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The development and impact of VR fieldtrips on Geoscience Curricula

Thesis presented by

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for the degree of

Master of Science by Research

University College Cork

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Abstract

Fieldwork is the cornerstone of geography education, allowing students to develop hands-on expertise through the direct observation and data collection of the physical environment. As such, fieldwork is crucial for understanding geographical phenomena while developing transferable skills that are valuable in various academic and professional settings. However, recent studies highlight the exclusionary dimensions of fieldwork, where barriers deter student participation and skill acquisition. Notably, barriers to participation have hindered students from engaging in on-site field activities and acquiring relevant skills. These barriers highlighted the significance of valuing students' needs in geography fieldwork education and the importance of developing measures that promote inclusion and accessibility.

Research into overcoming these barriers has been partially supported by technological advances that foster inclusion and equality. Multimodal approaches using videos, imagery, and mobile applications are linked to significant knowledge gains and positive user experiences. Furthermore, the emergence of Extended Reality (XR) has enabled the creation of immersive VR (Virtual Reality) educational environments that replicate virtual labs and fieldtrips. These can integrate realistic representations of sites along with interactive activities and immersive elements. Novel techniques such as SfM (Structure-from-Motion) photogrammetry allow the production of high-quality 3D models by using overlapping aerial and ground images of a site. This method is significant in the integration of 3D environments in the VR environment.

This thesis focuses on the creation of a Virtual Reality fieldtrip (VRF) using well-developed photogrammetric workflows and integrating it within the geography curricula at UCC (University College Cork). The key aims of the research are the following:

I. Develop a VRF of a relevant Irish site tailored specifically to the Irish geography curriculum
II. To use qualitative and quantitative methods to assess the impact and effectiveness of this VRF in support of student learning.

Multiple 3D models of Garryvoe Beach (Cork, Ireland) were developed from UAV and smartphone imagery processed using SfM photogrammetric software. Point clouds and texturised meshes were produced at sub-centimetre resolution. These were imported into the

Unity game engine to create a VR environment with interactive activities and sensory elements. The VRF was delivered to students enrolled in a geography fieldwork module either before, after or in place of an in-person fieldtrip to Garryvoe.

Results showed that the workflow was successful in producing a multisensory experience that integrated multimodal approaches to learning and that included a number of interactive learning tasks. Each task was developed to address specific learning outcomes and was structured to accommodate various learners within the course. Several limitations were identified, primarily related to technological constraints, software and hardware requirements, and usability challenges.

However, the activity revealed that students had positive attitudes towards the use of VR and that they recognised its learning value. Students who completed VR before fieldwork stated the effectiveness of the VRF as a preparatory exercise. It allowed them to become familiar with the site and engage with tasks in advance, thereby reducing cognitive overload and enhancing knowledge retention. This group reported a more positive overall experience and performed better compared to students who completed the VR activity after the fieldwork. The use of the VRF as an alternative to on-site fieldwork was also assessed and revealed the potential and the limitations of using such an approach to replace fieldwork. Results highlighted the importance of such a resource when students cannot partake in fieldwork, contributing to overcoming known barriers. Although the activities at each virtual stop were designed to replicate authentic fieldwork tasks, they could not fully reproduce key elements of fieldwork such as hands-on practice, social interactions and true spatial immersion.

This thesis demonstrates that well-developed VRFs can engage and support students in field-based learning. A more inclusive design that integrates specific learning goals and instructional scaffolding of tasks and information plays a significant role in students' experience and performance. Implementation is also crucial and should promote an integrated approach in which VRFs are used both as preparatory and reflective tools to further enhance field learning and the overall educational experience.

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List of abbreviations

AR	Augmented reality
ADHD	Attention-deficit hyperactivity disorder
AfI	Assessment for Inclusion
DEM	Digital Elevation Model
DOM	Digital Outcrop Model
DT	Digital Twin
GPS	Global Positioning System
HMD	Head-mounted display
SfM	Structure-from-Motion
RQ	Research Question
UAV	Uncrewed Aerial Vehicle
UCC	University College Cork
URP	Universal Render Pipeline
VRF	Virtual reality fieldtrip
VR	Virtual reality
XR	Extended Reality

Declaration

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property.



Signed

Irene Loriga, author.



Dr Aaron Lim, supervisor



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Dr Therese Kenna, co-supervisor



Dr Larissa Macedo Cruz de Oliveira, co-supervisor

1. Introduction

Fieldwork plays an important role in geography education, fostering real-world enquiry and deep learning through first-hand experience (Butler, 2008). While most geoscientists value fieldwork for its cognitive benefits, others emphasise the significant barriers that limit accessibility for many students. The primary obstacles to participation are:

I. Financial issues: Students from low-income backgrounds are often hindered from participating due to the costs associated with personal field gear and travel (Abeyta et al., 2021). Although many institutions offer financial support, it is often insufficient to cover all educational expenses.
II. Mobility impairments: physical ability emerges as a major concern when undertaking fieldwork. Students can be prevented from travelling long distances and moving to areas where safety cannot be ensured (Hall et al., 2004).
III. Mental and physical health disorders: many students with conditions such as ADHD, epilepsy, chronic diseases, as well as hearing and vision difficulties, often face significant barriers (Kessel, 2008) due to unfamiliar environments and lack of support structures (Birnie and Grant, 2001).
IV. Caring responsibilities: amongst all students, mature students, especially women, are often affected in their career progression by caring responsibilities (Carlin et al., 2024), posing a significant barrier to fieldwork participation.
V. Pandemics: the emergence of COVID-19 and efforts in reducing its spread forced many universities globally to shift courses from on-site to online (Aristovnik et al., 2020). This posed a significant barrier to fieldwork learning for most undergraduate students.

Given these recognised issues in fieldwork education, the design and implementation of supplementary fieldwork experiences is required (Hopkins et al., 2018). In this regard, technology plays a crucial role. Widespread adoption of Extended Reality (XR) tools such as Augmented Reality (AR) and Virtual Reality (VR) has revolutionised the way people interact with and experience the physical world. VR, especially, has proven effective in providing interactive and immersive experiences that replace the physical world (Harknett et al., 2022). Specifically, VR can recreate a real-world site by means of realistic and high-quality 3D models.

A key benefit is that users don't have to be *in situ* to be able to access the digital information, making it readily available to a wider demographic.

Structure-from-Motion (SfM) photogrammetry is a technique that employs a series of overlapping images to reconstruct 3D surface models (Eltner and Sofia, 2020). This method is significant in geoscience applications, especially geography, as it allows production of accurate and georeferenced 3D models from 2D images. UAV imagery plays an important role in ensuring accuracy and quality in the production of these 3D models. This technology improves mapping efficiency, ensures increased accuracy and enables capture of data from hazardous areas (Ok, 2025). While Google Maps typically employs satellite imagery with meter to submeter resolution, UAVs survey areas with high-resolution digital cameras that can capture images at <1 cm/pixel resolution. This results in highly detailed 3D models with high-resolution textures, enhancing feature visualisation and enabling detailed surface analysis and measurement. Applications range from topographic monitoring (Gonçalves and Henriques, 2015) to archaeological studies (Kanun et al., 2021) and geological mapping (Honarmand and Shahriari, 2021). In education, it can be used to produce accurately scaled and georeferenced terrain models for VR fieldtrips (VRF), where activities are integrated digitally. Thus, SfM photogrammetry and VR can serve as an additional resource for in-class teaching and fieldwork, useful for preparation, reflection or as an alternative to support students' learning in undergraduate education.

At present, there is a lack of VR field courses designed around Irish field sites, and a limited number of Irish studies evaluating the impact of VR on learning outcomes and engagement. Without evidence from national institutions, it's difficult to formally integrate VR into curricula as a fieldwork or in-class learning method. As VR teaching gains global traction, projects such as this allow Irish geoscience curricula to advance accordingly while generating VRFs that showcase Ireland's landscape globally.

1.1 Aims and Research Questions

Given the shortcomings listed above, the research outlined here aims to bridge the gap between the posed challenges and potential solutions. Consequently, this thesis seeks to achieve two primary aims:

1. To develop a VRF tailored specifically to the third-level Irish geography curriculum.
2. To employ qualitative and quantitative methods to assess the impact and effectiveness of this VRF in support of student learning.

To address these two aims systematically, this thesis seeks to answer three research questions (RQs):

RQ1: What is the impact of VRFs in the geoscience third-level education?

RQ2: How should VRF be best implemented?

RQ3: To what extent can VRFs allow students to replace fieldwork?

These RQs will expand our knowledge beyond current understanding. The objective of RQ1 is to understand the effectiveness of using VR in support of third-level geography field-based learning, outlining the benefits and limitations on students' learning and experience. Demonstrating the impact of this initiative on Irish geoscience curricula will support decision-making for higher education investment in digital learning. The objective of RQ2 is to determine whether or not the completion of a VRF before commencing fieldwork or after enhances learning. Understanding the best implementation strategy will enable educators to properly integrate VR tools in laboratory sessions, pre-assessment revisions and fieldwork experiences. The objective of RQ3 is to determine how effectively VRFs can achieve learning outcomes in place of actual field-based learning and assess the role of VR in promoting formal inclusion in geography education. There are many cases where students cannot participate in field-based learning as a result of disabilities, financial constraints, illness, or pandemics. For

this reason, it is important to explore ways in which VR technology can help mitigate these issues and provide a more inclusive learning experience.

1.2 Thesis outline

The work in this thesis documents a turning point in the use of digital technologies in third-level education by providing a novel method to enhance field-based learning. Each chapter outlines the work developed towards achieving the aforementioned objectives as follows:

Chapter 1 outlines the rationale of this project, highlighting the challenges and opportunities associated with fieldwork in geography education. This is followed by a description of the aims and objectives. The final section examines the existing literature on the application of Extended Reality (XR) technology, with a particular focus on VR and UAV SfM photogrammetry in education.

Chapter 2 presents the results of the first aim of this project: to develop a VRF tailored specifically for the Irish geography curriculum. First, it provides an overview of the importance of fieldwork in geography education, outlining the learning gains and implications for inclusive education. It moves on to discussing the existing barriers associated with fieldwork and the recent advances in technology, such as Digital Twins (DT), SfM photogrammetry and extended Reality (XR) in the creation of 3D products and their integration in VR for enhanced visualisation. A workflow was developed to create an immersive and interactive VRF of Garryvoe Beach (Cork, Ireland). This involves the use of UAV and smartphone imagery, Agisoft Metashape as a photogrammetry software and Unity as the VR platform. The technical aspects of designing and creating the VRFs are covered, along with the expected learning outcomes. A comparative assessment with other VRFs is then presented, and the advantages and limitations of using this method are also outlined. This chapter significantly contributes to providing grounds for the aim of Chapter 3 and to answering the aforementioned research questions.

Chapter 3 presents the results of the second aim: to both employ qualitative and quantitative methods to assess the impact and effectiveness of this VRF in support of student learning. Firstly, it offers an introduction to the benefits and limitations of employing digital tools in education. It then briefly describes the Garryvoe fieldtrip and the VR field course, providing

information on the participants and assessments. This chapter presents a novel approach that combines qualitative and quantitative methods to assess student performance and experience with VR in support of fieldwork learning. The results offer valuable insights into the implications of using VR in geography education as a fieldwork activity, while providing valuable insights into inclusive practices. To this end, Chapter 3 aims to answer the three main research questions:

RQ1: What is the impact of VRFs on the geoscience third-level education?

RQ2: How should VRF be best implemented?

RQ3: To what extent can VRF allow students to replace fieldwork?

Chapter 4 presents a conclusion to the thesis, summarising the key findings, accomplishments, and concluding remarks. It then offers suggestions for future research and developments.

1.3 Literature Review

The primary purpose of this review is to determine whether there is compelling evidence for the use of immersive virtual reality in education, as well as the methods used to reproduce virtual environments. The material presented proposes different approaches to virtual reality in scientific education and outlines the use of photogrammetry in the acquisition of data needed to create 3D digital models of sites. The review starts with an introduction to extended reality (XR), which explains the difference between virtual reality (VR) and augmented reality (AR) technology, followed by a section that covers the advantages and limitations of VR in enhancing students' experiences and learning in geography education. The last section covers the potential of integrating SfM (Structure-from-Motion photogrammetry) with VR to produce immersive environments that display high-quality models of sites.

Extended reality

The term extended reality (XR) is used to define the combination of virtual and physical realities generated by computer technologies. VR and AR are types of XR technology that present fundamental differences: AR differs from VR in that it combines the digital and the real world. In other words, 2D and 3D graphics are added to the real world via mobile devices or head-mounted displays such as the Google Glass (Boyles, 2017). By contrast, VR is defined by the presence of a human-computer interface that simulates a realistic environment (Zheng et al., 1998). VR can be categorised into immersive and non-immersive (Lavoie et al., 2025). The immersive VR allows users to interact with the digital world by using a combination of haptic devices, hardware, and software components (Wohlgenannt et al., 2020). These can provide a direct manipulation method for users to work with 3D graphics (Zheng et al., 1998). Non-immersive approaches often consist of interacting with the VR environment on a computer screen via different input devices with limited sensory involvement (Piccardi et al., 2025).

VR in education

Different studies have claimed that the integration of multimedia into conventional classroom education was important to enhance learning (Mishra and Sharma, 2004; Mukherjee, 2018; Vagg et al., 2020). Notably, Mayer (2002) discussed the suitable multimedia design that can benefit users in education. He claimed that appropriate verbal and visuospatial thinking

allows meaningful learning of concepts. His findings indicated that students learn more effectively when presented with narrations, familiar words, and pictures. Other studies have highlighted the value of integrating multimedia into traditional classroom instruction to improve learning outcomes (Vagg et al., 2020; Neo and Neo, 2004; Rackaway, C., 2012; Williams and Patrick Harkin, 1999). Specifically, multimedia can help students better understand and retain knowledge, thus improving the overall quality of education (Rumiantseva et al., 2023; Vijayalakshmi and Reddy, 2020; Hill and Nelson, 2011).

Virtual reality experiences, offering interactivity and immersion, are gaining importance across different disciplines. Bell and Fogler (1995) demonstrated VR's effectiveness in visualising abstract chemical engineering concepts using Vicher. However, the study acknowledged the limitations related to the technology that hindered students from fully engaging with the VR module. Fabris et al. (2019) found that VR supports self-directed learning, active participation, and knowledge retention in biomedical practical courses, enhancing knowledge retention.

In the field of geoscience education, VR proved to be of importance to students completing fieldwork modules to enhance their field-based learning while addressing issues related to cost, remoteness of field sites and disabilities (Guillaume et al., 2023; Harknett et al., 2022; Horota et al., 2022; Minocha et al., 2018; Butler, 2006). This was highlighted as being particularly beneficial during the COVID-19 pandemic (Evelpidou et al., 2021; Peace et al., 2021; Thönnessen and Budke, 2020) when in-person field trips were not possible. However, several studies have highlighted some of the disadvantages of VR. The main aspect identified was the inability to recreate the immersive and sensory elements of the cultural and physical landscape (Pugsley et al., 2022; Arrowsmith et al., 2005). The social factor also plays an important role in fieldwork. Students learn to cooperate, make friends and build trust, qualities that are difficult to reproduce in a VRF (Cook et al., 2025; Spicer and Stratford, 2001). Students might also not be comfortable using the technology and develop feelings of disorientation in the virtual world (Cliffe, 2017; Tuthill and Klemm, 2002). Nevertheless, the advantages of using VR in education are many and have been covered in several studies. Arrowsmith et al. (2005) developed the Grampians National Park VRF to prepare second-year geospatial science students for on-site fieldwork. Students reported a positive experience using VR, finding it useful for preparation, obtaining a strong topographic overview of the site.

Cook et al. (2025) conducted an immersive virtual field trip exploratory case study of Garden Ridge (Virginia, U.S.), claiming that the fieldtrip successfully simulated navigable geological spaces in which students developed a strong sense of presence. Guillaume et al. (2023) highlighted the use for effective multi-scale geological observation. Watson et al. (2024) employed a VRF of Iceland to support third-year students studying physical volcanology. The VRF aided geological interpretation, as well as improving spatial interpretation skills. Qiu and Hubble (2002) recognised that one of the many advantages of VRFs is that they display data at different scales and allow visualisation of the landscape from multiple viewpoints simultaneously and on multiple occasions. Similarly, the concept of spatial scalability has been mentioned by Granshaw and Duggan-Haas (2012), who acknowledged the importance of observing the site from multiple viewpoints. The authors outlined the importance of VRFs in pre-trip debriefing as well as post-field trip reflection. These studies also agree that it's important to consider that VRFs must be designed with well-established learning goals and the skills to create meaningful learning. Bricken (1991) claimed that using VR in education can become the most effective tool in enhancing students' performance when tailored according to different learning needs. Oyler (2014) demonstrated that VR has a significant impact on comprehension and vocabulary achievement in students with learning disabilities. Chen and Ismail (2005) claimed that guided VR experiences have the potential to accommodate students with different learning styles.

