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The use of immersive virtual reality for teaching fieldwork skills in complex structural terrains

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ABSTRACT

Innovations in virtual reality (VR) technology have led to exciting possibilities in teaching earth sciences, allowing students to experience complex geological sites that, due to cost and logistical reasons, they would not normally be able to experience. The need for high quality online digital learning resources and blended learning was brought to the forefront during the SARS-CoV-2 pandemic, as courses with a traditional physical field work component were forced to move online and provide alternatives to students. While it is unlikely that virtual field trips (VFT) would be accepted by students as a replacement of real-world fieldwork moving out of the pandemic, research shows promise that using IVR experiences can lead to enhanced learning outcomes in geosciences, warranting its inclusion on the curricula. This paper presents the outputs of a project to improve student learning in complex geological environments using VR. Here we outline a workflow that was developed to collect high resolution imagery using remote sensing to create digital outcrop models (DOM) of complex geological sites. Using this framework, this paper will then explore the use of VR for an investigation of the Husavik Triple Junction, a complex structural site in northern Iceland, explaining how the drone data was converted to a 3D DOM and demonstrating how VR can be used to simulate real world field mapping. Finally, we describe how these IVR activities have been integrated into taught modules at postgraduate level and discuss how the use of IVR experiences can complement existing geoscience curriculum design.

1. Introduction

Fieldwork has for a long time been held as an effective and essential learning component in geoscience training (Geikie, 1912; Boyle et al., 2007; Schiappa and Smith., 2018). Fieldwork promotes an understanding of geological concepts taught in the classroom, allowing students to enhance skills such as rock and surface feature identification and mapping, data recording and reporting and importantly how to visualise and think about the subsurface in three dimensions. Students undertaking extended field trips in geology show significant improvements in their understanding of geoscience concepts when compared to standard campus-based activities alone (Elkins and Elkins., 2007). Spatial awareness is at the core of geosciences and students require a knowledge and understanding of location when undertaking place-based learning (Semken and Freeman., 2008). Interpreting and visualising spatial data acquired during field data collection, and its subsequent integration within Geographical Information Systems (GIS),

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Acronyms and abbreviations

(VFT	Virtual field trip
IVR	Immersive virtual reality
VR	Virtual Reality
HMD	Head mounted display
DOM	Digital outcrop model

are now essential tools in geoscience learning (Baban, 2002).

Helping students acquire this spatial awareness should then form a key part of any geoscience course. Virtual field trips (VFT) are often utilised to prepare students for real-life field work (Cliffe, 2017) and VFT's have been successfully implemented onto curriculum and implemented in a 2D capacity for decades (Hurst, 1998). Research shows that the primary benefit of VFT's is as a preparation tool prior to actual field work. (Arrowsmith et al., 2005). They allow students to view sites not always practical for scientists to visit for field observation. This typically involves the study of 2D cartography and photography and some element of photo interpretation, GIS or data analysis (Carmichael and Tscholl., 2011). It has been found that while students saw VFT's as valuable learning experiences, they did not see them as a direct replacement for real field trips (Spicer and Stratford., 2001; Bond and Cawood., 2021). Traditional VFT's also do not address conceptual difficulties such as relating field observations of outcrops to geological maps, visualising the evolution of geologic structures through time and understanding the 3D nature of geologic structures and how they intersect topography are skills that students find challenging to master in a classroom setting and are often easier to visualise when taught in the field (Whitmeyer et al., 2009). Developments in augmented reality technology could help to bridge this gap, where in-class mapping activities are augmented by other data visualised through a headset. Students have shown increased interest and engagement when using augmented reality in geology (Bursztyn et al., 2017), and that using AR enhanced maps significantly improves three-dimensional geological understanding and development of spatial orientation skills (Carbonell Carrera and Bermejo Asensio, 2016).

VFT's can be further enhanced using 3D environments, created using UAV-SfM surveys to generate elevation data and mosaiced aerial images, typically viewed on desktops using a 3D model viewer such as ArcScene. The availability of low cost unmanned aerial vehicles (or drones) that capture high resolution aerial imagery makes this technology now widely available. Utilising game engine technology, such as the Unreal engine, it is possible for VR environments to be created from these 3D scenes. The increased availability of affordable VR technology, with headsets that can run on standard desktop computers, creates opportunities to build high quality virtual environments that can be explored by students in more immersive ways than traditional 2D geological field teaching allows in the classroom.

