How are VR and AR used in Geoscience? Interview of Geologists for Immersive Reality system requirements gathering

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Immersive Reality (IR) technologies are becoming more prevalent in Geoscience. However, while there is research into their design and use within education, this is not the case for academic applications. This paper aims to fill the gap by exploring the attitudes of academics towards IR applications in geoscience, as well as document how they work with data. 16 Participants were interviewed regarding their tools and processes working with data, their attitudes to IR and their needs regarding data gathering and analysis. These interviews were analysed using Thematic Analysis, and design recommendations made regarding the production of IR technologies in geoscience going forward.

CCS Concepts: • **Applied computingEarth and atmospheric sciences**; • **Human-centered computingVirtual reality**; • **Human-centered computingMixed / augmented reality**; • **Human-centered computingUser studies**;

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1 Introduction

Geoscientists rely on a combination of field study and remote data as part of their collaborative discovery and sense-making process[42]. Field study is important as it can provide ground truth for the data, as well as context from the environment[17]. Field work includes taking physical samples and measurements of rock features, but also contextual activities such as mapping or scanning using handheld instruments [69]. While these activities are largely carried out in person using a mixture of hand tools and handheld digital instruments. However, fieldwork is not always easily accessible, as in the case of cultural heritage sites[21] or locations of conflict. Otherwise it can be completely inaccessible, for example inside volcanoes, space or planetary exploration and deep ocean research. Some sub-fields of geoscience, such as planetary science, rely entirely on remote samples and data from drones or robots, like the Mars rover missions[12]. Study of active volcanoes can require seismic sensors that measure tremors and tectonic activity beneath the earths surface. Deep sea exploration uses sonar imagery to reconstruct sea bed. In these situations, access to the field is mediated by instruments, with in-person access impossible. In addition to these challenges to field work, geoscientists are globally distributed, making in person collaboration and data analysis difficult. Recent advancements in Immersive Reality (IR) technology, such as see through head mounted displays (HMD) can generate virtual and augmented environments through use of cameras and graphics. These can be used to overlay data in in-situ

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environments [68], or allow drone scans of environments to be virtually recreated into models that can be walked around [35]. As such, IR technologies lend themselves naturally to these situations by promoting virtual presence.

While there are prior studies into the use of Immersive Reality (IR) within academic geoscience[12], the focus has been on technical or visual fidelity (see [25]for a review), with few papers focusing on the design requirements of geoscientists[42]. Despite the potential of IR technologies, there is limited research on how these tools can be designed to meet the specific needs of geoscientists. Understanding the workflows, data interaction preferences, and collaboration requirements of these users is crucial for developing effective virtual reality (VR) tools. Their use has been studied within education (e.g. [57, 67]). Immersive analytics has shown the utility of using virtual and augmented environments to analyse data in other fields, allowing natural gestures and tangible interaction with data [14]. Desktop virtual analysis of geodata was also demonstrated in the 90s and early 2000s, providing an in depth way for researchers to explore and manipulate their data [31, 47]. However there are few studies exploring fully virtual HMD environments for academic use [55]. Finally there is a lack of exploration of how immersive analytics and virtual environments could be combined to provide in situ analytics within virtual environments, leveraging both manual interaction with data and the contextual cues of the environments the data was gathered in. A gap exists in this field for human-centered design. Research that seeks to provide insights into this domain and understand how academics and domain experts use the current tools, could result in better design in virtual tools and lead to the unlocking of potential these digital systems possess.

This study aims to bridge the gap between traditional fieldwork methodologies and the emerging virtual technologies, particularly VR. The increasing inaccessibility of field sites due to conflict, site preservation or wide scale disease such as COVID-19, and the current limitations of remotely collected data highlight the need for innovative solutions. The augmentation of data through contextual analysis within virtual field environments poses new ways to interact with remote data. VR's potential to simulate real and impossible environments provides an avenue to enhance data comprehension, contextual understanding, and collaborative research in geosciences. This investigation is particularly pertinent given the escalating use of VR in geoscience, e.g. in GIS packages [1]. GIS tools are usually desktop software packages that can be used to aggregate, map and analyse geological data. Two prominent packages ARCGIS and QGIS [1] have been used within geoscience for decades, but there is still a lack of HCI methods in the design of these systems [77]. By comprehensively analyzing the tools and methods currently employed by geoscientists, we aim to align VR technology development with their specific needs and workflows.

We interviewed 16 geoscientists to delve into their current practices regarding data gathering and analysis, both remotely and in the field. We had three research questions to examine these practices, and their attitudes and potential utility for VR within geoscience:

- **RQ1:** What processes and tools do geoscientists employ for data collection and analysis?
- **RQ2:** What are geoscientists' perspectives on IR technologies?
- **RQ3:** What recommendations can we make based on the needs and processes of geoscientists to develop future IR applications?

Our findings show that VR and augmented reality (AR) are already being used within some areas of Geoscience, although uptake for data analysis is slow despite access to equipment such as HMDs. There are several barriers to the use of IR, including workflow integration, perception of effort vs utility, and lack of easy data integration with tools. Benefits of IR tools include its manual interaction with spatial data sets, its ability to convey a sense of presence and scale, as well as an ability to provide researchers with views that would be unachievable in the field. Our findings can inform the design of an effective VR tool tailored for geoscientific data analysis, with suggestions such as the integration of haptic feedback, and collaborative features. Another suggestion is to allow active data exploration and manipulation within an IR environment, instead of passive viewing. This paper contributes to the literature by describing the workflow of geoscientists and elaborating on their needs, thereby addressing the under-documented area of user-centered design in VR applications within this field.

2 Literature review

2.1 Affordances of Immersive Reality for Scientific Discovery

Don Norman described affordances as "... the possibilities in the world for how an agent (a person, animal, or machine) can interact with something." [54]. Applied to IR there are several affordances of both VR and AR that enable interaction with virtual objects and data in a similar manner to real life, for instance manual interaction and gesture [73], haptic feedback and proprioception [22, 51]. These can produce a sense of "being there" or presence, ownership of virtual body and a sense of immersion [62–64]. In addition, VR also gives affordances that cannot be replicated in real life, such as multiple points of view [60], real time long distance collaboration [55] and augmented visual information [68] [49]. These qualities make it well suited to supporting scientific discovery [55].

Virtual Reality (VR) and Augmented Reality (AR) technologies, two forms of Immersive Reality Technologies (IR) are becoming more prevalent in geoscience, with applications such as remote field trips [58], augmented data analysis [18] and 4D geographical [29] visualisations among recent developments. Immersive Reality within the field of geology has been a subject of interest in the last decade [46, 47] and beyond [14]. Encompassing both VR and AR technologies, Immersive Reality is being recognised for its potential in geoscientific applications, but is still not in widespread use in the field [42]. These technologies, operating along the Reality-Virtuality Continuum[52], offer novel ways to interact with and analyze geospatial data. While VR creates completely artificial environments for users, AR blends digital elements with the real world, enhancing the user's perception and interaction with their surroundings (Microsoft HoloLens | Mixed Reality Technology for Business, n.d.). The unique affordances of IR, such as 3D visualization, six degrees of freedom (6DOF) of movement, gestural interaction, and avatar representations, are particularly suited for remote data analysis and collaborative work in geosciences[24, 25] because geoscience data is 3d visual based [34, 42]. IR's capacity for 3D visualization allows for a detailed analysis of large-scale models like high-density point clouds, offering more accurate representations than 2D screens[12, 42, 75]. The ability to analyze data within a situated environment in VR improves recall and contextual understanding[11, 33, 65]. Studies have shown that embodied cognition, enabled by VR and AR, aids in better data comprehension. For instance, [19]'s work on Immersive Axes in VR facilitated novel, intuitive interactions with data, while [75] emphasized the effectiveness of manual input in spatial layouts for data analysis.

Despite these advantages, the use of IR in academic geoscience remains relatively nascent. Pioneering works in the 1990s, such as the use of CAVE for seismic data analysis[20, 47], laid the groundwork for current VR applications in geoscience. [42] highlighted VR's advantages in geodata analysis, including enhanced 3D visualization and interaction accuracy. Recent studies, like [61], have compared VR with traditional 2D systems, finding a preference for VR's 3D visualization and embodied interactions, especially with complex data sets. [12] exploration of VR in analyzing remote planetary data demonstrated how VR could bridge the gap between remote sensing data and geoscientists, allowing for immersive, accurate analysis akin to fieldwork.

2.2 Examples of VR used within Geoscience

Where IR technologies have already demonstrated their potential within geoscience education since the 1990s [46]. VR has applications ranging from classroom tools, to visualisations of drone captured landscapes, to augmented analysis tools. The following section will discuss the existing literature.

2.2.1 Geodata applications for geoscience. Immersive Analytics (IA) is the study of data viewing, manipulation and analysis within a Virtual environment [14]. As geoscience is a heavily visual science in terms of data analysis, there is much overlap between IA and geoscience, resulting in several applications for viewing and manipulating geodata. For example, there have been several VR based map exploration tools, which allow users to view maps from multiple view points [23], compare different presentations of maps within VR [74] and showed the effects of embodied interaction with maps [53]. Another common application is LiDAR data which can be analysed in VR [26] and field site replication, or VFTs. LiDAR scans of outcrops and other environments are able to be viewed in VR as point clouds [43] and more recently as high resolution images [70, 71] that can be manipulated [7]. These 3D images are immersive and interactive, allowing a deeper analysis [39].

2.2.2 Virtual Field Trips. VFTs, have emerged as a practical application of VR within geoscience useful for aggregating data for inaccessible areas on earth[67, 76], as well as planetary bodies such as the moon [45] Gale Crater on Mars [12] and other planetary environments [4]. These in-situ visualisations allow researchers to make discoveries that were not possible without VR by enabling measurement of remote captured landscapes using traditional field methods[12], [67]. VFTs can be delivered using a range of different technologies, including CAVE simulations[57], desktop computers[58], immersive VFTs delivered through head-mounted displays[28, 41], and some in-field AR applications have been produced[27]. They replicate many of the visual features of a field site through various forms of visualizations such as 360 panoramic photographs, high-resolution still photography, LiDAR scans, and 3D models of outcrops[15, 58]. These are often combined with other features of field site visits, including maps of the area, aerial photography, as well as samples taken at the site [3]. Other virtual tools have been used for outcrop analysis and reconstruction [34, 61], as well as remote collaborative geodata analysis[12, 45]. These have demonstrated novel data interaction methods[18] and have enabled scientists to discover new findings in the data[76].