While XR technologies such as VR and AR are transforming education by offering immersive and interactive learning experiences (Jana et al.,2025), barriers in their application in education are diverse and complex (Samala et al., 2024; Beh et al., 2022). XR devices come with high costs, largely because of their advanced hardware and software. This aspect can represent a barrier in less well funded institutions that lack the resources to effectively implement XR learning experiences (Samala et al., 2024; Alnagrat et al., 2022; Ozdemir, 2021). Other relevant challenges to consider are infrastructure limitations, as institutions might lack adequate internet connectivity to support effective use of XR devices (Jana et al.,2025), as well as instructors' limited ability to use the technology effectively (Alzahrani, 2020).

Regarding VR technologies, the inability to recreate the immersive and sensory elements of the cultural and physical landscape particularly emerged as a relevant limitation (Puglsey, 2022; Arrowsmith et al., 2005). As previously stated, students learn to cooperate, make

friends and build trust while doing fieldwork, qualities that are difficult to reproduce in a VRF (Cook et al., 2025; Spicer and Stratford, 2001). The reduced level of peer interaction can lead to social isolation and hinder the possibility of working in a team and communicating (Arrowsmith et al., 2005). Physical discomfort was also considered a challenge of VR, often related to motion sickness and fatigue of the various senses (Burke et al., 2025; Sofiadin, 2024). Furthermore, Friess et al. (2026) reported that students using VR technology may struggle to engage with multiple elements of the virtual environment simultaneously. Similarly, Cliffe (2017) noted that virtual environments can induce feelings of disorientation, which may hinder students' engagement with learning materials (Stainfield et al., 2000; Spicer and Stratford, 2001; Baggott la Velle, 2005; Garner and Gallo, 2005). Distractions within VR environments have also been highlighted as a concern, as students may focus more on the technology itself than on the educational content (Sofiadin, 2024). Due to the absence of real-world experience in VRFs compared to traditional fieldwork, students may fail to develop certain essential skills, particularly those requiring hands-on practical engagement (Friess et al., 2026; Stainfield et al., 2000).

In addition to students experiencing challenges using this technology, instructors face several obstacles when implementing VRFs. Designing and employing a VRF requires specific technical knowledge and instructors may need to learn how to effectively use VR technology for teaching (Burke et al., 2025), a type of preparation that can represent a challenge for some people.

Despite the broad literature on VR applications in geography education internationally, there is a lack of VR studies in Ireland. While the use of VR in education has been explored (Cowan and Farrell, 2023; Walsh et al., 2019; O'Leary et al., 2025), there is a significant shortage of publications based on the development and creation of VRFs in geography education at a national level.

SfM Photogrammetry and VR

Photogrammetry is defined as a method that derives metric information of objects through measurements taken on their photographs (Mikhail et al., 2001). Structure-from-Motion (SfM) photogrammetry is a low-cost method that varies from conventional photogrammetry in that camera positions and orientation are solved thanks to the automatic identification of

corresponding features in overlapping images (Westoby et. al., 2012). When combined with Uncrewed Aerial Vehicle (UAV) surveys, SfM has proven to be useful in geoscience applications (Anderson et al., 2019).

Photogrammetry has become an important tool in geoscience for monitoring and modelling diverse environments. In river and coastal contexts, terrestrial, UAV, and ground-based SfM methods have been used to assess erosion, gully morphology, and shoreline change (Nikolakopoulos et al., 2019; Koci et al., 2017; Casella et al., 2014; Barker et al., 1997). In marine environments, SfM photogrammetry has enabled high-resolution, non-destructive 3D mapping of reefs and the seabed (de Oliveira et al., 2021; Bayley et al., 2019; Burns et al., 2015).

In geoscience education, UAV photogrammetry has been integrated into VR environments to support students in-class and as part of field learning. Sefercik et al. (2021) tested the potential of UAV imagery to create high-quality 3D models and integrate them into a VR environment for a 3D Unity virtual tour. The results demonstrated the potential of such tours in exploring and collecting information remotely. Harknett et al. (2022) used UAV photogrammetry to create digital outcrop models (DOM) of the Husavik Triple Junction in Northern Iceland. These high-quality models (4 cm per pixel) were integrated into a VR environment, allowing students to obtain detailed structural observations in a remote location. Furthermore, Tibaldi et al. (2020) employed SfM photogrammetry to develop a series of VRFs to teach volcanology. The project features the use of 3D DOMs from UAV imagery to display complex features at high resolution (8 mm/pixel), enabling accurate remote measuring of features in inaccessible environments.

The use of SfM photogrammetry is well understood and applied in educational settings, therefore providing a good method for the creation of VRFs. Further applications are necessary to evaluate the effectiveness of the integration between this method and VR to support students in fieldwork learning.

This review presents an overview of the importance of VR in geoscience education. It was established that VR enhances students' learning, offering immersive exploratory experiences that promote active participation and contribute to the retention of knowledge. One important aspect of such experiences is that VR field trips must be designed using valid

methods for the accurate reproduction of sites. Notably, the efficiency of photogrammetry in the reconstruction of 3D landscapes has been validated by different studies in coastal, terrestrial, and marine applications and has been shown to be effective in producing realistic immersive experiences. Nevertheless, several studies claimed that VR field trips cannot replace the real experience, as their immersion and interactivity are often limited within the virtual world. However, VR benefits a large variety of students who must face different issues in geoscience education. The current gaps remain in understanding the broader contributions of VR in Irish geography education, as well as identifying the most effective strategies for implementing VR in classrooms to support student learning, enhance outcomes, and promote inclusivity.

2. The development of VR fieldtrips for Geoscience Curricula

Irene Loriga, Aaron Lim, Larissa Macedo Cruz de Oliveira, Therese Kenna and Mohit Tunwal

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This chapter addresses the first aim of this MSc research: the development of a VR fieldtrip (VRF) tailored to the Irish geography curriculum, and a version of this has been submitted to the Journal of Geography in Higher Education In response to the lack of VRFs of Irish fieldwork sites, this research explores the capabilities of current technologies to obtain high-quality photogrammetric data to create scaled and georeferenced 3D models and to integrate these into a VR immersive and interactive environment. This chapter outlines the activities and expected learning outcomes of the VRF, systematically compares its capabilities with similar projects and identifies aspects that need to be further explored. Thus, this chapter contributes to informing future research about the available technology and data needed for VR applications.

Candidate contributions to the study: Irene Loriga conceptualised the study, developed the methodology, data collection, software, carried out the investigation, analyses, writing of the original draft, review, submission and editing.

The project, which led to the work developed in this chapter, was funded by the Geological Survey Ireland through the Masters by Research Scholarship 2023. Dr Aaron Lim, who is the PI of the project, contributed to the funding acquisition.

Irene Loriga conceptualised the study, developed the methodology and data collection in Garryvoe (Co. Cork) with the support of Dr Aaron Lim and Dr Larissa Macedo de Oliveira, who also supervised the project. Irene was responsible for the processing of the photogrammetric data acquired in Garryvoe, the creation of the 3D models and the development of the VRF. The supervisory team additionally included Dr Therese Kenna and Dr Mohit Tunwal. These co-authors also contributed with editing and proof-reading of the manuscript.

Abstract

Fieldwork is a central component of geoscience education. It provides students with significant cognitive benefits and allows them to develop essential professional skills through direct engagement with the real world. However, recent studies uncovered the challenges and the exclusionary dimension of fieldwork. This is particularly relevant for students with disabilities, as well as financial and accessibility constraints. Moreover, the recent COVID-19 pandemic posed a significant threat to fieldwork globally, emphasising the need to explore viable alternatives to enhance fieldwork accessibility. To address these issues, this project proposes a workflow to develop VR (Virtual Reality) fieldtrips for geoscience curricula at University College Cork. This is accomplished using UAVs (Uncrewed Aerial Vehicles) to acquire high-resolution photogrammetric data, which are processed via Agisoft Metashape into 3D reconstructions of Garryvoe Beach in South-East Cork. These are scaled and georeferenced models that are imported into Unity, a cross-platform game engine, and integrated into the 3D VR environment. In this project, Unity is used to develop an interactive and immersive "walk-through" of the fieldtrip, drawing upon its recent successful applications within the Geosciences. This can be used as a desktop version and as a VR version for a more immersive experience and is used to measure students' experience and the effectiveness of VR in enhancing their field-based learning. The results demonstrate the effectiveness of employing UAV photogrammetry in generating 3D models that retain real-world scales and display high-quality textures, significant to fieldwork investigation and analysis. The Garryvoe VRF complements this capability with the integration of a series of learning activities that include multiple formats, including infographics, videos and audio materials. These elements are combined into a multisensory, immersive experience that recreates realistic terrain features, environmental effects, and authentic soundscapes. Limitations primarily relate to technological challenges, hardware and software requirements and usability issues associated with VR technology. Despite these constraints, the findings of this study demonstrate the effectiveness of employing the proposed workflow to develop VR-based field courses for geoscience education.

2.1 Introduction

Geoscience is a challenging subject that combines theoretical knowledge and practical fieldwork, requiring a distinctive set of thinking and investigative skills unique to this discipline (King, 2008). While fundamental concepts are taught in the classroom, field experiences provide students with the opportunity to apply these concepts and develop a number of transferable skills that are essential for pursuing a career in the geoscience industry. Notably, in Ireland and the UK, fieldwork has become a compulsory activity for all undergraduate geoscience students (Boyle et al., 2009) and field experience is often a key requirement for many geoscience employers (Mosher and Keane, 2021).

Bonello (2001) argues that skills acquired during fieldwork can be divided into two broad categories: personal skills and technical skills which contribute to enhancing both the cognitive and affective dimensions of students' learning (Petcovic et al., 2014). In line with this, King (2008) identifies five educational attributes of geoscience education, suggesting that geoscience involves retrodictive thinking, holistic system thinking and advanced spatial thinking. Furthermore, King highlights the importance of developing a time perspective and cultivating advanced analysis and synthesis skills. In addition, Butler (2008) claimed that fieldwork is relevant to solving real-life interdisciplinary problems and working on self-reliance and leadership skills.

Two relevant statistical studies by Boyle et al. (2007) and Petcovic et al. (2014) examined the perception of fieldwork among geoscience curricula and the broader geoscience community. Both studies revealed that the majority of participants had a positive attitude towards fieldwork and recognised it as an essential component of undergraduate education. However, the studies also highlighted some challenges associated with fieldwork which, according to Boyle might reflect changing backgrounds, genders and experiences of students entering higher education.

Higher Education Authority statistics (2024) highlight the diversity within the student population in Irish higher education institutions. According to the data, approximately 30% of students enter higher education through access pathways, with about 5% being mature students. Additionally, 20% of students in higher education have a disability, and approximately 25% of students are of non-Irish ethnicity. These figures highlight the varied

backgrounds and needs of the student body as well as highlight potential barriers each group might face in succeeding in higher education. This issue is heightened further by financial pressures, as outlined in the Student Union Report on the Cost of Living in County Cork in Ireland (Rountree, 2024). Based on interviews with approximately 3,000 students, the report reveals that most students are struggling with rising living costs and emphasises the economic challenges students face in covering expenses tied to higher education.

The Higher Education Act (Higher Education Authority Act, 2022) states that education has to follow a Universal Design to ensure that it is accessible and inclusive. However, these principles are not reflected in the broader geoscience community, which has shown low representations of ethnic minorities and disabled students (Carlin et al., 2023; Hall et al., 2004). This lack of inclusion is particularly evident in geoscience fieldwork, which has been identified as an area of exclusion for historically underserved groups (Núñez et al., 2021). Lawrence and Dowey (2022) outlined six simple steps that can contribute to making fieldwork more inclusive; one of the principles regards planning and ensuring that alternatives to fieldwork are available to the students. For instance, digital resources can be made available to enhance students' fieldwork experience, such as smartphones (Tavani et al., 2022; Welsh and France, 2012) and XR technology (Jiménez et al., 2024; Janeras et al., 2022).

The term Extended Reality (XR) refers to those technologies that enhance the user's perception of the real world with digital elements (Augmented Reality) or create a computer-generated digital environment (Virtual Reality). While Augmented Reality (AR) allows users to display digital elements in the real-world environment (Ardiny and Khanmirza, 2018), VR (virtual reality) allows the creation of a virtual environment where the participant is part of an immersive experience (Al-Ansi et al., 2023). Haptic devices, such as VR controllers, allow users to interact with the virtual world, whereas head-mounted devices provide a sense of immersion, replicating the visual and sound effects of the real world (Dangxiao et al., 2019). This technology can offer a viable alternative for a large number of students who face barriers to fieldwork (Chiarella and Vurro, 2020).

For this reason, this study aims to employ SfM photogrammetry to create accurately scaled 3D models of Garryvoe Beach (Co. Cork) that can be integrated into an immersive VR-generated environment using Unity 3D. This will enable students to interact with the environment and perform basic fieldwork tasks. By creating an immersive VRF, this study

seeks to create a pilot for geoscience education where VR technology can be integrated into fieldwork and classroom learning.

2.3 Rationale: Barriers to fieldwork

Fieldwork is widely regarded as an essential component of geoscience education (Mogk and Goodwin, 2012; Stokes and Boyle, 2009). The benchmark statement for the Earth Sciences, Environmental Sciences and Environmental Studies (QAA, 2007) emphasises that only by exposing students to field-based teaching is it possible to develop a satisfactory understanding. However, in recent years, researchers have started to highlight the barriers produced by traditional fieldwork (Carlin et al., 2023; Hall et al., 2004). These can hinder the full participation of different groups of students, thus potentially limiting the opportunities available to them. These barriers particularly affect students from marginalised and underrepresented contexts. For instance, disabled students are a minority in undergraduate courses that include a fieldwork component (Chasen et al., 2024; Hall et al., 2004). Often, students with physical disabilities are hindered from travelling long distances or navigating field sites where their safety can't be ensured. Hall et al.'s (2004) study on disabled students' experiences in fieldwork revealed that physical mobility strongly emerged as a pressing issue when undertaking fieldwork. Additional issues include the removal from familiar environments and support mechanisms, as well as physical well-being and information gathering. Furthermore, they claimed that the field is both a physical and a social domain, which can also produce social barriers. Kessel (2008) observed that the majority of students registered with a disability experience non-visible impairments. These include epilepsy, ADHD, mental health disorders, vision and hearing difficulties, and other chronic illnesses. These contribute to highlighting the potential barriers that can arise in fieldwork. Financial issues are also recognised as a significant barrier. Many higher education institutions require students to cover the full cost of fieldwork, creating an issue for those with limited financial resources (Abeyta et al., 2021). In addition to transportation costs, geoscience students are often required to purchase fieldwork gear to comply with health and safety regulations. Abeyta et al. (2021) highlighted that students from disadvantaged backgrounds find it difficult to overcome any challenges associated with the cost of personal field gear, travel and dependent care. Caring responsibilities pose a significant barrier to women's participation in fieldwork (Carlin et al., 2023). The duty of looking after children and elderly family members is often

placed on women, limiting their ability to take part in extended field trips (Hamylton et al., 2023; Vila-Concejo, 2018).

2.4 Recent advances

The COVID-19 pandemic is a recent example of how social distancing measures prevented students from partaking in fieldwork and acquiring essential skills as part of their degree programs. Education was one of the worst-affected sectors, causing governments to temporarily close higher education institutions, with over 60% of students in 144 countries shifting from in-class to remote learning (Szyrocka et al., 2023). The E-learning system rapidly became the new teaching method that most institutions adopted globally. This significantly impacted courses with fieldwork components, which often had to be cancelled or redesigned. Notably, several institutions adopted alternative methods to deliver fieldwork classes using VR technology (Guillaume et al., 2023; Peace et al., 2021). Although these solutions were effective in supporting students' learning, they represent only a few examples available to the students at the time of the COVID-19 quarantine.