Pre-Pandemic studies show that using immersive VR (IVR) in geology teaching was thought of as a promising field but was often not implemented onto existing curriculum and remained a tool for researchers rather than students. (Fowler., 2015; Jiayan Zhao et al., 2017; Radianti et al., 2020). However, delivering high quality VFT's has taken on greater importance due to the rapid increase in blended learning and online digital learning during the global COVID-19 pandemic. Studies undertaken during this time have shown that immersive virtual experiences in geology can support the development of students spatial skills in the absence of traditional field work (Barth et al., 2022; Paz- Álvarez et al., 2022). VR offers many advantages for students including an increased sense of presence and spatial orientation (Detyna and Kadiri., 2019; Bond and Cawood, 2021) as well as enhanced understanding and learning outcomes when compared to traditional 2D classroom teaching (Klippel et al., 2019; Barth et al., 2022).

While most studies conclude that VFT's, even those including immersive virtual experiences, cannot replace the experience of boots on ground fieldwork (Paz- Álvarez et al., 2022; Barth el al, 2022; Bond and Cawood, 2021), it is clear that advancements in VR and UAV-SfM technologies provide promising learning tools post pandemic for supporting geosciences field-based learning. Considering the benefits discussed it becomes apparent that integrating this technology into classroom activities and onto current teaching curriculums is important when emerging from the pandemic and addressing the rising demand for blended and online learning.

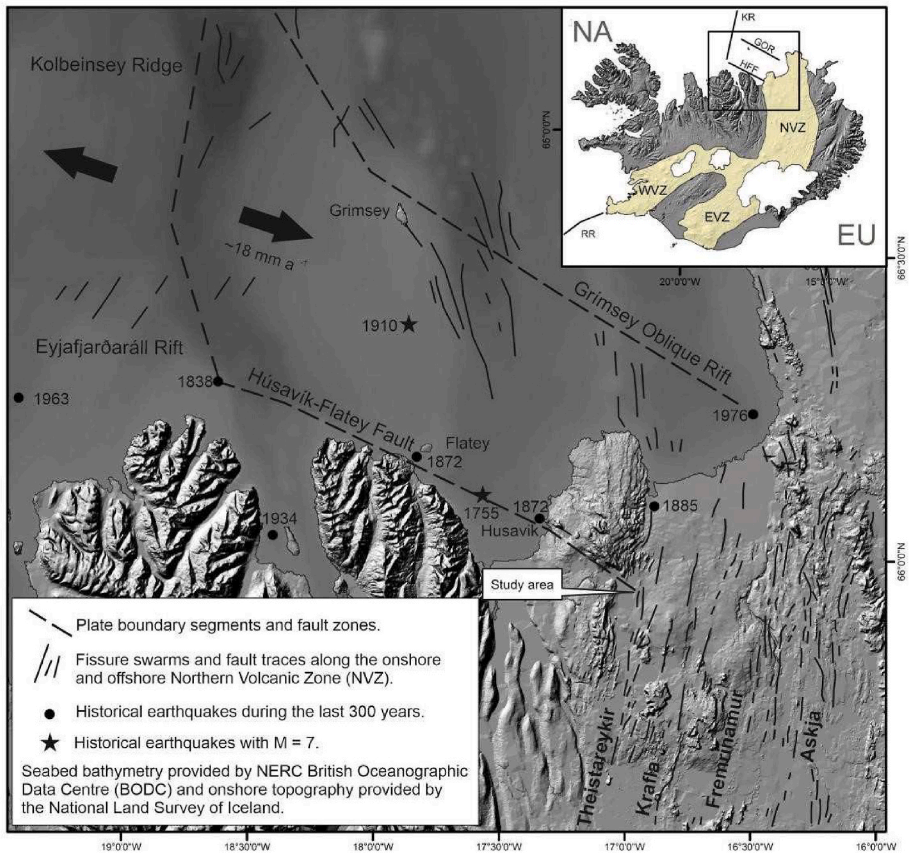
The case study presented here focuses on a DOM of a unique subaerial rift-transform triple junction in the north east of Iceland. Developed from high-resolution drone imagery collected in 2016, this DOM presents a complex tectonic region that holds a great deal of potential for geoscience learning in a remote and unique geologic locale that students would otherwise likely never have the opportunity to visit. Using GeaVR (https://geavr.eu), a VR software package developed by 3DTeLC and Argo3D, we present a method for generating 3D environments, explore current capabilities of the software and focus on the potential applications in teaching geosciences using a complex structural site such as this. We will draw on first-hand experience of using VR technologies and our development of course content using these models, discussing the benefits to geoscience learning a site like this provides and addressing the limitations of the technology and the barriers to fully implementing IVR as a part of the geoscience curriculum.