Virtual field sites have been used to allow remote collaboration between researchers [37], some allowing tangible collaboration [66]. Use of 3D data visualisations have been shown to increase knowledge transfer between geoscientists and stakeholders [50]. Complex concepts such as the effects of climate change on forestry can be conveyed through immersive environments that allow naturalistic and intuitive interaction [36]. Commercially available virtual meeting places have been found to encourage collaboration and facilitate discussion of results among coral geoscientists [55]. Virtual collaboration in the field was also found to increase feelings of team membership [56].

2.2.3 Haptics for geodata analysis. Although the current virtual geodata analysis programs have a heavy focus on visualisations, some focus on multi-sensory and haptic data augmentation.Several examples used haptic and multisensory data exploration in VR in the early 2000s [30–32], where data was explored using a Phantom desktop interactive device. More recently, haptic data exploration in VR was investigated as a way to assist analysis of very large data sets, to overcome visual occlusion of data [6]. Other systems exist that allow embodied interaction with geodata, which was favourably tested with users [59, 73].

Although there is a range of research covering several aspects of academic use of VR, these mainly focus on technology demonstrations, particularly with respect to visual data analysis(e.g.[9, 38, 43, 66, 75, 76]) with few small sample evaluative tests or case studies with geology experts, often with no follow up [6, 27, 46, 47, 61, 72]. In some cases, these were tested with novice users with no background in geology [3, 23, 49, 73]. While only Kreylos et al [42] discussed the development of their VR system with reference to a set of user requirements for geoscientists, and made mention of evaluating the system with users, these results are not reported. There is an evident gap researching the needs and requirements of users to inform the usability, features and capability of VR analysis systems for geoscientists.

2.3 Summary

As discussed, while there are some prior studies into the use of IR within academic geoscience[55], the focus has been on technical or visual fidelity (see [25] for a review), with few papers focusing on the design requirements of these users[28, 42]. A gap exists in this field for human-centered design. Despite this potential, there is limited knowledge about the specific needs of scientists within Geoscience, their workflows and their current use of of Virtual Reality the context of academic discovery and sensemaking. “[this is] an area of research with enormous potential but with little or no awareness in geosciences. The advent of low-cost virtual reality devices opens new possibilities for scientists to experience different locations and time frames, to explore datasets and annotate findings and possible hypotheses.” [2]“2015 Workshop on Intelligent and Information Systems for Geosciences”, 2015, p. 13)”. Research that can provide insights into this domain or the perceptions and needs of the domain experts, such as understanding how academics use the current tools, can help better virtual tools to be designed.

3 Method

A series of semi-structured interviews was conducted with academics who were selected from English speaking universities across the world as the interview team only speak English. The following section will describe the participants, the recruitment procedure and the Thematic Analysis process, including second author code reviews.

3.1 Participants and recruitment

The recruitment process entailed reviewing departmental websites of universities in Australia, New Zealand, and the UK, chosen for their English-speaking populations and compatible time zones. Selection criteria focused on scientists with expertise in planetary science (encompassing both Earth and non-Earth planets), proven experience in utilizing remote data, and fieldwork expertise. Participants had a range of VR and AR experience.

Approximately 100 scientists who met these criteria were identified and subsequently contacted via email. Around 20 participants responded, and another was recruited through snowball sampling. The majority of respondents were from Australia and New Zealand. Ultimately, 18 scientists were scheduled for interviews. To appreciate their contribution, each participant received a $20 AUD Amazon gift voucher as reimbursement. For confidentiality, participants were assigned unique ID numbers (e.g. P01) during the interview process. The interviews were conducted between September 2021 and March 2022.

3.2 Participant overview

This study engaged a diverse group of academics from various specializations within geosciences, each bringing unique insights based on their field of research, academic role, and the types of data they typically utilize in their work (see table:1. Their collective expertise offered a comprehensive overview of the current state and challenges in various sub-disciplines of geosciences.

Participant	Field	Role	Data Types	Gender	Location
P01	Potential Field Geophysics	Associate Professor	Geophysical surveys	Male	Australia
P02	Seismology & Tectonics	Lecturer	Seismology sensor data	Male	New Zealand
P03	Petroleum Geology	Professor	Various geological data	Male	Australia
P04	Seismology & Mathematical Geophysics	Professor	Seismology sensor data	Male	Australia
P05	Structural Geology	Associate Professor	Core samples	Female	Australia
P06	Field Structural Geology	Senior Research Fellow	Mapping	Male	Australia
P07	Structural Geophysics	Professor	Field samples/rocks	Male	Australia
P08	Climate Geoscience	Associate Professor	Geophysical surveys	Male	Australia
P09	Metamorphic Geologist	Professor	Field samples/rocks, Rock thin sections	Male	Australia
P10	Structural Geology/Tectonics	Professor	X-Ray fluorescence spectrometry, Geochemical analysis, Rock thin sections	Male	Australia
P11	Structural Geology	Research Affiliate	Core samples	Male	Australia
P12	Structural Geology/Tectonics	Associate Professor	X-Ray fluorescence spectrometry	Female	Australia
P13	Astronomy & Planetary Microbiology	PhD student	Satellite images	Non Binary	USA
P14	Volcanology	Senior Research Fellow	Ash cloud maps	Male	New Zealand
P15	Marine Geology	Associate Professor	LiDAR/SONAR imagery	Male	Australia
P16	Geology & Geochemistry	Professor	Drone Photogrammetry, LiDAR	Male	Australia

Table 1. Participant role, specialism, data types used age and location of work

3.3 Procedure

Two interviewers conducted hour long semi-structured interviews with the recruited planetary scientists. The interview topics included: the participants current use of IR technologies, the methodologies employed in data gathering and analysis, the tools used in these processes and how the researchers collaborated across these tasks. The full protocol is in the appendix Scientist interview protocol.pdf. The interviews were conducted over a video conferencing tool, and were recorded and transcribed. Of the 18 scientists initially interviewed, data from 16 were ultimately used in the study. The exclusion of two interviews was due to recording issues and the respondents' lack of direct relevance to the field-specific requirements of the study.

3.4 Thematic Analysis

The interview data was analysed using Reflexive Thematic Analysis, adhering to the methodology outlined by [10]. This process involved a series of structured steps: familiarization with the data, generating initial codes, consolidating these codes into themes, reviewing themes and codes, defining themes, and finally reporting the findings. This method is commonly used in Human-Computer Interaction (HCI) research. It is particularly effective in extracting insights from qualitative data, especially in research areas where existing literature is limited. Reflexive Thematic Analysis facilitates an iterative approach that accommodates a wide range of topics without the need for preexisting theoretical frameworks. Furthermore, this approach allows the researcher to actively engage in the analysis, leveraging their expertise to guide the investigation. In this study, the researcher's background in HCI and design was instrumental in identifying emerging opportunities within the data.

The interview transcription process utilized Otter AI, supplemented with manual corrections by the principal researcher and two additional researchers. Out of the 18 interviews conducted, two were excluded from the analysis—one due to technical issues and the other for its lack of relevance to the research focus.

QualCoder, a qualitative data analysis software, was employed to facilitate the coding and thematic analysis. This process involved several collaborative reviews with co-authors at multiple stages. Initially, the first author immersed themselves in the data to gain a comprehensive understanding. This was followed by inductive coding performed by the same author on four of the interviews, with the resulting codes subsequently reviewed and refined in collaboration with a co-author.

The next phase entailed a secondary coding process, where all of the interviews were coded. The codes were further refined and renamed, and initial themes were developed. These preliminary themes were discussed and refined with the co-authors. For the third phase interviews were re-coded a final time. Codes were renamed for clarity and allocated to the final theme groupings. Finally, the themes were discussed with co-authors and renamed as per the table below, culminating in the final definition and naming of the themes, which encapsulated the core insights derived from the interviews.

Theme	Code
Data Practices	Data gathering Data analysis Tools Collaboration
Data Qualities	The importance of visualisation in analysis The importance of subsurface data Tactile interaction and manipulation of data helps understanding The importance of data quality and resolution
Pain points	Logistics Attitudes to current stuff Tools and software
Engagement with IR	Data Analysis and display A sense of immersion Different perspective Immersive visualisations
Issues with IR	IR didn't work IR didn't work well VR resolution is poor The perception IR is only a novelty

Table 2. Themes and Codes Produced During Thematic Analysis

4 Results Themes

This section includes an overview of the results, a summary table of the codes and themes Table 2 from the Thematic Analysis. The results will be discussed as they relate to the research questions.

4.1 Data Practices

Overall the workflows varied from researcher to researcher, depending on their field of expertise, access to data and their focus of research. Although all of the researchers broadly followed a standard scientific process, the start and end points were vastly different, some starting with questions and hypothesis, others starting with a data set.

On the whole, all participants stated that research was both an iterative and interpretive process. Research usually informed more research in a loop of data gathering and analysis.*"I probably think I know what the question is initially. And what I realize is, I don't actually know what the question is, and I need to re-frame it. So I think it's very iterative." (P16)* . Data is also also open to interpretation, there is no fixed answer. *"And then of course, then we look at the results, and then we use knowledge to interpret that information." (P10)* As such, data gathering and analysis can often happen simultaneously, often in the field using techniques such as mapping. In many cases, the whole research process of collecting data, analysis and reporting were carried out in the same GIS tools, and were in part the same iterative process. For example, mapping in the field is a common component of research, which is used in the planning, data gathering and analysis stages throughout.

4.1.1 Data gathering. We identified four primary data gathering methods employed by the participants. Firstly, physical rock samples are collected during fieldwork and later taken to laboratories for detailed processing and analysis. This traditional method remains fundamental in geoscience research. Secondly, various sensors are deployed in the field to gather data, including seismic and gravity readings. These sensors can either be left onsite for continuous monitoring or used as handheld devices for immediate scanning and data collection.