Pathak and Upadhyay (2024) discussed the potential of Digital Twin (DT) technology to support academic institutions. DT is a digital set of information that describes a physical product and links the virtual system to the physical equivalent (Grieves and Vickers, 2017). The physical product can be replicated in software and its behaviour can be studied and predicted (Crespi et al., 2023). Since the introduction of the DT concept by Michael Grieves in 2002 in the context of product lifecycle management, interest in its application across disciplines has grown significantly. Along with its popularity, its definition has expanded to encompass purely static visualisations, e.g. 3D reconstructed objects, often called “digital shadow”, to dynamic, bidirectional links between physical and virtual environments, e.g. DestinE. During the COVID-19 pandemic, institutions began adopting immersive technologies such as virtual labs and immersive VRFs to address the challenges in remote teaching (García-Estrada and Prasolova-Førland, 2022; García-Vela et al., 2021; Schulze et al., 2021). Although there remains a debate across disciplines regarding what qualifies as a digital twin, the digital technologies shared within the DT umbrella can make simulation-based and fieldwork learning possible for disciplines like medicine and sciences in which expertise in real-world processes is of fundamental importance (Choi et al., 2025; Heidarinejad and Srivastava, 2023;

Lo and Tsai, 2022; McKnight et al., 2020). Notably, photogrammetry software enables the creation of digital twins, or digital shadows, through workflows that generate a digital representation of the world (Demetrescu et al., 2020; De Paolis et al., 2020). Photogrammetry offers a highly precise method that uses high-resolution images to create accurate 3D models of real-world objects (Borg et al., 2020). Structure-from-Motion (SfM) is a branch of photogrammetry that provides a more automated approach in which camera positions and orientations are solved by the automatic identification of corresponding features in overlapping images (Westoby et al., 2012). As a result of the efficiency and low cost of this method, its application extends to many areas, including geosciences, where it has been employed to monitor and obtain high-quality data from geologically relevant sites (Bayley et al., 2019; Nikolakopoulos et al., 2019; Casella et al., 2014). This method, coupled with XR, can have great potential in geoscience education, in particular, in fieldwork applications in which sites or features relevant to students can be recreated digitally (Zulhilmi and Hayakawa, 2025; Harknett et al., 2021; Fink et al., 2023).

Recent advances in XR, particularly in VR, have highlighted the importance of such an approach for 3D visualisation. Applications such as Google Expeditions and Google Earth are already being used in various educational settings (Andrews et al., 2019). In the clinical context, XR is applied for skills training and pre-operative planning, such as the HoloAnatomy AR app by the Case Western Reserve University, which features holographic models of anatomical structures (Richards, 2023). XR applications also extend to geoscience to integrate digital models of real-world geographic data into immersive VR experiences. These allow users to explore, experience and analyse complex geographic phenomena in the VR environment (Çöltekin et al., 2020). Within the geosciences, VR has found several applications in the field of geological mapping, supporting data collection and analysis in remote and dangerous sites (Marinos et al., 2025; Antoniou et al., 2020).

2.5 Methodology

For this study, a series of fieldwork learning activities was designed to align with the learning outcomes that each student is expected to achieve by the end of their geoscience module. These activities are distributed across various stops throughout the chosen site. For each activity, data were collected and visualised within a suitable VR setting. The proposed

methodology for data collection and processing is summarised in Figure 1. It integrates UAV (Uncrewed Aerial Vehicles) surveys and smartphone photo collection to obtain high-resolution photogrammetric data. The data were processed using SfM photogrammetry (via Agisoft Metashape Professional), a method widely used in geoscience applications to obtain spatial information on landforms (Westoby et al., 2012). The resulting scaled 3D models, generated from overlapping offset images, are subsequently imported into Unity, a cross-platform game engine. Unity facilitates the integration of tools, interactions, infographics and other elements in the VRF experience.

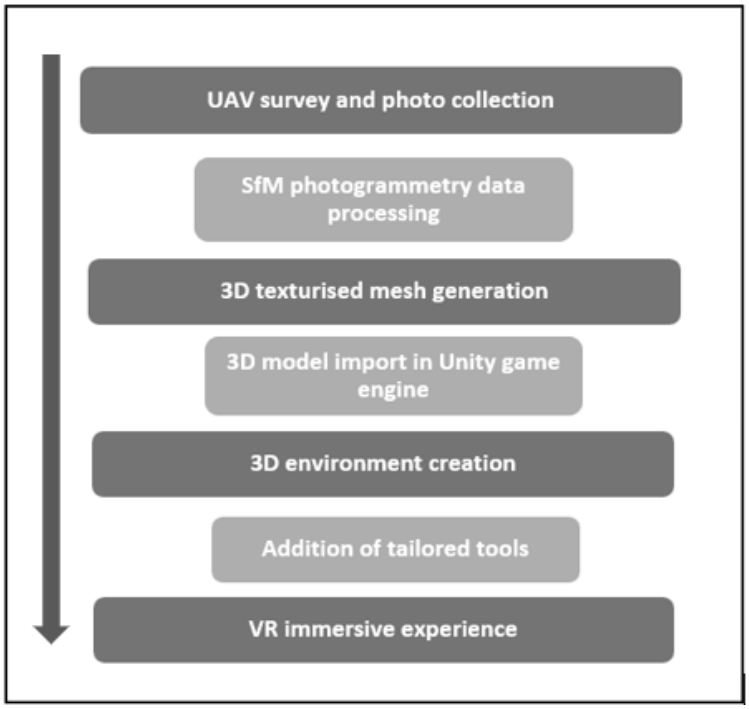


Figure 1. Schematic representation of the proposed methodology, with the darker boxes indicating the four principal stages: data collection, processing for 3D model generation, and the import and development of the immersive VRF.

2.6 Study Area

Garryvoe Beach is part of Ballycotton Bay and is located close to the village of Garryvoe in south-east Cork (Figure 2). The bay is characterised by two sheltered inlets, which receive the flows of a number of small rivers. The site is of geological importance as it lies within the

Cloyne Syncline and rises on a bed of Carboniferous Limestone (Sleeman and Pratch, 1994). The bay is enclosed by the Late Devonian and Carboniferous Cork Limestone and Old Red Sandstone extending to Knockadoon Cliffs in the north and Ballycotton Cliffs in the south (Figure 3). The Cloyne syncline was formed during the Variscan Orogeny event, which caused the rocks in south Munster to compress, producing fold ridges (anticlines) and troughs (synclines) with an east-west orientation. The north side of Garryvoe Beach is characterised by sea cliffs. These extend for c. 1 km and comprise glacial deposits from the last Ice Age (around 20,000 years ago), deposited on a raised beach. The sea cliffs display Quaternary sediment sequences of the south coast of Ireland, mainly composed of Irish Sea Till (Hennessy et al., 2023). To manage coastal erosion, coastal protection was introduced for a few kilometres along the back of the beach. The Ballynamona Strand is located on the edge of Ballycotton Village, south of Garryvoe Beach. The dune system in the area that divides the beach from the fields is an essential part of the coast and, therefore, is classified as a protected habitat.



Figure 2. Location of the study area at Garryvoe Beach in south-east County Cork, Ireland, shown on Google Earth. The inset provides a closer view of the coastal setting.

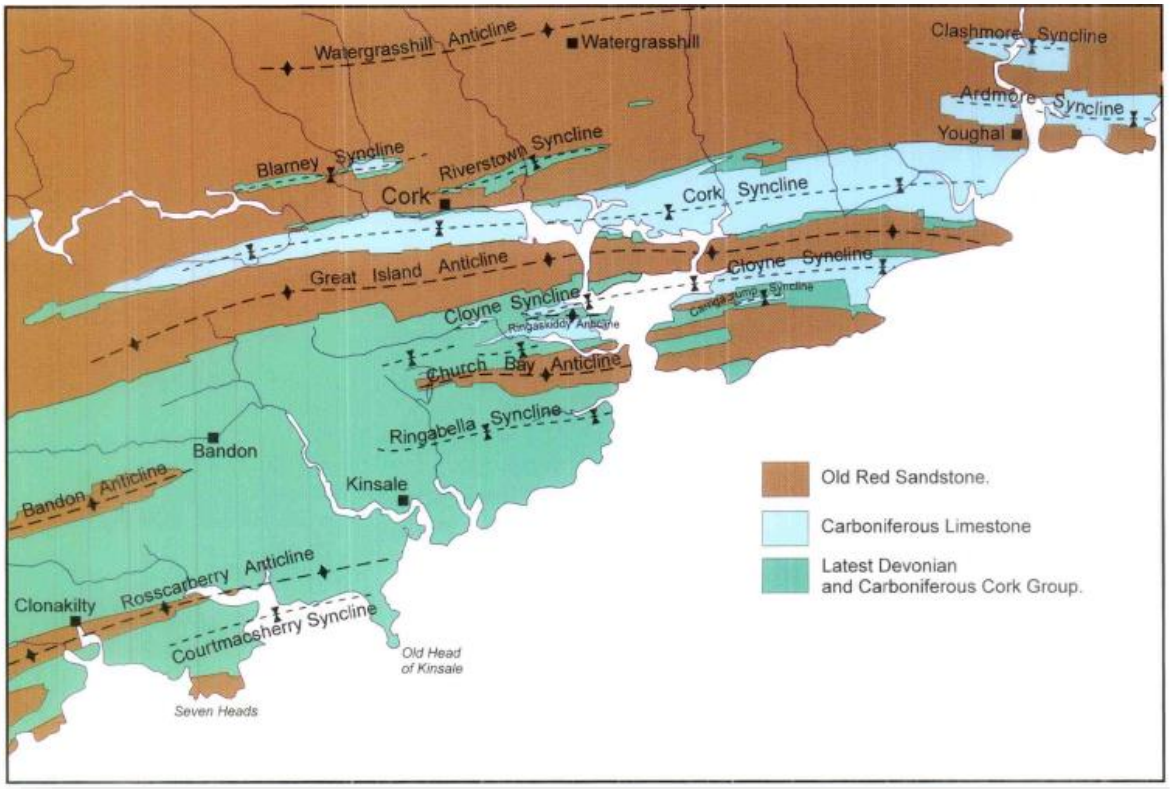


Figure 3. Geological setting of South Cork (after Sleeman and Pratch, 1994). The bay is underlain by Carboniferous Limestone, deposited between 355 and 290 million years ago, which controls the bay's configuration through inward erosion.

2.7 Data collection

Field data collection was conducted using a DJI Mavic3 UAV equipped with an onboard autopilot and a GPS receiver. The UAV was programmed to survey a pre-defined grid optimised for SfM photogrammetry. With the gridline flight plan, the camera is enabled to take photos at pre-determined intervals, ensuring different levels of overlap between photos. Each aerial image taken incorporates the GPS locations at specific points. The study site was equipped with fixed ground control points that served to rectify the aerial images during the processing phase. Prior to the survey, the site was divided into three areas (Figure 4), with a dedicated flight plan for each. This subdivision allows for the collection and processing of high-resolution data (<1 cm/pixel), which is then used to generate separate 3D models of the site. This

approach surpasses the resolution of satellite imagery (1-30 m/pixel), producing highly detailed 3D models that closely reflect the level of detail expected in the field.

Area 1 comprises a section of the sea cliff, measuring 0.21 km^2 and was surveyed via a gridline flight path with the drone oriented 100% down-facing. Aerial imagery of the ground surface was captured at a fixed altitude of 30 m, achieving a resolution of 0.81 cm/pixel and producing 2954 photos with 70% side overlap and 80% frontal overlap. Area 2 includes the coastal protection and it was surveyed following the same parameters as Area 1. Area 3 comprises the Ballynamona Strand, located south of Garryvoe Beach. The total area surveyed was 0.40 km^2, and data were captured via a gridline path, 100% downward-facing drone. Imagery for the area was captured at an altitude of 66 m and a spatial resolution of 1.79 cm/pixel. The imagery acquired from the drone survey was significant in producing centimetric resolution (<5cm/pixel) georeferenced 3D models of the site.

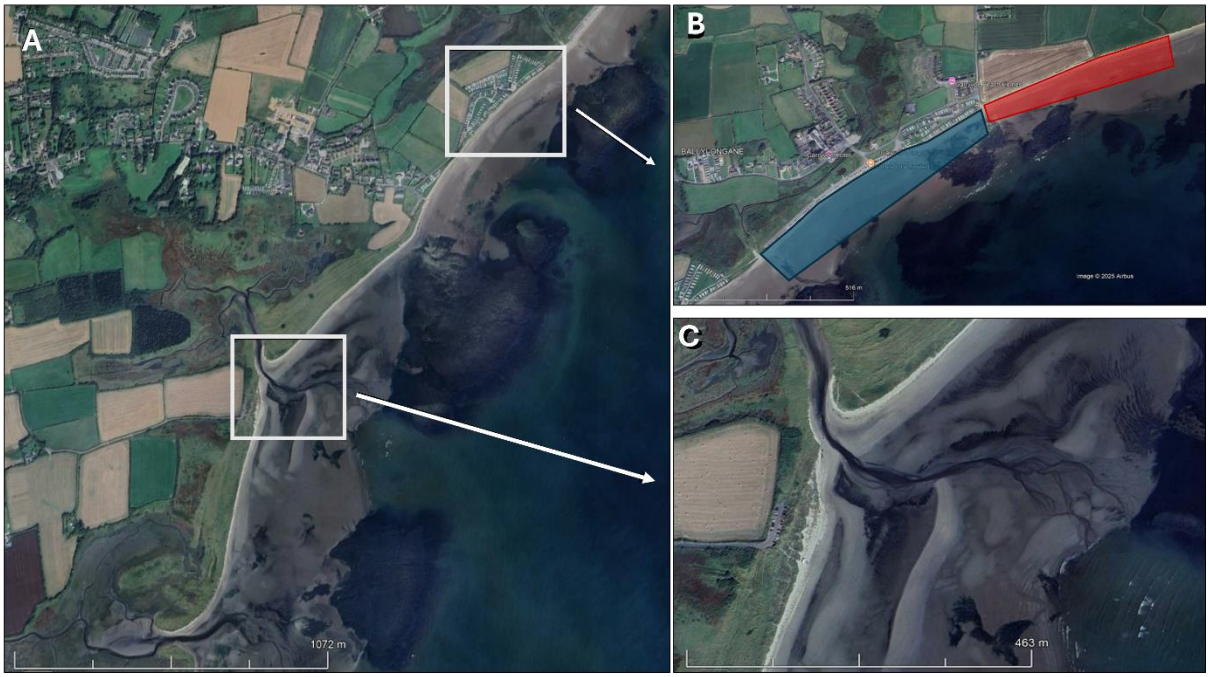


Figure 4. The images above show the subdivision of the survey site into two areas (as outlined in picture A). Picture B shows Area 1 (red), which comprises the sea cliffs, whereas Area 2 (blue) comprises the coastal protection. These two areas were surveyed separately using two different flight plans but with the same parameters. Picture C features the location of Area 3 in the Ballynamona Strand, situated south of Areas 1 and 2.

While the drone was flown with autopilot for dedicated flight plans, smaller features were surveyed via manual flight operations using an oblique or forward-facing camera angle to better capture centimetric-scale details such as cliff texture and stratigraphic layers. These features include a portion of the cliff face (Area 1) and a section of the coastal protection. For finer details, smartphone cameras were used to collect data on beach sediments and close-up images of the cliff face. Manual drone flights allowed to capture high-resolution imagery of the cliff face, showing fine details in the stratigraphy (Figure 5). Similarly, the manual flight operation was used to capture photos of a section of the coastal protection, allowing to record surface details of the rocks (Figure 6). A smartphone was used to gather data of smaller features at much higher spatial resolution. Figure 6 shows a 3D model created with smartphone images collected with 90% overlap. The photographs obtained from the surveys were post-processed using Agisoft Metashape (version 2.0.4). The images were aligned and camera locations were optimised. A high-quality point cloud was generated from the aligned images using the aggressive depth filtering setting to remove unreliable points. The point cloud was later used to create a high-quality mesh. To create a Unity-compatible file, the mesh was decimated from 2,000 to a maximum of 300 triangles for each 3D model, and a compatible texture was created. Two additional textures were created for each 3D model: an occlusion map and a normal map.