2. Husavik Triple Junction

This case study will use drone imagery acquired at the Husavik triple junction in northern Iceland, produced by the intersection of the Husavik-Flatey fault (HFF) and rifting in the western margin of the Northern Volcanic Zone (NVZ) called the Theistareykir Fissure Zone (TFZ) in northern Iceland. This is marked by a belt of normal faulting and eruptive fissures referred to as the Theistareykir fissure swarm (Fig. 1). This site was chosen because it represents a rare subaerial example of a triple junction, with excellent field examples of a range of surface structural features that have been well documented by field measurements (Rust and Whitworth., 2019). Two drone surveys have been undertaken at the site; the first in 2014 formed the basis for the Rust and Whitworth (2019) study and a second extended drone survey was undertaken in 2016, which forms the basis for this study.

The Husavik Triple Junction is part of the divergent Eurasian - North American plate boundary that extends through Iceland, linking the Reykjanes ridge south of the island with the continuation northwards of the mid-Atlantic spreading axis as the Kolbeinsey ridge (Fig. 1). The HFF represents the principal onshore component of the TSZ and is thought to have been initiated 7–9 Ma ago (Rögnvaldsson et al., 1998). Over an on-land extent of some 25 km the HFF displays classic features of active strike-slip tectonics, GPS data suggest a current slip rate of ~6.8 mm a^{-1}, and four major earthquakes with an estimated magnitude of 6.5 or greater have occurred since 1755 (Opheim and Gudmundsson., 1989; Garcia and Dhont., 2005; Homberg et al., 2010, Fig. 1). Initiation of the NVZ is estimated to have occurred about 8–8.5 Ma after an eastward jump in the rift axis (Garcia et al., 2003). For the NVZ the most notable historical activity is the 1975-84 Krafla eruption, centred about 25 km south of the study area, which was accompanied by episodic rifting deformation amounting to several metres horizontally, and a few metres vertically, as well as by numerous M5.0–6.5 earthquakes (Tryggvason, 1980, 1984; 1986; Bjornsson., 1985; Jouanne et al., 2016).

Beyond the immediate study area, mapping documents the very complex regional interaction between rifting and transform faulting (Gudmundsson et al., 1993; Gudmundsson, 2007; Iceland GeoSurvey, 2012; Hjartardóttir et al., 2015; Pasquarè Mariotto et al., 2015; Tibaldi et al., 2016). Of importance for the purposes of the present study, the deformation structures are developed in an extensive sheet of pahoehoe lava flows, constrained to about 12.5 ka BP (Slater, 2001; Stracke et al.,

