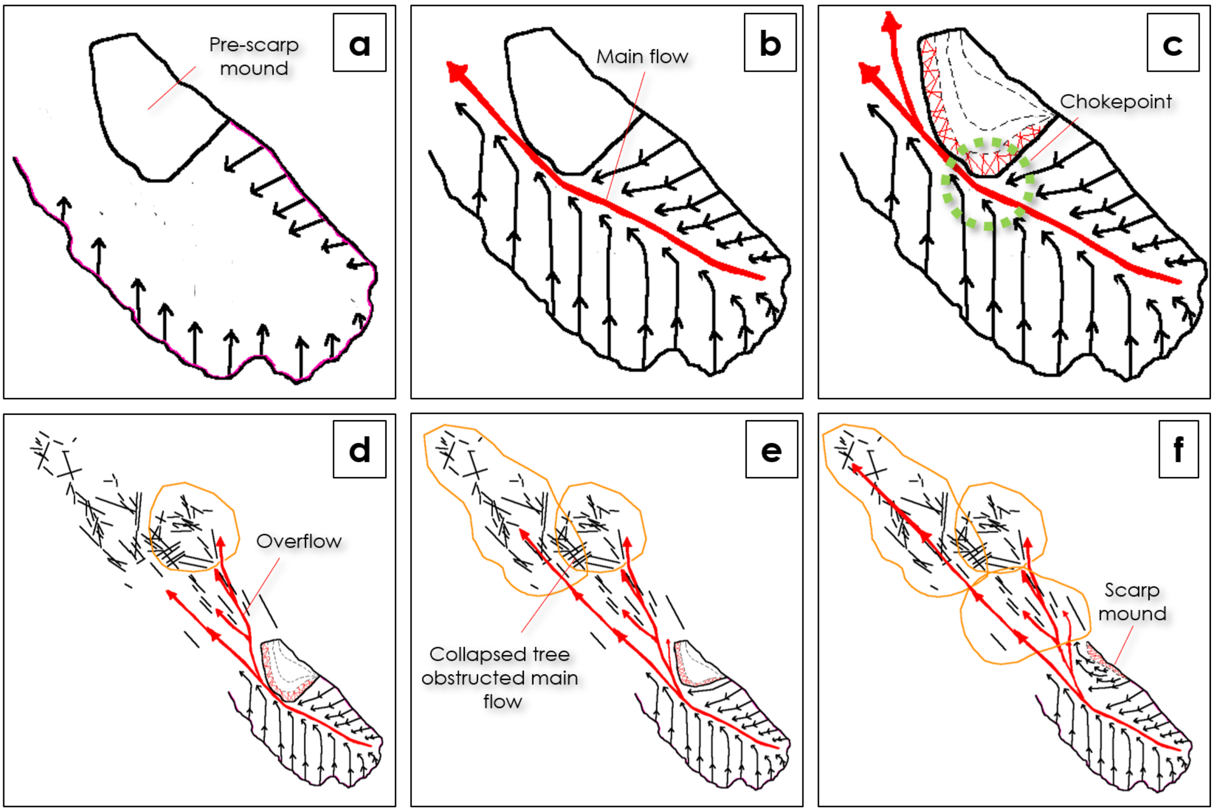

Fig. 3.6 Pre-liminary field interpretation sketch of the landslide's progression stages based on VR observations and data. a) Initiation of scarp b) Main flow development c) Overflow and contact abrasion d) 1st deposition and momentum loss e) 2nd deposition and momentum loss f) Final deposition

3.3.3 VR and TR measurements

VR measurements for both sides of the landslide are averaged (Tables 3.2, 3.3, and 3.4). Raw measurements are displayed as scatter plots and bar charts (Fig. 3.7). Right flank slope angle measurements showed a mean of 32° for VR LiDAR and 33° for VR SfM, deviating by 2° and 3° from the TR mean of 30°. For the left flank, both TR and VR LiDAR measured 36°, while VR SfM-MVS measured 35°, with deviations of 0° and 1°, respectively. Overall, VR measurements deviated by an average of 1° from TR values. These results indicate the right flank is generally gentler than the left.

The mean slope direction of the right flank is 268° for TR, 280° for VR LiDAR (12° deviation), and 269° for VR SfM-MVS (1° deviation). For the left flank, TR is oriented at 0°, with VR LiDAR and VR SfM-MVS at 354° and 357° (3–6° deviation). Overall, VR measurements deviate by 1–3° from TR. These findings suggest the right slope generally faces west, while the left slope faces north.

Significant deviations exist between TR and VR scarp measurements. TR shows an average scarp height of 0.95 m (1.0 m right, 0.9 m left), while VR LiDAR averages 1.4 m (1.4 m both sides), and VR SfM-MVS averages 1.55 m (1.6 m right, 1.5 m left), with deviations attributed to vegetation and canopy interference in SfM-MVS samples 6 to 9. The deviation between TR and VR measurements ranges from 0.4 to 0.5 m. Although VR LiDAR aligns more closely with TR than SfM-MVS, both show significant gaps from actual values.

Table 3.2

Average Landslide Measurement in True Reality

Left Slope (°)	Right Slope (°)	Left Scarp (m)	Right Scarp (m)	Left Slope Direction	Right Slope Direction
36	30	0.9	1.0	000 N	268 W

Note. 31st October 2023

Table 3.3

Average Landslide Measurement in Virtual Reality LiDAR

Left Slope (°)	Right Slope (°)	Left Scarp (m)	Right Scarp (m)	Left Slope Direction	Right Slope Direction
36	32	1.4	1.4	354 N	280 W

Note. 21st November 2023

Table 3.4

Average Landslide Measurement in Virtual Reality SfM-MVS

Left Slope (°)	Right Slope (°)	Left Scarp (m)	Right Scarp (m)	Left Slope Direction	Right Slope Direction
35	33	1.5	1.6	357 N	269 W

Note. 21st November 2023

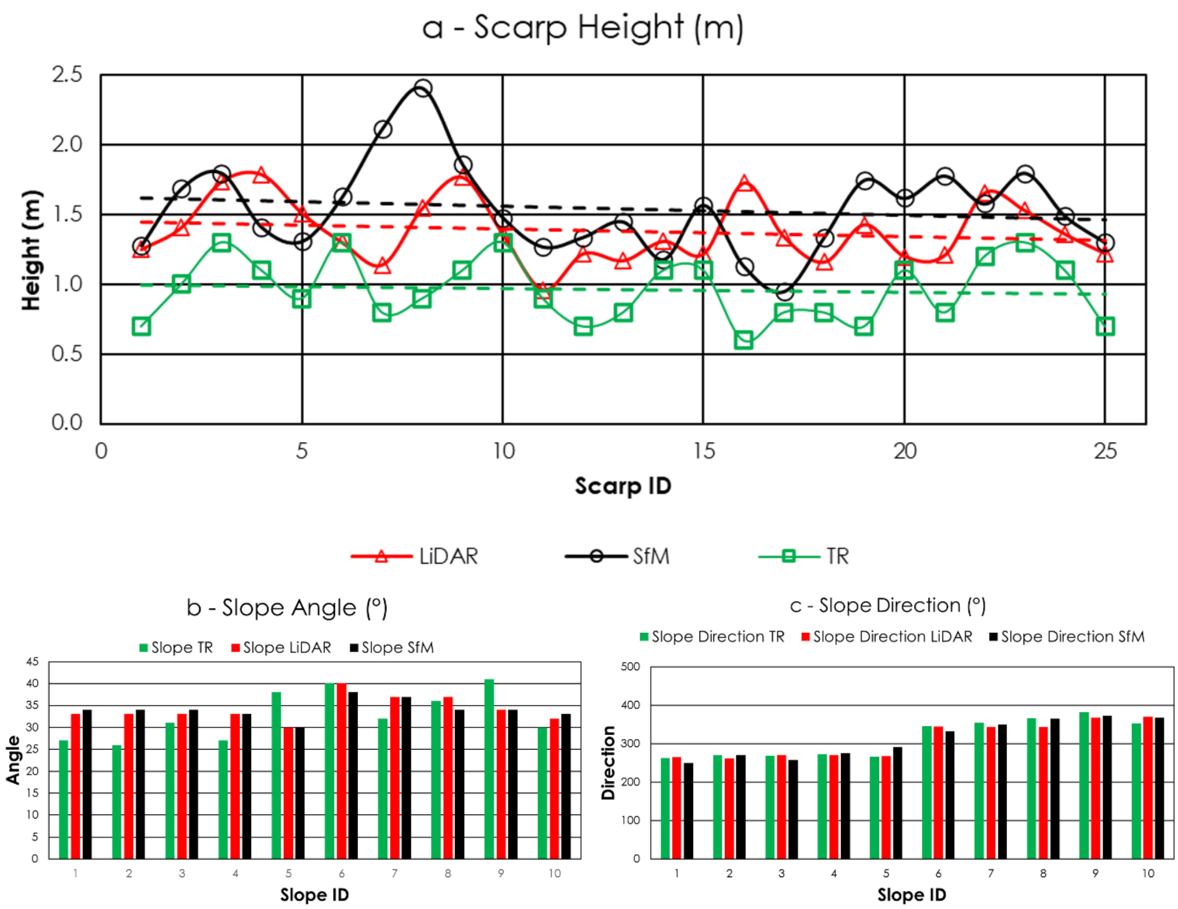

Fig. 3.7 Bar chart representing the raw data (a) scarp height, (b) slope angle, and (c) slope direction

3.4 Discussion

3.4.1 VR measurement comparison

Slope angle data shows the gentlest slope is the right flank (32–33°), followed by the left (35–36°), with only ~ 1° deviation between VR and TR (Tables 3.3 and 3.4). These findings align with typical HEIE 2018 landslide angles (20–40°) (Osanai et al. 2019; Zhang et al. 2019). VR measurements closely match TR values, with negligible errors. Minor discrepancies likely stem from the lower-quality point cloud of the low-cost UAV LiDAR compared to SfM-MVS. The right flank slope generally faces west and the left faces north, with orientation deviations of 1–

5° from TR, which are considered minor. The most significant offset is in scarp measurements. VR LiDAR shows a height deviation of 0.4–0.5 m, and VR SfM-MVS deviates by 0.6 m from TR, with VR LiDAR being closest to actual values. However, both VR methods exhibit a noticeable gap in scarp measurements, making them unreliable for interpretation.

Several field conditions can impact the quality of VR environments generated by UAS remote sensing workflows. Aerial SfM-MVS is sensitive to vehicle and subject movement (Liao et al. 2021). For example, influenced by factors like wind, uneven lighting, dead vegetation, moving objects (e.g., swaying trees), and occlusion. Wind drafts may alter UAV flight paths, while uneven lighting complicates feature matching, hindering tie-point generation (Cawood et al. 2017). Dead biomass on landslide surfaces occludes sensors, adding noise instead of capturing ground surfaces. Vegetation can distort point cloud accuracy, affecting mesh height (Obanawa et al. 2020). Additionally, equipment calibration may introduce further uncertainty.

LiDAR methods typically generate fewer point clouds than SfM-MVS (Cawood et al. 2017; Kalacska et al. 2021; Obanawa et al. 2020). In this study, LiDAR produced 998,302 points, while SfM-MVS yielded 3,182,394. Lower point cloud density in LiDAR can result in a smoother mesh surface compared to the more detailed, rougher surface from denser SfM-MVS (Sánchez-Aparicio et al. 2020).

LiDAR VR scarp measurements align more closely with TR than SfM-MVS (Fig. 3.7), due to dense Sasa bamboo along the scarp edge, which blocks the laser from reaching the true surface, merging grass height with scarp height. SfM-MVS further exaggerates height due to wind-swayed grass, making conditions less ideal (Obanawa et al. 2020; Rotnicka et al. 2020). Future studies might consider mobile LiDAR for closer, more accurate capture of occluded areas.

In summary, LiDAR and SfM slope measurements are both accurate, deviating from TR by only 1°. However, both methods showed significant errors in scarp measurements, making them unreliable for this purpose. If vegetation obstructions are minimal, UAS LiDAR is recommended for geomorphologically accurate VR environments, while SfM offers a cost-effective alternative with negligible deviation. Flying the UAS closer to the subject is advised to capture finer details, although this was not feasible here due to elevated trees posing collision risks. Adopting this approach would improve VR environment accuracy for both methods.

3.4.2 VR observations

Three main observations were made during the VR fieldwork.

The first VR observation focuses on the incomplete scarp formation on the landslide's right flank (Figs. 3.5a and b). From an aerial view, this feature isn't immediately clear, but VR's 3D perspective enhances identification, highlighting one principal advantages of VR. It is hypothesized that this scarp was not activated but experienced "contact abrasion" from debris of activated scarps. Supporting evidence includes its location on the gentler slope (Tables 3.2, 3.3, and 3.4), the presence of a scarp mound instead of a clear scarp (Fig. 3.5j), and its lower, more stable elevation (all suggesting this area may not have met landslide initiation criteria).

Buried trees with consistent orientations, observable in VR (Figs. 3.5d and e), indicate the landslide's flow path, extending from the tail to the lobe (Fig. 3.8). The flow direction is northwest, at ~ 320° based on VR measurements. The landslide has two main slopes (one west and one north) which theoretically, based on vector addition, if there is flow along these slopes of equal material and momentum, would combine to a flow direction of 315°. The slight 5° deviation toward ~ 320° is likely due to the steeper and wider left flank, which held more debris than the gentler right flank, influencing the flow's momentum and direction.