The third method involves the manual mapping of field sites. Participants often use hand-drawn maps or tablets equipped with mapping software to document geological features. This process typically includes detailed annotations of rock formations, faults, feature orientations, landmarks, vegetation, and GPS coordinates, providing rich contextual data from the field. Photogrammetry also plays a crucial role, where both drones and handheld devices are used to capture 2D images. These images are then transformed into 3D models, offering a comprehensive view of the surveyed area. Additionally, LiDAR scans are utilized to produce detailed 3D point cloud data of the surroundings. In a similar vein, bathymetry data is gathered using sonar technology, yielding analogous 3D outputs.

Lastly, satellite data collection is a significant component of their data gathering process. Whenever satellites are within range, a combination of photographic and sensor data, such as magnetic readings, is captured. This method provides a broader, large-scale perspective, complementing the more localized data gathered through other methods.

4.1.2 Data analysis. Data types reported by participants ranged from 2D illustrations such as maps and stratigraphy diagrams, to 3D models, such as point clouds and LiDAR scans, to time series analysis or 4D models which changed over time. Although all participants discussed the use of maps, they were often used in conjunction with other kinds of data as an overlay. See table 1 for an overview of types of data used by participants. Several processes were discussed by participants. Mapping in the field featured prominently. As maps are a fundamental part of geoscientific exploration, in providing both ground truth for sample data and an iterative analysis process in its own right, they are used across preparation, data gathering, analysis and reporting. Mapping is done both digitally using GIS tools (P11) *"So particularly QGIS, in the field, connected to GPS."* (P11) and hand drawn using paper (P06). Maps within GIS tools can be used as a base on which to overlay data: *"data that we actually collect, it tends to be rocks...and sampling things, and also building up new maps... we're actually out there collecting geospatial information and storing it in the GIS, [to] build up a new version of the map... with an underlay of the geophysical data."* (P07)

Overlaying data is also another critical process. Several participants worked in multidisciplinary groups, and aggregated different data types together to provide a combined interpretation.

4.1.3 *Tools.*

The tools employed by geoscientists in the field encompass a blend of digital and traditional instruments. Digital tools include devices like smartphones, GPS units, various sensors, and tablets. These are broadly used for fieldwork and analysis. On the other hand, traditional handheld field tools, such as hammers, hand lenses, and compasses, remain integral to many researchers' fieldwork. The choice between digital and non-digital tools largely depends on the specific requirements of their field activities. For tasks like field mapping, which is often done manually, or when making in-person field visits, traditional tools are particularly valuable. Conversely, when relying on remotely gathered data, digital tools and sensors are more predominant.

Software	Used by	Description
Gaia 3D	P06, P08	Photogrammetry and 3D models /teaching
Oasis Montaj	P01, P06, P10, P07, P11	3D package with GIS integration. Geophysics modeller
ARC GIS	P01, P05, P06, P08, P07, P09, P10, P11, P14, P16	Commercial GIS tool
QGIS	P02, P06, P08, P07, P09, P10, P11, P14	Open Source GIS tool
LOOP	P06, P07, P11, P10	Large software suite used for many of processes, inc 2D map to 3D modelling
Stereonet	P06, P09, P14	Phone or desktop based software to model planes or faults from dip and strike field measurements
Fleidermaus	P06, P15	Suite of programs used within geoscience to view the 3D models such as LiDAR scans or sonar data models

Table 3. Geodata analysis tools used by participants

Digital tools and software used in both data collection and analysis are shown in table 3. GIS tools such as ArcGIS and QGIS are used across many stages, including prep work, data gathering and collation, and data analysis and reporting. GIS tools can import a range of data types, maps and other information and combine them. Nearly all of the participants used the tools from table 2 across all stages of their work. Digitised forms of data from field samples and recordings can also collated within GIS tools.

A key insight from the interviews is the enduring need for non-digital tools and the importance of physical interaction with the field site. Despite technological advancements, traditional methods still hold significant value for gathering non-visual data and facilitating hands-on analysis. As one researcher articulated, "*Obviously, we use GPS for location. But you know, the traditional compass is still a very much useful thing. And just, you know, eyes and scratching stuff.*" (P01). This statement underscores the synergy between modern technology and classic field techniques, highlighting the multifaceted nature of geoscientific research.

Eight participants discussed the need to customise or modify tools (P01, P02, P04, P05, P06, P07, P14, P16). In some cases researchers directly write their own code for analysis in languages such as Python or FORTRAN (P01, P02)*"the same techniques are available open source. So we tend to use them mainly because you can customize them. You're not stuck with someone else's idea of what needs to be done, you can change it if you want." (P01).* Another reason was the ability to combine different types of analysis code or outputs, such as Generic Mapping Tool which can be used with CartoPy. Some researchers used customisable code for highly specialised calculations that were performed regularly (P04, P06).

However,these pieces of code were then made open source to share with the research community. *"And we use some pretty specialist codes for that that are, most of them are open source now, (P01).* Open source packages are becoming more prevalent within Geosciences, and are frequently used *"These days, there's a lot more open source development...You get a little tool to do one thing." (P07).* Open source code is prized for its ability to be customisable as well as free, and there seems to be a general move towards using more open source packages within Geoscience.

4.1.4 Collaboration. Collaboration was different for each participant, and varied due to role, teaching load, size of department, and preference of tools. The participants all used a variety of collaboration methods. These main methods were identified:

In person collaboration occurred across several stages. Field work was carried out in teams, collaborating in person. Teams could range from 2-3 to large teams in the tens and twenties. Participants stated that collaboration was easy, and more focused as you had no where else to be, and also that conversations at times of rest were likely to happen.

Meetings were also often carried out in person at institutions. Several of the participants expressed a desire to meet in person as incidental conversations were more likely to happen (P11).

Remote collaboration over zoom were frequently mentioned. Zoom meetings are used for global collaborations where it isn't possible to meet in person. P12 felt that zoom meetings facilitated conversations, whereas P11 felt that they were prohibitive to actually meeting. *"And now, it's actually been amazing how many more conversations I've had with people because this exactly what you're doing is so easy now. And so now most things would happen online."* Remote asynchronous collaboration was also mentioned by several participants. Use of email, GIS tools and repositories allow researchers to collaborate on joint projects asynchronously. In many cases the researchers are responsible for one part relating to their specialism (P05). Some researchers also collaborate on code through coding repositories such as Git (P02, P11).

4.2 Data qualities

4.2.1 The Importance of Visualization in Analysis. Visualization emerged as a crucial component in the analysis phase, with all participants incorporating it into their workflow. Participants viewed 3D models as superior to 2D for conveying information such as the height of local landmarks or the depth of seismic events. However, challenges were noted, particularly regarding the navigation of 3D data on 2D screens: *" ...working with a 3d plot on a 2d screen is never particularly satisfying. And I really struggled with navigating matplotlib 3d plots. And I've tried a couple of other things and still found that found the controls really difficult to navigate through those kind of 3D plots." (P02)* Participant P14 described the transformative impact of VR on seismic data analysis: "*...looking at it in VR has been incredible because you can actually see structures that are moving in and out and you can go in and click on each earthquake and it tells you the depth time and everything.*" This emphasis on visualization underscores its indispensable role in modern geoscience, bridging the gap between complex data sets and tangible understanding. Despite the challenges in navigating 3D data on conventional 2D interfaces, the enhanced depth, clarity, and interactivity provided by advanced visualization tools like VR have fundamentally enriched the analytical process, offering geoscientists novel perspectives and deeper insights into their data.

4.2.2 The Importance of Subsurface Data in Geology Research. Subsurface data was highlighted as crucial by several researchers. Five participants (P04, P06, P07, P08, P14) emphasized the need to visualize subsurface information, especially in regions where surface data is obscured, such as jungles or soil-covered areas. Participant P07 explained, "*...using the satellite data isn't as useful. But the airborne geophysical data, which is still a remote data set is crucial in our ability to undertake the work in South America, because it's mostly under jungle...*" This reliance on subsurface data extends to various applications, including studying magma chambers, tectonic movements, and the Earth's core composition, necessitating long-term seismic recording.

4.2.3 *Tactile Interaction and Manipulation of Data Helps Understanding.*

Tactile interaction was highlighted as significant both in the field and during data analysis. Physical engagement with the environment was seen as key to understanding the contextual aspects of the data. Participant P01 remarked, "*...the traditional compass is still very much useful thing...it's quite a tactile thing.*" This sentiment was echoed by others who found that manual interaction enhanced their comprehension of geological relationships. Participant P09 detailed how virtual field trips enabled students to explore geological relationships interactively, underscoring the value of hands-on experience.

This emphasis on tactile interaction was contrasted with digital experiences, highlighting a balance between physical presence and virtual simulations. The manipulation of 3D models was particularly appreciated for providing different perspectives and a deeper understanding of geological formations. Participant P16 observed, "*I think the biggest advantage is the appreciation of scale...* " This reflects the importance of a multi-faceted approach that combines hands-on fieldwork with advanced visualization techniques, allowing for a more comprehensive understanding of geological data.

4.2.4 *Data quality and resolution are important.*

For researchers working with remote data sets, the data quality affected their workflow. In some cases, prior work could be incomplete or only targeting certain types of data. This could prompt more data gathering in the field, or can take time and resources to filter/ edit something. For researchers working with 3D models and photogrammetry of the field environment, particularly in VR, the resolution of the model was important, but also difficult to come across.*"That sort of, quality 3d photogrammetry is quite rare." (P09)* Several researchers felt that drone scans did not capture enough detail *" the clarity is not easy to get but but yeah, that's one of the main limitations." (P06)*, or all of the features present (P11), or the kinds of data that can be detected in the field in person. High resolution photogrammetry takes a long time and is large, so is difficult to find in data repositories. *"I guess using photometry, to like, create a 3d model of this entire region, it, it would just require a... lot of high resolution data. I couldn't even imagine how many like bytes of data that would ...have to have to run." (P13)* In these cases, working with 3d models and photogrammetry data was considered useful in some situations, such as for teaching, but not good enough to rely solely on for research.

4.3 Pain points in fieldwork and geosciences practice

Barriers to work fall broadly under three categories, logistics, attitudes to existing technology and tools/software.