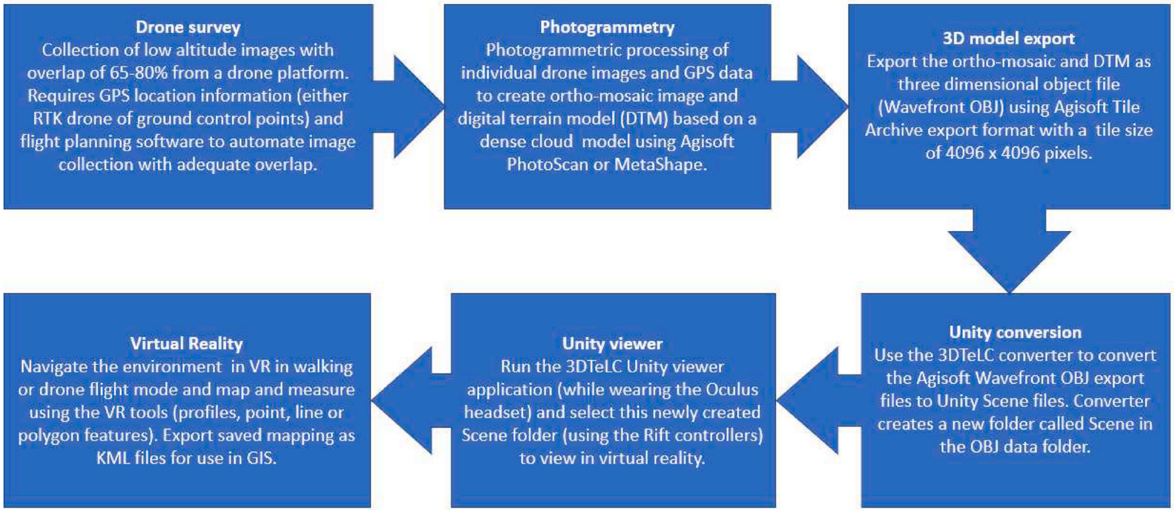


Seabed bathymetry provided by NERC British Oceanographic Data Centre (BODC) and onshore topography provided by the National Land Survey of Iceland.

Fig. 1. Regional context of the study area at the subaerial triple junction formed by the intersection of the Húsavík-Flatey Fault and the Theistareykir fissure swarm on the western margin of the Northern Volcanic Zone (NVZ). The NVZ marks the boundary between the European and North American plates in northern Iceland. Inset map shows the location in relation to the plate boundary components that cross Iceland, the Reykjanes Ridge (RR), Western Volcanic Zone (WVZ), Eastern Volcanic Zone (EVZ) and the NVZ, HFF, Grimsey Oblique Rift (GR) and Kolbeinsey Ridge (KR). (modified from Rust and Whitworth, 2019).

2003) and emitted from the Theistareykir central lava shield to the south of the study area, a smooth and planar *tabula rasa* that provides a uniquely preserved long-term record of subsequent structural interactions (Figs. 1 and 2). More recently the 2.4 ka 'Theistareykjhraun' lavas, easily distinguished by their blocky character, advanced from the shield northwards, and were constrained to the SE corner of the study area by tectonic uplift at the triple junction (Figs. 2 and 3). These fortuitous circumstances, coupled with only minor vegetation development, create an area of ~1 km^2 containing innumerable fault features displayed in exquisite detail. From the ground, features such as piercing points, slip directions and amounts, and other structural features can be recognised and measured very accurately.

A survey on foot also enables primary lava features, such as fracturing associated with inflation and deflation in the pahoehoe flow field,



Drone survey
Collection of low altitude images with overlap of 65-80% from a drone platform. Requires GPS location information (either RTK drone of ground control points) and flight planning software to automate image collection with adequate overlap.

Photogrammetry
Photogrammetric processing of individual drone images and GPS data to create ortho-mosaic image and digital terrain model (DTM) based on a dense cloud model using Agisoft PhotoScan or MetaShape.

3D model export
Export the ortho-mosaic and DTM as three dimensional object file (Wavefront OBJ) using Agisoft Tile Archive export format with a tile size of 4096 x 4096 pixels.

Unity conversion
Use the 3DTeLC converter to convert the Agisoft Wavefront OBJ export files to Unity Scene files. Converter creates a new folder called Scene in the OBJ data folder.

Unity viewer
Run the 3DTeLC Unity viewer application (while wearing the Oculus headset) and select this newly created Scene folder (using the Rift controllers) to view in virtual reality.

Virtual Reality
Navigate the environment in VR in walking or drone flight mode and map and measure using the VR tools (profiles, point, line or polygon features). Export saved mapping as KML files for use in GIS.

Fig. 2. Flow chart illustrating the different stages in the conversion of raw drone imagery acquired over a site of interest to a DOM that can be navigated in VR using an Oculus rift HMD. The first step involves a UAV-SfM survey, followed by post processing and export of this georeferenced imagery using photogrammetry as one combined 3D data set (steps 2 and 3). Steps 4 and 5 utilise software specifically developed during the 3DTeLC project to convert the DOM for use in VR. The final step utilises 3DTeLC tools to navigate, map and measure in virtual reality, replicating real world field mapping and data collection activities which can later be exported for use in GIS.