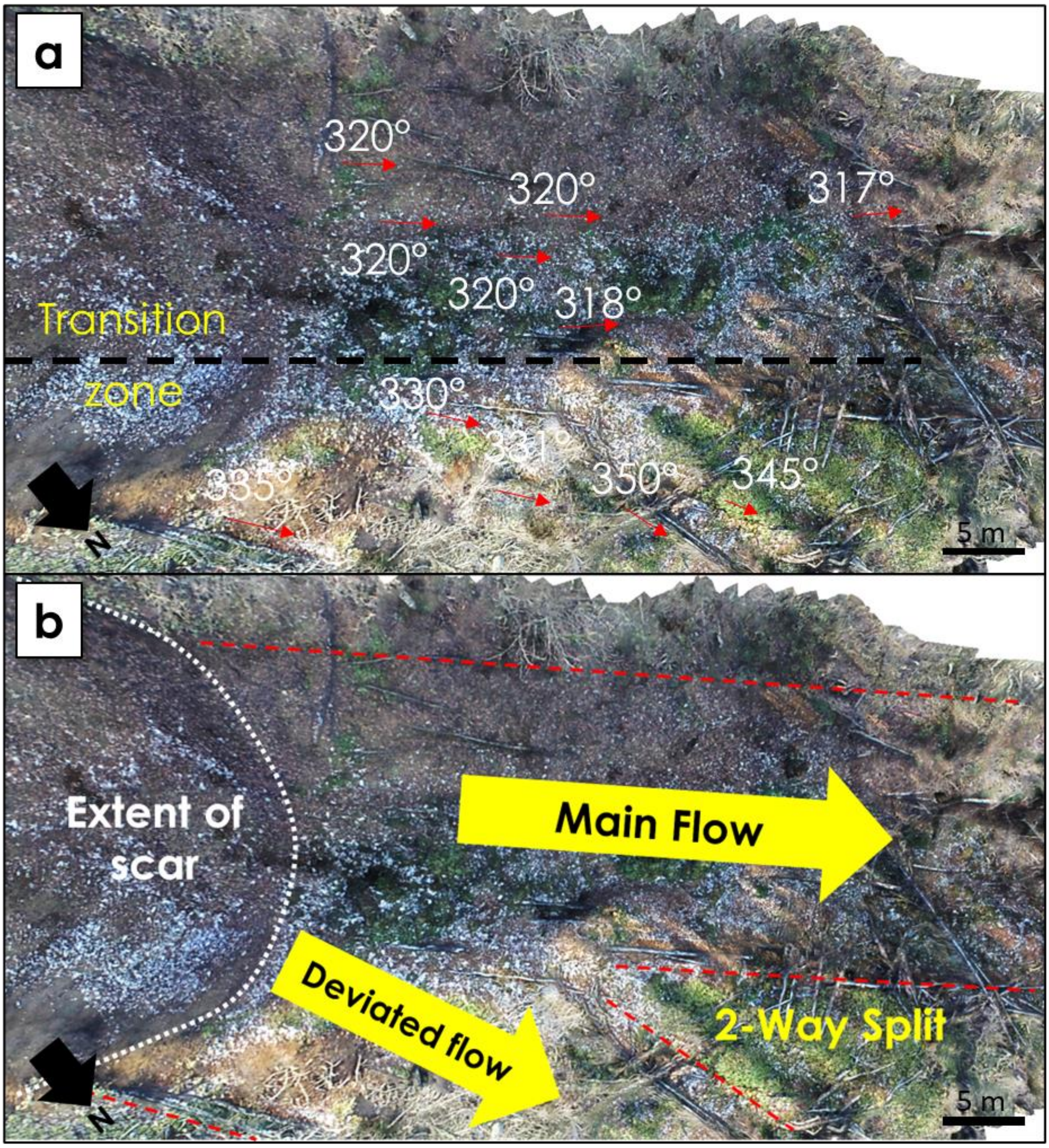

Fig. 3.8 a) Aerial VR perspective of the track area of the landslide showing the sampled tree deposit's orientations: main flow (317-320°) and overflow (330-350°). b) The two flow directions relative to the scar body

The final observation is the deviation in the landslide's flow path (Figs. 3.5g and h). The deposit appears to shift from the original flow (~ 320°) to a new orientation of ~ 350°, as seen in the buried trees' gradual change in alignment (Fig. 3.8a). This deviation (Fig. 3.8b) likely results from several factors: a greater pre-event material load on the steeper and wider left flank, initial scarp material being obstructed by stationary material (pre-scarp mound) from the unactivated scarp, and multiple material feeds (left, right scarps, and abrasion of the obstructing unactivated landslide scarp material. These factors likely created a "chokepoint," causing overflow and the large (> 10–30°) directional shift.

The VR SfM-MVS environment provided a more detailed mesh of buried trees, while the VR LiDAR environment struggled to detect them. This difference is due to the entry-level LiDAR sensor used, which produced a lower point cloud density compared to the more detailed photogrammetry. An industrial-grade LiDAR might resolve this issue. As a result, VR SfM-MVS preserved more surface details due to its higher point cloud count, whereas VR LiDAR offered a more summarized view. In TR, such features are typically hard to identify due to poor visibility unless specifically sought.

In summary, observations made in VR, such as those that were encountered, can be frequently overlooked when done in a conventional fieldwork setting or through static photograph assessments due to the inherent complexities of the real-world environment. The field presents an abundance of sensory distractions that can obscure features of interest, including visual elements like dense foliage, soil, shrubbery, color variations, shapes, and textures (Orion and Ault 2007). Additionally, physical challenges such as navigating steep terrain, climbing, and restricted lines of sight may further contribute to the potential for oversight. In the VR environment, the simplified nature of the VR landslide subject coupled with the freedom of movement such as flight, intangibility, ease of traversal, and limitless stamina allows for different angles of perspective not usually explored in conventional fieldwork. This makes 3D features that are difficult to identify in the field and aerial photographs much more prominent and obvious in VR.

3.5 Conclusions

In this article, a landslide was explored and assessed using VR technology with the theme of using VR tools inspired by traditional geological measuring methods. By doing so the research produced results, conducted analysis, made suggestions, and disseminated knowledge from the perspective of VR. This study concludes that VR can be applied as a tool for field investigation, identification, and interpretation for geological fieldwork. Based on the results, this research recommends the SfM-MVS workflow as a starting pathway to generate reliable, versatile and cost-effective VR fieldwork environments that can be replicated for most geomorphological subjects. The concluding advantage of VR technology for fieldwork is that it is a capable tool for preliminary investigations, planning, and interpretations which provides an additional angle for supplementing a more comprehensive study of a geomorphological and geological subject. VR is currently the only technology that is capable enough to fill the immersive niche for geoscientists that no other conventional technology or methods can replicate. Afterall, geomorphology and geology is an observational science.

Future studies may consider fusing different types of geological data creating a more immersive hybridized dynamic field investigation experience compared to this research’s more static one. The findings of this research contributes a supporting perspective to the current knowledge consensus of the HEIE 2018 landslides and also highlight some of the possibilities offered by VR technology in its application in geoscience. This has the vast capacity to benefit not only scientists, but also stakeholders, and educators alike, serving VR as a platform for communicating science, creating collaborations, and research opportunities.

Chapter 4

Usability and motivational impact of a fast-paced immersive virtual reality lecture on international middle school students in geoscience education

4.1 Introduction

Geoscience education can be referred as the structured teaching and learning that focuses on the earth's physical features, processes, and systems. It is important that when teaching geoscience, students may need to develop observational and spatial thinking skills, as it is an observational science. In particular, field experiences in geoscience require a level of thinking, mental visualization, and investigative skills not commonly found in other scientific fields (King, 2008; Liben et al. 2011). Therefore, it is necessary for educators of geoscience to emphasize on transferring these key skills to their students.

Conventional geoscience teaching methods using textbooks and lectures often fail to effectively convey the reality of the nature, including three-dimensional (3D) features of the Earth. These approaches tend to rely on pseudo-3D visualizations to express the earth which is challenging because it places additional cognitive burden on learners to mentally visualize complex 3D geometrical concepts that they may not be very familiar with (Fitzpatrick & Hedley, 2024; Havenith et al. 2019). Hands-on activities like fieldwork, museum visits, and lab activities help address this limitation, but access is often restricted due to practical issues like finance, health, socioeconomic, and logistical barriers. Addressing these challenges is vital for advancing geoscience education for the masses.

Immersive Virtual Reality (VR) offers a promising solution to tackle this issue. VR provides an immersive, interactive, and realistic 3D experience accessible through head-mounted displays (HMD) and their respective peripherals. It addresses the accessibility and visualization challenges of traditional geoscience teaching methods by enabling fully immersive realistic exploration of geological data in 3D, with intuitive motion-based interaction while also leveraging physical and cyber portability. This makes VR a potentially versatile and highly useful tool for geoscience education and communication.

4.1.1 Literature Review

One of the major global challenges today is ensuring quality education. As outlined by the Sustainable Development Goal 4 in United Nations (2015):

"Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" (p. 14).

The geoscience community has made significant strides in communicating geoscience to the broader public, facilitating knowledge dissemination beyond the scientific community. While traditional communication methods, such as lectures, museums, and workshops, have been widely utilized, advancements in technology now provide more innovative outreach approaches.

Studies on 3D printing in geological education highlight its benefits: Gutierrez et al. (2023) demonstrated that 3D-printed models improve undergraduates' spatial and visualization skills while enhancing understanding of geological structures. Similarly, Chenrai (2021) found that integrating 3D printing into geoscience curricula bolstered structural interpretation and spatial visualization abilities.

Virtual Field Trips (VFTs) are effective tools for geological outreach: Watson et al. (2022) found personal computer (PC)-based VFTs engaging for teaching physical volcanology through 3D visuals and videos. Tibaldi et al. (2020) described VR approach using 3D digital outcrop models for teaching, learning, and research in volcanology suggest that VR is capable for engaging public and can be value to promote environmental site protection and development. De Paz-Álvarez et al. (2022) demonstrated VFTs' usefulness in teaching mapping skills but noted they cannot fully replace traditional courses. Klippel et al. (2019) showed immersive VFTs with VR headsets improved lab performance and enthusiasm compared to traditional field trips. Harknett et al. (2022) used VR for teaching students' structural geology fieldwork skills in structurally complex volcanic terrains noting its potential role to play in existing geoscience education curricula.

Other VR applications show promise in geoscience communication: Yamauchi et al. (2022) used VR to visualize underground heritage (Taya Cavern in Yokohama, Japan), boosting interest and encouraging potential real-world visits. Alene et al. (2024a) developed "QuickAware," a VR tool raising awareness of quick clay landslides, effectively enhancing hazard understanding. Graebling et al. (2024) introduced "VR-EX," a storyline-based VR application for learning geological electrical resistivity tomography experiments at Mont. Terri underground Laboratory (Switzerland), which fostered high engagement, immersion, and knowledge transfer. Jong et al. (2020) applied spherical video-based VR and found positive results on its pedagogical effectiveness on teaching physical geography.

As these studies demonstrate, geoscience outreach methods are expanding beyond traditional methods with the integration of innovative technologies and concepts like 3D printing, VFTs, and immersive VR experiences. However, despite these growing strategies, a gap remains in evaluating the effectiveness of VR-based pedagogies (Hagge, 2024; Harknett et al. 2022; Jong et al. 2020), such as in formal geoscience education. Further contribution is necessary, especially in integrating the lecture component of traditional geoscience education with VR. By combining the interactive nature of VR with the structured learning of lectures, a more dynamic and immersive approach to geoscience education could be achieved, potentially enhancing both engagement, knowledge retention, while ideally, improving communication to a wider audience.

4.1.2 Objectives

This chapter explores the effectiveness of VR-based geoscience lectures in teaching middle school students, addressing the limited focus on this demographic in VR-related geoscience research. Additionally offering an opportunity to introduce the students to geoscience concepts typically inaccessible at their educational level. The study emphasizes geoscience topics related to the 2018 Hokkaido Eastern Iburi Earthquake (HEIE). A fast-paced, portable, VR lecture was developed for this purpose, and its effectiveness is compared to traditional teaching methods. To the author’s knowledge, this approach using VR lectures in geoscience education has not been explored before. This study is part of a larger project examining the feasibility of VR in geoscience education. In this chapter the focus primarily addresses the motivational and usability aspects of the VR application.

This study narrows on these key objectives: It evaluates the usability of the fast-paced VR lecture format and how it compares to the traditional teaching methods in terms of motivational preference by the participants at this educational level. Furthermore, the study explores the ability of the VR experience to incite interest and curiosity in the geological environment, identifies its strengths and limitations, and outlines potential directions for further development of such teaching approach.

4.2 Methodology

4.2.1 Participants and Setting

The VR outreach program was conducted on the morning of September 19, 2024, at Hokkaido International School (chosen for its diversity of students), running from 9:00 AM to 11:45 AM. The session engaged middle school students (11-14 years old) from grades 6 (G6) through 8 (G8), with a total of 60 participants: 18 from G6, 21 from grade 7 (G7), and 21 from G8. The students came from a variety of international backgrounds, including: East Asia, North

America, Oceania, Europe, and Eurasia. This ensures that any bias toward a single perspective in the results is minimized. Hokkaido International School, a private institution, follows a Western-style education system with English as the medium of instruction.

The research workflow consists of three key stages: VR lecture development, survey formulation, and outreach execution. The VR lecture was designed to replicate traditional lectures within a VR environment while leveraging VR-specific advantages, such as visualizing 3D VR models, and animated contents. The survey aimed to evaluate middle school students' motivation and usability experience of the VR lecture, and comparison between traditional teaching methods. The traditional teaching methods are the lecture and hands-on session. The entire outreach program was strictly limited to 165 minutes by the school and accommodated 60 students.

4.2.2 VR lecture development

The VR lecture had to adhere to the limitations of time and participant numbers. Furthermore, the goal was to fully leverage the unique capabilities of VR for presenting geoscience materials. To the best of the author’s knowledge, no existing applications met this specific need, so it was a requirement to develop a custom designed method that aligns with the principles of VR-based lectures.