4.3.1 *Logistics.*

There were three main logistical barriers faced by the participants. The first was cost or time cost. Both of these affected all aspects of work, including use of software, length of time in the field, and even whether aspects of the role such as data analysis was performed by a post doctoral worker or themselves. Although open source software was praised for its low cost, some researchers preferred well funded software (P13, P03 or P15) as they had better usability or more up to date features. *"I don't have access to the newest version of the software programs, which makes it difficult... you need a license. So you need to pay money and I usually access them through my institution, but they don't pay and they're not updated." (P13)*

The second barrier was movement restrictions. At the time, COVID lock downs prevented many aspects of research carried out in person, including travelling to the field, attending conferences and even being on campus or in offices. Some researchers discussed using virtual field trips to enable work, although availability of these was not universal. Another participant discussed the impact to mental health (P11), and collaboration between students and other researchers.

The third logistical barrier was difficulty accessing the field beyond COVID restrictions. These included inaccessibility (P13 Antarctica and Mars, P05 or P14), danger (P14 volcanoes), or cost (P09).

4.3.2 Attitudes to existing technology. The following section shows attitudes that the participants had towards technology that was a barrier to its uptake, continued use, or generally a source of irritation. Seven participants felt poorly towards software or a process that didn't fit into their existing workflows (P01, P03, P05, P08, P10, P14, P16). Some software was considered too hard to use, with issues including: inability to install (P02), lack of technical support (P13), difficulty with data interoperability (P01), licensing issues (P13, P01, P03) and glitchy software (P05, P01). Speed of software was a barrier (P11, P10, P07), especially as booting up some software took too long compared to the time of use. This impeded frequency of use. In some cases, participants felt that parts of their work were or should not be "their job", such as field work and data gathering (P08), installing and maintaining software (P05), or learning new tools or platforms((P01, P14, P06). Additionally the attitude that things "are not worth my time" was felt towards tasks such as digital note taking equipment (P01), especially for learning new digital field tools (P06), indicating some mental barriers to learning new tools. Some participants felt that there was no substitute for being in person, for example communicating in person (P08), or needing to go to the field because alternatives aren't as detailed (P06, P10) or lack tactile feedback (P10). Some forms of data can only be collected by hand rather than remotely (P09). Several participants felt that learning 3D was hard for students, because using computers or remote data reconstructions doesn't give enough information such 2D screens made it to visualise 3D data (P11). Another participant (P16) felt going to the field consolidated and allowed application of classroom knowledge as they felt that students rely on digital platforms giving them their answer instead of using observational data(P16).

4.3.3 Tools and Software. The following issues were around specific shortcomings of tools used throughout data gathering and analysis.

One barrier to uptake or continued use of software was a lack of support (e.g., P02, P03, P07, P13). Another barrier discussed was switching software and data compatibility and interoperability. Often large pieces of software such as GIS tools or other large analysis tools were chosen and then continued to be used. One reason was that the steep learning curve prohibited switching easily to another. If the research group had knowledge in that area then it was unlikely that the team would use another (P03). Inter-operation between packages is also considered to be poor (P01, P03, P04). Some data formats need to be changed to work with certain programs (P04, P05). There are issues around altering the format of data so that it fits the packages, which can take a lot of time (P10, P05) or need specialist help (P04). The need for an integrated system with data capture and analysis was desired (P05, P16) *"there's a lot to be said for people migrating into workflows that capture data in a way that's seamlessly interoperable with all of these systems... because often it's that inertia that kills people to say 'it's too much too much. It's too hard. I'm just going to do things that I always do'." (P16)* Another part of this is managing group data. As research is collaborative, and different specialists use the data and programs, managing data between them is difficult. Users often have different preferences for software *"At the moment, it's just kind of, it's really difficult to get one system that everybody is happy to use." (P08)*. Being able to find the large amounts of data after a project was a desirable thing but difficult (P09). While this isn't a main focus for this project, data storage and format need to be considered as they have an impact on workflow and usability, which are large barriers to tool use. In summary researchers have a lot of pressure to stay within the same systems, although they need specialist tools. As mentioned in tools section above, they want something that is flexible enough for them to tailor it to their use, but also be compatible with a large range of data. As a lot of time is invested in learning these systems, there is little impetus to change unless it provides something of great value that cannot be replicated. The support needs to be good to enable a smooth transition without use of local expertise.

4.4 Engagement with IR technologies

The majority of participants had some experience with VR and AR (PO1, P02, P03, P04, P05, P06, P07, P14, P13, P15, P16). Around a third of participants had used VR or AR on more than one occasion. Participants had experienced IR in a variety of ways, including HMD (P02, P16), CAVE or immersive room (P03 and P06), and in situ AR (P06). The applications ranged from augmented field sites, to data display, to recreation of field sites and outcrop mapping.

4.4.1 Data analysis and display. This was only briefly mentioned by participants, as the systems were rarely used. P03 and P06 discussed large facilities at their institutions that were intended to be used for immersive analysis of data, however were generally were used to promote the department or to be used for leisure. *"the most use they got was for watching the World Cup soccer, rather than looking at the data." (P03)*

4.4.2 A sense of immersion. VR outcrop models were also considered useful for a sense of scale (P16) or documenting the physical distance between areas (P09). It was used for providing a connection to country for traditional land owners when the land was no longer accessible (P08). "So that provides a really tangible connection to that, to that sea country and provides a new opportunity for this traditional owner groups take ownership of that space."

4.4.3 Different perspective. VR also allowed participants to have a different perspective of the area they were viewing. For example, P08 found that VR environments allowed stakeholders and members of the public to experience land that had been lost thousands of years ago, and gain an emotional connection. P16 found that VR could provide multiple different view points of the land, such as aerial views from drone flights. P15 was able to use 3D models to navigate through deep sea trenches which are inaccessible to humans. P14 found that it gave a new way of experiencing topography, which is usually done with 2D maps.

4.4.4 Immersive visualisations. VR improves visualisations, allowing better access to 3D models (P16), showing real time visualisations of seismic data (P14), and allowing better inspection of large amounts of earthquake data (P02). VR also allows researchers to manipulate the data (P09) using a "VR headset, probably better than you can using the website... rotating the thing, backwards and forwards" P09. VR also incorporates "spatial visualization" (P16), and allows multiple data sets to be combined to be "interrogating plots...in a field location." (P16). Finally, VR enabled (P04) to "move through that space, and try to understand the spatial relationships better" Several users also discussed using VR for data overlays. P16 has used HMD displays to augment data from core logging to aid mineral analysis. P14 has used VR in the field to show a comparison between the environment and the magma chamber model under the earth to demonstrate active volcanology. P06 has used AR headsets in the field to augment a mining environment with data to aid field work.

4.5 Issues with VR/AR

Participants also discussed issues with how VR worked for their fieldwork or analysis. In addition to the issues described below, VR was reported to cause nausea in themselves or their team by 5 of the participants (P01, P02, P06, P11, P16).

4.5.1 IR didn't work properly. Several researchers found that early use cases of IR did not work in their experience (P11, P06). Issues ranged from AR registration not working (P06) so the overlay did not function properly, to poor battery life (P06) and heavy hardware (P11). In situ AR was also considered quite dangerous, as it obscured the physical environment (P11). Two participants mentioned the lack of availability of VR can create barriers to it being used collaboratively (P16). "Not everyone has access to VR. (P14)". VR was also considered too difficult compared to existing methods. For example, data integration was too difficult (P01). Despite 3D models being available, they were not easily available "So there's not really anything that consolidates everything? No, not that I'm aware of anyway (P16)" VR also did not provide all the features researchers wanted. "In fact, all the VR system I've used have failed because they even recently, they only give you the one user point of view.(P06)"

4.5.2 VR resolution is poor. Several participants complained that current VR resolution is poor, or not high enough for their work (P03, P06, P09, P14). P03 felt there was a "limit" to the size and the "Level of detail that you can get down to". P06 felt the clarity was poor, and while they're "awesome for education...you'll never get the same coverage" as being in the field, thus affecting area of work. P14 was concerned about the ability of newer students to "filter out...the important features of a particular scene", which she felt needed a lot of field proactive. These things suggest that current field recreations are not captured in enough detail to be of use for analysis, and cannot cover a large enough area.

4.5.3 IR as a novelty. Several researchers, including some who are heavily in favour of VR felt that VR was a bit of a novelty, used to impress people (P01, P05, P06, P16). P01 liked the idea of virtual outcrops for students, but felt it was only useful for novices who "are not used to thinking in three dimensions...once you get used to thinking of three dimensions,...you can work on a two dimensional screen" P01 felt that VR for analysis was "it seems a lot of faff and a bit gimmicky", particularly as they were experienced in viewing 3D models on desktop. P03 described how their expensive VR suite was rarely used "most use they got was for watching the World Cup soccer, rather than looking at the data." P05 was also aware of a large VR table in their organisation, although "I haven't seen it work yet." P06 discussed their use of a VR room "each time I've used facilities since 1996, it was to make a demonstration to some ministers...and we wanted to wow them. It's never been for science ... which is a frustration." P15 stated that they wanted to to use VR because "I don't want to say gimmick, but I guess just the different mode of of interacting with someone, I really just wanted to experience it."

Several researchers felt that VR didn't necessarily add anything to their workflow (P01, P08, P03, P15, P11). "all the information I need to do the work that I do, can be done without VR, right. (P08). P03 felt that there was rarely even "incremental benefit of looking at something in a stereoscopic projection, as opposed to a 3D viewer on the screen in front of you". P15 reported that they didn't think "VR is gonna help me understand how these things work any better." While P11 liked the idea of VR for analysis, the current state did not allow interaction with data, so was of less value. "ends up becoming a bit of a show and tell."

4.6 Design Considerations for VR Tools

Our interviews with geoscientists revealed key insights into desired features for VR tools in collaborative analysis, including enhanced visualization utilities, situated data analysis capabilities, and interactive options like gesture and tactile interaction.

4.6.1 Situated Data Analysis. Several participants (P06, P10, P14, P13) expressed interest in using VR or AR for embedding data within the context of fieldwork. Use cases ranged from aids to contextual recall (P12), to a proxy for difficult site access, such as Antarctica (P13). P06, for instance, wanted to overlay models onto physical features in the field for both display and in-situ analysis, emphasizing the need for realistic integration of models and physical environments, "*I think we need to come up with clever ways to make you know a model stick out of the ground or* *do something to actually add the visualizations...*". While field recreations were the most familiar application of VR technology, their current limitations are that they are low in resolution, or do not cover a large enough area of interest in enough detail to be of use. However, drone technology and sensor resolution are improving, and with larger access to digital sample databases, it may be possible to build higher fidelity environments without the need for a great increase in resolution. The benefits of contextual recall have been widely studied in psychology, and for those that had used them frequently, the benefits of spatial awareness and contextual data analysis was already apparent. In addition, their utility for exploring inaccessible field areas has already been proven in other geoscience applications.