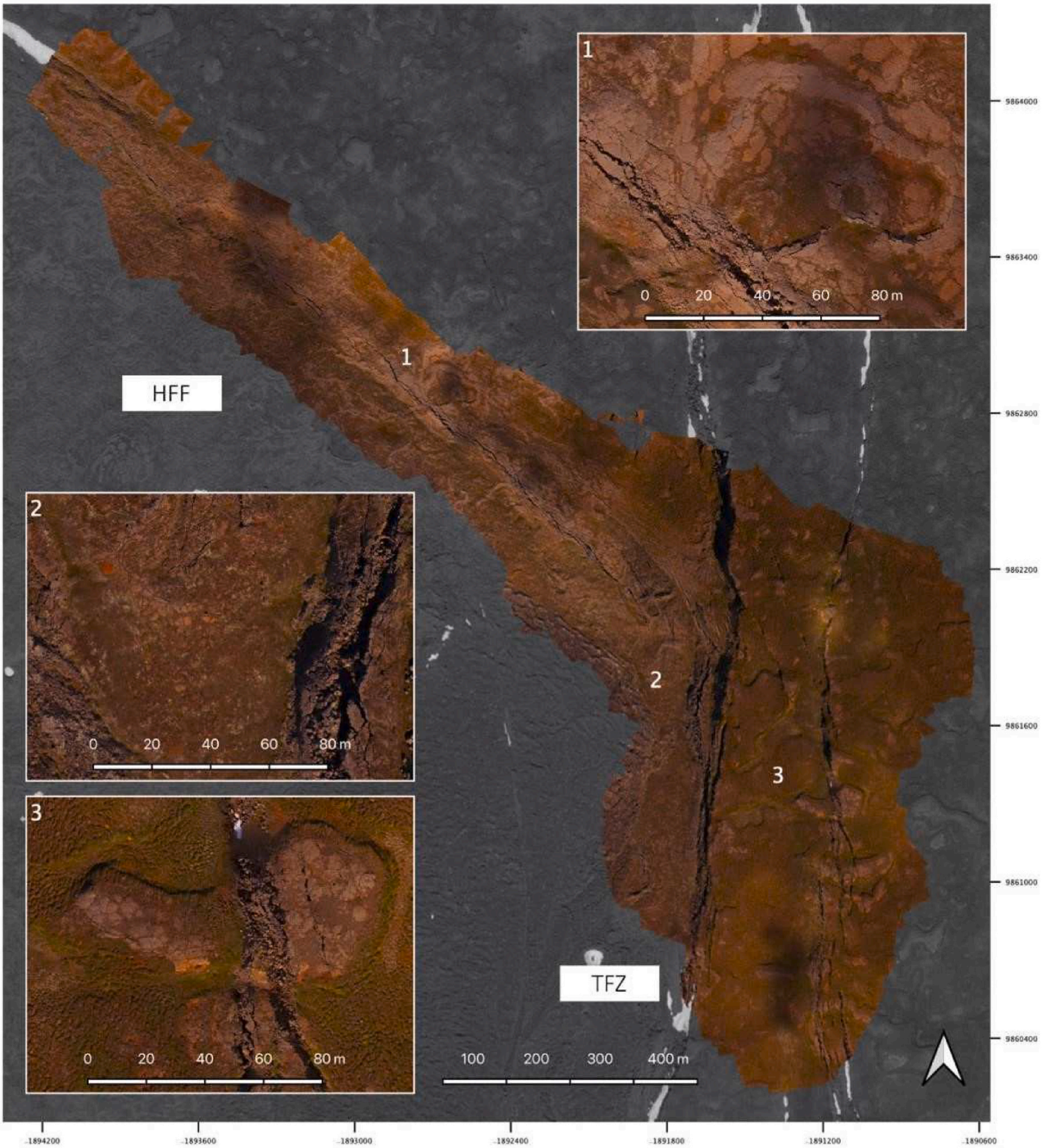


Fig. 3. Map showing the full extent of the imagery created from the UAV-SfM survey in 2016. Extending north-west along the Husavik-Flatey Fault (HFF) and covering the full extent of the intersection with the Theistareykir Fissure Zone (TFZ). Inset 1 shows a closeup of a collapsed pahoehoe lava domes along the HFF, inset 2 shows the intersection of the HFF and. TFZ and inset 3 shows the north-south striking extensional rift in a small lava flow in the TFZ.

to be recognised. However, crucially, distinguishing between these primary fractures and the subsequent innumerable tectonic fractures is often extremely difficult at ground level and demands the bird's eye perspective provided by low-altitude drone imagery.