This chapter defines VR lecture as such only when it meets at least the following key attributes:

- Delivered in a fully immersive 3D VR environment primarily accessed through immersive VR technology
- Designed to teach in a structured manner with defined learning objectives
- Conducted by a lecturer represented as an avatar, featuring voice and expressive body language

- Participants must have the ability to listen, visualize, navigate using VR-based locomotion, and engage with the lecture and its content within the virtual space
- Incorporates teaching aids that is possible only in VR to enhance understanding
- Capability of being adapted to various instructional settings

The VR lecture is designed in this manner: At the beginning, students will spawn into the starting lobby and is guided to the lecture room after entering a doorway (Fig. 4.1a). After standing on a designated spot on the floor the lecture will commence. The lecture featured a dummy virtual lecturer delivering a ~5 min oral commentary on the geoscience topics (Fig. 4.1b). The lecture is fully voiced and showcased virtual teaching aids including images, 360-degree photospheres, animated models, and 1:1 scale field replica to enhance understanding (Fig. 4.1c-f).

The 3D models were prepared using photogrammetry in Agisoft Metashape and 3D modelling in Blender. Voice lines were recorded using Microsoft's windows sound recorder application. Unity game engine was used for implementing, animating, and displaying these assets, while VRChat served as the platform for hosting the lecture during the outreach day. The processing was performed on a desktop PC equipped with an RTX 3080 Ti graphics processing unit (GPU), AMD Ryzen 5 7600x central processing unit (CPU), and 16 GB of random-access memory.

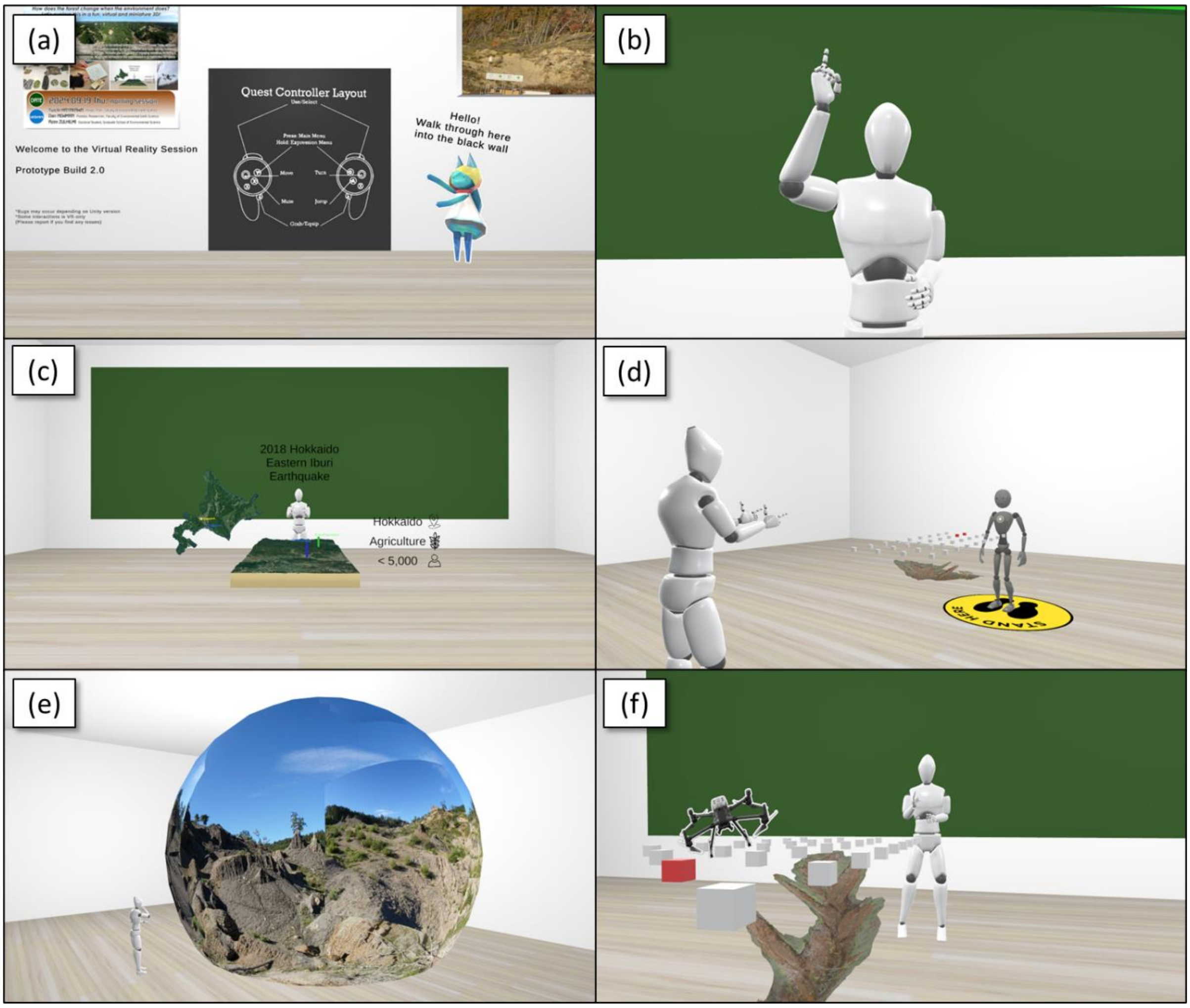

Figure 4.1. World setting for VR lecture (a) the starting lobby room with tutorial board (b) the VR lecturer (c) VR lecturer explaining about the 2018 HEIE (d) participant standing on the trigger zone (e) photosphere showcase of the deep-seated landslide (f) VR lecturer teaching about drones and 3D models

During the prototype phase, which is critical for smooth implementation (Novotny et al. 2019), the VR lecture was tested on graduate students from Hokkaido University's Graduate School of Environmental Science. This process identified technical and content-related issues, allowing the team to refine and finalize the lecture experience. The resulting optimized blueprint was used for the outreach program (Fig. 4.2).

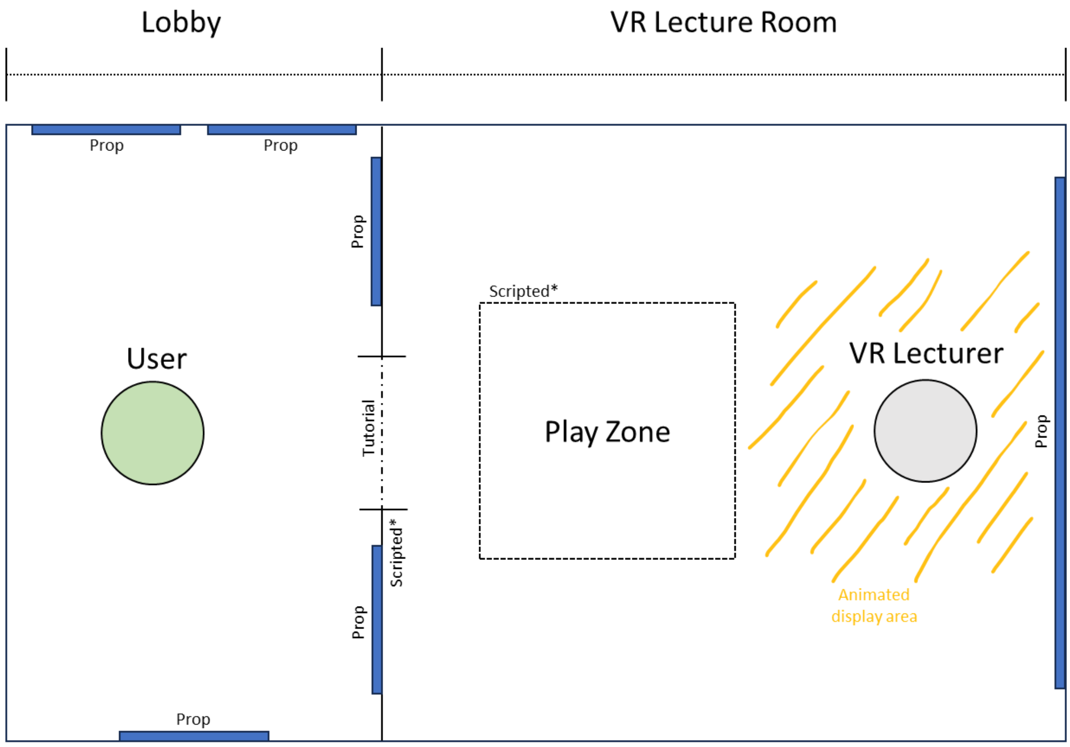

Figure 4.2. VR lecture world blueprint

4.2.3 Survey design

The survey design was inspired by the System Usability Scale (Brooke, 1996), which measures how easy a product is to use, and Intrinsic Motivational Inventory (Ryan & Deci, 2000) for measuring subjective experience of the user in relation to a specific target activity in laboratory experiments. These surveys have been used in previous studies (Carbonell-Carrera et al. 2021; Huang & Liu, 2024; Meulenbroeks et al. 2024).

The author's version of the survey was modified for the prepared VR lecture scenario and adapted to accommodate the time constraints and student amount of the outreach program. After the VR experience, students completed a 10-minute survey consisting of the following sections (refer Appendix B-D):

1. *VR Usability survey*: This section assessed five categories - Discomfort, Effectiveness, Satisfaction, Immersion, and Accessibility; using a 5-point Likert scale.

2. *VR/Lecture/Hands-on Motivational survey*: This section evaluated six categories – Interest/Enjoyment, Perceived Competence, Perceived Choice, Effort/Importance, Pressure/Tension, and Value/Usefulness; using a 7-point Likert scale.

3. *Open Comments*: Students could provide feedback on positives, negatives, and suggestions regarding the session.

To ensure reliable responses, Cronbach's Alpha (Cronbach, 1951; Gliem & Gliem, 2003) was used, with interpretations based on George & Mallery (2002) thresholds (≥ 0.9 excellent, ≥ 0.8 good, ≥ 0.7 acceptable, ≥ 0.6 questionable, ≥ 0.5 poor). The full questionnaires are provided in the Appendix section.

4.2.4 Outreach approach

The outreach program followed a structured schedule: early morning setup, student gathering and briefing, program initiation, and survey data collection (Fig. 4.3). Equipment deployed included four HMDs (Oculus Quest 2, Meta Quest 2, and two Meta Quest 3 units) supported by an Oculus Link and three third-party link cables. Four PCVR workstations (MSI GS65, HP OMEN, ASUS ROG Zephyrus G14, and HP ZBook Firefly 14 G8) were used, each running Windows OS with integrated CPUs and GPUs.

Figure 4.3. Pictures of the VR outreach session. a) students gathering for outreach briefing b) example of a VR workstation c) outreach staff setting up VR stations d) students at the VR stations e) the survey station

The VR sessions were conducted based on the prepared floorplan (Fig. 4.4). Each session lasted 55 minutes, allowing for three rotations between the three sessions to fit within a total timeframe of 165 minutes. The setup comprised four VR stations, a survey station, and a waiting area. Students were divided into four rows, with each experiencing the VR lecture for approximately five minutes before completing the surveys at the survey station (10 minutes). Those that completed the task moved to the waiting area.

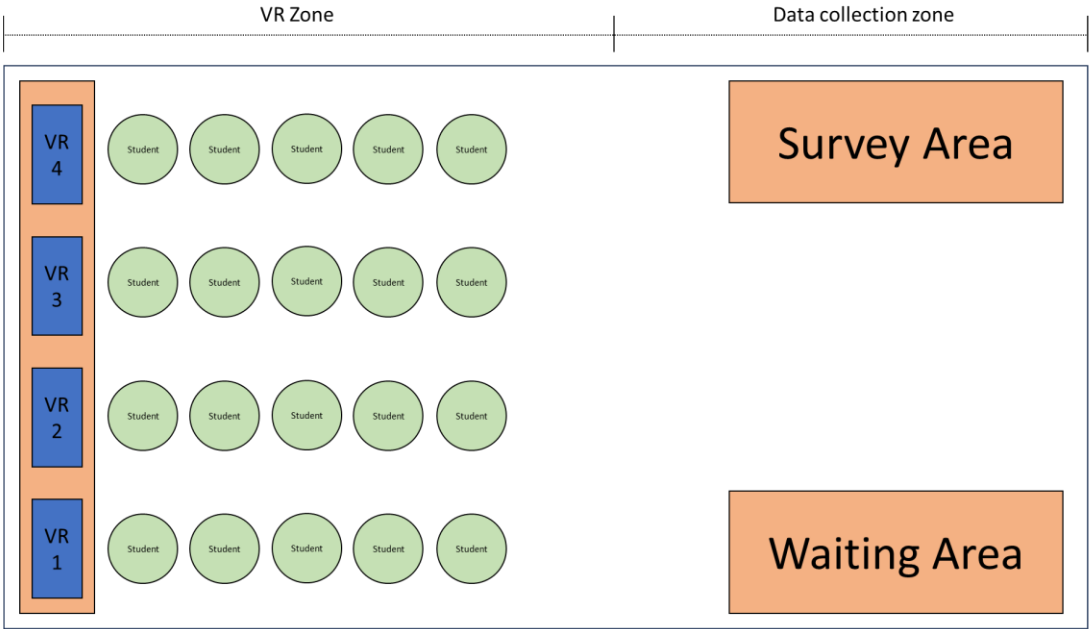

Figure 4.4. The floorplan for the VR outreach program

For other lecture and hands-on sessions, the structure is 40 minutes allocated to activities or lectures and 15 minutes for surveys and transitions. This schedule enabled efficient coverage of all three grades within the allotted time, ensuring a streamlined outreach program.

4.3 Results

4.3.1 VR lecture Usability

The overall Cronbach's alpha value for VR usability was at 0.90, indicating excellent reliability. The VR lecture usability survey results were as follows (Table 4.1):

- Comfortability: Scored 3.81 (Standard Deviation (SD) = 1.23), reflecting a positive (reverse coded) outcome. This suggests that students disagreed with feeling discomfort during the 5-minute VR lecture.
- Effectiveness: Scored 4.01 (SD = 0.83), indicating a positive outcome. Students agreed that the VR lecture was easy to use and helped them understand the landslide and the author's research.