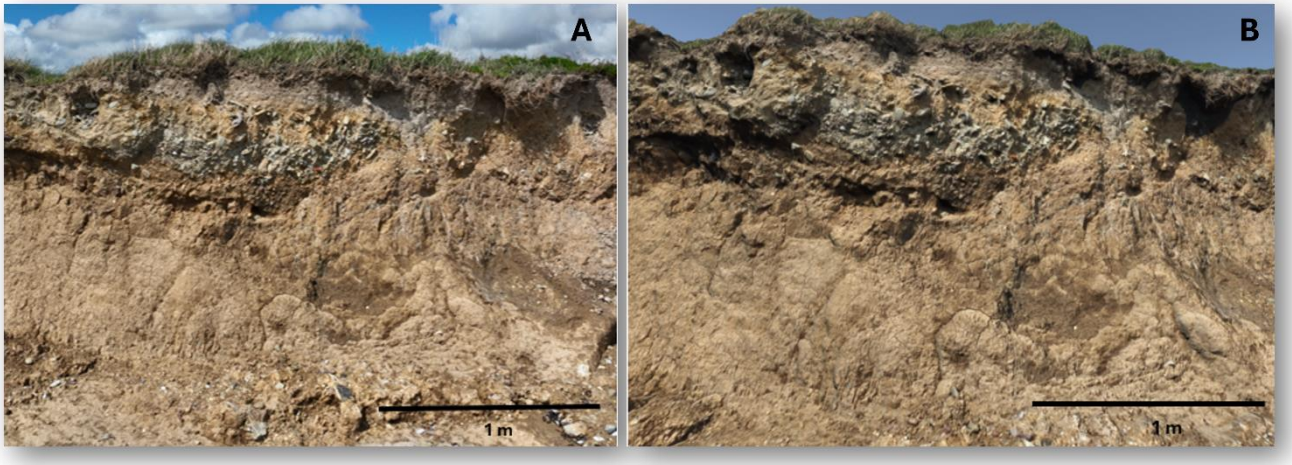


Figure 5. The two pictures show a section of the sea cliff at Garryvoe at a 1m scale. Picture A was taken during the survey, while picture B shows the 3D model of the same section generated on Agisoft. This appears to retain a high level of surface detail from the cliff.



Figure 6. The image shows a portion of the coastal protection 3D model. Low-altitude manual drone flights were used to acquire imagery of features, allowing display of fine details in the rocks, such as the quartz veins in the limestone.

2.8 VR fieldtrip development

The Garryvoe VRF was developed using Unity (version 2022.3.1). Unity is a cross-platform game engine that allows the creation of 2D and 3D projects for computers, consoles, and mobile devices. The key strength of Unity is that it allows realistic graphics to be achieved using Universal Render Pipeline (URP) and High Definition Render Pipeline (HDRP). For this project, URP was adopted to create the VR environment. URP allows deployment of Unity projects on over 17 platforms, including VR. The model generated in Agisoft includes GPS coordinates from the UAV images, referenced using the WGS84 coordinate system. The model is then converted to Local Coordinates (m) for integration into Unity. When imported into Unity, the model maintains accurate scale, enabling true horizontal and vertical scaling. For each 3D model, each texture file (diffuse, occlusion and normal map) was added to the Unity settings. This serves to enhance the 3D model rendering. Once the OBJ file output for the 3D model is imported, the scale factor is set to 1 m, allowing Unity to preserve the real-world size of the model, while the different textures are upscaled to match the original resolution.

Besides having a terrain generator tool, Unity offers a range of free digital elements, known as assets, that can be used to build a realistic 3D environment. Key features in the virtual landscape, including sea, sky, portions of the beach and rocks, were created using Unity assets. Specifically, the sea was implemented using the Simple Water Shader URP package, while parts of the beach were generated using the terrain tool and enhanced with high-definition textures sourced from the Asset Store. To enable VR functionality, it was required to implement the XR Interaction Toolkit package (version 2.5.4). This toolkit provides a framework for creating VR and AR experiences and includes interactor and interactable components tied by an Interaction Manager. The interactors, such as the Ray Interactor, handle user inputs such as selecting or pointing at objects and are enabled using the left and right controllers, whereas the interactables are objects that interactors can manipulate with.

The VR was designed according to pre-established learning outcomes that the students have to achieve. Based on each learning outcome, a series of activities was included at different stops (A, B, C, D, and E). These are summarised in Table 1.

Table 1. List of Learning outcomes and corresponding activities. These are distributed across a series of stops that students have to complete.

Stops	**Learning outcome**	**Activities**
Stop A	Become familiar with the geology of the area and how this affects the configuration of the embayment	Rock identification (Acid Test and Mohs Hardness Scale)
Stop B	Sketch the important elements of the physical landscape	Drone mode exploration and field sketch
Stop C	Become familiar with the concept of coastal protection and its role	Sea level simulation and tide slider

Stop D	Document and evaluate data through the creation of a stratigraphic log	Analysis and measuring of a 3D model (vertical face of the sea cliff)
Stop E	Make basic interpretations of data in a field setting	Offshore wind farm scenario project

The VRF is structured into several scenes: an introductory scene, a main scene and multiple supplementary scenes. The introductory scene provides students with an overview of the site and outlines the tasks to complete. This is followed by the main scene, which features 3D models of Areas 1 and 2 within a Unity-built environment that replicates the main features of the beach's surroundings. This scene includes five designated stops that users can visualise along the beach. Each stop includes activities (Table *1*) and learning material in various formats, including slides, audio clips, and videos. Users can navigate the VR experience in "walk mode" to simulate walking on a ground surface, and in "flight mode", which enables users to fly above the ground. Users can easily switch from walking mode to flying mode while completing each task. Interactions within the VR environment include basic interactions, such as touching objects to show infographics and the use of advanced tools, like a measuring tool for point-to-point horizontal and vertical measurements and a slider that demonstrates tidal variations (low to high tide) at the site. Selected stops enable users to jump into supplementary scenes to complete different tasks. These scenes include high-resolution close-up models of different beach sections (Figure 6). These detailed reconstructions, created from high-resolution imagery, offer enhanced visualisation of specific features.

2.9 Discussion

2.9.1 Case Study: Garryvoe Beach, Co. Cork

The VRF features five different stops, each including a number of activities. At Stops A and B, the students' task is to identify the two main lithologies present in the area and reflect on how these geological features contribute to the bay's arc-shaped configuration. At these stops, students have access to a range of tools that enable them to complete specific tasks and achieve their learning outcomes. At Stop A, a high-resolution 3D model of the coastal

protection allows users to observe rock surface characteristics, including colour and mineral presence. Students also have access to written information, audio, video, and an “acid test” tool, which enables them to distinguish between sandstone and limestone rocks. At Stop B, students are tasked with producing detailed field sketches of the site and can fly above the beach to record features from different angles, enabling them to visualise the shape of the bay and reflect on how the geology affects this configuration based on the activities carried out in Stop A. At Stop C, students examine the role of coastal protection in preventing erosion. Here, they have access to a tool demonstrating tidal variations (from low to high tide), as well as a video simulating conditions during a storm event at the site. At Stop D, students record a stratigraphic log using a close-up, high-resolution model of a section of the sea cliff. Figure 5 shows a comparison between a real-world and a VR view of the sea cliff at the site. The digital model accurately captures key geological elements, such as the change in stratigraphy throughout the vertical section, with a strong emphasis on the colour difference between each layer. Moreover, the presence of numerous clasts throughout the bottom layer, along with pockets of sediments of glacial-fluvial origin, is also observable from this view. While recording these features, students have access to a measuring tool that can provide both vertical and horizontal measurements. In addition, this stop allows users to explore past geological processes through infographics, audio, and a Unity-generated 3D diagram illustrating how sediments were shaped and deposited during the last glaciation in Ireland and how this relates to the sediments present at Garryvoe. Stop E is part of a supplementary scene in which the Ballynamona strand (Area 3) 3D data were implemented. Here, students engage in an offshore wind farm scenario project, where they identify suitable locations for a cable route within the site. They apply the knowledge acquired in the previous stops and make basic interpretations of data using measuring tools, maps, and different modes of exploration (walking and flying) to survey the site from both below and above.

The current version of the Garryvoe VRF is compatible with Microsoft Windows 10 and 11 operating systems. It was developed and tested on a computer equipped with 13th Gen Intel® Core™ i7-1370P (1.90 GHz) and 32.0 GB of RAM. The lowest configuration tested is a PC with A6 9210 / 2.4 GHz and 4GB RAM. The VRF package is 13.2 GB in size and is downloaded as a folder containing multiple packages, including the executable file required to launch the Unity application. The fieldtrip can be accessed in VR immersive mode using the Meta Quest Link

app via Wi-Fi connection. This allows users to connect the computer to the headsets and run the VRF. The headsets used are Meta Quest 2 and are equipped with two controllers that facilitate interactive engagement within the virtual environment. The fieldtrip can also be accessed in non-VR mode, available without the use of headsets. This version allows users to navigate the experience using the keyboard and mouse. While this mode is less immersive, it functions as a standalone desktop application that can be used offline.

A complete version of the VRF will be accessible via an online repository (https://doi.org/10.5281/zenodo.15837355).

2.9.2 Comparative capabilities

Recent studies have shown the potential of using virtual reality in education. Details of each study are shown in Table 2 from which capability comparisons can be made with this study. The majority of the studies below have focused on developing VRFs for geoscience applications (Bonali et al., 2024; Genge et al., 2024; Grosser et al., 2023; Harknett et al., 2021; Tibaldi et al., 2020; Zhao et al., 2020; Chenrai and Jimahantakul, 2019; Zhao et al., 2019).

Table 2. Comparison of VRFs in geoscience and non-geoscience applications.

Publication	**Data processing**	**Data outputs**	**VR software**
Pugsley et al. 2022	Structure-from-Motion (SfM) photogrammetry	3D virtual outcrops and DEMs 360° images	Lime 2.2.2 Google Earth Pro
Grosser et al. 2023	360° panoramic stitching	360° images from UAV survey and digital camera	Pano2VR
Chenrai and Jimahantakul, 2019	360° panoramic stitching	360-degree photos	Google Street View
Bonali et al. 2024	Structure-from-Motion (SfM) photogrammetry	3D tiled model 3D model from historical aerial photos	Unity 3D
Harknett et al. 2021	Structure-from-Motion (SfM) photogrammetry	DSM and Orthomosaic from UAV surveys and GPS ground control points	Unity 3D
Genge et al. 2024	Structure-from-Motion (SfM) photogrammetry	UAVs survey for DEM Digital camera photos	Unity 3D
Keil et al. 2021	DEM rasterisation and transformation	DEM and 3D models (Open.NRW)	Unity 3D
Zhao et al. 2019	LiDAR scanning and Structure-from-Motion (SfM) photogrammetry	Topographic Satellite optical imagery DEM (ArticDem)	Unity 3D

		LiDAR	
Zhao et al. 2020	360° panoramic stitching and Structure-from-Motion (SfM) photogrammetry	Photo collection for 360° images	Unity 3D
Tibaldi et al. 2020	Structure-from-Motion (SfM) photogrammetry	3D Digital Outcrop Models (DOMs) from UAS survey	Unity 3D
Maghool et al. 2018	NA	SketchUp Pro 3D models	LADUVR
Edler et al. 2018	NA	OpenStreetMap 3D models	Unreal engine
Castagnetti and Rivola 2017	Terrestrial laser scanning (TLS) point cloud processing and 360° panoramic stitching	360° images 3D laser scan data	Easypano Tourweaver v.7.98

Table 2 shows that SfM photogrammetry is the most commonly used method for data processing. Other studies have focused on producing 360-degree panoramic photos (Grosser et al., 2023; Pugsley et al., 2022; Zhao et al., 2020; Chenrai and Jimahantakul, 2019; Castagnetti and Rivola, 2017), often integrating them with Digital Elevation Models (DEMs) as well as 3D models (Keil et al., 2021). 360-degree panoramic images, widely used on platforms like Google Maps, offer high-resolution, photorealistic representations of real environments, providing an immersive and realistic experience. In addition, they have a large capture range, reducing the number of images needed and thus limiting data processing time (Erazo-Rondinel and Melgar, 2024). However, these images have a static vantage point, restricting the exploration of the data to the perspective from which they were taken (Ritter and Chambers, 2022). In addition, the lack of detailed information in 360-degree images becomes an issue when taking measurements. In contrast, SfM photogrammetry captures scene geometry, camera positions and orientations, enabling the creation of scaled 3D models that allow for precise spatial data and accurate measurements. This method is particularly useful for geospatial applications, where it can gather high-resolution topographic data from large sites (Iheaturu et al., 2020). As shown in Table 2, Unity 3D software is employed by the majority of the studies (Bonali et al., 2024; Genge et al., 2024; Harknett et al., 2021; Keil et al., 2021; Tibaldi et al., 2020; Zhao et al., 2020; Zhao et al., 2019). However, six studies opted for different VR platforms. Pugsley et al. (2022) developed their VRFs of Utah and the Pyrenees

using Lime (version 2.2.2) and integrating virtual outcrops and DEMs in the VR environment. This software allows for additional interaction through lines (for mapping and measuring), 2D information panels, 3D planes, and points (used as place markers or to access links). In addition, Custom views help to build a storyline through the VRFs. Grosser et al. (2023) used Pano2VR Pro to create an interactive virtual tour from 360-degree photos and videos, incorporating hotspots with infographics, videos, links, and audio. Similarly, Chenrai and Jimahantakul (2019) used Google Street View to display 360-degree photos during the VRFs, allowing users to view and analyse the photos along with associated infographics. Castagnetti and Rivola (2017) employed the software Easypano Tourweaver (version 7.98) for their Archaeological VR project, which integrates 360 panoramic images and 3D models. Hotspots and symbols are used to represent points of interest which users can access to obtain supplementary information.

One study by Edler et al. (2018) adopted Unreal Engine as a VR software. Unreal Engine is considered the leading engine in realistic visualisation, vegetation, and terrain creation (Šmíd, 2017). Like Unity, Unreal Engine offers a variety of tools for creating interactive content across platforms and devices (Morse, 2021). Edler et al. (2018) developed an interactive cartographic Virtual Reality environment featuring a 3D map of an urban area with buildings modified and texturised in Blender, allowing for unique surface textures and a more realistic appearance. Different from the other studies, Maghool et al. (2018) developed a VR experience using LADUVR. This integrated 3D models of buildings and architectural components using SketchUp Pro for Windows. The authors relied on SketchUp materials and shapes to produce replicas of real-world structures. This VR application was designed for architectural education, allowing users to carry out in-depth observation of architectural details, complete a step-by-step house building simulator and construct architectural details using materials provided in the VR simulation.

While the above-mentioned game engines have shown advanced capabilities, Unity 3D remains a common choice, excelling in interaction implementation and graphic capabilities. Our VRF and those from Bonali et al. (2024) and Tibaldi et al. (2020) display the most user interaction. Both enable users to explore the VR field site using different navigation modes (walk, drone and flight modes) and allow for vertical and horizontal measurements.

Bonali et al. (2024) integrated various capabilities into three VRFs developed for different locations: Mt Etna (Italy), Eastern Iceland and Northern Iceland (rift zone). Besides having different navigation modes and measuring tools, the VRFs include GPS tools and data collection tools. The GPS tools enable users to record both location and elevation and add waypoints that can be exported. In addition, the VRF integrates a tool that enables users to collect field survey data such as notes, photographs, and measurements that can be exported as different shapefiles. Similarly, Tibaldi et al. (2020) integrated a different range of tools for measuring distances and features, as well as recording parameters that are customized to meet the needs of geologists in the field. Two other studies from Genge et al. (2024) and Harknett et al. (2022) also integrated different navigation modes and measuring tools in their VR projects. The latter also added immersive elements to their VR field trip. These, as in the Garryvoe VRF, evoke the sounds and images that are found in the real world. For instance, the water shader is used to show the water's surface and the wave motion; the grass, the trees, and the sound emitter to play footsteps as the player moves are all integrated into these two fieldtrips. These contribute to conveying a sense of reality and immersion and producing stronger effects in the VR experience (NewMan et al., 2022). The Garryvoe VRF complements the technical capabilities found in other VR studies by incorporating sensory realism and immersive engagement. This is combined with detailed spatial modelling, aligning with the growing trend in VR educational design towards experiences that prioritise both high-quality data and immersive realism.

2.9.3 Synopsis: Strengths, Weaknesses, and Upgrades

The Garryvoe VRF demonstrates the capability of displaying a three-dimensional field site that integrates learning activities in an immersive environment adapted for geoscience fieldwork. This compares favourably with the other VRFs developed for educational purposes (Table 2). A key strength of the Garryvoe VRF is its ability to display a field site using high-resolution, scaled 3D models. Users can explore different sections of the field site with detailed 3D reconstructions, facilitating the analysis and completion of specific tasks. This is essential when users are required to analyse smaller features, such as sediments or analyse the stratigraphic layering. To achieve this, 3D models must be produced at a millimetre scale. While most advanced drones can capture high-resolution images (4K-3840 x 2160 pixels), their flight plan is restricted to altitude limitations, which can impact the overall spatial resolution.