3. Methodology

This study describes the use of IVR for geological survey, structural mapping and analysis of the tectonic features at the Husavik-Flatey Triple Junction, northern Iceland, a remarkable site formed from the subaerial triple-junction intersection between the Husavik-Flatey Fault (HFF) dextral transform and rifting in the Northern Volcanic Zone (Fig. 1). The site was initially surveyed in detail and drone imagery was acquired in 2014 (Rust and Whitworth., 2019); and again in 2016. Subsequent to this, both sets of drone data have been used to create a high-resolution VR model of the area, fully navigable using VR headsets and controllers. The model allows the user to navigate the immersive environment, either by flying or walking, when using the headset, undertake GIS style feature mapping (dropping points, line and polygon features using the controllers) and export these features in a spatial rich format for desktop GIS processing and visualization (for an overview of the VR workflow, see Krokos et al., 2019, Antoniou et al., 2020 and Tibaldi et al., 2020).

Fig. 2 illustrates the key stages in the conversion of raw drone imagery acquired over a site of interest to a full VR model that can be navigated using Oculus Rift headset and controllers. In this methodology section we will detail these steps prior to presenting our observations from a virtual walkover survey and mapping in the VR environment for the Husavik site.

3.1. Field data mapping and measurement

The original field mapping was undertaken to address the need for very detailed mapping of small-scale tectonic structures; this involved a field survey coupled with detailed GPS referenced ground measurements and field surveys with mapping at approximately 1:200 scale using imagery obtained from low-altitude GPS-controlled drone surveys. Field data collection involved a small team working systematically across the mapping area; piercing points were identified and measurements of slip direction and displacement amount were recorded. Each piercing point was carefully selected, so that only those with a clear match on either side of the fracture opening were used to measure the opening direction and opening amount. A handheld GPS was used to locate each piercing point location, and a measuring tape and compass were used to measure the offset (opening direction and amount). A total of 120 piercing points were identified across the entire area, for which horizontal offset amount and direction were recorded. The plunge (vertical offset) of the slip directions were too small to be accurately measured and were disregarded from this study.

During the walk over survey, it was common to encounter localised gravity collapse of the lava sheets into the voids created by the open fracture system. This mass movement exploited the columnar jointing that is pervasive through the lava sheets, causing individual columns to become detached and the surrounding joints to become dilated, thereby obscuring piercing point directions and exaggerating opening amounts. Consequently, it was necessary to carefully differentiate between those open fractures caused by this gravity driven collapse of the lava sheets and only record piercing points representing true fault slip offset amount and direction.

This field data collection was supplemented by a contemporaneous survey using an.

Unmanned Aerial Vehicle using a Structure from Motion (UAV-SfM) data processing framework. Aerial imagery was acquired using a small multi-rotor unmanned aerial vehicle which was then post-processed to generate an ortho-rectified mosaiced colour image and Digital Surface Model of ground elevation (DSM). The drone used was a DJI Phantom 3 quadcopter fitted with onboard autopilot and GPS receiver, capable of automatic mission planning. A drone mounted camera captured vertical overlapping photographs of the ground surface at a resolution of 12 megapixels. GPS ground control points were installed across the study area using white markers to provide GPS calibration for post processing of the photography. The imagery acquired from the drone survey provided very high-resolution georeferenced image mosaic that was visualised in GIS to help extend field observations beyond visible line of sight. This highlighted spatial relationships between tectonic deformation features and helped distinguish them from primary features, such as the emplacement of the lavas or areas of mass movements and lava toppling, which at ground level were difficult to differentiate from other fault structures.