- Satisfaction: Scored 4.45 (SD = 0.86), showing an overwhelmingly positive outcome. Students strongly agreed they were satisfied with the VR experience, enjoyed it, and would recommend it to others.
- Immersion: Scored 3.99 (SD = 1.03), resulting in a positive outcome. Students agreed they felt immersed in the experience and wanted to continue beyond the time limit.
- Accessibility: Scored 4.03 (SD = 0.93), demonstrating a positive outcome. Students agreed the VR application provided sufficient support and was easy to use, regardless of prior VR experience.

Table 4.1. *VR Usability Result of Middle School Students*

Subscale	G6 score		G7 score		G8 score		Total score	
	M	SD	M	SD	M	SD	M	SD
Comfortability	3.88	1.31	3.65	1.39	3.94	1.00	3.81	1.23
Effectiveness	3.84	1.05	4.18	0.71	3.97	0.70	4.01	0.83
Satisfaction	4.34	1.24	4.56	0.62	4.41	0.64	4.45	0.86
Immersion	4.00	1.37	4.00	0.93	3.97	0.79	3.99	1.03
Accessibility	3.78	1.10	4.23	0.97	4.03	0.65	4.03	0.93

Note. G = Grade; M = Mean; SD = Standard Deviation

4.3.2 Motivational Results

The overall Cronbach's alpha value for the VR lecture motivational survey was at 0.88, indicating good reliability. The survey results are summarized below (Table 4.2):

- Interest/Enjoyment: Scored 6.18 (SD = 1.27), indicating an overwhelmingly positive outcome. Students strongly agreed that the VR activity was interesting and enjoyable.

- Perceived Competence: Scored 4.97 (SD = 1.41), showing a slightly positive outcome. Students slightly agreed they understood the session, felt confident in their knowledge, and believed they performed better than their peers.
- Perceived Choice: Scored 5.50 (SD = 1.45), resulting in a positive outcome. Students agreed they participated willingly and felt a sense of freedom during the activity.
- Effort/Importance: Scored 4.44 (SD = 1.61), indicating a slightly positive outcome (effort item reverse coded). Students slightly agreed they put effort into the session and found the activity meaningful.
- Pressure/Tension: Scored 4.92 (SD = 1.92), showing a slightly positive outcome (both item reverse coded). Students slightly disagreed that the activity caused tension or anxiety.
- Value/Usefulness: Scored 5.23 (SD = 1.36), reflecting a slightly positive outcome. Students slightly agreed the activity was valuable for their future and useful for enhancing geological knowledge, improving their motivation in geoscience.

Table 4.2. *VR Motivational Results of Middle School Students*

Subscale	G6 Score		G7 Score		G8 Score		Total Score	
	M	SD	M	SD	M	SD	M	SD
Interest/ Enjoyment	5.71	1.93	6.42	0.72	6.33	0.79	6.18	1.27
Perceived Competence	4.27	1.54	5.37	1.33	5.16	1.14	4.97	1.41
Perceived Choice	5.44	1.93	5.78	1.21	5.26	1.15	5.50	1.45
Effort/ Importance	4.53	1.61	4.45	1.72	4.33	1.51	4.44	1.61
Pressure/ Tension	4.50	2.20	5.35	1.86	4.81	1.65	4.92	1.92
Value/ Usefulness	4.81	1.68	5.62	1.15	5.19	1.13	5.23	1.36

Note. G = Grade; M = Mean; SD = Standard Deviation

The overall Cronbach's alpha value for the lecture session was at 0.86. Indicating good reliability. The survey results are summarized below (Table 4.3):

- Interest/Enjoyment: Scored 5.39 (SD = 1.36), indicating a positive outcome. Students agreed the lecture was interesting and enjoyable.
- Perceived Competence: Scored 4.67 (SD = 1.44), showing a slightly positive outcome. Students slightly agreed they understood the session, felt confident in their knowledge, and believed they performed better than peers.
- Perceived Choice: Scored 4.86 (SD = 1.15), resulting in a slightly positive outcome. Students slightly agreed they participated willingly and felt some freedom in their choices.
- Effort/Importance: Scored 4.45 (SD = 1.48), indicating a slightly positive outcome (effort item reverse coded). Students slightly agreed they invested effort and found the activity meaningful.
- Pressure/Tension: Scored 5.10 (SD = 1.57), showing a slightly positive outcome (both item reverse coded). Students slightly disagreed that the session caused tension or anxiety.
- Value/Usefulness: Scored 5.18 (SD = 1.51), reflecting a slightly positive outcome. Students slightly agreed the lecture was valuable for their future and useful for enhancing geological knowledge, improving their motivation in geoscience.

Table 4.3. *Lecture Motivational Results of Middle School Students*

Subscale	G6 Score	G7 Score	G8 Score	Total Score

	M	SD	M	SD	M	SD	M	SD
Interest/ Enjoyment	5.46	1.21	5.52	1.20	5.19	1.62	5.39	1.36
Perceived Competence	4.80	1.65	4.80	1.19	4.40	1.46	4.67	1.44
Perceived Choice	5.03	1.08	5.03	1.23	4.53	1.08	4.86	1.15
Effort/ Importance	4.92	1.56	4.55	1.48	3.89	1.23	4.45	1.48
Pressure/ Tension	4.58	1.86	5.75	1.19	4.89	1.43	5.10	1.57
Value/ Usefulness	5.39	1.52	5.23	1.32	4.91	1.66	5.18	1.51

Note. G = Grade; M = Mean; SD = Standard Deviation

The overall Cronbach's alpha value for the hands-on session was at 0.95, demonstrating excellent reliability. On a 7-point Likert scale, the survey results are as follows (Table 4.4):

- Interest/Enjoyment: Scored 5.40 (SD = 1.27), indicating a positive outcome. Students agreed the hands-on activity was interesting and enjoyable.
- Perceived Competence: Scored 4.95 (SD = 1.25), showing a slightly positive outcome. Students slightly agreed they understood the session, felt confident in their knowledge, and believed they performed better than peers.
- Perceived Choice: Scored 4.91 (SD = 1.33), resulting in a slightly positive outcome. Students slightly agreed they participated willingly and felt some freedom in their choices during the hands-on.
- Effort/Importance: Scored 4.51 (SD = 1.61), indicating a slightly positive outcome (effort item reverse coded). Students slightly agreed they invested effort and found the activity meaningful.

- Pressure/Tension: Scored 4.91 (SD = 1.77), showing a slightly positive outcome (both item reverse coded). Students slightly disagreed that the session caused tension or anxiety.
- Value/Usefulness: Scored 5.21 (SD = 1.11), reflecting a slightly positive outcome. Students slightly agreed the hands-on activity was valuable for their future and useful for enhancing geological knowledge, improving their motivation in geoscience.

Table 4.4. *Hands-on Motivational Results of Middle School Students*

Subscale	G6 Score		G7 Score		G8 Score		Total Score	
	M	SD	M	SD	M	SD	M	SD
Interest/ Enjoyment	5.39	1.50	5.73	1.07	5.07	1.18	5.40	1.27
Perceived Competence	5.18	1.45	4.95	1.21	4.73	1.07	4.95	1.25
Perceived Choice	4.97	1.53	5.48	1.30	4.18	0.67	4.91	1.33
Effort/ Importance	4.58	1.80	4.58	1.65	4.37	1.35	4.51	1.61
Pressure/ Tension	4.18	2.04	5.83	1.22	4.50	1.57	4.91	1.77
Value/ Usefulness	5.39	1.23	5.35	1.04	4.79	0.92	5.21	1.11

Note. G = Grade; M = Mean; SD = Standard Deviation

4.3.3 Open comments

The open comments provided valuable insights into the positive and negative traits of each session as perceived by the participants. Not to be mistaken for concrete frequency data pertaining these traits but only what was noticeable and mentioned by the participants. Students' feedback ranged from single words to more detailed responses, which required the author to code them individually according to a keyword-based guideline (Table 4.5). The frequency of responses for each code reflects the traits that were most mentioned, highlighting the strongest impressions of the sessions. While even a single mention indicates a positive or negative trait, the most frequently cited elements point to the most prominent experiences of the participants.

Table 4.5. *Coding procedure based on keywords*

Code	Example keywords
Accessibility	Difficulty, freedom, mobility, clarity, familiarity
Content	New knowledge, examples, materials, chapters, 3D materials, information, explanation, summary page, figures
Discomfort	Sickness, eye pain, cumbersome
Engagement	Style, fun, interesting, cool, enjoyable, satisfying, entertaining, interactive, positivity, delivery
Immersion	Presence, realism, visuals
Inaccessibility	Difficulty, lack possession, confusion, difficulty, equipability
Insufficient content	Lack content, simplicity, lack pictures, lack activity, lack explanation
Interaction	Hands-on, classroom interaction
Management	Distractions, lack instructions
Novelty	New experience, unique
Poor Engagement	Zoning out, boring, awkward, lack of interactions, lack participation, sitting, lack freedom, repetitive, passive
Technical Issues	Audio, bugs, glitches, lagging
Technology	VR device, drone
Time	Time limit, waiting time, long speech, long lecture
Value	Experience, usefulness, exposure

In terms of positive aspects, the VR session received the most positive feedback for its engagement, followed by the content, immersion, technology, accessibility, novelty, and interaction (Table 4.6). The lecture session was most appreciated for its content, with engagement, accessibility, value, and interaction also receiving positive mentions. Similarly, the hands-on session was praised for its content, engagement, and interaction, followed by technology, accessibility, and value. The primary takeaway from the VR session was its ability to engage students, while the lecture and hands-on sessions were most valued for their content.

Table 4.6. *Open comments on positive aspects of the sessions*

Code	VR (from 47 response)	Lecture (from 45 response)	Hands-on (from 37 response)
Accessibility	4	10	2
Content	11	28	22
Engagement	32	17	12
Immersion	8	0	0
Interaction	2	3	10
Novelty	3	0	0
Technology	7	0	8
Value	0	4	1

On the other hand, the negative aspects identified in the feedback revealed areas for improvement. For the VR session, the most frequently mentioned negative aspects included technical issues, discomfort, inaccessibility/management, insufficient content, and time constraints (Table 4.7). For the lecture session, the main concerns were inaccessibility, poor engagement, insufficient content, and time limitations. The hands-on session received similar negative feedback, with inaccessibility, poor engagement, and insufficient content being the most common complaints. The key negative issue for the VR session was the presence of technical problems, while the lecture and hands-on sessions were predominantly affected by accessibility challenges.

Table 4.7. *Open comments on negative aspects of the sessions*

Item	VR (from 30 response)	Lecture (from 26 response)	Hands-on (from 13 response)
Inaccessibility	5	13	8
Insufficient content	3	4	1
Discomfort	7	0	0
Management	5	0	0
Poor Engagement	0	10	4
Technical Issues	13	0	0
Time	2	2	0

4.4 Discussion

4.4.1 VR usability impacts

Overall feedback on VR-related discomfort was positive (Table 4.1), with most middle school students reporting no significant issues during the 5-minute lecture. However, seven students experienced discomfort, including eye strain, headset heaviness, and motion sickness (Table 4.7). Motion sickness, or cybersickness, is a known challenge in VR adoption (Chang et al. 2020; Chattha et al. 2020; Keshavarz et al. 2011). The positive experience likely resulted from the short lecture duration, minimal movement, simple design, and optimized performance, all of which could have reduced discomfort triggers. Previous studies indicate that longer sessions, complex tasks, and unrealistic locomotion increase motion sickness risk due to sensory conflict (Dużmańska et al. 2018; Reason & Brand, 1975; Saredakis et al. 2020). By keeping the experience brief and straightforward, these issues were effectively minimized.

The effectiveness of the VR experience received positive feedback (Table 4.1), with students finding it easy to use, navigate, and effective for learning geoscience topics. The lecture was designed to be simple and time-efficient, requiring minimal interaction; students only needed to stand, look, and listen. Open comments confirmed that students gained new knowledge, with 3D models being particularly helpful for understanding and visualizing discussed concepts (Table 4.6). Research on penetrative thinking (Bagher et al. 2020) and spatial abilities (Gittinger & Wiesche, 2024) supports that VR can benefit low spatial ability learners. Therefore, strategically designed VR lectures with 3D models can enhance geoscience teaching and improve learning effectiveness.

The satisfaction category received overwhelmingly positive feedback, with students across all grades enjoying the VR experience (Table 4.1). Open comments emphasized the excitement of learning geoscience in an engaging way, enhanced by a variety of 3D geological examples (Table 4.6). Similar positive responses to VR in educational settings have been reported across age groups, from high school to university (Graebling et al. 2024; Visneskie et al. 2020; Yamauchi et al. 2022). These findings compliment those literatures, suggesting that VR is well-received by students, even at the middle school level.

The immersion category also received positive feedback, with students feeling absorbed and expressing a desire for longer VR sessions (Table 4.1). The VR lecture's immersive design, featuring a scripted virtual lecturer, detailed 3D content, and animations, likely enhanced this effect. Students highlighted the visuals, sense of "being there," and freedom of movement as key contributors to their sense of immersion (Table 4.6). Similar findings have been observed in geological VR research, including simulations, role-playing, and visualization (Alene et al. 2024a; Graebling et al. 2024; Klippel et al. 2019). These results support that VR effectively immerses students, fostering a sense of presence with the geoscience content.

The accessibility category received positive feedback, with students finding the VR lecture easy to use despite having no prior experience. The simple tutorial (hypothesized to pose some difficulties for students), featuring a single panel with basic instructions (Fig. 4.1a), was generally sufficient, though G6 students were more neutral, possibly needing additional guidance or time to consult it. Some negative feedback pointed to the tutorial's simplicity and lack of detail (Table 4.7). This aligns with literatures that had outline the need for a robust familiarization phase (Harknett et al. 2022; Papadopoulou et al. 2022; Wright et al. 2023). While the current tutorial was adequate for most of the students, improvements for younger audiences, like G6, are recommended. Future studies should explore ways to enhance the tutorial or familiarization process for younger audiences.