Participants highlighted various potential applications of 3D photogrammetry in enhancing fieldwork and data analysis. They saw its value particularly when returning to the field was not feasible, as it would provide a more accurate reference than relying on memory (P01). For field trip planning, 3D photogrammetry could help identify ground hazards such as trees for helicopter landings, which are not visible on maps (P02, P05). Additionally, it was considered useful for field preparation, enabling early analysis with broad details like rock orientation to help researchers "get a feel" for the site (P05). Integrating field recreation into the workflow was also seen as beneficial for documenting and analyzing large data sets, and for observing changes in the landscape over time (P09). There was interest in combining photogrammetry with VR to automatically pick geometries and boundaries in 3D, enhancing the analytical process. Moreover, creating immersive models from photogrammetry data was noted for its potential to improve the mapping and analysis of terrain, making geological maps more immersive and interactive (P10).

4.6.2 *Augmented Visualization.*

Enhancing visualization was seen as a major benefit of VR. Combining different data types, adding metadata, and layering information in a virtual environment was seen as a significant advancement. P04 expressed the desire for a spatial understanding of data, highlighting the limitations of 2D representations and the advantages of exploring data in a 3D space:

> ...we work with these two dimensional maps… Very often, these 2D images also give you like, a false sense of good coverage, for example, right? But then you produce something more sophisticated in 3d and you realize, “Oh, I actually don’t have that good coverage there"... (P04)

With the more widespread adoption of stand alone HMD and AR headsets, the ability to overlay augmentation on samples, data sets or even environments is possible. While there are several off the shelf tools for building virtual environments, these lack easy integration with geodata, despite there being easy and ready access to data repositories the world over. An outstanding problem is how to make the large amount of data accessible to a user inside VR, or allow a geoscientists to collate data within a 3D immersive environment without needing a lot of other expertise.

4.6.3 *Gesture or Tactile Interaction.*

Tactile and gestural manipulation of data in VR was highlighted as a desirable feature by participants like P10, P16, P06, and P02. They viewed it as a more intuitive and realistic way of interacting with data, adding a new dimension to data manipulation and comprehension.

> being able to see aerial imagery was a big thing for us, we need our sights to not be not be covered by high trees again, so we can land a helicopter, and that we can deploy a solar panel and see the sky. So having those images to couple with the topography, and actually being able to try and try and manipulate things in 3d was a was a big change for us... (P02)

A tension between use of digital tools and traditional hand tools in the field was discussed by the participants. It might be useful to include a set of digital versions of hand tools within any IR application. Firstly, it could be a good learning tool for any students to be able to have an interactive experience. Secondly, more widespread integration of hand tools within a virtual environment for academic use could be useful. In some cases, field data gathering such as rock feature measurement has been carried out within VR using digital replicas of hand tools [12], [3]. The inclusion of tools may augment other types of analysis as well, and leverage existing skill sets that all geologists have. For example, being able to map and examine AR models within the field environment allowing the models to be pulled apart and manipulated, would speed up analysis (P11). *"immersive technologies are a way to do that" (P01).* In addition to gestural data interaction, the inclusion of haptic feedback could provide a benefit to data analysis. Haptic integration into geodata analysis packages has already been explored in the early 2000s, however has not been widely adopted in current VR technology. Current haptic technology is expanding beyond vibrotactile only feedback into pressure sensing and responsiveness to shape which can open up the area to new tactile sensations. These could augment collaborative analysis within VR, as well as potentially aid other forms of data exploration, as shown by technologies such as IMAxes *"And that's something that we've implemented actually,...that does have haptic feedback, and which I think really helps like when you're combining axes or twisting data. And so there is that version of feedback, which which add something to the experience," (P16)* Therefore, gestural interaction and haptic feedback should be considered in applications designed for data analysis.

4.6.4 Communication of Scientific Data. Another participant found the idea of using VR models for reporting and data communication more interesting than traditional written publication, as it is possible to show the relationships between geometry *"Because always we used long, long sentences that ... everyone gets bored and doesn't want to listen to anymore." (P11).* The researcher also discussed the potential to take colleagues to specific sites in the virtual models "in person" to discuss geological features (P11). Some participants also discussed the desire for physical interaction *"it's the boundary between the tactility of being there in person...there's this balance... you should be able to have this tactile experience." (P10)*

4.6.5 Summary. The reluctance to use or learn new tools stemmed mainly from their lack of integration, difficulty of use, or lack of technical expertise, leading to sporadic use or abandonment. Tools that allowed for customization and coding integration were highly valued. Desired VR tool features highlighted by the geoscientists included augmented visualization in the field, enabling the combination of various information sources within the environmental context. The integration of gestural or tactile interaction was also a significant consideration, facilitating more natural and intuitive user engagement with the data. Additionally, the capacity for collaborative functionalities was emphasized to enable effective remote collaboration for analysis and dissemination of results. These insights underscore the importance of user-friendly, customisable, and collaborative features in the design of VR tools for geoscientific applications, catering to the specific needs and workflows of researchers in this field.

5 Discussion

The primary aim of this study was to explore and understand the various aspects of geoscientific work, particularly focusing on how geoscientists use VR, and how they interact with data and tools throughout their research process. To achieve a comprehensive understanding, the study was guided by three research questions that were designed to provide a holistic view of the current state of data interaction in geoscience and to identify areas where VR technology could bring significant improvements and innovations. The insights gained from addressing these questions were intended to inform the development of VR tools tailored to the specific needs and practices of geoscientists. For a visualisation of themes and their relationship to the key takeaways from the discussion, see Study 1 Thematic Map.png in the appendix. The research questions are as follows:

- **RQ1:** What processes and tools do geoscientists employ for data collection and analysis?
- **RQ2:** What are geoscientists' perspectives on IR technologies?
- **RQ3:** What recommendations can we make based on the needs and processes of geoscientists to develop future IR applications?

The first research question aimed to uncover the specific processes and tools employed by geoscientists in gathering data. The focus was on understanding the range of methodologies, from traditional fieldwork to advanced remote sensing techniques, and the tools that facilitate these methods. The findings reveal a blend of traditional and digital methodologies in data gathering among geoscientists. While field studies remain crucial for context and ground truth [16], the increasing reliance on remote data collection methods, such as LiDAR scans and photogrammetry [42], signifies a shift towards more technologically advanced approaches. GIS tools are commonly used by geoscientists and have been available for a long time, however they are complex and time consuming to learn [77]. For our participants, they do not perform all the tasks that are required, necessitating the use of other tools, which may not be completely compatible with the GIS software. Understanding the processes adopted by geoscientists and their pain points with existing software can help inform design considerations for future virtual reality tools.

The second research question focuses on the experience geoscientists have when using IR applications. These positive and negative experiences are identified and used in conjunction with the findings of research question one to underpin the design recommendations used to answer research question three. IR is used across all aspects of research, from field planning to mapping, analysis and communication. While several researchers found VR useful, it was still considered immature by many to be used for field recreation. Some of the missing features highlighted in Section 4, such as the collaborative capabilities of HMD have been addressed in the time since the interviews were conducted. However, our participants hinted that VR did not contribute enough to be worth using, or was only a novelty, which has been previously highlighted by Kinsland and Borst [40]. By analysing current use of IR technologies, and contrasting them with the existing workflows and desires of geoscientists for VR use, we are able to draw several recommendations for future VR systems. The findings suggest several opportunities for development of systems to explore and analyse geographical data.

5.1 Styles of interaction and forms of feedback

Participants described the desire to interact with their data through gesture and tactile feedback, as it provided a more natural way to inspect their data. Prior work suggests that interaction styles are instrumental to being able to analyse data within a virtual environment [48]. If the interaction is imprecise, this can make a system unsuitable for data interaction. Kinsland and Borst suggested that interaction techniques being worse than desktop was a reason VR interest waned in geoscience [40].

Gestural support within VR through either hand recognition or gloves could provide a more natural way of interacting that could also leverage field data gathering skills.The move towards increased use of technology while maintaining traditional field tools and practices suggest a merging of these techniques. As shown in Immersive analytics, manual interaction in VR can not only support natural gestures, but also develop new interaction styles such as snapping together graphs, or support rapid exploration of data sets not possible in real life [19]. With the advancement of gloves and other gestural supporting haptic feedback devices, it may be possible to emulate more of the physical side of field study and analysis within VR. Field tools have been successfully used within VR environments, which have resulted in new findings [3, 12]. It is suggested that these could be a main part of VR for Geoscience to enable deeper interaction and analysis.

While situated environments were also discussed by participants, there has been the most research conducted on these within IR geoscience applications (e.g. [3, 12, 45]). Future research could focus on an integration of situated environments and tactile or haptic feedback.

5.2 Interoperability of software and data sets

Lack of interoperability of software and data was a pain point in this study. Tasks switching to use specific programs is time consuming and requires a large amount of time to learn a range of complex tools. These tools rely on software to be well supported to make this worthwhile. Participants mentioned the time they spend formatting their data to make it compatible between programs. The desktop tools currently used by a broad range of geoscientists lack the ability to do everything needed, resulting in lots of plug ins, or potentially bespoke program or code being written.

There is an opportunity to create a virtual environment that not only is interoperable with many types of analysis tools and programs but also take a wide range of data to collate, as this was also considered a sticking point for use of 3D environments. There is no one program that does everything currently within a virtual space and many of them seem bespoke. This was also found in prior literature [48] An IR environment for viewing, manipulating and analysing geoscience data would be well-served by utilising the existing range of open-source programs and libraries for accessing common data sources and formats that geoscientists use. For example, using existing QGIS APIs to work directly with VR environments, or using a SketchFabb client, as Sketchfabb hosts several 3D models of geological environments, which would enable easy access to models in that repository.