3.2. Structure from motion (SfM) photogrammetry

Two drone surveys were undertaken to map the Husavik-Flatey Triple Junction site. This study used the second of the two drone surveys that was flown in 2016; the first survey in 2014 has been described by Rust and Whitworth (2019). The 2016 drone survey adopted an Unmanned Aerial Vehicle (UAV) with Structure from motion (SfM) framework. Firstly, high-resolution aerial photography was acquired from a low altitude drone. The drone was flown on a mixture of autopilot and manual flight plans, at a height of approximately 90 m above the ground surface in order to capture images with a ground surface distance of 4 cm per pixel. GPS control points were deployed across the study area to provide GPS calibration for subsequent SFM post-processing. Six separate flight lines were required to image the extended area of interest, resulting in acquisition of some 600 separate photographs in each survey. The resulting individual photographs and GPS information were post-processed using the commercial software package Agisoft PhotoScan version 1.4 to create a colour ortho-mosaiced image and DSM of the survey area by stitching the individual photographs. The image ortho-mosaic generated from the drone survey is shown in Fig. 3 and a comparison of the ortho-mosaic generated from the drone survey and the same area in Google Earth imagery is shown in Fig. 4. The full extent of the technical background of this approach is not detailed here, but the use of UAV-SfM for geological and geomorphological applications has been described by Bemis et al. (2014), Carrivick et al. (2016) and Smith et al. (2016).

3.3. Virtual reality model creation

The final stage of the workflow involved conversion of the 3D Tiled model into files compatible for VR Unity engine for viewing using a head mounted display (HMD) (in this study, we used Oculus Rift and Oculus Quest headsets, see https://www.oculus.com). This is the final stage of the workflow and involves capturing the output from SfM process in Agisoft Photoscan to create Unity VR compatible files (https://www.unity.com). To achieve this, a 3D Tiled model is created in AgiSoft Photoscan from the completed model including both mesh and texture components (using the elevation model and colour orthomosaic created from the individual aerial photographs, as inputs). To perform this conversion, Agisoft Tile Archive - OBJ file export format is selected, with a medium quality set-up with a tile size of 4096 × 4096 pixels, these OBJ files are then compatible with the Unity file converter that creates the Scene files required for VR viewing in Unity. These scene files are loaded using the GeaVR viewing tool. Both the converter and viewer tools were created as part of the Erasmus+ funded project 2017-1-UK01-KA203-036719 and the MIUR project ACPR15T4_00098–Argo3D (http://argo3d.unimib.it/). The GeaVR software used in the study is available at https://geavr.eu and all learning resources are available to download from http://www.3dtelc.com. For an example application and description of the workflow using these tools, see Krokos et al. (2019), Tibaldi et al. (2020) and Antoniou et al. (2020).

3.4. Virtual reality set-up

The VR viewer requires scene file inputs to create the virtual environment, these have been created from the Photoscan OBJ file output. These scene files are chosen at startup (Fig. 5 shows the scene selection options in GeaVR) and allows the user to define the start location for their avatar in Unity, prior to the creation of the virtual environment.

The 3D environment is created from the elevation model that provides the height map and the colour imagery that generates the image texture for the model. Fig. 6 shows an example view from the user's avatar illustrating the VR experience. Once inside the VR model, the user has a choice of three traversal options including 1) walking, 2) drone and 3) flight modalities. Walking mode allows the user to traverse the area on foot, simulating normal field navigation in the virtual environment. The user is fixed to the ground but can move in any direction at a fixed speed and avatar height set to 1.8 m. The drone mode replicates the vertical, lateral and rotational movements of a quadcopter drone and allows the user to pan along outcrops, not possible on foot. The flight mode, by contrast, replicates the action of an aerial platform, whereby the user's viewpoint is in a fixed position looking vertically downward from beneath the aircraft. Traversing using either of the two virtual flight modes gives the user a bird's eye view of the VR model. The system allows rapid switching between the three navigation modes, allowing the user to switch from aerial view to ground surface view and vice versa, not possible with normal field mapping.