Overall, the VR usability of this VR lecture experience was positive with a strong level of satisfaction. With rooms for improvements for discomfort, effectiveness immersion, and accessibility to obtain a stronger opinion.

4.4.2 VR motivational impacts

The VR session outperformed the lecture and hands-on sessions in Interest/Enjoyment, receiving overwhelmingly positive feedback (Table 4.2, 4.3, and 4.4). Its immersive 3D content and interactive experience led to strong engagement, with no reports of poor engagement. This aligns with similar studies in geoscience education (Graebling et al. 2024; Visneskie et al. 2020). However, critiques of the VR session primarily focused on its limited duration. Lectures and hands-on sessions were praised for content delivery, with lectures benefiting from teacher interaction and hands-on sessions excelling in interactivity. Traditional methods, however, faced issues like poor engagement and excessive session length (Table 4.7), which could induce boredom (Mann & Robinson, 2009). While VR's immersion is effective for engagement, the novelty may diminish with repeated use, warranting further studies.

All sessions showed slightly positive outcomes in Perceived Competence, with no significant preference among students (Table 4.2, 4.3, and 4.4). Likely, VR's 3D models and immersive content supported comprehension and spatial reasoning (Bagher et al. 2020; Gittinger & Wiesche, 2024). Students reported that VR aided mental visualization of geological concepts, though the absence of subtitles, lack of interactivity, and fast pacing affected younger students (G6). Lectures achieved positive outcomes for their content and clarity, but some students desired more in-depth clarifications. Hands-on sessions benefited from interactive 3D models and drones but occasionally struggled with complex content. To improve confidence and comprehension, the VR activity could incorporate aiding elements (e.g. subtitles), interactive features, and slower pacing, while adjusting content based on grade level.

Perceived Choice was rated positively for all sessions, with VR slightly outperforming others (Table 2, 3, and 4). Students appreciated VR's novelty and the freedom to explore models from different angles. Individual presence in virtual worlds can foster a sense of freedom and agency, allowing users to explore and interact with objects in ways impossible in the physical world (Chirico et al. 2018). Lectures offered interaction with instructors, and hands-on sessions excelled in exploration and drone demonstrations. VR's lower score in this category stemmed from limited content, non-interactive models, and short session durations, compounded by having only four VR stations. VR's high cost could limit classroom implementation if resources are scarce. Nonetheless, VR's immersive environment provided a unique sense of autonomy, motivating engagement and fostering independence. Longer, more interactive sessions are recommended, possibly by increasing VR workstation availability.

All sessions received slightly positive outcomes for Effort/Importance, indicating slight importance without being too effort demanding (Table 4.2, 4.3, and 4.4). VR was praised for simplifying content with 3D materials but may have been seen more as a fun tool than a serious learning medium, reducing its perceived importance (Table 4.6). However, this fun factor may be important as it will encourage exploration which could lead to a feeling of self-ownership in learning (Paige et al. 2024). Lectures were appreciated for clear explanations and future potential relevance, while hands-on sessions excelled in interactivity but likely required more effort to understand the small-scale geology models. Emphasizing educational value in VR and incorporating more detailed interactive elements could enhance perceived effort and relevance.

Pressure/Tension outcomes were slightly positive across all sessions, reflecting minimal stress or anxiety (Table 4.2, 4.3, and 4.4). VR's immersive environment and low complexity may contribute to a relaxed experience, this aligns with research on virtual presence (Pavic et al. 2023). However, issues like peer interference and the 5-minute time limit occasionally caused frustration. Lectures and hands-on sessions benefited from engaging materials and supportive instructors, though content density with complexity could have contribute to increased perceived tension. Addressing timing, peer distractions, and content difficulty may reduce pressure and improve the perception of the VR lecture.

Finally, all sessions scored slightly positive for Value/Usefulness, with students recognizing benefits in geoscience knowledge and motivation but not finding them highly impactful (Table 4.2, 4.3, and 4.4). VR was praised for enhancing visualization of landslides through 3D models, but the short duration and limited real-world applications diminished its impact. Lectures were valued for content and clarity, while hands-on sessions excelled in interactivity. The entertainment-oriented perception of VR, stemming from its origins in the entertainment industry (Havenith et al. 2019; Hornsey & Hibbard, 2024), may have influenced their perception outcomes. Future studies should connect geoscience concepts to practical applications and try to extend VR session durations to increase perceived value and usefulness.

4.4.3 VR architecture and pedagogical value

VR offers the unique capability to present geoscientific content in fully immersive 3D formats (e.g., photospheres, scaled models, and dynamic-realistic perspectives which are difficult or impossible to replicate in traditional classroom settings). This enables both a new type of experiential (Kolb, 1984) and embodied learning (Johnson-Glenberg et al., 2014): the former by virtually transporting students to field sites that would otherwise be inaccessible or unsafe (unlocking accessibility to younger audience for such type of learning), and the latter by allowing students to engage physically with content through bodily movement and interaction, which is typically restricted in conventional lecture formats.

As discussed in previous sections, VR significantly enhances a student's sense of autonomy and elevates interest in geoscientific topics. Unlike standard slide-based lectures that restrict interaction, VR allows learners to dictate their own learning experience by providing avenues for independent self-exploration, data manipulation, and content immersion in ways that satisfies their curiosity, which may bolster their increased engagement and motivation (Makransky & Lilleholt, 2018). The lack of embodied experience and independence in traditional classrooms may, in part, likely explain the reduced engagement observed in such settings.

Student feedback further supports this. Several participants reported a sense of boredom during traditional lectures due to the passive nature of the experience. This was reflected in an average interest/enjoyment Likert score of 5.39. While hands-on sessions involving physical tools like drones and hand specimens slightly improved the score to 5.40, the interactive possibilities remained limited: hand models can be observed but not manipulated beyond basic handling, and drones are restricted to flight and visual observation.

In contrast, VR enables tailored learning experiences aligned with specific educational goals. For example, hand specimens can be scaled to life-size or beyond, allowing students to virtually examine landslide features in situ, or magnified for students to observe microscopic structures, such as the porosity of pumice (e.g. Chapter 4). While 2D media such as videos and images can support learning to some extent, they lack the immersive niche that only VR can conveniently provide such as depth perception and spatial interactivity. According to Dede (2009), immersion enhances education by enabling participants to experience multiple perspectives, fostering situated learning, and promoting transfer of knowledge. In contrast, 2D content operates within a fundamentally flat, pseudo-3D framework, which fails to capture the inherently three-dimensional nature of geoscientific phenomena which limits well-rounded learning.

Thus, integrating VR into geoscience curricula is not merely beneficial but essential for aligning educational practices with the interactive and spatial demands of the discipline.

In order to clarify the originality and pedagogical value of the VR lecture, it is important to describe the specific content that distinguishes it from conventional teaching formats. In our approach, students engaged with a curated VR lecture supplied with VR geoscientific material regarding the landslide in Atsuma. They were able to move freely within the scene, examine the geoscience content (photosphere, 1:1 scale landslide, rock specimen models, animated geoscience content) from different perspectives, and observe the VR lecturer giving a talk about the content.

In contrast, the traditional lecture presented similar related content regarding the landslide through 2D content (photos/videos). Similarly, while hand models were showcased in the classroom, the VR session allowed for the visualization of dynamic VR geoscience content. These content-specific affordances of VR correlated with open-ended student feedback emphasizing “realism,” “being inside the site,” and “seeing the rock up close.” Such responses reflect the embodied spatial learning that VR enables, and which is difficult to achieve through physical specimens or 2D slides alone. Therefore, the advantage of VR is not only in engagement, but in the precise alignment of content delivery with geoscientific learning goals, particularly for topics that require spatial reasoning, contextual awareness and 3D thinking abilities.

4.4.4 Advantages and disadvantages of the VR lecture

From the study it revealed that there are several advantages and disadvantages of delivering VR lectures in a school setting most evident from the open comment entries by the participants (Table 4.6 & Table 4.7) and the results of the survey (Table 4.1, 4.2, 4.3, & 4.4).

The project demonstrated VR's advantages for geoscience education. The fast-paced VR lecture was enough to engage middle school students showcasing its ability to attract and motivate effectively. Its short duration minimized VR-related discomfort. Its immersive nature offered a safe exploration of hazardous sites, enhanced understanding through 3D models, and bridged abstract and practical concepts not easily achievable through traditional means. Additionally, the novelty of VR technology in the geoscience curriculum excited and appealed to the students, while the freedom to explore the virtual environment, including free-roaming capabilities and interaction with the VR system, further enriched their learning experience.

Despite its strengths, the VR lecture presented several challenges. Although majority of students did not experience discomfort, there were still some that did (e.g., motion sickness, eye strain, HMD weight), and technical issues like individuals changing audio on shared headsets, glitches, and lag were common. VR experience can also vary depending on the developers' expertise, time, and budget, posing a potential challenge for standardized implementation. VR is also not yet widely adopted in current educational settings and requires time for users to learn the system for efficient usage. High costs limit headset availability, necessitating shared use, which leads to shorter sessions and extended wait times. Addressing these issues requires thoughtful planning, resources, and financial support especially considering implementation for geoscience education.

The time and cost factor may be a significant barrier for the global adoption of VR lectures in geoscience education, although it can offer additional benefits that traditional methods often struggle to deliver as discussed (e.g., taking young students to dangerous field sites and various data presentation possibilities). Even if both VR and traditional methods yield similar learning gain in the short term, the long-term impact of VR should be considered as well, such as improved retention, increased motivation, and the ability to intuitively grasp complex spatial relationships of geological subjects, may justify the additional time and cost. Furthermore, as VR development tools for geosciences become more standardized and user-friendly, the initial investment in content creation may be repaid over repeated use, making it a potentially viable long-term educational strategy.

4.4.5 Influence on survey results

The survey results may have been influenced by the session rotation sequence and the students' grade level. The VR outreach sessions were conducted in the order of G6, G8, and G7. While differences between the grades were relatively minor, some patterns emerged. For instance, G6 generally reported slightly lower usability and accessibility scores compared to G7 and G8. Satisfaction ratings for G6 averaged 4.34 on the Likert scale, compared to 4.56 for G7 and 4.41 for G8 (a difference ranging from 0.07 to 0.22). Similarly, accessibility ratings were 3.78 (G6), 4.03 (G7), and 4.23 (G8), with a Likert score gap of 0.25 to 0.45.

These differences may be partially attributed to the early start time of the session (9:00 a.m.), which could have affected the students' alertness and engagement. Research suggests that adolescents and pre-adolescents exhibit reduced cognitive performance during early morning hours due to their sleep-wake cycles (Wolfson & Carskadon, 1998). Additionally, developmental differences in their cognitive maturity may likely explain why G6 students found the fast-paced session more challenging. According to the theory of cognitive development, younger students are generally less adept at formal operational thinking than their older peers (Piaget, 1972), which can impact their ability to adapt to immersive technologies. More recent work also confirms that cognitive processing and executive function continue to mature across early adolescence (Kuhn, 2009).

For example, in the "pressure/tension" metric, G6 reported a lower score of 4.18, compared to 5.83 for G8 and 4.50 for G7. The fast-paced format, combined with the early morning hours, may have presented greater cognitive and emotional demands for younger students.

However, these interpretations remain speculative due to the small sample size within each grade level, which limits the statistical robustness of the findings. Future studies with larger and more balanced samples are necessary to draw firmer conclusions. Given these limitations, the aggregate student feedback across all grades is considered a more reliable indicator of the overall impact of VR technology on middle school learners. As emphasized in usability studies of VR in education, factors like satisfaction and accessibility must be interpreted carefully, especially when introducing immersive tools to younger or less knowledgeable populations (Jensen & Konradsen, 2018).

4.5 Conclusions

This study developed a 5-minute, fast-paced, automated VR lecture to evaluate its usability and motivational impacts on international middle school students learning geological topics. To the best of the author's knowledge, it is the first known attempt to assess VR-based geoscience lectures for this demographic, it also showcases an efficient method for gathering substantial data within a limited timeframe. Results demonstrated that the VR lecture was usable, with students reporting high satisfaction levels. Motivational impacts were positive, excelling in fostering interest and enjoyment, and perceived choice. Overall, students showed a clear motivational preference for VR when compared to the traditional teaching methods.

But regardless, there remains for more potential improvements in the VR lecture architecture particularly to further enhancing its usability and motivational aspects. Future research should address the limitations identified in this study to achieve consistently strong verdict across all survey categories. Additionally, insights from challenges in traditional teaching methods can also be used to guide the further refinement of VR implementation in middle school education. This study highlights the potential of VR as a potential platform for engaging diverse audiences and disseminating geoscientific knowledge.

Chapter 5
General discussion

5.1 The emerging role of VR in Geoscience: Potential and Future

Modern immersive VR although gaining traction is currently a relatively niche and infrequently used technology within the geoscience community, largely because it has only recently become accessible to consumers in 2016. As a result, there is a limited range of dedicated tools available for geoscientific purposes. Since modern VR was initially developed for entertainment rather than scientific use (Havenith et al., 2019), there exists a gap in practical, research-oriented applications. Consequently, geoscientists are often left with two options: rely on external developers within the VR industry to produce tools that meet their needs or undertake the challenging task of developing them independently. This has led to a prevalence of prototype-based studies, and, due to the absence of standardized architectures or development frameworks in VR geoscience, progress in the field has been fragmented, inconsistent, and somewhat isolating.

As experienced during the development of the research projects for chapters 3 and 4, there exist no applications that met the specific requirements of the plan, necessitating the development of a custom methodological pipeline to support the thesis's objectives.