In contrast, smartphones equipped with high-resolution 4K cameras can be used to generate smaller, highly detailed 3D models.

Additionally, the Garryvoe VRF is a highly interactive field learning exercise. It incorporates real-world fieldwork interactions (Acid Test and measurement tasks) and VR-specific features (tide-level slider) to simulate what-if scenarios like coastal flooding and climate change. These interactive simulations provide valuable insights into site processes and potential future threats. Combining these elements, alongside auditory and visual effects, creates a more immersive experience. By replicating real-life sounds and imagery, the VRF offers a more authentic fieldwork environment. The integration of images, audio, and text in the Garryvoe VRF supports diverse learning styles. Interactive diagrams, videos, images, and audio can be beneficial to students who learn best through visual or auditory methods, making complex concepts more accessible.

In terms of accessibility, the VRF allows students with mobility impairments to access the VRF without having to face the risks associated with fieldwork. They can move freely around the VR environment and complete the experience without restraints. This is also valid for other groups with accessibility constraints, such as students with financial issues, illnesses and caring responsibilities. In fact, the use of the VRF is free of cost and can be accessed by students in the university or at home.

However, a significant limitation of the Garryvoe VRF is the reliance on computers with moderate to good processing power and moderate graphics capabilities. For example, the Meta Quest Link PC app requires a minimum of an Intel i5-4590 or AMD Ryzen 5 1500X processor—hardware that is typically not found in lower-end systems. Additionally, the high-resolution 3D models used in the VRF require substantial asset size, which may lead to overloading delays on less powerful devices. One potential solution is the adoption of a virtual reality desktop infrastructure or VDI (Pugsley et al., 2022). VDI allows the VRF to be hosted on a central server that acts as a terminal, enabling students to access it remotely, regardless of their device's processing power and graphics. This infrastructure has been widely used in education to enable remote access (Al-zoubaidi et al., 2021). Similarly, Miseviciene et al. (2012) highlighted the use of VDI to provide easy access to staff and students to projects and courses that might not be supported on their personal computers. Another cloud-based alternative is CloudXR, a technology that processes virtual scenes on the remote server

(Liubogoshchev et al., 2021). This server converts the VR scene into a real-time video stream, transmitting it frame by frame to an XR headset. The headset can capture the user's motion via sensors and send the control commands to the server. This receives the commands and responds to them in real time.

Another limitation associated with the use of this VRF is the potential for motion sickness experienced by some users while navigating through the VR environment. This response can result in discomfort, disorientation and nausea, which may discourage students from fully engaging with or completing the VR experience. One potential solution to mitigate this issue consists of limiting the VR simulation to a short amount of time and allowing users to complete it at different intervals while sitting down. In this way, participants can proceed at their own pace without compromising the overall educational value of the experience. While this VRF does not require prior expertise in VR technology, it may nonetheless present challenges for students who are less familiar with VR equipment and interface controls. This can potentially affect the overall learning experience and may discourage some students from fully engaging with the technology. To mitigate this, during the VR simulation, students are encouraged to become familiar with the technology and learn its controls.

This project offers a number of opportunities both within the academic context and in broader and professional settings. Primarily, this VRF has significant potential to support a wide array of institutions, national and international, by providing a platform for student fieldwork training and for fostering a deeper understanding of the Irish landscape. This VRF integrates basic fieldwork activities with learning material related to the geology and environmental aspects of the site. It can be used by educators as either a pre-departure exercise or as a post-fieldwork debrief activity, both of which can enhance students' retention of field-based knowledge and skills. Importantly, this VRF can be adapted across multiple educational levels. At the secondary level, it offers an innovative resource for introducing students to geosciences and the fundamentals of fieldwork while being useful in guiding students toward potential careers. As Gunderson et al. (2020) claimed, technological skills will be the foundation for the next era of geoscience innovation and for this reason, this VRF can be beneficial to a large number of institutions outside of UCC, national and international, that are willing to integrate digital technologies to train students in fieldwork. In addition, this project holds considerable value for initiatives such as DEIS (Delivering Equality of Opportunity in Schools) in Ireland. DEIS

is a government-funded program that aims to promote equality within the educationally disadvantaged groups within the school system (Department of Education, 2024). The use of a VRF can be relevant to this program, offering a cost-effective and accessible means of engaging with field-based learning experiences, thereby mitigating barriers to participation and enhancing educational outcomes.

This study offers an opportunity to train students in acquiring their data and presenting their work in VR format. Notably, the workflow adopted for this project demonstrates that effective data acquisition does not necessarily need specialised equipment; rather, it can be conducted using standard devices such as digital cameras and smartphones. Moreover, Unity 3D is a free-access game engine that requires minimal knowledge in programming and interface navigation, making it easy for users with different levels of technological expertise to develop their own VR experience. It also offers complete online documentation and tutorials, which guide users through data import and command implementation. While Agisoft Metashape Professional is a commercial software application that requires a license to fully function, it provides a 30-day trial with full functionality that enables users to process and export data without limitations. This offers an opportunity for students to gain hands-on experience with data acquisition, analysis, and presentation while promoting active learning.

Beyond academic applications, the VRF holds considerable importance for professional training across a variety of sectors (Narciso et al., 2021). It can be used to prepare practitioners in fieldwork practices, providing a cost-effective and risk-free environment in which to explore site challenges. The coastal focus of this VRF can support research on issues related to climate change. For instance, the VR setting can support studies on landscape transformation along Ireland's southern coastline. This not only supports research but also aids in public engagement and policymaking by making complex changes more visually understandable.

Further improvements to the Garryvoe VRF can be achieved through additional upgrades. Unity offers a VR Multiplayer Template that includes pre-installed packages essential for developing multiplayer VR experiences. This feature can be beneficial to students participating in the same fieldtrip. The multiplayer mode enables them to cooperate and achieve their learning objectives (Komscha, 2024). Moreover, multiplayer VR environments have been shown to increase user engagement and social interaction (Firmansyah and Rosmansyah, 2024), which are crucial aspects of fieldwork-based learning. However, this feature requires a

higher processing power than a single-player VR experience, potentially leading to challenges with player synchronisation and 3D environment rendering.

2.9.4 Value and Limitations of the Garryvoe VR Fieldtrip

Research has shown the growing application of VRFs in education, particularly in the geosciences. SfM emerges as the most widely employed data processing method in the development of VRFs, thanks to the ability to generate 3D models by capturing accurate spatial geometry (Westoby et al., 2012). Because real-world scales and geographical coordinates are preserved in the 3D models, SfM photogrammetry enables users to conduct quantitative analyses and record different types of measurements. This capability makes it an important method when combined with VR in the development of immersive educational experiences, especially in the field of geoscience, where spatial relations are an essential component of fieldwork learning (Mogk and Goodwin, 2012). The Garryvoe VR enhances this approach by integrating UAV photogrammetry with smartphone photogrammetry, obtaining millimetre-scale resolution of smaller features within the site. These combined resolutions allow for detailed examination of features such as rocks and sediments. The Garryvoe VRF successfully integrates diverse navigation modes, tools, interactions, and simulations within five different learning stops. Furthermore, it provides an immersive experience in which the addition of sensory elements such as nature sounds, realistic water shaders and terrain textures aims to closely resemble real-world settings. A significant strength of the Garryvoe VR fieldwork is its emphasis on interaction and structured learning. Students are presented with a number of guided activities with tasks to complete, with each supported by various multimedia formats, including audio, videos and slides that seek to accommodate different learners in support of inclusive learning. The VRF offers substantial benefits in overcoming barriers associated with fieldwork. Specifically, it provides an alternative activity for students who, more generally, face mobility, health, and financial constraints. Importantly, it can benefit inclusive educational initiatives such as DEIS in Ireland by offering a cost-effective and equitable approach to learning.

Despite these strengths, several limitations must be acknowledged. While the Garryvoe VRF provides remote access to users, it heavily relies on computers with moderate to high processing and graphics capabilities. This can significantly disadvantage students who are only

able to complete the VR field course outside the university and do not possess such devices. Potential issues in the performance of the VRF might exacerbate this issue.

In terms of barriers related to the usability of the VRF, user comfort might limit students' ability to fully engage with the technology. Motion sickness is also a well-known effect of using VR technology (Burke et al., 2025; Sofiadin, 2024). Students unfamiliar with VR interfaces may initially experience difficulty navigating the environment, which might negatively impact their learning experience. Finally, while the VRF attempts to incorporate some sensory aspects of fieldwork, it fails to fully reproduce the social dimensions of traditional field experiences. These, including peer collaboration, discussions, and feedback, are limited in a single-user VRF and that can’t be fully captured using a multiplayer VR alternative.

This project demonstrates the use of UAV photogrammetry to generate accurately scaled 3D models of Garryvoe Beach and integrate them into an immersive VR environment employing Unity 3D. The resulting VRF functions as an educational tool designed to support geoscience students through pre or post-fieldwork exercises or as a potential alternative where physical fieldtrip access is limited. This approach supports active learning in a VR setting where geospatial accuracy is ensured. Future work will aim to address the existing technical limitations, including the high system requirements needed to run the VRF. Expanding users' accessibility will be essential to ensure broader inclusivity across different educational settings.

3. The Impact and Implementation Strategies of VR Fieldtrips in Geoscience Education

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This chapter seeks to fulfil the second aim of this MSc research project: to assess the impact and effectiveness of the VR fieldtrips (VRFs) described in chapter 2 in support of student learning. This chapter systematically addresses the existing challenges in the geography fieldwork and presents the first case study in Ireland for the implementation of a VRF in 3rd level geography education. Students participated in the VR experience at Garryvoe Beach either before, after or in place of fieldwork, undertaking their fieldwork digitally, interacting with the VR environment and completing the activities. This study highlights the cognitive gains and the experience of students relative to the use of VR technology as a preparation, reflection or alternative to fieldwork. Thus, this chapter contributes to informing future research about the impact of VR in geography education and its broader implications for inclusion.

Candidate contributions to the study: Irene Loriga conceptualised and developed the methodology of the study with Dr Aaron Lim. Irene Loriga carried out the data collection, investigations, analyses, writing and editing of the original draft.

The project, which led to the development of this chapter, was funded by the Geological Survey Ireland through the Master's by Research Scholarship 2023. Dr Aaron Lim, the PI of the project, contributed to the funding acquisition. Dr Therese Kenna and Dr Maedhbh Nic Lochlainn were responsible for organising the fieldwork day in Garryvoe, with the contributions of Irene Loriga and Dr Aaron Lim. Irene Loriga organised and carried out the VR field course and was responsible for the data collection, analysis and interpretation. The project was supervised by Dr Aaron Lim, Dr Therese Kenna, Dr Larissa Macedo de Oliveira and

Dr Mohit Tunwal. These authors also contributed with editing and proof-reading the manuscript.

Abstract

Fieldwork is a cornerstone of geographical education. However, existing barriers to fieldwork, such as accessibility and financial constraints, can hinder students' ability to fully engage in field-based learning as well as compromise inclusive education for all students. To address these barriers, recent technological innovations offer valuable alternatives through the creation of digital replicas of field sites. For this reason, the present study explores the use of a Virtual Reality Fieldtrip (VRF) of Garryvoe Beach (Co. Cork, Ireland), designed for undergraduate geography students at University College Cork (UCC). The aim is to evaluate the effectiveness of VR as a tool to support and enhance students' field-based learning and experience in using such a VRF. For this purpose, we combine quantitative data from a field worksheet with qualitative data gathered through reflective statements, with the aim of assessing students' performance and students' experience with the VRF. Results following the implementation indicate that students reported having a positive learning experience when the VRF was used. Findings suggest that VR is particularly effective when implemented prior to traditional fieldwork, helping students to become familiar with the site, introducing new concepts and preparing for field tasks. Post-fieldwork use also demonstrated benefits in enhancing learning, serving as a debriefing activity aimed at strengthening key concepts. The use of VR was also explored as an alternative method when fieldwork participation was not possible. Despite the fact that positive outcomes were reported by the students they also emphasised the limitations of VR technology in the display of a real-world setting and the development of key fieldwork skills. Importantly, the study does not propose VR as a replacement for real-world fieldwork, but rather as a complementary tool that can support student learning before, after, or in place of fieldwork when participation is not otherwise possible.

3.1 Introduction

Digital technology has significantly transformed the way students learn in a classroom setting, with educational applications increasingly used to support and enhance student engagement (Haleem et al., 2022). One area where digital tools are making a substantial impact is

geoscience fieldwork, a core component that requires physical presence in the field. Field-based learning plays a crucial role in promoting active learning and helping students gain fundamental skills in observation, analysis and problem solving (Krakowka, 2012; Kwan and So, 2008). Although valuable, fieldwork can present barriers to participation due to financial limitations, physical disabilities, and accessibility challenges (Hall et al., 2004; Abeyta et al., 2021; Carlin et al., 2023). In addition to these, several other issues tend to hinder students from fully engaging in the field training. Kessel (2008) refers to invisible disabilities such as epilepsy and mental health issues, while Bond and Cawood (2020) explain that practical concerns such as weather conditions, safety and students' inexperience in fieldwork can affect personal comfort and interactions with peers and instructors.

In the Irish context, where the case study for this paper is located, a recent profile of students with a disability in higher education in Ireland that responded to the Equal Access survey revealed that about 17.8% of undergraduate entrants reported having a disability. Learning Conditions (37%) and Psychological or Emotional Conditions (31.2%) appeared to be the most common disabilities. Mature students prevailed among those students with multiple conditions (13.7%) and physical conditions (11.2%) (Higher Education Authority, 2023). Financial constraints are also becoming a pressing issue in fieldwork participation. According to the Irish Independent (2023), the proportion of Irish undergraduates facing serious financial issues rose from 26% in 2019 to 33% in 2023, with these difficulties negatively impacting students' social and academic lives. Therefore, the growing diversity of learners and their needs highlights the importance of providing inclusive, accessible, and equitable learning opportunities.

Inclusive education, according to Slee (2018), involves the dismantling of barriers to education through any policy, program or practice that increases access, presence, participation and success for all students in education. It is considered a continual effort within our dynamic contexts to redistribute quality learning opportunities and challenge exclusionary practices (Waitoller et al., 2013). A key aim of inclusive learning is to recognise and value diversity in education, disposition, circumstances and culture (Thomas and May, 2010) while considering how these characteristics intersect. This aim seeks to create a learning environment that celebrates a diversity of learners and engages them effectively in their learning experiences (Moore-Cherry et al., 2016). Following the United Nations' Salamanca Statement in 1994, the

concept of inclusive education has gained global importance, declaring that inclusive schools are the most effective means of reducing discrimination, fostering social inclusion, and ensuring education for all (Messiou, 2017; Lindsay, 2003). Since then, educational institutions worldwide have explored ways to enhance equity and remove barriers (Lawrence and Dowey, 2022; Juvonen et al., 2019; Arthur-Kelly et al., 2013; Rouse, 2006). University College Dublin (UCD) has devised an Assessment for Inclusion (AfI) Framework with the main aim of providing equitable assessments that enable all students to enhance and demonstrate their learning. This framework includes 10 design principles, which serve as guiding statements for inclusive and equitable assessment.

Recent advances in technology have led to the exploration of XR as a tool for promoting inclusion in higher education (Hamash et al., 2024; Gatto et al., 2022). XR technologies either enhance (AR) or replace (VR) the user's perception of the real world. Augmented reality (AR) overlays digital information onto the physical environment, while Virtual Reality (VR) creates fully simulated environments using computer graphics (Burdea and Coiffet, 2003), enabling users to interact through haptic devices such as controllers. Because of this differentiation, the core characteristics of VR contrast significantly from those of AR and include interactivity, immersion, and (tele)presence (Wohlgenannt et al., 2020). The head-mounted displays (HMDs), used to visualise the VR environment, were initially designed for gaming; however, their usage has been broadened to different areas such as job training, tourism, manufacturing, marketing and healthcare (Rauschnabel et al., 2022). In geoscience education, VR has been effectively combined with Structure-from-Motion (SfM) photogrammetry to produce immersive VRFs. These experiences employ georeferenced and scaled 3D models of real-world sites. Despite known limitations, such as the inability to fully replicate the true immersion in the real landscape and physical outdoor environment, VRFs offer a realistic and accessible alternative to on-site fieldwork, which can significantly improve the learning process (Pugsley et al., 2022; Bonali et al., 2024; Tibaldi et al., 2020) and can also facilitate remote access to otherwise inaccessible locations (Vandelli et al., 2024).