5.3 Collaborative environments

The ability for multiple users to engage within an IR platform was desired, particularly for collaborative viewing and interaction with data. Very few of the commercial software has been shown to support collaborative activities within geoscience such as presentation and brainstorming [55], or simultaneous data analysis [49]. As mentioned in 4.6.5, some researchers want to be able to demonstrate features of the terrain to other colleagues in virtual field environments. Other examples of collaborative geological software facilitated mapping exercises allowing some interpretations to be performed in a preparation phase to maximise time in the field [37]. However, the participants interviewed also discussed the need for asynchronous collaboration, which could take the form of working on separate parts of a report, contributing to a code base, or adding to the library of samples available, e.g. [5]. As well as enabling interoperability between data sets and IR programs, adding to databases or submitting publicly accessible code should also be considered.

5.4 Perceptions and attitudes

One of the problems described by participants was the perception that VR did not add anything to their analysis. This was also found in prior literature [40]. Some participants felt that their desktop environment allowed them to carry out everything they needed to. However, studies have demonstrated that VR environments can allow the discovery of features and geometries that would not be possible in person, as the sites are inaccessible [3, 12]. Measuring tools recreated in VR allow interaction with photogrammetry models, enabling new discoveries. One solution may be to broaden the availability of VR. While headsets are becoming cheaper and more available, accessible software is still a barrier to VR use. This may also be due to existing tools being designed without input from HCI methods, such as design thinking or collaborative design, which would ensure tools are developed with the end users in mind.

The geoscientists identified digital literacy as a barrier to adopting VR and other tools. A steep learning curve and a lack of technical understanding were cited as major obstacles. Currently, VR systems and other similar software require specialist knowledge to create. Although game engines such as Unity can be used to create VR environments, these also have a fairly steep learning curve to create environments that can be used for complex analysis. To mitigate these, an approach may be to develop a simplified framework for development of VR environments [44]. However, increasing technical literacy is a deep and complex issue, which may require inclusion in learning from undergraduate education or earlier [13].

It is clear from the interviews that many of the same needs outlined in by Lin and Loftin [48], and many of the issues discussed in Kreylos et al [42] and Kinsland and Borst [40] still remain. These issues around workflow integration, specialist knowledge needed for in depth use of VR and the view that "VR doesn't add anything" are still present. This pervasive attitude shows a clear need for inclusion of HCI methods in the development of VR tools within geoscience. Even though the literature has shown that VR used within teaching geoscience is fairly well utilised and researched (e.g. [8, 58]), academic geoscience is still slow to adopt. While VR and AR may slowly filter into academic geoscience as the students of today become the researchers of tomorrow, many of these current researchers are heading departments, mentoring early career researchers, and still in control of both workflow and budgets to some degree. These will have an impact on adoption. Several researchers do see the benefit of VR use, and so with involvement of the geoscience research community, it may be possible to design IR environments that will satisfy the needs of the end users.

5.5 Limitations

This study acknowledges several limitations that may impact the breadth and depth of its findings. Firstly, the inherent diversity within the geoscience disciplines presented challenges in recruiting a large and representative sample from each specialized field. This diversity, while enriching in terms of perspectives, might have led to a certain level of heterogeneity in responses that could affect the coherence and applicability of the findings. This reflected the inclusion of all voices and perspectives across the interviews conducted. The design recommendations, therefore, will not be applicable to everyone, but should be tailored to specific contexts and user needs or used as a starting point in a co-design process.

Secondly, the participant sample was predominantly drawn from universities in English-speaking countries. This geographic and institutional limitation might introduce a bias in the findings, potentially affecting their generalisability to the global geoscience community. The perspectives and experiences of geoscientists from non-English speaking regions or different institutional backgrounds might differ significantly, thereby necessitating a broader and more inclusive approach in future research.

Thirdly, the participant pool exhibited a gender imbalance, with a majority of male participants. This was in part due to the nature of the responses to the interview invitations. Every attempt was made to ensure the gender balance at the time of recruitment. While this imbalance might reflect wider industry trends, it is important to note that a more gender-balanced and diverse sample could provide a richer and more inclusive array of insights, and should be more actively pursued in future studies. The inclusion of more diverse voices would not only enhance the representativeness of the study but also contribute to a more holistic understanding of the needs and preferences of the geoscience community regarding technological tools like VR.

6 Conclusion

This research aimed to identify the design requirements for an effective VR tool tailored for geoscientific applications. By conducting in-depth interviews with geoscientists, this study delved into their workflows encompassing data gathering, analysis, and the communication of results. The focus was on understanding the VR and AR tools currently in use and attitudes towards them. Employing Thematic Analysis, we were able to distill key insights into both the advantageous and challenging aspects of current practices. This approach facilitated the identification of design recommendations for future VR tools that align with the needs and preferences of geoscientists, such as reducing the barriers to VR adoption and use, collaborative analysis, access to field environments and tailored interaction methods. Based on the findings from the Thematic Analysis, the recommendations are as follows:

- **S**upport multiple forms of collaboration in IR, remote and in-person, real time and asynchronous.
- **M**ake IR interoperable with other software and data sets within the workflow.
- **S**upport gestural, embodied and situated platforms that enable data analysis.
- **D**esign IR systems in collaboration with Geoscientists, to meet their needs and expectations.

These recommendations should form the basis of an iterative participatory design approach when developing new IR environments.

Our investigation into the utilization of VR in geoscience revealed a complex landscape. While VR emerges as a promising medium for data visualization and analysis, its practical integration into the routine workflows of geoscientists is fraught with challenges. The study highlights a clear demand for VR tools that are not only intuitive and interactive but also support the unique collaborative nature of geoscientific research. Such tools need to accommodate the specific requirements of geoscientists, including seamless integration with existing data analysis processes, the ability to handle diverse and complex data sets, and facilitating effective communication and collaboration among researchers of different disciplines.

The development of VR tools that are finely tuned to the characteristics of geoscientific data and workflows has the potential to revolutionise how geoscientists engage with their data, interpret complex geographical phenomena, and collaborate with peers. The realization of such tools could lead to more efficient and insightful analyses, foster innovative research approaches, and ultimately contribute to a deeper understanding of our and other planets' geology.

References

[1] 2011. ArcGIS Desktop:. Place: Redlands, CA: Environmental Systems Research Institute..

[2] 2015. *2015 Workshop on Intelligent and Information Systems for Geosciences.* Technical Report. National Science Foundation, USA. https://dl.acm.org/doi/book/10.5555/2856633

[3] Varvara Antoniou, Fabio Luca Bonali, Paraskevi Nomikou, Alessandro Tibaldi, Paraskevas Melissinos, Federico Pasquaré Mariotto, Fabio Roberto Vitello, Mel Krokos, and Malcolm Whitworth. 2020. Integrating Virtual Reality and GIS Tools for Geological Mapping, Data Collection and Analysis: An Example from the Metaxa Mine, Santorini (Greece). *Applied Sciences* 10, 23 (Jan. 2020), 8317. https://doi.org/10.3390/app10238317

[4] Victor Ardulov and Oleg Pariser. 2017. Immersive data interaction for planetary and earth sciences. *2017 IEEE Virtual Reality (VR)* (2017), 263–264. https://doi.org/10.1109/VR.2017.7892277

[5] Geoscience Australia. 2024. Australian Stratigraphic Units Database. https://www.ga.gov.au/data-pubs/datastandards/stratigraphic-units Type: Text tex.copyright: CC BY 4.0.

[6] Ayush Bhardwaj, Sungjoo Kang, and Jin Ryong Kim. 2022. Data Abstraction for Visual and Haptic Representations in Flow Visualization. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology (VRST '22)*. Association for Computing Machinery, New York, NY, USA, 1–2. https://doi.org/10.1145/3562939.3565651

[7] Magali I. Billen, Oliver Kreylos, Bernd Hamann, M. A. Jadamec, Louise H. Kellogg, Oliver G. Staadt, and Dawn Y. Sumner. 2008. A geoscience perspective on immersive 3D gridded data visualization. *Computers & Geosciences* 34, 9 (Sept. 2008), 1056–1072. https://doi.org/10.1016/j.cageo.2007.11.009

[8] Fabio Bonali, Elena Russo, Fabio Vitello, Varvara Antoniou, Fabio Marchese, Luca Fallati, Valentina Bracchi, Noemi Corti, Alessandra Savini, Malcolm Whitworth, Kyriaki Drymoni, Federico Mariotto, Paraskevi Nomikou, Eva Sciacca, Sofia Bressan, Susanna Falsaperla, Danilo Reitano, Benjamin Van Wyk De Vries, Mel Krokos, Giuliana Panieri, Mathew Stiller-Reeve, Giuseppe Vizzari, Ugo Becciani, and Alessandro Tibaldi. 2021. How Academics and the Public Experienced Immersive Virtual Reality for Geo-Education. *Geosciences* 12, 1 (Dec. 2021), 9. https://doi.org/10.3390/geosciences12010009

[9] Fabio Luca Bonali, Fabio Vitello, Martin Kearl, Alessandro Tibaldi, Malcolm Whitworth, Varvara Antoniou, Elena Russo, Emmanuel Delage, Paraskevi Nomikou, Ugo Becciani, Benjamin van Wyk de Vries, and Mel Krokos. 2024. GeaVR: An open-source tools package for geological-structural exploration and data collection using immersive virtual reality. *Applied Computing and Geosciences* 21 (March 2024), 100156. https://doi.org/10.1016/j.acags.2024.100156

[10] Virginia Braun and Victoria Clarke. 2022. *Thematic analysis: a practical guide.* SAGE, London ; Thousand Oaks, California.

[11] Ross Brown, Peter Bruza, Wesley Heard, Kerrie Mengersen, and Justine Murray. 2016. On the (virtual) getting of wisdom: Immersive 3D interfaces for eliciting spatial information from experts. *Spatial Statistics* 18 (Nov. 2016), 318–331. https://doi.org/10.1016/j.spasta.2016.07.001

[12] Gwénaël Caravaca, Stéphane Le Mouélic, Nicolas Mangold, Jonas L'Haridon, Laetitia Le Deit, and Marion Massé. 2020. 3D digital outcrop model reconstruction of the Kimberley outcrop (Gale crater, Mars) and its integration into Virtual Reality for simulated geological analysis. *Planetary and Space Science* 182 (March 2020), 104808. https://doi.org/10.1016/j.pss.2019.104808

[13] Andréa Cartile. 2020. Barriers to Digital Literacy: Learning to Program. *Proceedings of the Canadian Engineering Education Association (CEEA)* (June 2020). https://doi.org/10.24908/pceea.vi0.14177 tex.copyright: Copyright (c) 2020 Proceedings of the Canadian Engineering Education Association (CEEA).