VR is frequently cited in the literature to be of a high cost of technology, which may act as a barrier to adoption and development (Cerfontaine et al., 2016; Strzałkowski et al., 2024; Lawton et al., 2024). This raises a critical question, is the investment of time, money, and effort in developing VR applications for geoscience justifiable, especially when similar outcomes may be achieved using conventional 2D tools? In our exploratory studies, significant costs were incurred through the use of multiple VR headsets, VR-ready computers, UASs, specialized software licenses, and field instruments. While more affordable alternatives exist, opting for these may compromise the quality of the development pipeline, potentially reducing the overall effectiveness, user experience, and research output.

That said, immersive VR introduces novel ways to communicate the inherently three-dimensional nature of geoscience concepts especially beneficial for educational settings. It allows for more intuitive and engaging experiences for students and learners, capturing their attention and interest (refer chapter 4, Table 4.2 and Table 4.6) that could have some form of long-term benefit, an area that requires future attention. Additionally, as the field continues to evolve, it holds great potential for further exploration and innovation.

Future work is likely to find more accessible entry points for implementation and research within VR geoscience education and science communication, as these areas are currently the most well-studied and established (Chapter 2). As numerous methodologies have already been trialed for educational purposes, including virtual field trips for geoscience instruction (Spero et al., 2022; Harknett et al., 2022)), public outreach efforts (Skinner, 2020), geohazard training (Alene et al., 2024a; De Lorenzis et al., 2024), and even disaster response simulations (Maragkou et al., 2023).

However, the success of VR applications remains highly domain dependent. Fields involving inherently 3D physical structures or spatial data are more naturally suited to VR implementations. In contrast, disciplines focused on abstract or minuscule processes such as geochemistry or mineralogy may face greater challenges in VR adaptation. While it is technically possible to develop immersive experiences for these areas, the lack of intuitive visual representations and also associated technical works to bring them to realization may hinder further development and adoption.

In our case, technologies like SfM-MVS and LiDAR, which allow for the extraction of 3D morphological features, enabled us to conveniently extract the geometry of the field and emulate it in the VR environment for traditional geological fieldwork within VR (Chapter 4). However, not all subdisciplines have access to similarly compatible data formats (Table 2.2; e.g. Mineralogy/Crystallography). Despite these challenges, we maintain that VR's most compelling value lies in education, where it can be broadly applied across geoscientific domains to enhance the communication of complex concepts. This also highlights the need for continued tool development and innovation tailored to geoscience-specific applications.

5.2 2D vs VR visualization

Immersiveness refers to the extent to which a user feels present and engaged within a virtual environment, often described as the sensation of “being there.” Immersive VR technology can evoke this sensation through features such as a wide field of view, stereoscopic 3D visuals, real-time tracking of user movements, multisensory inputs, and interactive, contextually rich content design. A high level of immersion enhances user engagement, spatial awareness, and cognitive involvement, which can in turn support more effective learning, decision-making, or behavioral outcomes depending on the application (Dede, 2009).

In educational contexts, immersiveness contributes significantly to embodied learning (a pedagogical approach that emphasizes the integration of bodily actions, sensory experiences, and motor functions in the learning process). Rather than viewing learning as purely cognitive, embodied learning acknowledges the importance of the learner’s physical interaction with the environment. In VR this is possible due to the motion tracking technologies integrated to modern VR peripherals, translating human motion and human interaction into the digital VR environment.

For example, in geomorphological education, VR-based exploration offers advantages over traditional 2D interfaces such as Google Maps. Immersive VR can lessen cognitive load by unlocking intuitive spatial understanding while also providing capabilities not possible in the real world (e.g. levitation, movement through solid terrain ("phasing"), unrestricted viewpoints, enhanced safety, and unlimited stamina). These features allow users to explore complex terrain more freely and safely, fostering a sense of autonomy and engagement. As discussed in Chapter 2, this liberation of movement and perspective offers a compelling middle ground between physical fieldwork and passive 2D screen exploration, making VR a powerful tool for geoscience education.

Alternatively, configurations such as projection-based VR systems can also deliver a strong sense of presence and engagement. Systems like CAVE, Uralaa (developed by Forestdigital), and cylindrical-type VR theaters (Tanaka et al., 2022) immerse users in a surrounding display environment that supports collaborative interaction within a shared space. Although these systems may differ from HMDs in terms of sensory isolation and visual depth cues, they still offer high levels of spatial immersion and embodied experience (such as when paired with motion tracking and responsive environments). These alternatives can overcome the social isolating nature of HMDs, fostering better communication, coordination and group learning. As such, the sense of immersion and presence typically associated with VR is not exclusive to HMDs but can also be effectively achieved through well-designed projection-based systems.

5.3 Advantages provisioned by VR technology in Geoscience

The advantages of VR technology benefit both the practical and educational dimensions of geoscience. However, as discussed in Chapter 2, the application of VR in practical geoscientific work remains relatively limited compared to its growing use in socially or educational oriented contexts. This is largely due to the current developmental stage of VR within the geosciences. Conventional methods remain more mature, efficient, and standardized for many practical tasks.

Nonetheless, VR offers unique practical benefits particularly its capacity to support remote field investigations. For example, by creating digital twins using technologies like SfM photogrammetry, users can conduct virtual fieldwork from anywhere in the world. This approach enhances safety and allows unrestricted exploration of geological features, including in terrains that are physically inaccessible, as demonstrated in Chapter 3. The ability to change perspectives freely in VR provides interpretive advantages that are not feasible in real-world settings. Researchers can exploit these capabilities to develop perspective-based analyses, potentially contributing to improved risk assessment and disaster management strategies. Moreover, VR tools can be manipulated intuitively in ways not bound by natural laws, for instance, initiating stasis, and axis locking. This flexibility enables geoscientific studies to achieve a balance between realism and experimental control, offering a hybrid of authenticity and convenience that no other current technology can provide for fieldwork.

From an educational or communicational standpoint, VR holds even greater promise. As supported by the literatures reviewed in Chapter 2, VR is poised to become a cornerstone of future geoscience education. Its immersive, sandbox-like environment, combined with increasingly sophisticated hardware, enables novel forms of experiential learning. VR not only brings 3D geological data to life in engaging ways but also allows for the collection and analysis of human motion data within geoscientific contexts useful, for example, in disaster response training or the refinement of pedagogical strategies. As demonstrated in Chapter 4, VR allowed us to transform traditional teaching methods by enabling students to interact directly with 3D geological concepts. For the first time, field experiences, 360-degree photospheres, and detailed 3D models can be safely and effectively presented to younger audiences. This expands access to field-based learning without exposing students to the inherent dangers of environments like landslides. Such accessibility is especially beneficial for individuals with physical disabilities who might otherwise be excluded from such fieldwork opportunities.

In a broader sense, VR offers a cost-effective alternative for addressing geoscientific objectives related to travel and training. It revitalizes existing research data by enabling their reuse in outreach and public education, and it supports environmental sustainability by reducing the need for travel and its associated carbon footprint. Unlike traditional 2D screens, VR presents objects in true three-dimensional form, enhancing spatial understanding. It also facilitates collaborative exploration and research among geoscientists worldwide. Finally, the immersive nature of VR engages multiple senses, enabling communication that transcends expertise, language, and cultural barriers very important in the present globalized research and educational landscape.

5.4 Insights and innovations from this thesis

This thesis contributes to the growing field of VR in geoscience through three key chapters, each addressing a distinct aspect of VR application.

Chapter 2 investigates the current global landscape of VR technology in geoscience. It examines insights into geographic trends on the use of VR, the strengths and limitations of the technology, and how it is presently being applied within the field. It also identifies the existing boundaries of VR adoption in geosciences, providing a foundation for readers to explore future research directions relevant to their specific subdisciplines.

Chapter 3 focuses on replicating traditional geoscientific fieldwork and interpretative methods using VR. In this study, VR was employed to investigate sedimentary depositional patterns from a landslide triggered during the HEIE 2018, supported by the development of custom VR-based geological field tools. This chapter demonstrates an alternative approach to the prevailing communication-focused VR applications by contributing to a deeper understanding of a relatively overlooked small-scale landslide in Atsuma and supports existing literatures from a

VR-based perspective. Additionally, it offers practical guidance for research practitioners on initiating VR fieldwork approaches.

Chapter 4 pioneers the concept of VR lectures within geoscience education, an area that until now, has largely centered on static 3D data visualization. Unlike studies that have come before, this chapter introduces for the first time a fully immersive VR lecture format tested in a school setting with defined learning objectives. The research shows that VR's capabilities go beyond simple visualization, offering immersive experiences that can enhance user engagement and attentiveness. Given that lectures are a foundational element of educational practice, this chapter explores how VR can enrich traditional teaching formats. It also provides insights into how students at different grade levels interact with geoscience content in VR and highlights areas for improvement in future implementations.

5.5 Limitations of the thesis

It is advised that readers understand the limitations of this work as it will be helpful when using it as a reference.

Chapter 2. Firstly, the review approach may overlook highly niche and specialized subjects. Additionally, limiting the selection to the first search results page may result in the exclusion of relevant articles that could enhance the reliability of this review. To mitigate this, any relating potential publication were extracted from the other search string variations' search results so that the choices are not restricted to that singular page for a particular subdiscipline. Next, some publication titles were ambiguous, making it difficult to determine their relevance to VR in Geoscience, potentially leading to further omissions. This is an issue of terminology standardization (discussed more detailed in chapter 2). Furthermore, access restrictions prevented full-text retrieval in certain cases, limiting the assessment to abstracts and constraining the decision-making process.

The search focused on publications from 2016 onward, aligning with the commercial availability of immersive HMDs. However, earlier VR research, including prototype systems and precursor immersive technologies such as Cave automatic virtual environment (CAVE), may not be fully represented. Many publications also exhibit a hybrid nature, making it challenging to classify them within a single subdiscipline.

Additionally, some degree of selection bias may be present due to the influence by the author's own knowledge of each discipline in the classification process. Finally, the review was limited to English-language publications. For non-English papers, only their English abstracts were considered for analysis.

Chapter 3. A limitation of VR-based interpretation is that it may require further aid through TR fieldwork to truly validate observations, as VR observation quality depends on the quality of the data used for creating the VR environment. While SfM-MVS offers photorealistic textures, low resolution data can result in simplification of mesh geometry that can mis-represent real features, leading to the problem of potential misinterpretations, especially for finer details like cracks or surface roughness. Additionally, VR environments lack dynamic real-life elements, limiting their authenticity as just 3D static snapshots of the field. Although the lack of realism is a significant challenge for this study VR environment, it also serves as a key area of focus for continuous improvement when considering a VR-based approach.

Regardless, VR significantly enhances this study interpretation process by making obscured features more visible through VR visualization (with detailed 3D depth) compared to typical 3D-pseudo representation, enabling the extraction of critical observational data often overlooked in traditional methods. These insights provide essential context for a comprehensive understanding of the landslide phenomena. Additionally, VR's scalability, complete immersion, and vast locomotion freedom improve observational capabilities, allowing for making detailed and accurate interpretations. At present, VR stands as the best effective immersive tool for closely simulating geoscience fieldwork.

Chapter 4. Researcher bias could influence the interpretation of qualitative open comments, despite adherence to coding guidelines (Table 6), as student responses varied from vague to detailed. Furthermore, session delivery styles differed among chairs, potentially affecting student experiences. Additionally, the survey was adapted for a young audience and time constraints, limiting its comprehensiveness; future studies with fewer constraints could address this. Moreover, while the sample was international, it lacked true global representation. These difference in a countries' learning culture may influence how individuals learn (Joy & Kolb, 2009). Also, not all students completed the questionnaire, especially open comment sections, due to factors like unwillingness to provide feedback or logistical issues. Although the VR session had the highest response rate, no session achieved full participation. Lastly, the study's fast-paced design, while efficient for collecting data, compromised survey depth and the VR experience quality, which could have been enhanced with additional time.

Future research should expand the sample to include more countries, capturing cultural differences and offering a broader global perspective. Investigating the perceptions of students with extensive VR experience could provide insights into how familiarity influences outcomes, potentially through repeated exposure experiments to mitigate the novelty effect over time. Another promising avenue is testing VR in multiplayer settings, where students collaborate to learn geological concepts. Additionally, live, teacher-led VR lectures could be compared with scripted formats to explore how educators adapt to VR and how students benefit versus traditional methods. Hybrid approaches combining traditional and VR-based learning also warrant further exploration.

5.6 Recommendation on future studies in fieldwork and education

VR holds significant potential for field-based geoscience subdisciplines, particularly geomorphology, marine geology, petroleum geology, planetary geology, stratigraphy, structural geology, and volcanology. These areas rely heavily on the interpretation of 3D spatial data and geological features. For instance, in Chapter 3, we used photogrammetry to generate a digital twin of the Atsuma landslide, allowing virtual measurements such as dip angles, slope directions, and scarp dimensions. Similar methods can be applied in marine settings to investigate seafloor morphology or underwater faults, and in planetary geology to study the surface features of distant planets. Research by Paige et al. (2024), for example, showed that VR enhances feature recognition of participants simulating a Martian analog. Stratigraphy can benefit from VR by enabling multiple outcrops to be visualized together, improving spatial interpretation and helping geologists correlate discontinuous exposures to produce more accurate regional maps. Petroleum geology can use VR to simulate underwater field environments and integrate 3D seismic data, enhancing well placement strategies and helping identify more locations cap rocks and hydrocarbon boundaries. In volcanology, VR provides a safe way to study active or hazardous volcanic areas by virtually recreating lava flows, deposits, and eruption features that would be difficult or dangerous to observe in person.

Beyond fieldwork, VR lectures offer wide-ranging benefits across all geoscience disciplines by transforming traditional teaching into immersive learning experiences. Complex topics that require spatial reasoning or expert interpretation become more accessible to students. For example, Liang et al. (2019) used VR to help visualize workflows in reservoir engineering, making technical processes easier to understand for participants. Environmental geology can incorporate VR simulations of floods, earthquakes, or fragile ecosystems like peatlands, allowing students to learn without disturbing natural systems. In mining geology, VR replicas of ore bodies and veins can train students in ore identification and mining strategies.