The COVID-19 pandemic further accelerated the adoption of digital fieldwork alternatives due to social distancing restrictions (García-Morales et al., 2021). Although rushed, many solutions enabled remote access to field sites and allowed students to perform basic tasks. Several studies showed the effectiveness of using XR as a result of the pandemic lockdown, in

particular VR, to recreate fieldtrips experiences (García-Vela et al., 2020; Evelpidou et al., 2021). The findings emphasised the key role of VR technology in enhancing students' understanding of concepts and performing highly technical tasks adequately. However, the main drawbacks identified included the inability to achieve learning outcomes and the limitations in capturing students' attention throughout the simulation.

Research into digital approaches to fieldwork highlights both the potential and the limitations of these methods. Whitmeyer et al. (2020) demonstrated that real-time video, imagery, and specialised field applications were successful in providing access to field sites and promoting collaborative inclusion among participants. Hill and Nelson (2021) emphasised the value of podcasts as additional resources that support revision and assessment, particularly for visual learners, while acknowledging that such tools cannot fully replace fieldwork experiences. Similarly, Wang et al. (2023) on the use of VR technology, argued that it fails to replicate the experiences that come from interaction with the physical environments and interaction with peers (Garcia et al., 2023). Nonetheless, research indicates that it can foster inclusion by supporting the development of cognitive skills in students with Autism Spectrum Disorders (Silva et al., 2025) as well as increasing motivation and helping students visualise and understand abstract and complex concepts more effectively (Alazmi et al., 2024; Hicks, 2016). Furthermore, it has proven effective in fostering critical thinking, enabling students to investigate and evaluate digital representations of place and space (Bos and Bull, 2022).

Considering the potential of digital technologies, in particular VR, in enhancing learning and fostering inclusion, we developed a VRF of Garryvoe Beach, County Cork (Ireland) using photogrammetric data and Unity as a VR platform. This VRF was designed to complement fieldwork undertaken by second and third-year students as part of their fieldwork module. Through a combination of quantitative and qualitative research methods, this study aims to determine: what impact can VRF have on geoscience third-level education; how should VRF be best implemented and to what extent, if any, can VRFs allow students to replace fieldwork?

Understanding the impact that VRFs can have on 3rd level geography education will enable educators to contextualise whether or not their use has any beneficial or detrimental impact on student learning. Importantly, evaluating the use of the VRF either as a preparatory tool before fieldwork or as a reflective activity afterwards will provide a clear understanding of the effectiveness of each approach in supporting students' field-based learning and experience.

Furthermore, investigating the advantages and limitations of VR technology will help determine the extent to which VRFs might replace on-site fieldwork, while also providing insight into the broader implications for promoting inclusivity within geography education.

3.2 Garryvoe fieldtrip and learning outcomes

The implemented VRF features Garryvoe Beach, located in south-eastern County Cork. Designed following the workflow outlined by Loriga et al., 2026 (In revision) (Figure *7*), the VRF showcases a coastal site of particular relevance to undergraduate geoscience education due to its distinctive geology and active coastal processes. Situated within the Cork Syncline, the area is underlain by Carboniferous Limestone (Sleeman and Pratch, 1994), which contributes to the bay's characteristic arc-shaped form. The site provides clear evidence of coastal erosion, visible in the retreating sea cliffs to the north and the coastal protection structures along the southern shoreline.

The site was surveyed using UAV data, photographs and videos. These data were processed using Structure-from-Motion (SfM) photogrammetry to generate high-resolution 3D models. The resulting models were imported into Unity (version 2022.3.1), a cross-platform game engine, to build the immersive VRF environment. The VRF addresses topics such as coastal geomorphology and sea level changes.

The field day is structured into different activities that take place along the beach. Students are guided through five stops where they are asked to carry out tasks and report their observations and findings in a worksheet. Learning outcomes are associated with each stop (as outlined in Table 3) and they define what students are expected to achieve at the end of each activity. The fieldtrip aims to help students understand how the geology of the area influences the configuration of the bay and how active coastal processes are shaping the site. To do so, students are expected to apply their observational, analytical and sketching skills throughout the fieldtrip. At Stops A and B, they have to distinguish between the two main lithologies present in the area and reflect on how these geological features contribute to the bay's arc-shaped configuration. At Stop C, students examine the role of coastal protection measures in preventing erosion. At Stop D, they record a stratigraphic log and explore past geological processes. Finally, at Stop E, students engage in an offshore wind farm scenario project, where they have to identify suitable locations for a cable route within the site.

The Garryvoe VRF is a complementary activity that students carry out before, after or instead of their on-site fieldwork. It is structured into different scenes, and it includes similar activities to the actual fieldtrip in a digital format, that students must complete to develop skills and achieve their learning outcomes (Table 3). The experience includes introductory slides, videos, audio clips, and tools for making horizontal and vertical measurements which the students engage with at each stop. Users can navigate the environment by either walking through the site or surveying it from above using “flight mode”. The VRF is accessible through Meta Quest headsets via the Meta Quest Link app. For the implementation stage, the VRF was made available to students through the tutor's laptop and the UCC Meta Quest 2 headsets. A desktop alternative (non-immersive) was also developed and made available to accommodate students who experience motion sickness and to help mitigate some of the barriers associated with immersive VR technology (Creed et al., 2024). Further details on the Garryvoe VRF are comprehensively described in Loriga et al. (2026) (In revision).



Figure 7. The images show high-resolution 3D reconstructions of the sea cliff (top) and coastal protection structures (bottom) at Garryvoe Beach. The models were generated from low-altitude manual flights, achieving centimetre-scale detail that improves the visualisation of key surface features. The sea cliff model highlights colour variations between stratigraphic layers and sediment distribution along the vertical profile, while the coastal protection model captures fine-scale rock textures and structural detail.

Table 3. The Garryvoe VRF stops and learning outcomes.

Stops	Learning outcomes	Activities
Stop A	Become familiar with the geology of the area and how this affects the configuration of the embayment	Rock identification (Acid test and Mohs Hardness Scale)
Stop B	Sketch the important elements of the physical landscape	Drone mode exploration and field sketch
Stop C	Become familiar with the concept of coastal protection and its role	Sea level simulation and tide slider
Stop D	Document and evaluate data through the creation of a stratigraphic log	Analysis and measurement of a 3D model (vertical face of the sea cliff)
Stop E	Make basic interpretations of data in a field setting	Offshore wind farm scenario project

3.3 Study Participants

The VRF was tested on geography students enrolled in the Geography Fieldwork module at UCC (GG2022) following the project's ethical guidelines (see Appendix I). The diverse student population included students with mixed backgrounds who are in the 2nd year of their BA programme. Typical enrolment in this fieldwork module ranges from 30 to 40 students.

A total of 40 students were enrolled in the fieldwork module in 2023-24. Of those 40 students, 16 volunteered to participate in the research and test the VRF. Within the participant group, 5 students were selected as a control group, and 11 students formed the experimental group, most of whom had no prior experience with VR technology. For this study, the experimental group was further divided into 3 subgroups based on when they completed the VRF: before,

after, or instead of the physical fieldwork (Table 4). Dividing the class into three smaller groups allows some students to use the VRF as a preparatory tool before the field trip, enabling them to access all the learning material and complete the activities ahead of time. The VRF is also used by some students to reflect on their fieldwork experience, and can strengthen their understanding of topics covered during the fieldtrip. In addition, the VRF is used by students who are absent on the day of the fieldtrip, providing an alternative to help them achieve the same learning outcomes.

Table 4. The table below categorises participants into four groups. Group 1 is the students completing the VRF before the fieldtrip. Group 2 is students completing the VRF immediately after fieldwork, and Group 3 comprises students using the VRF as a substitute for on-site fieldwork. Group 4, the control group, is formed of students who don't participate in the VRF experience and only carry out fieldwork at the site.

Groups	**Total participants**	**Female**	**Male**
Group 1- VR before	6	2	4
Group 2- VR after	4	3	1
Group 3- VR only	1	1	0
Group 4- Fieldwork	5	3	2
Total:	16	9	7

3.4 Assessment: Quantitative and Qualitative Methods

Students' performance is assessed through a series of structured activities outlined in a worksheet (Table 3). These activities are organised across five distinct stops, each designed to build specific skills and knowledge. Students who completed the VRF before entering the field were given a sample worksheet to consult during all the stops, while the other students only received the worksheet during the actual fieldwork. At every stop, students were guided by their tutor and introduced to the activity with a brief overview. The fieldwork begins at Stop A, where students encounter a coastal protection structure composed of large, stacked boulders. Here, students are tasked with identifying the lithology of these rocks through a

series of observational tasks, which involve using the Mohs Hardness scale. This exercise helps them distinguish between sandstone and limestone and provides an introduction to the geology of the site. At Stop B, students develop their field sketching skills by producing two annotated sketches of the site. As part of this stop, students must identify key elements and reflect on the beach's configuration. Stop C revisits the coastal protection structure. Here, students are asked to deepen their understanding of the concept of coastal protection and reflect on its role at the site. At Stop D, students examine the sea cliffs located on the northern side of the beach. They analyse a vertical section of the cliff face and record their findings in a stratigraphic log, enhancing their understanding of sedimentary structures. The final activity, at Stop E, shifts focus to an environmental planning scenario. Students use their observations from the beach and the surrounding area to design a cable route for offshore wind farms. Here, students are involved in surveying the terrain and determining an appropriate path for the cable route. Students who completed the VRF after the fieldwork had the opportunity to review and revise their worksheet while revisiting all the stops in the virtual environment. Performance at each stop was evaluated using an assessment rubric. This rubric defines clear criteria for achieving learning objectives and outlines performance levels ranging from "attempted" to "excellent", which correspond to decimal grades ranging from 40% (attempted) to 100% (excellent). These scores are later used to calculate the mean performance for each group.

Students' experience is assessed based on the use of a reflective statement. Students who completed the VRF are asked to complete the reflective statement (Appendix II) at the end of their fieldwork. The reflective statement consists of two parts: part one features a Likert scale (rating from 1 to 5) with various statements regarding the VR experience. Part two includes six open-ended questions inviting students to share feedback on how VR supported their learning. This set of questions is intended to evaluate students' experience using VR to: i) support their learning, ii) enhance visualisation and understanding of geological phenomena, iii) address challenges and iv) assess applicability.

3.5 Data analysis and results

Out of 40 students, 25% of the class chose to participate in the use of the Garryvoe VRF. The participants were divided into four groups (see Table 4):

- Group 1: Six students who completed the VRF before doing the fieldwork.
- Group 2: Four students who completed the VRF after the fieldwork.
- Group 3: One student who completed the VRF instead of the physical fieldwork.
- Group 4: Five students who did not complete the VRF (control group).

3.5.1 Students' performance and experience on the use of VR pre-field trip

Worksheet evaluation results (Table 5) revealed that Group 1 scored the highest average (mean 54.83%) and median (55.20%) with a low standard deviation (0.051). These results showed that students had a consistent performance and were able to achieve their learning outcomes.

To assess students' experience, the Likert scale used a rating scale of 1 to 5 with 1= strongly disagree, 3= neither agree nor disagree, and 5= strongly agree; Results from this scale, shown in Figure *8*, revealed a positive experience from students who completed the VRF. The students from Group 1 expressed a slightly better experience than those who did it after fieldwork, scoring 5 (strongly agree) and 4 (agree) in most statements in favour of the use of VR (Figure 8).

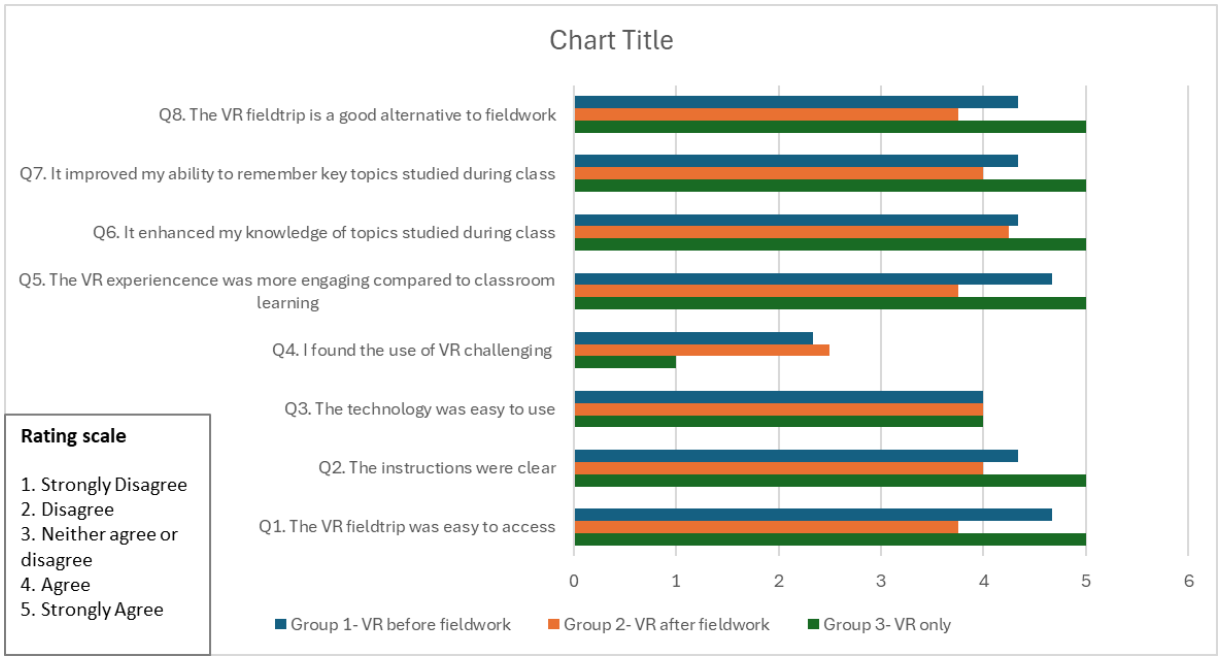


Figure 8. Results from the Likert scale analysis of students' reflective statements are presented, using a Likert Scale ranging from 1 (strongly disagree) to 5 (strongly agree). Overall, students reported a positive experience with VR, with particular reference to engagement, usability and skills development, with no particular issues encountered employing the technology.

Part 2 of the reflective statement involved six open-ended questions whose answers are reflected in Figure *8*.Figure *8.* Results from the Likert scale analysis of students' reflective statements are presented, using a Likert Scale ranging from 1 (strongly disagree) to 5 (strongly agree). Overall, students reported a positive experience with VR, with particular reference to engagement, usability and skills development, with no particular issues encountered employing the technology. Students who completed the VRF before visiting Garryvoe (Group 1) generally agreed that VR worked as an effective preparation. They reported that engaging with the VR experience before fieldwork allowed them to easily absorb the learning material, resulting in building a solid foundation of knowledge before carrying out the activities and faster work during the actual fieldwork. As two students noted:

“I felt more prepared during fieldwork, and I worked faster; I understood tasks much better.” (Participant 1, Group 1).

“It gave me time before the fieldwork to absorb and digest the information that we would be discussing in Garryvoe. Knowing the topics was very handy” (Participant 2, Group 1).

“Knowing what things would look like and how big they'll be helped my expectations”. (Participant 2, Group 1).

Students also highlighted that VR helped them visualise geological features and understand their scale, which improved knowledge retention. Students emphasised that increasing the exposure to the field area, even digitally, was perceived as beneficial:

“Doubling up on the amount of exposure to the study areas helped me to retain more information”. (Participant 2, Group 1).

Many also saw value in VR as a preparation tool for future field trips and as an alternative to cancelled fieldwork. Some suggested VR could increase access to both Irish and international field sites. However, technical limitations were mentioned. While some found VR technology easy to use, one student described having trouble getting familiar with the commands, whereas others reported poor performance, which caused delays in completing all the stops.

3.5.2 Students' performance and reflections on the use of VR post-field trip

Worksheet evaluation revealed that this group had a lower average (46%) and median (45%) with a moderate standard deviation (0.097), suggesting more variation and less consistent performance, with some students failing to achieve the learning outcomes.