[14] Tom Chandler, Maxime Cordeil, Tobias Czauderna, Tim Dwyer, Jaroslaw Glowacki, Cagatay Goncu, Matthias Klapperstueck, Karsten Klein, Kim Marriott, Falk Schreiber, and Elliot Wilson. 2015. Immersive Analytics. In *2015 Big Data Visual Analytics (BDVA).* 1–8. https://doi.org/10.1109/BDVA.2015.7314296

[15] Piyaphong Chenrai and Sukonmeth Jitmahantakul. 2019. Applying Virtual Reality Technology to Geoscience Classrooms. *Review of International Geographical Education Online* (Dec. 2019). https://doi.org/10.33403/rigeo.592771

[16] Dan Chiappe and John Vervaeke. 2018. The Experience of Presence in the Mars Exploration Rover Mission. *Presence: Teleoperators and Virtual Environments* 27, 4 (Nov. 2018), 400–409. https://doi.org/10.1162/pres_a_00337

[17] Dan Chiappe and John Vervaeke. 2021. Distributed Cognition and the Experience of Presence in the Mars Exploration Rover Mission. *Frontiers in Psychology* 12 (June 2021). https://doi.org/10.3389/fpsyg.2021.689932

[18] Maxime Cordeil, Benjamin Bach, Andrew Cunningham, Bastian Montoya, Ross T. Smith, Bruce H. Thomas, and Tim Dwyer. 2020. Embodied Axes: Tangible, Actuated Interaction for 3D Augmented Reality Data Spaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems.* ACM, Honolulu HI USA, 1–12. https://doi.org/10.1145/3313831.3376613

[19] Maxime Cordeil, Andrew Cunningham, Tim Dwyer, Bruce H. Thomas, and Kim Marriott. 2017. ImAxes: Immersive Axes as Embodied Affordances for Interactive Multivariate Data Visualisation. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17).* Association for Computing Machinery, New York, NY, USA, 71–83. https://doi.org/10.1145/3126594.3126613

[20] Carolina Cruz-Neira, Daniel Sandin, Thomas DeFanti, Robert Kenyon, and John Hart. 1992. The CAVE: audio visual experience automatic virtual environment | Communications of the ACM. *Comunications of the ACM* 35, 6 (1992), 64–72. https://dl.acm.org/doi/10.1145/129888.129892

[21] Natalia Irma Deligne, Gill E. Jolly, Tony Taig, and Terry H. Webb. 2018. Evaluating life-safety risk for fieldwork on active volcanoes: the volcano life risk estimator (VoLREst), a volcano observatory's decision-support tool. *Journal of Applied Volcanology* 7, 1 (Aug. 2018), 7. https://doi.org/10.1186/s13617-018-0076-y

[22] Adam Faeth, Michael Oren, and Chris Harding. 2008. Combining 3-D geovisualization with force feedback driven user interaction. In *Proceedings of the 16th ACM SIGSPATIAL international conference on Advances in geographic information systems (GIS '08).* Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/1463434.1463466

[23] Jorge A. Wagner Filho, Wolfgang Stuerzlinger, and Luciana Nedel. 2020. Evaluating an Immersive Space-Time Cube Geovisualization for Intuitive Trajectory Data Exploration. *IEEE Transactions on Visualization and Computer Graphics* 26, 1 (Jan. 2020), 514–524. https://doi.org/10.1109/TVCG.2019.2934415

[24] Cael Aidin Gallagher, Mackenzie Muir, David Conroy, Ross Andrew Brown, Christoph Eckart Schrank, and Selen Türkay. 2023. An Immersive Fold Instruction Module for Training Undergraduate Geologists. In *Proceedings of the 34th Australian Conference on Human-Computer Interaction (OzCHI '22).* Association for Computing Machinery, New York, NY, USA, 241–247. https://doi.org/10.1145/3572921.3572950

[25] Cael Aiden Gallagher, Selen Turkay, and Ross Brown. 2021. Towards Designing Immersive Geovisualisations: Literature Review and Recommendations for Future Research.. In *Australian Conference in Human Computer Interaction.*

[26] Joseph V. Gardner, Timothy Warner, M. Duane Nellis, and Tomas Brandtberg. 2003. Virtual reality technology for lidar data analysis, Nickolas L. Faust and William E. Roper (Eds.). Orlando, FL, 48. https://doi.org/10.1117/12.496914

[27] Nicolás F. Gazcón, Juan M. Trippel Nagel, Ernesto A. Bjerg, and Silvia M. Castro. 2018. Fieldwork in Geosciences assisted by ARGeo: A mobile Augmented Reality system. *Computers & Geosciences* 121 (2018), 30–38.

[28] Insook Han. 2021. Immersive virtual field trips and elementary students' perceptions. *British Journal of Educational Technology* 52, 1 (2021), 179–195. https://doi.org/10.1111/bjet.12946

[29] Kristian Hansen. 2022. *VolcanoVR: The visualization of geological data in a 3D virtual reality environment as a multipurpose research, monitoring and outreach tool.* phd. Open Access Te Herenga Waka-Victoria University of Wellington. https://doi.org/10.26686/wgtn.21077260

[30] Chris Harding, Ioannis Kakadiaris, and Bowen R. Loftin. 2000. Multisensory Data Investigation: Adding Touch and Sound to Geoscientific Visualization and Modeling. 50 (2000), 169–177. http://archives.datapages.com/data/gcags/data/050/050001/0169.htm

[31] Chris Harding, Ioannis A. Kakadiaris, John F. Casey, and R. Bowen Loftin. 2001. A Case Study in Multi-Sensory Investigation of Geoscientific Data. In *Data Visualization 2001 (Eurographics)*, David S. Ebert, Jean M. Favre, and Ronald Peikert (Eds.). Springer, Vienna, 3–14. https://doi.org/10.1007/978-3-7091-6215-6_2

[32] C. Harding and R.R. Souleyrette. 2010. Investigating the use of 3D graphics, haptics (touch), and sound for highway location planning. *Computer-Aided Civil and Infrastructure Engineering* 25, 1 (2010), 20–38. https://doi.org/10.1111/j.1467-8667.2008.00591.x

[33] Joel Harman, Ross Brown, Daniel Johnson, Stefanie Rinderle-Ma, and Udo Kannengiesser. 2016. Augmenting process elicitation with visual priming: An empirical exploration of user behaviour and modelling outcomes. *Information Systems* 62 (Dec. 2016), 242–255. https://doi.org/10.1016/j.is.2016.01.005

[34] David Hodgetts. 2017. Application of Virtual and Augmented reality to geoscientific teaching and research. (April 2017), 15888. https://ui.adsabs.harvard.edu/abs/2017EGUGA..1915888H

[35] Mehdi Honarmand and Hadi Shahriari. 2021. Geological Mapping Using Drone-Based Photogrammetry: An Application for Exploration of Vein-Type Cu Mineralization. *Minerals* 11, 6 (May 2021), 585. https://doi.org/10.3390/min11060585

[36] Jiawei Huang, Melissa S. Lucash, Robert M. Scheller, and Alexander Klippel. 2021. Walking through the forests of the future: using data-driven virtual reality to visualize forests under climate change. *International Journal of Geographical Information Science* 35, 6 (June 2021), 1155–1178. https://doi.org/10.1080/13658816.2020.1830997

[37] Leanne Hughes, Luke Bateson, Jonathan Ford, Bruce Napier, Christian Creixell, Juan-Pablo Contreras, and Jane Vallette. 2017. Virtual Field Reconnaissance to enable multi-site collaboration in geoscience fieldwork in Chile. *19th EGU General Assembly* (April 2017).

[38] David A. B. Hyde, Tyler R. Hall, and Jef Caers. 2018. VRGE: An Immersive Visualization Application for the Geosciences. In *2018 IEEE Scientific Visualization Conference (SciVis)*. 1–5. https://doi.org/10.1109/SciVis.2018.8823763

[39] A. Kayser, A. Kellner, H.-W. Holzapfel, G. Van Der Bilt, S. Warner, and R. Gras. 2005. 3D visualization of a rock sample, Rotliegend sandstone, Southern Permian Basin: Applications for core analysis and petrophysics. *Petroleum Geology Conference Proceedings* 6, 0 (2005), 1613–1620. https://doi.org/10.1144/0061613

[40] Gary L. Kinsland and Christoph W. Borst. 2015. Visualization and interpretation of geologic data in 3D virtual reality. *Interpretation-a Journal of Bible and Theology* 3, 3 (Aug. 2015), SX13–SX20. https://doi.org/10.1190/INT-2014-0252.1

[41] Alexander Klippel, Jiayan Zhao, Danielle Oprean, Jan Oliver Wallgrün, Chris Stubbs, Peter La Femina, and Kathy L. Jackson. 2020. The value of being there: toward a science of immersive virtual field trips. *Virtual Reality* 24, 4 (Dec. 2020), 753–770. https://doi.org/10.1007/s10055-019-00418-5

[42] Oliver Kreylos, Oliver G. Staadt, Dawn Y. Sumner, Gerald Bawden, Tony Bernardin, Magali I. Billen, Eric S. Cowgill, Ryan D. Gold, Bernd Hamann, Margarete Jadamec, and Louise H. Kellogg. 2006. Enabling scientific workflows in virtual reality. In *Proceedings of the 2006 ACM international conference on Virtual reality continuum and its applications - VRCIA '06*. ACM Press, Hong Kong, China, 155. https://doi.org/10.1145/1128923.1128948

[43] Mel Krokos, Luca Bonali, Fabio Vitello, Varvara Antoniou, Ugo Becciani, Elena Russo, Fabio Marchese, Luca Fallati, Paraskevi Nomikou, Martin Kearl, Eva Sciacca, and Malcolm Whitworth. 2019. Workflows for Virtual Reality Visualisation and Navigation Scenarios in Earth Sciences:. In *Proceedings of the 5th International Conference on Geographical Information Systems Theory, Applications and Management*. SCITEPRESS - Science and Technology Publications, Heraklion, Crete, Greece, 297–304. https://doi.org/10.5220/0007765302970304

[44] M Lambers. 2016. Lowering the entry barrier for students programming Virtual Reality applications. (2016).