Palaeontology can use VR to preserve fossils in a 3D library, supporting engaging, interactive lectures that explore fossil formation, morphology, and evolutionary patterns. Sedimentologists can demonstrate complex facies models and sequence stratigraphy in immersive cross-sections, enhancing comprehension compared to flat 2D diagrams. Hydrogeology benefits from VR by visualizing underground aquifers, water flow, and water tables (or any hydrogeological concepts that are difficult to convey otherwise). Similarly, mineralogy and crystallography can use VR to illustrate atomic structures, crystal systems, and lattice forms, helping students connect abstract concepts with the mineral properties.

Chapter 6
Conclusion

6 Conclusion

This study explored the potential of VR across multiple dimensions of geoscience. In Chapter 2, a systematic literature review revealed a growing body of VR-related research, with contributions from various geoscientific subdisciplines. However, applications remain domain-specific, and current trends show a stronger emphasis on social and educational uses rather than technical or scientific advancements. Chapter 3 demonstrated VR's practical role in virtual field investigations focusing on emulating traditional geological fieldwork, highlighting its use for data collection, interpretation, and analysis. In Chapter 4, we developed and tested a fast-paced, automated VR lecture in a middle school setting. This was the first ever study on such concepts, and the results showed high usability, strong motivational impact, and positive user satisfaction, underscoring the promise of VR lecture as an efficient method for immersive geoscience education.

Looking ahead, VR holds vast potential to transform how geoscientific knowledge is explored, communicated, and taught. Its ability to immerse, engage, and inform makes it a powerful medium not only for researchers but also for educators and decision-makers. Not only within players in the field but it has the potential to also close the distance between communication and expertise of various fields and most importantly to the public sphere which is quite a challenge in the current scientific dynamic. As the technology matures, it will be up the geoscientists of today to lead its integration into the field, paving the way for a future where learning and discovery may perhaps be much more interactive, inclusive, and impactful than ever before.

List of Findings

VR Geoscience systematic review

- VR has been applied in a wide range of geoscience subdisciplines
- However, at a local scale it remains limited and niche
- Social approaches are more prevalent than practical
- The field is still at its infancy & shows positive growth since 2016
- Publication output is domain dependent

VR landslide fieldwork and interpretation

- The landslide was influenced by transitions in the topography, non-cohesive scarp failures, and tree depositional material
- Presence of Sasa dwarf bamboo rimming the scarp line affects SfM model highly by exaggerating its height
- VR perspective enhanced feature identification and interpretation
- Contributes a supportive VR-based perspective the HEIE 2018 landslide phenomenon & understudied small scale landslide type
- Highlight some possibilities offered by VR in geoscience other than mere visualization and social applications

VR lecture for middle school students

- VR lecture is usable in a school setting
- Advantage in motivating interest and perceived choice
- VR materials supports comprehension and spatial reasoning
- Individual experience elevates feeling of self autonomy and ownership of learning experience
- Observed difficulties of younger students with VR

Fig. 6.1 Summarized list of findings

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Appendix A: Chapter 3 - Supplementary Figures

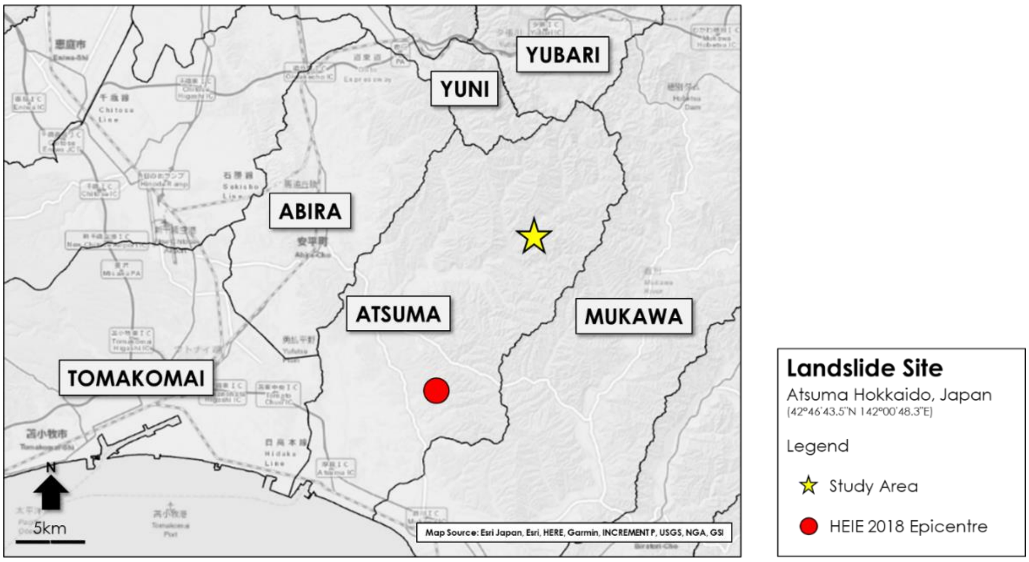

Fig S1. Location of the landslide in Atsuma respective to the earthquake (enlarged image).

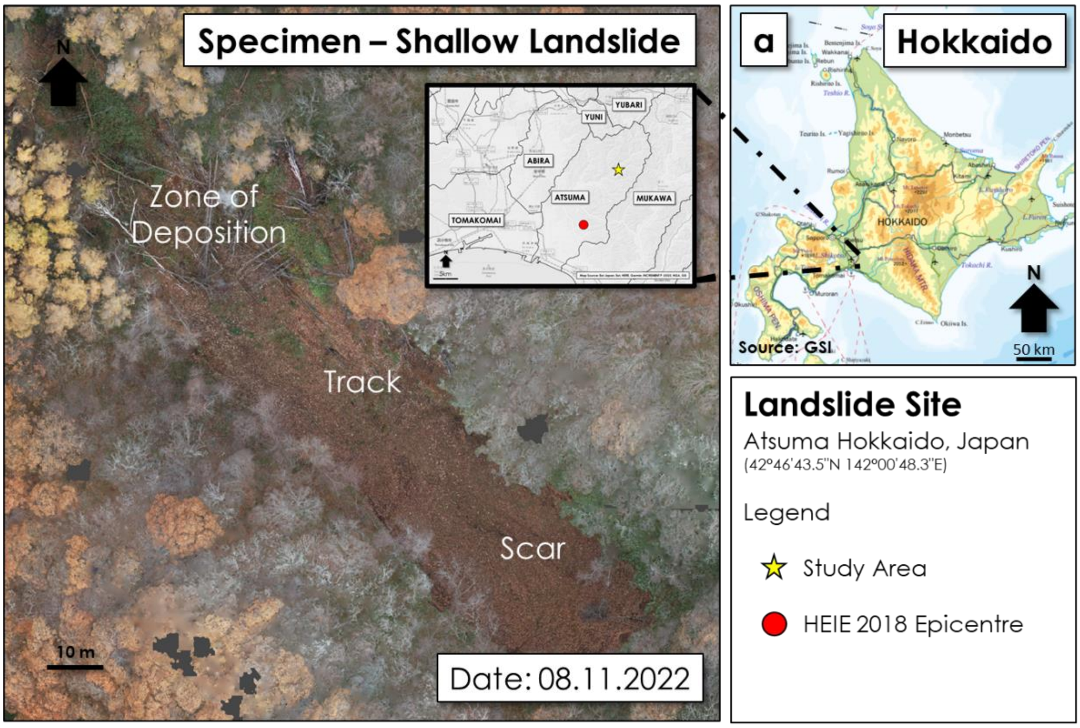

Fig S2. Study site location overview (Autumn 2022)

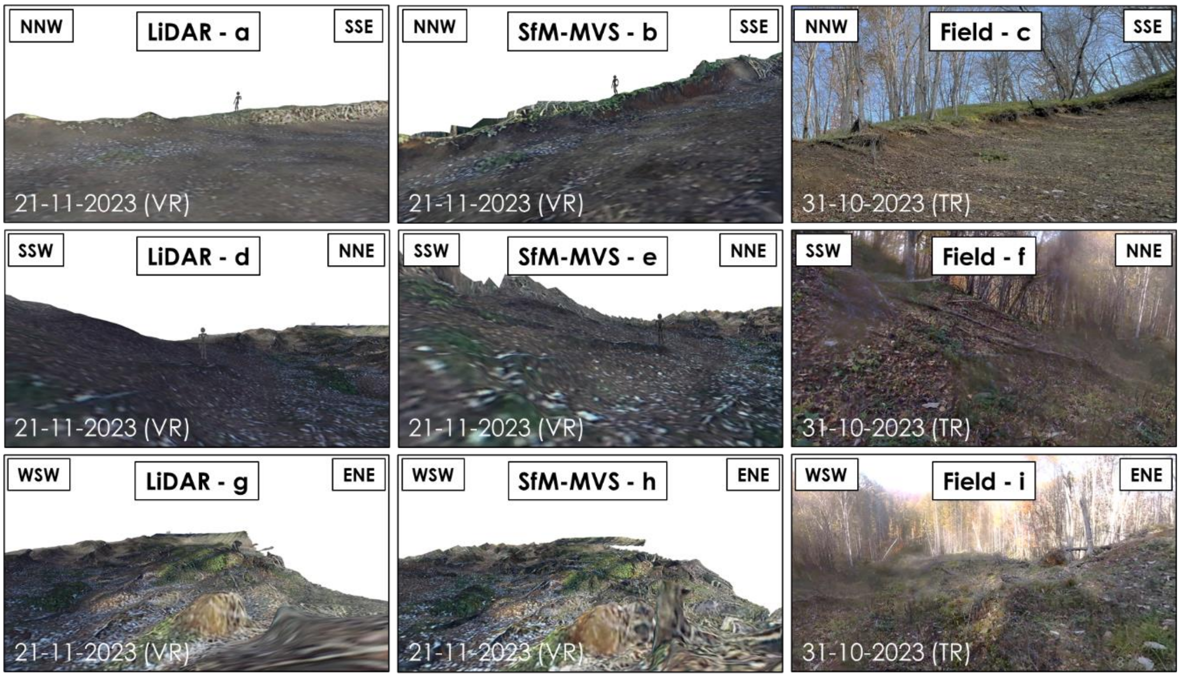

Fig. S3 Observed POIs as seen in VR LiDAR, VR SfM-MVS, and TR field (Autumn 2023 without outlines)

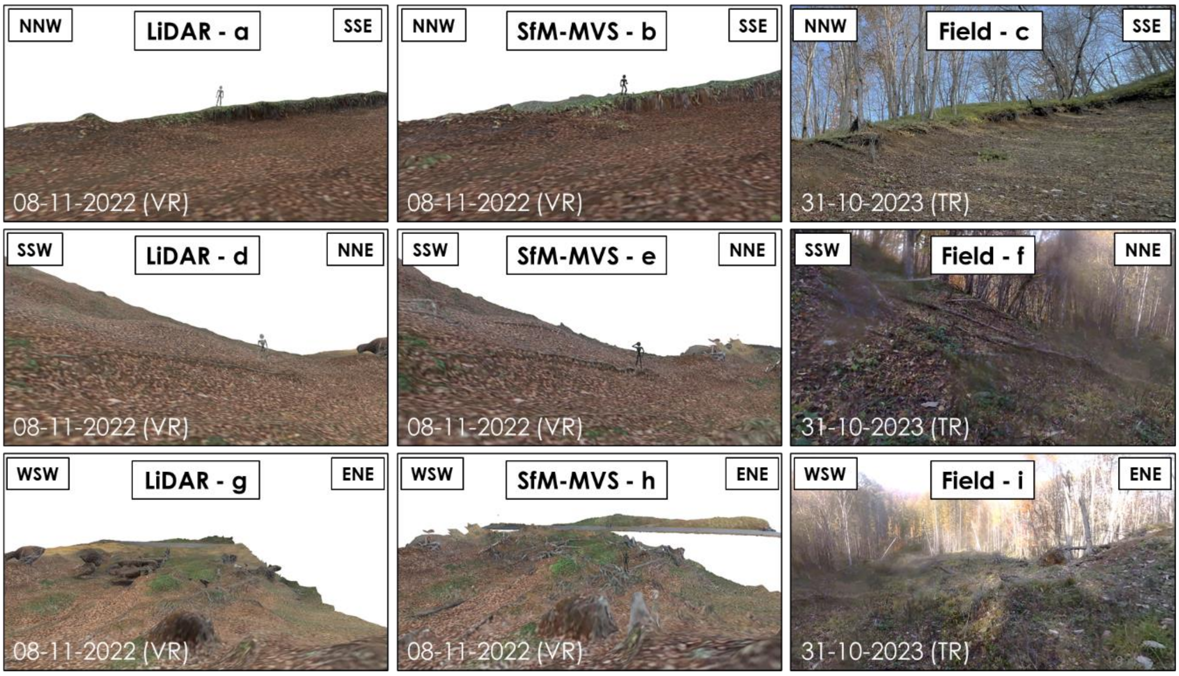

Fig. S4 Observed POIs as seen in VR LiDAR, VR SfM-MVS, and TR field (Autumn 2022 without outlines)