The Likert scale evaluation generally revealed that students were satisfied using the VRF. However, mixed answers were reported for the statement, which claimed that VR technology was challenging to use for some students. Students who completed the VRF after going to Garryvoe reported that it helped enhance their learning. They described the VR experience as a helpful debriefing exercise that deepened their understanding of the site and clarified what they had encountered during fieldwork:

“Allowed us to reflect on the fieldtrip after we went. I felt up close and did not have distractions I would have in the field” (Participant 3, Group 2).

“It gave more information”. (Participant 4, Group 2).

“The pop-ups at each stop were informative. Voiceovers were helpful and concise. It helped with learning” (Participant 5, Group 2).

Students from this group also expressed that VR was particularly effective as a visual and auditory aid. Features such as infographics and audio clips helped students better understand geological phenomena:

“I’m a highly visual learner so it helped massively”. (Participant 3, Group 2)

Regarding future use in geography classes, students expressed interest in applying VR to other modules or assignments. They appreciated the efficiency of VR and its potential to enhance understanding:

“Yes, it helped create a better understanding of the information. It would be helpful in future modules or assignments”. (Participant 5, Group 2).

The responses reveal the value of VRFs for students with different learning preferences and an ability to enhance learning through the provision of information and visuals to support learning.

3.5.3 Students' performance and reflections on the use of VR-only fieldtrip

The single participant in Group 3 scored 52% in the worksheet evaluation, resulting in the achievement of the learning outcomes of the VRF. Since this group includes only one student, variability cannot be assessed.

The student reported having a positive experience using VR, claiming that it served as a valuable alternative when on-site fieldwork was not possible. The student explained that the technology allowed for high-detail visualisation of relevant features, relevant to complete each task, and supported knowledge retention thanks to its interactive nature:

“I was able to see exactly what I needed and I was guided to each stop...It clearly showed each section”. (Participant from Group 3).

“It was easier to remember because it was interactive”. (Participant from Group 3).

Students who completed the fieldwork only, Group 4 (mean = 53%, median = 50.80%), performed slightly better than Group 2 (mean = 46%, median 45%), but had the highest variability (standard deviation = 0.123), indicating a wide range of individual scores.

Table 5. The table below shows the statistics of students’ performance across different groups. Group 1 (students who completed the Garryvoe VRF before fieldwork) had the most consistent results, shown by a low standard deviation (0.051). In contrast, Group 2 (VR after fieldwork) had a lower median (45%) and mean (46%), with a moderate spread in scores (standard deviation of 0.097). Group 4 (no VR) also showed a relatively high mean (53%) and a median of 50.80%, but had the widest spread, indicated by the highest standard deviation (0.123). Overall, Groups 2 and 4 exhibited greater variability in scores compared to Group 1.

	MEAN	**MEDIAN**	**STANDARD DEVIATION**
GROUP 1 (6 students)	54.83%	55.20 %	0.051
GROUP 2 (4 students)	46%	45%	0.097
GROUP 3 (1 student)	52%	52%	0
GROUP 4 (5 students)	53%	50.80%	0.123

3.5.4 Results

Analysis of students’ performance and feedback revealed clear differences between the groups. The group that used the VRF before fieldwork (Group 1) performed the most consistently and had the highest average and median scores. This suggests that using the VR tool as preparation may help reinforce key concepts before students engage in real fieldwork. Students' experience further strengthened this claim by highlighting the effectiveness of VR as a preparatory tool before fieldwork, helping students to build knowledge and skills before

their fieldtrip. This instructional scaffolding is reflected in the word cloud generated from the reflective statements (Figure 9).

In contrast, those who completed the VRF after fieldwork (Group 2) had more mixed results, and their scores were less consistent. However, students revealed that the VRF helped to consolidate information acquired during fieldwork, working effectively as a debriefing exercise and it was also deemed effective for assisting students with post-fieldtrip write-ups. Still, its effectiveness may have been reduced by fatigue after a full day in the field. Results from Group 3, who completed the VRF-only, showed that VR was able to replicate key aspects of the field experience in great detail, allowing the student to complete all activities virtually. The control group (Group 4), which didn't use VR, showed the widest variation in performance, with some students performing well, while others didn't, reflected in the high standard deviation. This inconsistency may reflect the absence of the guidance and reinforcement provided by VR.

No significant differences in performance were observed based on the gender of the participants. Although these trends are interesting, this indicative data poses a limit on the ability to generalise the findings. However, the results suggest the potential benefits of using VR technology as a preparatory tool in field-based education.



Figure 9. The word cloud above was generated from students' responses regarding the Garryvoe VRF. Students emphasised the VRF's role in providing information and enhancing their understanding, both in preparation for fieldwork and as a tool for reviewing completed activities.

3.6 Discussion

3.6.1 Impact of VR Fieldtrips in Geography Education

Results from students who engaged with VR provided valuable insights into their experiences and the value of VR for fieldwork in geography. Students reported that the fieldtrip was valuable as a preparation, reflection, or alternative fieldwork exercise. A key advantage of integrating VR into the fieldwork module was its ability to prepare students and help them deconstruct complex information. This scaffolding method was beneficial in allowing them to familiarise and learn new concepts and tasks. It closely aligns with Vygotsky's theory of Cognitive Development, which states that scaffolding provides temporary support and is crucial in helping students to progress within the Zone of Proximal Development (ZPD) by

promoting independent learning as the students become more familiar with the material (Vygotsky, 1978).

The Garryvoe VRF was intentionally designed with specific learning outcomes and was closely aligned with the curriculum, integrating information in multiple ways, from videos to slides to audio clips. The advantage of this multimodal method was that students could access the information in multiple ways and occasions, allowing for greater transparency and comprehension of complex information, as supported by Participants 2 and 3 (Group 1 and 2). This method was particularly beneficial for learners who rely on various learning methods, specifically those who utilise visual aids such as images and videos (Belanger and Jordan, 2000). The implication of such design is supported by Alabi (2024), who claimed the significance of employing VR and other interactive resources in support of visual learners in geosciences disciplines. They explained that knowledge retention and information processing were shown to be improved by multimedia resources. Additionally, they emphasise that integrating different learning modes is crucial to enhance inclusive learning and ensure that the diverse needs of students are met. Similarly, Anis and Khan (2023) have highlighted the importance of inclusive multimodal techniques. They argue that the integration of various modes of communication, like speech, images, and technology, enhances the learning experience of a wide group of people with different learning needs.

Another positive outcome noted in this study was the role of VR in reducing students' cognitive load. Participants 1 and 2 (Group 1) reported that completing the tasks in VR allowed them to better understand what was expected of them while increasing the chance of absorbing the information. The immersive VR experience appeared to help students focus more effectively on their tasks by removing real-world distractions (Participant 3, Group 2). This aligns with Baceviciute et al. (2020), who claim that shutting out potential distractions is effective in lowering cognitive load.

Students also emphasised the efficiency of the VRFs to allow them to retain information. Whether used before, after, or in place of the physical fieldtrip, students indicated that the virtual experience helped them remember key topics covered during the fieldwork. These findings align with the studies that describe VR as a tool that positively impacts memory retention (Baceviciute et al., 2020; Moreno and Mayer, 2004). Furthermore, the temporal flexibility offered by VR was identified as a key factor (Tuthill and Klemm, 2002; Belanger and

Jordan, 2000), allowing students to engage with the learning material at their own pace. One main finding from the students was that the presence of learning tasks in the form of stops was found to increase learner-centeredness and help avoid distractions in the field by allowing them to focus better on tasks, as claimed by Participant 3 (Group 2). One of the most significant benefits of the VR experience was the structure of the fieldtrip through defined "learning stops" that integrate visual and audio materials. As expressed by Participant 5 (Group 2), these features provided clarity, thereby enhancing learning. This scaffolding assessment allows students to follow structured steps and break tasks into smaller parts, minimising cognitive load, ensuring long-term retention of knowledge and supporting diverse learners (Sweller et al., 2011; Walqui, 2006).

All stops within the VRF were effective in supporting the learning outcomes, although some were more successful than others. Importantly, all five stops incorporated and combined multimodal approaches to each task, supporting diverse learners in understanding and completing each activity. For instance, Stop A provided a guided exercise that enabled students to engage with infographics, videos, tables, audio, and the use of 3D tools, thus providing different approaches to learning new concepts. Similarly, Stop C played a crucial role in enabling students to visualise the function of coastal protection through a video simulation of a storm event, combined with an interactive slider that allowed observation of tidal variation. These features integrated written material with live simulations, reinforcing the overall concept of coastal protection at the site. Stop D and its high-quality 3D model of the sea cliff's vertical face efficiently allowed students to visualise the key elements required for the creation of a stratigraphic log. Additionally, the integrated measuring tool enabled students to collect multiple measurements, retain a record of each, and compare results. A significant aspect of this stop is the integration of a 3D diagram. This, complemented by audio and written materials explaining sediment transport and deposition at the beach, is a live immersive simulation that increases learners' focus on the key geological processes.

Stops B and E were also effective in supporting the associated learning outcomes, although they presented some limitations compared to the other stops. In Stop B, students were required to sketch physical elements of the landscape and limitations occurred due to the accuracy of the visual representation of the VRF. In fact, the environment is restricted to 3D models from survey areas 1, 2, and 3, whose spatial resolution does not fully replicate real-

life landscapes or capture smaller-scale features (sub mm scale). Similarly, in Stop E, which focused on site surveying and data collection, it involved spatial limitations to fully complete the tasks, with some areas displaying more spatial details than others. This limitation in fully displaying large areas at very high spatial resolution represents one of the key constraints of the Garryvoe VRF. Creating a single, highly detailed 3D model of the entire site or incorporating numerous high-quality models may generate issues in the performance of the VRF. For this reason, three areas and several subareas were selected to be integrated into the VRF. Surveying the entire bay at low altitude to produce high-resolution models would have required significant time for data collection and processing and would likely have resulted in performance issues within the VR environment.

Amongst other limitations associated with the VRF, technological issues were identified. Several students, most notably those who used VR after fieldwork, reported having experienced issues with the technology. These included lagging and occasional blurriness, all of which disrupted their learning experience at times. As a result, some students had to pause or repeat certain sections of the fieldtrip while waiting for the screen to stabilise, which may have negatively impacted their ability to complete tasks appropriately and might have produced a certain level of physical discomfort. These issues might have influenced students' performance compared to the group that used VR before fieldwork, with post-fieldwork fatigue possibly contributing to this pattern.

It is important to consider the additional cognitive load and time requirements that are placed on students who use the VRF as a supplementary learning resource. Engaging with the VRF on the same day as fieldwork required students to interact with unfamiliar technology, complete tasks in the virtual environment, and repeatedly remove the VR headset to complete worksheets. This added workload may significantly increase fatigue and reduce students' capacity to engage fully with the VRF following their fieldwork. Similarly, the completing the VRF before fieldwork might, in some cases, increase fatigue in the field.

Along with student overload, dedicated staff might face a number of issues when developing and implementing VRFs for specific courses. Unlike pre-existing VRFs available on the web, those instructor-designed resources, like the Garryvoe VRF, require significant time for planning, data collection, VRF development and implementation. The time devoted to those actions entirely depends on the remoteness of the site and the size of the area to survey and

might be delayed by factors such as technological issues and weather conditions. This, coupled with the expenses associated with purchasing survey equipment and planning multiple site surveys, might represent a barrier. Furthermore, VRFs can be difficult to create (Cliffe, 2017) and require training in the use of the survey equipment, data processing software like Agisoft and a VR platform like Unity, which also necessitate learning basic coding skills. Additional training is required to ensure instructors can operate VR technologies effectively and integrate them meaningfully into teaching and learning practices (Samala et al., 2024).

Another known limitation of VR technology is the reliance on higher processing devices, as well as the use of VR headsets. While these devices are available to use within the UCC campus, they are often too expensive to be purchased for personal use. This hinders students with lower-end devices from accessing the VRF at home. Nevertheless, these technological challenges highlight the need to improve device accessibility in the design and implementation of VRFs to ensure that all students, regardless of their resources, can easily access these innovative learning tools.

3.6.2 How should VR fieldtrips be best implemented?

While fieldtrips are known to increase student interest (Garst et al., 2001), research has also shown that students often experience pre-fieldwork anxiety (Punch, 2012; Boyle et al., 2007). This anxiety can be mitigated when students understand what is expected of them and can establish realistic expectations, reducing the effects of cognitive overload and distraction (Lee et al., 2020; Jarvis and Pell, 2005; Kent et al., 1997). Therefore, briefing activities before fieldwork might reduce students' stress by becoming familiar with the specific objectives and increase their confidence when faced with the uncertainty of fieldwork (McKenzie, 2002). Students reported that VR helped them gain spatial familiarity with the site, especially for those who had never visited the location before, and allowed them to anticipate the number and type of field activities, including tasks like the acid test and stratigraphic logging. This aligns with the concept of novelty space, introduced by Orion and Hofstein (1994), which refers to the degree of unfamiliarity a student feels toward a space or activity. Novelty space is shaped by three factors: a) the level and type of prior knowledge; b) familiarity with field location and c) psychological preparation. Teachers should address these factors before fieldwork, aiming to reduce the novelty space and make the fieldtrips more effective learning

experiences. By accessing the site in VR mode before their fieldwork, students can address these three factors by familiarising themselves with the site, the concept and activities of their fieldwork. At the same time, students who engaged with the VR simulation after the fieldtrip found it valuable as a reflective tool, helping them process their experience and deepen their understanding of key concepts. However, it is also possible that these students experienced physical and cognitive fatigue after a full day of fieldwork, which might have negatively impacted their ability to fully benefit from the VRF. Nevertheless, the post-fieldwork VRF functioned as a debriefing activity, allowing students to review what they had seen and done in the field and to critically evaluate their choices. This was particularly beneficial to students with different learning styles, such as visual learners, to obtain clarity and retain more information.

Debriefing is widely recognised as a vital component of experiential learning. Notably, Kent et al. (1997) express that debriefing activities are a critical part of post-field learning and should follow fieldwork closely to be effective. However, they claim that debriefing is often overlooked due to time limitations after fieldwork. McKenzie (2002) argues that post-fieldwork reflection enables students to critique their experience and integrate new knowledge into their personal learning framework. Krogh et al. (2016) emphasise the importance of debriefing, in particular as a component of simulation-based education, to optimise learning outcomes.

While the data suggest that students who completed the VR experience before the fieldtrip performed better overall, the difference between the two groups is not substantial to conclude that one implementation is definitely more effective than the other. Instead, the findings point to a more integrated approach. Rather than choosing between pre or post-fieldwork implementation, the most effective use of VR may lie in employing it at both stages. As a preparatory tool, VR proved to be effective in offering structured learning steps that helped students to visualise features and written information before their fieldwork. This allowed them to reduce novelty, retain information and achieve the learning outcomes. At the same time, when used as a reflective tool, VR assisted students in processing the information acquired during fieldwork, providing clarity as well as providing visual and auditory resources to support different learners and enhance their learning. Therefore, both approaches support

students through preparation and reflection, increasing students' exposure to the field site to enhance the overall educational value of the fieldtrip experience.

3.6.3 To what extent can VR fieldtrips allow students to replace fieldwork?

Only one student completed the Garryvoe VRF as an alternative to attending fieldwork at the site. The student successfully achieved the intended learning outcomes and reported a positive experience using VR. Unable to attend the fieldtrip that day, they emphasised the importance of having a virtual alternative to avoid missing a key component of the module. In their reflective statement, the student noted that the VR simulation effectively presented essential features of the site, such as the sea cliff and coastal protection in high detail, allowing them to complete the same activities as their peers. The student carried out all the activities at the site and their results favourably compared with those of their peers who went to the field. However, the worksheet highlighted that the student struggled with the last activity, which required group work to plan an offshore wind cable route. This task required on-site exploration and identification of suitable and unsuitable areas and developing observational skills. Without the opportunity for peer interaction and physical exploration, the student found it challenging to fully engage with the activity as the other students did in the field. This suggests that the VR experience cannot be equally compared to the field experience.