[45] Stéphane Le Mouélic, Pauline Enguehard, Harrison H. Schmitt, Gwénaël Caravaca, Benoît Seignovert, Nicolas Mangold, Jean-Philippe Combe, and François Civet. 2020. Investigating Lunar Boulders at the Apollo 17 Landing Site Using Photogrammetry and Virtual Reality. *Remote Sensing* 12, 11 (Jan. 2020), 1900. https://doi.org/10.3390/rs12111900

[46] Ching-Rong Lin, R.B. Loffin, and T. Stark. 1998. Virtual reality for geosciences visualization. In *Proceedings. 3rd Asia Pacific Computer Human Interaction (Cat. No.98EX110)*. IEEE, 196–201. https://doi.org/10.1109/apchi.1998.704208

[47] C.-R. Lin and R.B. Loftin. 1998. Application of virtual reality in the interpretation of geoscience data. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST*. 187–194. https://doi.org/10.1145/293701.293725

[48] Lin, Ching-Rong, R.B. Loftin, and H.R. Nelson. 2000. Interaction with geoscience data in an immersive environment. In *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*. IEEE Comput. Soc, New Brunswick, NJ, USA, 55–62. https://doi.org/10.1109/VR.2000.840363

[49] Tahir Mahmood, Willis Fulmer, Neelesh Mungoli, Jian Huang, and Aidong Lu. 2019. Improving Information Sharing and Collaborative Analysis for Remote GeoSpatial Visualization Using Mixed Reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 236–247. https://doi.org/10.1109/ISMAR.2019.00021

[50] A. Mangeot, P. Tabani, B. Yven, S. Dewonck, B. Napier, C. J. Waston, G. R. Baker, and R. P. Shaw. 2012. 3D visualization of geo-scientific data for research and development purposes. (Oct. 2012). https://www.osti.gov/etdeweb/biblio/22110009

[51] Bob Menelas, Yaoping Hu, Herve Lahamy, and Derek Lichti. 2011. Haptic and gesture-based interactions for manipulating geological datasets. In *2011 IEEE International Conference on Systems, Man, and Cybernetics*. 2051–2055. https://doi.org/10.1109/ICSMC.2011.6083974

[52] Paul Milgram and Fumio Kishino. 1994. A Taxonomy of Mixed Reality Visual Displays. *IEICE Trans. Information Systems* vol. E77-D, no. 12 (Dec. 1994), 1321–1329.

[53] Rhys Newbury, Kadek Ananta Satriadi, Jesse Bolton, Jiazhou Liu, Maxime Cordeil, Arnaud Prouzeau, and Bernhard Jenny. 2021. Embodied gesture interaction for immersive maps. *Cartography and Geographic Information Science* 48, 5 (Sept. 2021), 417–431. https://doi.org/10.1080/15230406.2021.

1929492

[54] Don Norman. 2013. *The Design of Everyday Things*.

[55] Monsurat Olaosebikan, Claudia Aranda Barrios, Blessing Kolawole, Lenore Cowen, and Orit Shaer. 2022. Identifying Cognitive and Creative Support Needs for Remote Scientific Collaboration using VR: Practices, Affordances, and Design Implications. In *Creativity and Cognition*. ACM, Venice Italy, 97–110. https://doi.org/10.1145/3527927.3532797

[56] D. Oprean, M. Simpson, and A. Klippel. 2018. Collaborating remotely: an evaluation of immersive capabilities on spatial experiences and team membership. *International Journal of Digital Earth* 11, 4 (2018), 420–436. https://doi.org/10.1080/17538947.2017.1381191

[57] Gustav B. Petersen, Sara Klingenberg, Richard E. Mayer, and Guido Makransky. 2020. The virtual field trip: Investigating how to optimize immersive virtual learning in climate change education. *British Journal of Educational Technology* 51, 6 (Nov. 2020), 2099–2115. https://doi.org/10.1111/bjet.12991

[58] Jessica H. Pugsley, John A. Howell, Adrian Hartley, Simon J. Buckley, Rachel Brackenridge, Nicholas Schofield, Gail Maxwell, Magda Chmielewska, Kari Ringdal, Nicole Naumann, and Joris Vanbiervliet. 2022. Virtual field trips utilizing virtual outcrop: construction, delivery and implications for the future. *Geoscience Communication* 5, 3 (July 2022), 227–249. https://doi.org/10.5194/gc-5-227-2022

[59] Disha Sardana. 2023. Embodied Data Exploration in Immersive Environments: Application in Geophysical Data Analysis. (June 2023). https://vtechworks.lib.vt.edu/handle/10919/115343 tex.copyright: In Copyright.

[60] Kadek Ananta Satriadi, Barrett Ens, Maxime Cordeil, Tobias Czauderna, and Bernhard Jenny. 2020. Maps Around Me: 3D Multiview Layouts in Immersive Spaces. *Proceedings of the ACM on Human-Computer Interaction* 4, ISS (Nov. 2020), 201:1–201:20. https://doi.org/10.1145/3427329

[61] Thomas Seers, Ali Sheharyar, Stefano Tavani, and Amerigo Corradetti. 2022. Virtual outcrop geology comes of age: The application of consumer-grade virtual reality hardware and software to digital outcrop data analysis. *Computers & Geosciences* 159 (Feb. 2022), 105006. https://doi.org/10.1016/j.cageo.2021.105006

[62] Mel Slater. 2009. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364, 1535 (Dec. 2009), 3549–3557. https://doi.org/10.1098/rstb.2009.0138

[63] Mel Slater. 2018. Immersion and the illusion of presence in virtual reality. *British Journal of Psychology* 109, 3 (Aug. 2018), 431–433. https://doi.org/10.1111/bjop.12305

[64] Mel Slater, Daniel Pérez Marcos, Henrik Ehrsson, and Maria Sanchez-Vives. 2009. Inducing illusory ownership of a virtual body. *Frontiers in Neuroscience* 3 (2009). https://www.frontiersin.org/articles/10.3389/neuro.01.029.2009

[65] Steven M. Smith and Edward Vela. 2001. Environmental context-dependent memory: A review and meta-analysis. *Psychonomic Bulletin & Review* 8, 2 (June 2001), 203–220. https://doi.org/10.3758/BF03196157

[66] Payam Tabrizian, Anna Petrasova, Brendan Harmon, Vaclav Petras, Helena Mitasova, and Ross Meentemeyer. 2016. Immersive tangible geospatial modeling. In *Proceedings of the 24th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (SIGSPACIAL '16)*. Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/2996913.2996950

[67] A. Tibaldi, F. L. Bonali, F. Vitello, E. Delage, P. Nomikou, V. Antoniou, U. Becciani, B. Van Wyk de Vries, M. Krokos, and M. Whitworth. 2020. Real world–based immersive Virtual Reality for research, teaching and communication in volcanology. *Bulletin of Volcanology* 82, 5 (April 2020), 38. https://doi.org/10.1007/s00445-020-01376-6

[68] UniSA Geoscience - Project LIVE. 2022. LogAR: Augmented Reality Core Logging - Development Snapshot. https://www.youtube.com/watch?v=q2tpCJ2G28U

[69] Callum Walter, Fouad Faraj, Georgia Fotopoulos, and Alexander Braun. 2022. Augmenting geological field mapping with real-time, 3-D digital outcrop scanning and modeling. *Geosphere* 18, 2 (April 2022), 762–779. https://doi.org/10.1130/GES02452.1

[70] Weixi Wang, Zhihan Lv, Xiaoming Li, Weiping Xu, Baoyun Zhang, and Xiaolei Zhang. 2015. Virtual Reality Based GIS Analysis Platform. In *Neural Information Processing*, Sabri Arik, Tingwen Huang, Weng Kin Lai, and Qingshan Liu (Eds.). Springer International Publishing, Cham, 638–645. https://doi.org/10.1007/978-3-319-26535-3_73

[71] Xianying Wang, Cong Guo, David A. Yuen, and Gang Luo. 2020. GeoVReality: A computational interactive virtual reality visualization framework and workflow for geophysical research. *Physics of the Earth and Planetary Interiors* 298 (Jan. 2020), 106312. https://doi.org/10.1016/j.pepi.2019.106312

[72] Anna Wu, Gregorio Convertino, Craig Ganoe, John M. Carroll, and Xiaolong (Luke) Zhang. 2013. Supporting collaborative sense-making in emergency management through geo-visualization. *International Journal of Human-Computer Studies* 71, 1 (Jan. 2013), 4–23. https://doi.org/10.1016/j.ijhcs.2012.07.007

[73] Yalong Yang, Maxime Cordeil, Johanna Beyer, Tim Dwyer, Kim Marriott, and Hanspeter Pfister. 2021. Embodied Navigation in Immersive Abstract Data Visualization: Is Overview+Detail or Zooming Better for 3D Scatterplots? *IEEE Transactions on Visualization and Computer Graphics* 27, 2 (Feb. 2021), 1214–1224. https://doi.org/10.1109/TVCG.2020.3030427

[74] Yalong Yang, Bernhard Jenny, Tim Dwyer, Kim Marriott, Haohui Chen, and Maxime Cordeil. 2018. Maps and Globes in Virtual Reality. *Computer Graphics Forum* 37, 3 (June 2018), 427–438. https://doi.org/10.1111/cgf.13431

[75] Yidan Zhang, Barrett Ens, Kadek Ananta Satriadi, Arnaud Prouzeau, and Sarah Goodwin. 2022. TimeTables: Embodied Exploration of Immersive Spatio-Temporal Data. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Christchurch, New Zealand, 599–605. https://doi.org/10.1109/VR51125.2022.00080

[76] Jiayan Zhao, Jan Oliver Wallgrün, Peter C. LaFemina, Jim Normandeau, and Alexander Klippel. 2019. Harnessing the power of immersive virtual reality-visualization and analysis of 3D earth science data sets. *Geo-spatial Information Science* 22, 4 (2019), 237–250.

[77] Parker Ziegler and Sarah E. Chasins. 2023. A Need-Finding Study with Users of Geospatial Data. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–16. https://doi.org/10.1145/3544548.3581370