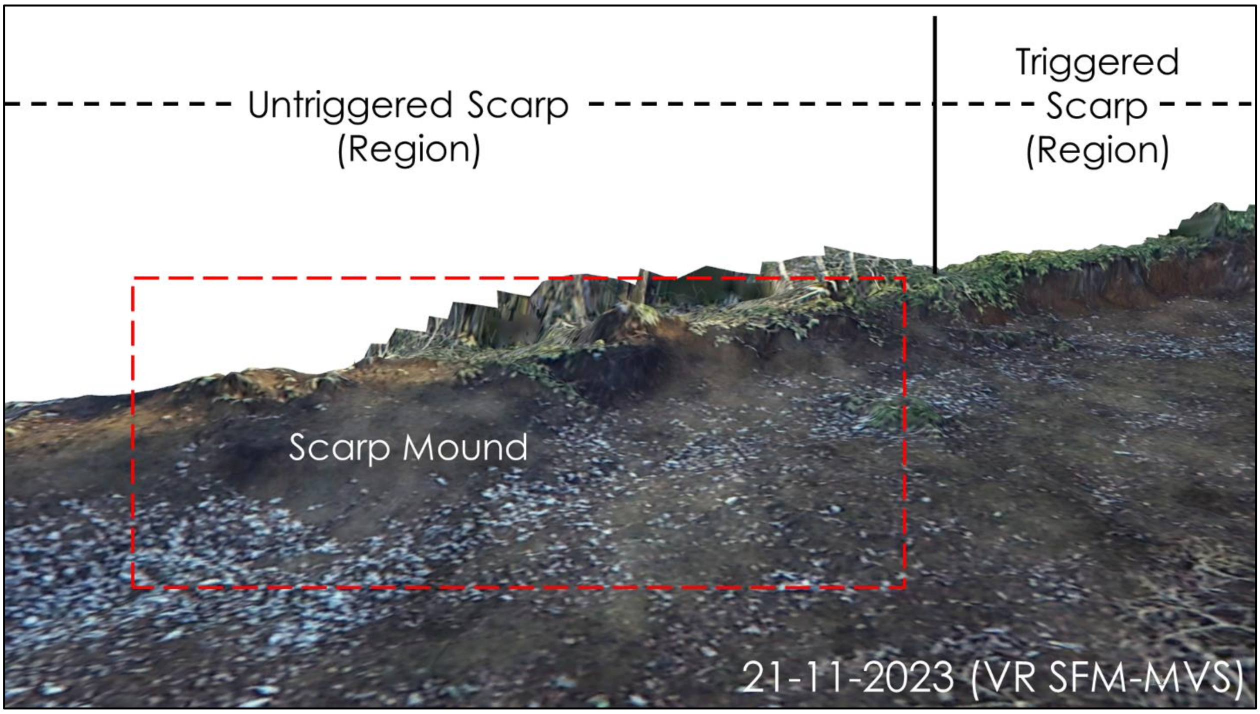

Fig S5. Scarp mound (Autumn 2023)

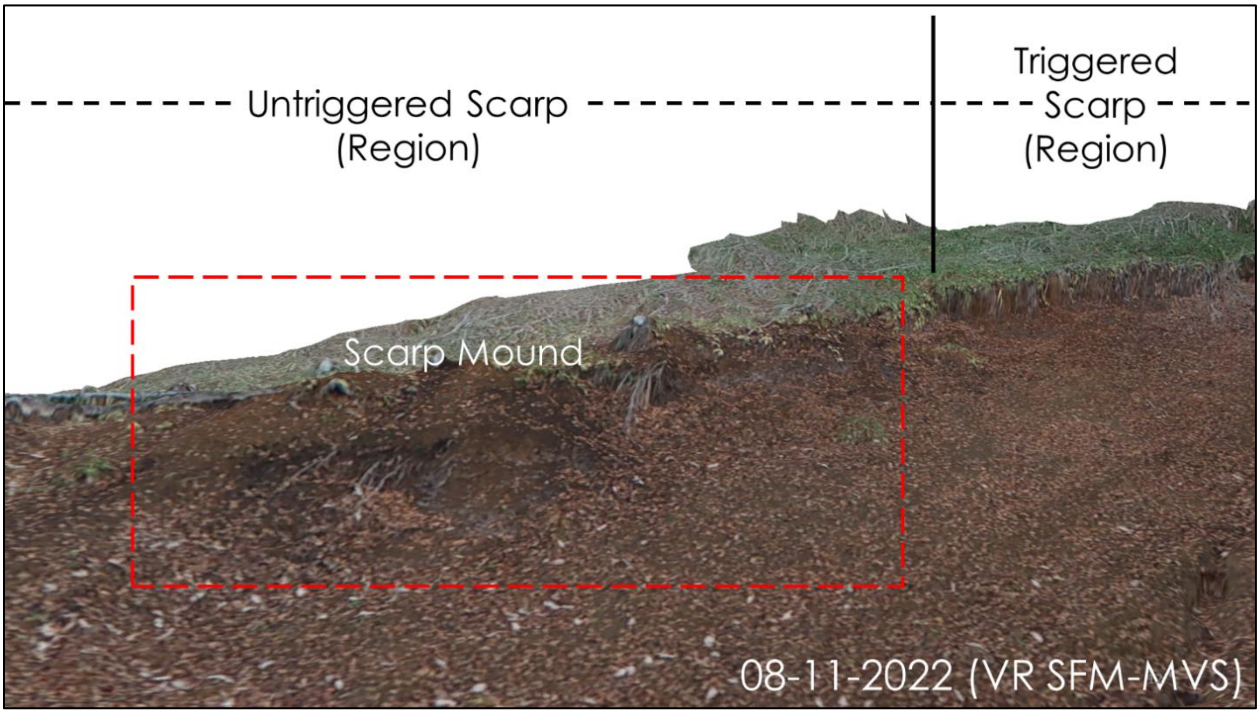

Fig S6. Scarp mound (Autumn 2022)

Slope Angle

Slope ID	Slope TR (°)	Slope VR LiDAR (°)	Slope VR SfM (°)
1	27	33	34
2	26	33	34
3	31	33	34
4	27	33	33
5	38	30	30
6	40	40	38
7	32	37	37
8	36	37	34
9	41	34	34
10	30	32	33

Slope Direction

Slope ID	Slope Direction TR (°)	Slope Direction VR LiDAR (°)	Slope Direction VR SfM (°)
1	263	265	250
2	270	262	270
3	269	270	258
4	272	270	276
5	267	268	292
6	346	345	333
7	354	344	349
8	366	344	365
9	382	368	372
10	353	370	368

Fig S7. Slope angle and direction measurements for VR and TR. VR measurements were taken on 21st November 2023 and TR measurements were taken on 31st October 2023

Scarp Height

Slope ID	Scarp Height TR (m)	Scarp Height VR LiDAR (m)	Scarp height VR SfM (m)
1	0.7	1.3	1.3
2	1	1.4	1.7
3	1.3	1.7	1.8
4	1.1	1.8	1.4
5	0.9	1.5	1.3
6	1.3	1.3	1.6
7	0.8	1.1	2.1
8	0.9	1.6	2.4
9	1.1	1.8	1.9
10	1.3	1.4	1.5
11	0.9	1.0	1.3
12	0.7	1.2	1.3
13	0.8	1.2	1.5
14	1.1	1.3	1.2
15	1.1	1.2	1.6
16	0.6	1.7	1.1
17	0.8	1.3	1.0
18	0.8	1.2	1.3
19	0.7	1.4	1.8
20	1.1	1.2	1.6
21	0.8	1.2	1.8
22	1.2	1.7	1.6
23	1.3	1.5	1.8
24	1.1	1.4	1.5
25	0.7	1.2	1.3

Fig S8. Scarp height measurements for VR and TR. VR measurements were taken on 21st November 2023 and TR measurements were taken on 31st October 2023

Appendix B: Chapter 4 - Usability Survey

Student ID: __________

VR Usability (VR Activity)

For each entry below, **circle the response** that best characterized how you feel about the statement.

Discomfort

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I felt some discomfort (e.g. sickness, eye strain etc.)	1	2	3	4	5

Effectiveness (ease of learning and using)

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
It was easy to use and navigate in VR	1	2	3	4	5
VR helped me understand the landslides and research work conducted in Atsuma better	1	2	3	4	5

Satisfaction

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I was very satisfied with the VR experience	1	2	3	4	5
I would recommend the VR activity to other students	1	2	3	4	5
I liked the VR experience	1	2	3	4	5

Engagement

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I wanted to continue the VR activity beyond the time limit	1	2	3	4	5
During the VR activity, it felt like I was really there	1	2	3	4	5

Accessibility

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The VR application provided sufficient help and support	1	2	3	4	5
I easily understood how to use the features of VR regardless of prior VR experience	1	2	3	4	5

Appendix C: Chapter 4 - Motivational Survey

Student ID: __________

Motivational Survey (__ Activity)

For each entry below, **circle the response** that best characterized how you feel about the statement.

Interest/ Enjoyment

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
The __ activity was fun & entertaining	1	2	3	4	5	6	7
The __ activity was enjoyable & satisfying	1	2	3	4	5	6	7
The __ activity was interesting & appealing	1	2	3	4	5	6	7

Perceived competence

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
I understood majority of the __ session	1	2	3	4	5	6	7
I felt I performed better than my peers	1	2	3	4	5	6	7
I felt more confident and capable about my newly acquired	1	2	3	4	5	6	7

knowledge after the __ activity							

Perceived choice

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
I was involved with the __ activity because I wanted to	1	2	3	4	5	6	7
I felt I had some freedom of choice during the __ activity	1	2	3	4	5	6	7

Effort/Importance

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
I had to put a lot of effort during the __ activity	1	2	3	4	5	6	7
It is important to me to do well during the __ activity	1	2	3	4	5	6	7

Pressure/Tension

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
The __ activity felt tense	1	2	3	4	5	6	7
I felt anxious during the __ activity	1	2	3	4	5	6	7

Value/Usefulness

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
The __ activity will value me in the future	1	2	3	4	5	6	7
The __ session is useful for my geological knowledge	1	2	3	4	5	6	7
This __ experience improved my motivation in Geology	1	2	3	4	5	6	7

Appendix D: Chapter 4 – Open Comments

Student ID: __________

Open entry (__ Activity)

- In your opinion, what are the positive parts of the __ experience?

- In your opinion, what are the negative parts of the __ experience?

- Please provide some suggestion to improve the __ activity and experience

Glossary

- **2D (Two-Dimensional)** – A representation with only width and height, commonly seen in images and flat maps.
- **3D (Three-Dimensional)** – A representation of objects with width, height, and depth, often used in computer graphics and modeling.
- **3D Models** – Digital representations of objects or terrain in three dimensions, used in simulations, games, and scientific analysis.
- **3D Modelling** – The process of creating a digital representation of a three-dimensional object using specialized software.
- **3D Printing** – A process of creating physical objects from digital 3D models by layering material.
- **AR (Augmented Reality)** – A technology that overlays digital content onto the real world, enhancing but not replacing the user's environment.
- **CAVE (Cave Automatic Virtual Environment)** – A room-sized VR system where projections on walls and floors create an immersive 3D experience.
- **CPU (Central Processing Unit)** – The primary component of a computer that performs most of the processing tasks, often referred to as the "brain" of the computer.
- **DEM (Digital Elevation Model)** – A 3D representation of terrain elevations, used in topographic mapping and analysis.
- **DOM (Digital Outcrop Model)** – A 3D representation of an outcrop, typically generated using LiDAR or photogrammetry for geological analysis.
- **Game Engines** – Software platforms used to develop video games and interactive environments.

- **GIS (Geographic Information System)** – A system for capturing, analyzing, and visualizing spatial and geographic data.
- **GPU (Graphics Processing Unit)** – A specialized processor designed for rendering images, videos, and 3D environments.
- **HEIE 2018 (Hokkaido Eastern Iburi Earthquake 2018)** – A major earthquake that struck eastern Hokkaido, Japan, on September 6, 2018, causing landslides.
- **HMD (Head-Mounted Display)** – A wearable device, like VR goggles, that displays immersive virtual environments directly to the user.
- **LiDAR (Light Detection and Ranging)** – A remote sensing method using laser pulses to measure distances and create high-resolution 3D models of terrain and objects.
- **MR (Mixed Reality)** – A blend of real and virtual worlds where digital objects interact with the physical environment in real time.
- **Mw (Moment Magnitude)** – A scale used to measure the size of earthquakes based on energy released; replaces older scales like the Richter scale for more accuracy in large events.
- **Outcrop** – An exposed section of bedrock or geological formation visible at the Earth's surface.
- **Photo Sphere** – A 360-degree panoramic image that captures the surroundings in all directions.
- **Point Cloud** – A collection of data points in 3D space representing the surface of objects or terrain, typically generated using LiDAR or photogrammetry.
- **POI (Point of Interest)** – A specific location or feature of significance.
- **PSU (Power Supply Unit)** – A hardware component that provides power to all other components in a computer system.

- **RAM (Random Access Memory)** – Temporary memory that stores data being used by active programs, affecting system speed and performance.
- **RTK (Real-Time Kinematic)** – A precise satellite navigation technique used to enhance the accuracy of GPS data, commonly used in drone mapping and surveying.
- **SDGs (Sustainable Development Goals)** – A set of 17 global goals established by the United Nations to address issues such as poverty, education, climate change, and sustainable development.
- **SfM-MVS (Structure-from-Motion Multi-View Stereo) / Photogrammetry** – A technique for generating 3D models from overlapping 2D images, commonly used in geospatial analysis and virtual reconstructions.
- **SSD (Solid State Drive)** – A high-speed storage device with no moving parts, used for quick data access and boot times compared to traditional hard drives.
- **TR (True Reality)** – Refers to the real, physical world as opposed to virtual environments.
- **UAS (Uncrewed Aerial System)** – A drone and its associated control system, used for aerial surveys, mapping, and remote sensing.
- **VFT (Virtual Field Trip)** – A digital simulation of a real-world field experience, often used for educational purposes in Geosciences.
- **Immersive VR (Virtual Reality)** – A fully immersive digital environment that replaces the real world, typically experienced through a head-mounted display.
- **VR Lecture** – An educational session delivered within a virtual reality environment, designed to teach educational concepts in VR.
- **XR (Extended Reality)** – An umbrella term encompassing VR, AR, and MR, referring to all immersive technologies that extend or alter reality.