Existing studies have consistently highlighted the limitations of VRFs (Garcia et al., 2023; Pugsley et al., 2022; Tuthill et al., 2002; Spicer and Stratford, 2001; Bellan and Scheurman, 1998). While high-quality 3D reconstructions can provide visual simulations, they often fail to replicate the full immersive experience of physical presence in the field (Pugsley et al., 2022). VR lacks the real multisensory experience that fieldwork creates, such as touch, smell, and temperature, which are essential for an enhanced understanding of a site (Belanger and Jordan, 2000). For example, handling rocks and examining sediment textures by touch was a key part of the Garryvoe fieldtrip, which VR could not replicate. Moreover, interacting with a virtual environment lacks the spatial awareness and scale that real field sites provide, thus often failing to convey the true three-dimensional nature of objects (Qui and Hubble, 2002). Equally important is the loss of the social dimension of on-site fieldwork (Garcia et al., 2023). In this case, the student completed the VRF alone, with only a tutor present, missing the opportunity for group work and collaborative learning. The lack of social interaction restricts

the development of social bonds and trust among students (Spicer and Stratford, 2001) as well as hindering the interaction between the student and the instructor in the field (Dost, 2023).

Nevertheless, VRFs hold considerable value when physical fieldwork is not feasible due to accessibility constraints or remoteness of field sites. Furthermore, it provides flexibility of participation, enabling virtual access at any time. This flexibility is especially important for those with caring responsibilities, who often struggle to balance their academic and personal lives (Carlin et al., 2023). In our case, the student could not attend fieldwork due to personal issues. In other situations, students decide not to participate due to perceived barriers or actual barriers. Despite the efforts in reducing these barriers to accommodate students with different kinds of disabilities, inclusivity remains an ongoing challenge that needs to be addressed (Chiarella and Vurro, 2020; Stokes et al., 2019; Hall et al., 2002). As claimed by Slee (2018), the very first step in achieving inclusive education is to break down barriers to education. VRFs can achieve that by addressing these challenges and contributing to the United Nations Sustainable Development Goal 4: "ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all" (UNESCO, 2017). Firstly, VR can allow students with physical disabilities to engage in remote fieldwork without having to consider the health and safety risks associated with being in the field (Elleven et al., 2006). They also improve accessibility for students facing financial challenges who can still develop field skills by accessing VRFs offered by universities. In Ireland, VRFs are particularly relevant in DEIS schools by offering an inclusive alternative or additional resource that supports equitable learning experiences to students who face socio-economic barriers that limit their access to traditional fieldwork.

As inclusive learning's key aim is to value diversity in education (Thomas and May, 2010), it is important to acknowledge the different learners that the undergraduate body represents. This requires employing tools that can accommodate and support all students. One way that VR contributes to this is by offering a multisensory learning environment which complements visual and auditory elements. VRFs offer structured, guided experiences with prompts that help students break down complex concepts and create meaningful learning. As reported by participants in Groups 1 and 2, the VRF supported their ability to process complex information through interactive features such as 3D models, infographics, and audio clips, which were

especially beneficial for visual learners. Therefore, this VRF aligns with some of the design principles outlined in the Assessment for Inclusion (AfI) Framework by UCD (University College Dublin, 2025). In particular, the principles regarding transparency, flexibility and scaffolding explain that assessment should ensure clarity, support different approaches and prepare students to successfully learn in different contexts and build new skills. Therefore, by offering flexible, repeatable experiences that integrate visual, written, and audio material, VRFs can help address the needs of each learner and support diverse and inclusive education (Dost, 2023; Qui and Hubble, 2002). They can also be purposefully designed to meet the needs of students with learning disabilities (Silva et al., 2025). Additionally, they reduce concerns related to cost and safety, providing accessible alternatives for students with physical disabilities or financial constraints (Minocha et al., 2018; Stainfield et al., 2000) and offering a safe, practical way to complete fieldwork, particularly in remote or hazardous locations (Tuthill and Klemm, 2002).

3.6.4 Pedagogical Value and Implementation of the Garryvoe VRF in Geography Fieldwork

Results of the implementation of the Garryvoe VRF highlighted that a multimodal approach in developing digital learning resources can significantly enrich geography fieldwork and strongly support students' learning. Successful integration of a VRF to traditional fieldwork widely depends on several contextual factors, including class size, the availability of trained staff, and access to adequate space, equipment, and technological resources. In this case, the Garryvoe VRF was specifically tailored to the geography curriculum, acknowledging the diverse learners that the student body represents. It was designed to provide well-structured, guided exercises aimed at introducing new geographical concepts. By integrating a scaffolding approach, the Garryvoe VRF includes structured steps in which tasks and information are deconstructed to provide clarity and improve knowledge retention. Each of the five stops integrates audio, video, visual and interactive elements aligned with specific learning outcomes. These stops, designed to guide students through different tasks, allow them to better focus on the activities to complete while minimising potential distractions.

The Garryvoe VRF was successfully implemented with a relatively small group of students, who particularly valued its use as a preparatory tool for fieldwork. As highlighted earlier, pre-fieldwork preparation is an essential resource for many learners as it allows them to gain

spatial familiarity with a new place (Orion and Hofstein, 1994) while clarifying expectations regarding field-based tasks and learning objectives. By reducing uncertainty before the fieldtrip, the VRF lowered students' cognitive load and enhanced knowledge retention, aspects that were reflected in their overall performance. Similarly, students who engaged with VR after their fieldwork highlighted its role in strengthening their understanding of key concepts, although these benefits were not always fully expressed in assessment outcomes.

The use of the Garryvoe VRF in place of fieldwork highlighted the value of alternative methods to field learning. It enables students to engage with field experiences when in-person participation is not possible, offering flexible access and helping to overcome known barriers that restrict student engagement in field classes (Minocha et al., 2018; Stainfield et al., 2000).

While the Garryvoe VRF aligns well with principles of inclusive assessment and has the potential to reduce barriers related to disability, cost, and safety, it may also introduce new challenges. The most significant barrier experienced by students involves the occurrence of technological issues. This largely depends on the processing device and access to high-speed internet. Adding this issue to the need to familiarise with the new technology, particularly after fieldwork, can contribute to increased fatigue and cognitive overload, negatively affecting student performance.

The Garryvoe VRF was designed to be used by availing of the resources provided within the institution, presenting students with an alternative activity when financial or accessibility issues hinder fieldwork participation. Conversely, its use in a home setting may be restricted by limited access to appropriate software and hardware, a challenge that could affect students who are unable to physically access university facilities. Furthermore, the social aspect of fieldwork is significantly missing from the VRF. In particular, group work, peer-to-peer and instructor-peer interaction are very limited. In addition, the spatial and sensory limitations of VR, such as the inability to fully reproduce the real size of objects, textures, smells and weather demonstrates that the VRF scarcely compare to real fieldwork. As such, VRFs should not be viewed as replacements for real fieldwork but rather as complementary or alternative tools when access to the field is not possible. It is therefore important to acknowledge that while VRFs cannot overcome all barriers associated with fieldwork, well-designed, curriculum-specific VR resources can provide valuable support to student learning when used appropriately.

3.7 Conclusion

This study highlights the potential of VRFs as a valuable tool in geoscience education, working as a multisensory experience that provides guidance, allows students to understand complex concepts and develop technical skills. While no significant differences in student performance were observed, the VR experience notably improved students' engagement and understanding, particularly when used before fieldwork. The findings suggest that VR is effective when integrated with traditional fieldwork, rather than as a replacement. However, in cases where fieldwork is not possible, VR offers an alternative that supports diverse learning needs. The strategic integration of VRFs in education can help overcome accessibility issues, promote inclusion, and enhance the field-based learning experience for all students. For future enquiries, we recommend increasing the number of participants to obtain valuable insights into the effectiveness of VRFs in enhancing students' performance.

For future applications of VR in education, we recommend that VRFs be designed to align closely with the specific learning outcomes and requirements of the curriculum. Such VRFs should incorporate a diverse range of interactive elements to accommodate varied learning needs. To enhance inclusion, universities should ensure VRFs can be used within the institution, ensuring that they are accessible to all students, including those with limited access to the VR hardware or high-speed internet. Furthermore, universities should ensure funding and resources to support staff in developing their own VR tools, which can be integrated as a complementary tool to in-class learning, lab or field-based learning. Finally, novel VR technologies can play a significant role in overcoming existing technical challenges, potentially reducing issues such as poor system performance and enhancing the quality and engagement of the learning experience.

4. Thesis Conclusions

4.1 Concluding remarks

This thesis presents the results of developing and implementing a VRF in the geography curriculum at UCC. These results have significant implications for creating VRFs that enhance students' learning and engagement.

In Chapter 2, we developed a method for creating 3D models using a UAV (Uncrewed Aerial Vehicle) to capture aerial images of Garryvoe beach, supplemented by smartphone imagery of smaller features. The data processing involved the use of Agisoft Metashape as the SfM photogrammetry software. This novel approach, employing the benefits of SfM photogrammetry (Westoby et al., 2012), generated scaled, georeferenced 3D texturised meshes that offer <1 cm/pixel resolution. These models enable enhanced visualisation of detailed reconstructions of the beach sections.

The resulting VRF, built in Unity, integrates these models into an interactive and immersive environment. Unity proved to be useful in implementing interactions and enhancing graphic capabilities. Users can navigate in the scene by walking or flying and perform tasks that include accessing infographics, taking vertical and horizontal measurements, and using a slider that simulates tidal variation at the site. The high-quality 3D models, especially the close-ups, display detailed surface features that are significant for tasks that require analysing changes in stratigraphy and physical properties of rocks. Furthermore, the integration of realistic sounds and visual effects provides sensory realism, replicating the experience of a real fieldtrip. Thus, this chapter contributes to informing future research on the technology needed to develop teaching material.

Chapter 3 offers valuable insights into the implementation of VRF into geography curricula, while acknowledging their limitations. This chapter fulfils the project's second aim: to assess the impact and effectiveness of this VRF in support of student learning. To this end, the chapter answered the following 3 research questions (RQs):

RQ1: What is the impact of VR in Geography education?

RQ2: How should VRF be best implemented?

RQ3: To what extent can VRF allow students to replace fieldwork?

The findings highlighted that the integration of VR into fieldwork as a tool for preparation, reflection and alternative learning can play a valuable role in helping students achieve their learning outcomes, specifically by reducing the cognitive load and improving knowledge retention. It was found that the VRF provided scaffolding through the use of learning stops and integration of audio-visual materials. This approach enabled students to deconstruct complex information and facilitated the understanding of concepts and tasks by both visual and auditory learners. This method is supported by literature, which states that multimodal approaches enhance memory retention and foster inclusion by ensuring that the diverse learning needs are met (Anis and Khan, 2023; Sweller et al., 2011).

A key advantage of using the VRF was observed when implemented as a preparation for fieldwork. Students reported gaining greater familiarity with the field activities and improved knowledge retention. This significantly reduced the cognitive load, thus making fieldwork experience more meaningful (Orion and Hofstein, 1994). This preparation allowed students to engage more effectively with the tasks, therefore enhancing the overall fieldwork performance and experience. At the same time, students who completed the VRF after fieldwork reported using it as a valuable reflective exercise that consolidated their understanding of key concepts and allowed visual learners to review tasks and evaluate choices. However, this cohort displayed poorer performance, possibly related to physical and cognitive fatigue post-fieldwork. Nevertheless, both implementations reflect the potential of the integration of these approaches, suggesting that VRFs are both effective as preparation and debriefing exercises. This approach enhances students' engagement before and supports students' revision after, ultimately increasing the educational value of fieldwork.

VR was also used as an alternative to fieldwork for a student who was unable to attend the day in the field. Results emphasised the importance of having such a tool to allow students access to the learning materials and avoid missing an important component of the module. The performance showed that the student successfully achieved the learning outcomes and deemed the VRF a good alternative to on-site fieldwork. However, many disadvantages were identified. The main challenge experienced was the lack of social interaction with classmates, which significantly hindered the completion of one of the tasks in the fieldwork module. At the same time, numerous advantages were discussed. In particular, the benefits of using VRFs to foster inclusion and overcome accessibility, financial and personal barriers were explored.

By offering a multisensory learning environment that complements visual, written, and auditory elements, this VRF can benefit a wide range of learners (Dost, 2023). Furthermore, the integration of structured learning stops can help students break down complex concepts and obtain positive learning gains. Finally, the VRFs offer a repeatable experience that ensures an accessible alternative to students with disabilities, financial issues and other accessibility constraints (Minocha et al., 2018).

While this study highlights the benefit of VRFs as an integrative method to fieldwork, it also emphasises the inability of VRFs to replace fieldwork. VRFs fail to fully reproduce the multisensory and social aspects of on-site fieldwork (Qui and Hubble, 2002). Physical exploration and tactile learning are integral aspects of geography fieldwork (Belanger and Jordan, 2000) and are difficult to replicate in a VR environment. This study also highlighted the technological limitations associated with VR technology. These included lagging, blurriness and reliance on high-performance computers. The cost and accessibility of VR equipment remain a barrier, especially for students without access to institutional resources.

4.2 Contributions

Considering the findings of this thesis, the main contributions are the following:

I. It demonstrates the capability of using UAV photogrammetry to capture high-resolution imagery for generating scaled and georeferenced 3D models of sites and features.

II. It establishes the potential of Unity 3D for integrating 3D models to create an interactive and immersive learning environment with applications for fieldwork education.

III. It provides evidence that VRFs have positive outcomes on students' learning and experience, especially on pre-fieldwork preparation and post-fieldwork reflection. Preparation builds initial knowledge and reduces the overall cognitive load, while reflection helps students consolidate understanding and address knowledge gaps.

It shows that VRFs are a valuable alternative to fieldwork that promotes access and inclusion when on-site participation is not possible. However, VRFs do not fully replace the experience or skills; therefore, an integrated approach is recommended.

4.3 Future Directions

This thesis highlights the potential of VRFs to enhance student field-based learning in geography education. As such, it proposes new directions for future research. The first direction regards the design of a VRF, which must be tailored to meet the specific needs of the curriculum. Future work should ensure these tools are developed in direct alignment with learning objectives while considering the needs of diverse learners. The second direction regards the implementation of such VRFs. As highlighted in this study, these offer valuable cognitive gains when implemented at multiple stages of the learning process, and for this reason, there is a need to integrate VR into in-class or fieldwork applications to support students in their field learning or as preparation for assessments. A critical area for development is enhancing the social component of the VR experience. Future research should focus on designing and implementing VR multiplayer experiences that allow students to interact with each other and complete VR fieldwork collaboratively, especially for tasks that require group work. For example, Unity offers a VR multiplayer template that can be used to develop VRFs that allow for multiple access. In terms of technological updates, future research should focus on overcoming the existing technological limitations that hinder students from accessing the software and engaging in the experience. The adoption of newer software and VR tools can potentially solve issues related to lagging and blurring during the VR simulation. Specifically, the high system requirements, access to high-speed internet and the use of the VR software represent an accessibility challenge. It is therefore crucial to ensure that VRFs can be accessed within the institution, ensuring wider adoption among all students.

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Appendix I

Ethics Approval

Ethical approval for this study was requested by the Social Research Ethics Committee (SREC) in advance of carrying out the research due to direct interactions with students to collect data on their performance and experience using the Garryvoe VRF.

In the application, the following documents were included:

- Information sheet for both worksheets and reflective statements, to inform students of the study's purpose and the fieldwork structure
- Research consent form for both worksheets and reflective statements, to obtain students' consent to participate
- Sample worksheet featuring fieldwork activities
- Reflective statement featuring a Likert scale and open questions

The ethics form was drafted and submitted on 13/10/2024 under the log number 2024-241 and subsequently approved on 20/12/2024.

Appendix II

Reflective statement

After completing your VR fieldtrip, you are asked to answer the questions in the following sections.

I. How strongly do you agree or disagree with these statements?

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
The VR fieldtrip was easy to access.	1	2	3	4	5
The instructions in the VR fieldtrip were clear.	1	2	3	4	5
The VR technology was easy to use	1	2	3	4	5
I found the use of VR challenging					
The VR experience was more engaging compared to classroom learning	1	2	3	4	5
The VR field trip enhanced my knowledge of topics discussed in class	1	2	3	4	5
This VR fieldtrip improved my ability to remember key topics studied during class	1	2	3	4	5
The VR field trip is a good alternative to fieldwork	1	2	3	4	5

II. Below you have five questions, for each provide a short answer based on your experience in using the VR fieldtrip.

1. Please provide reflections on how the VR fieldtrip supported or enhanced your learning in this module

2. Please reflect on the ways you felt the VR technology allowed you to visualize and understand geological phenomena.

3. Please reflect on the ways the VR technology helped you retain the information learnt in class

4. Please describe what you found to be challenging about using the VR technology.

5. In your opinion should VR technology be used more frequently in geography classes and if so, how could it be replicated in future modules or assignments?

6. In your opinion, what was the most important aspect of completing this VR fieldtrip to support your learning in this module?