Once inside VR, the GeaVR platform provides the user with a range of virtual tools (Fig. 6) that replicate navigation and field data collection. Firstly, depending on the traversal mode, the user can control the

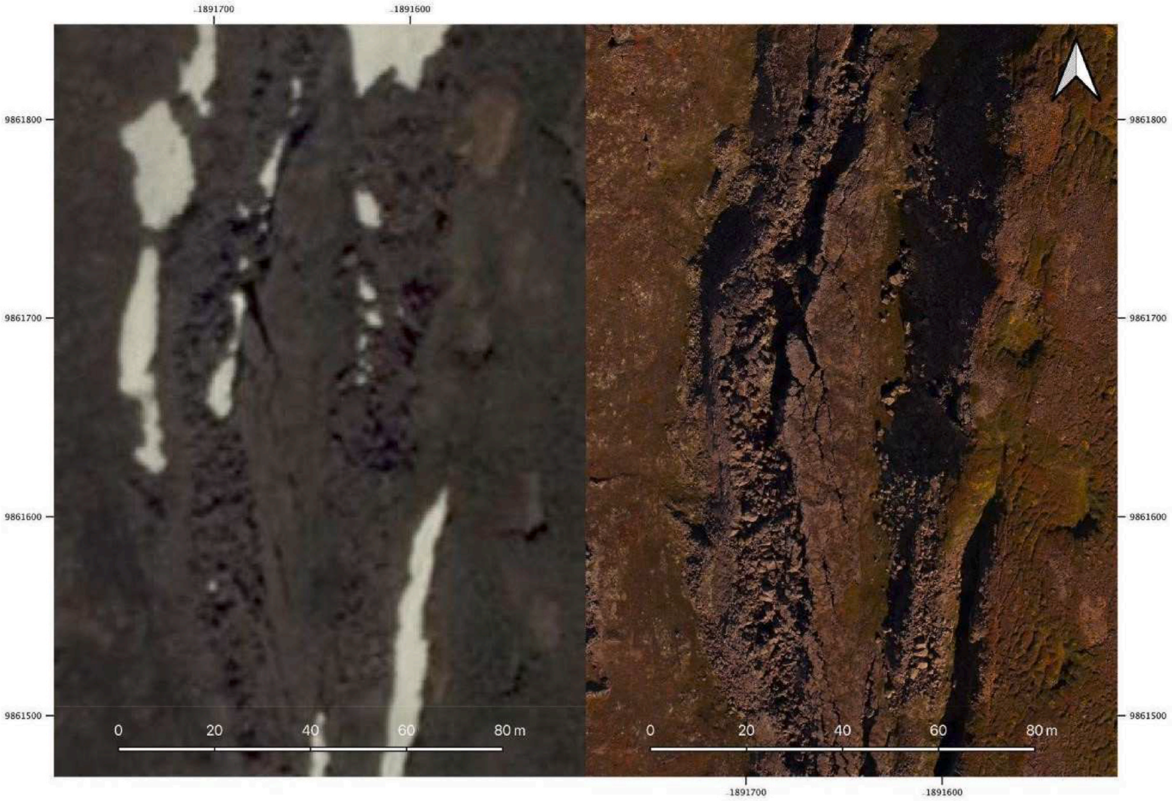


Fig. 4. A comparison of the image quality and resolution between Google Earth imagery (on the left) and the drone orthophoto (on the right) for the same region in the centre of the Husavik-Flatey Triple junction (labelled 2 in Fig. 2).

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C:\Users\44779\Desktop\Husavik Flatey Fault and Rift Extended Zone, Husavik, Iceland (2016 VR ready files in Scene folder)\NewHusavik 2016

C:\Users\44779\Desktop\Husavik Flatey Fault and Rift Extended Zone, Husavik, Iceland (2016 VR ready files in Scene folder)

Enter Folder Path...

Lat: 0.000000
Lon: 0.000000
Alt: 0.000000
Alt offset: 0.000000

Fig. 5. Screenshot of the selection tool used to choose the scene files for virtual reality viewing in GeaVR. The scene files are created from the Photoscan OBJ output files using the converter and are available to download from http://www.3dtelc.com along with the converter and viewing software.

movement of the avatar on the ground or in the air using the left of the two hand-held controllers that come with the HMD. Secondly, the user can activate a set of mapping and measurement tools for data collection while in motion, using the second controller. These tools include feature mapping by placing points, lines or polygons to delineate landforms on the ground surface, generating topographic profiles along a line between two points, measuring the distance between two points, orientation measurement using a compass, recording the dip, inclination and orientation of surfaces and taking georeferenced photographs of the user's viewpoint in VR using a virtual camera. All outputs can be exported for use outside of the virtual environment, for example, the points, lines or polygon mapping can later be exported for use in GIS, either in KML or CSV format and the profile data can be exported as CSV data for viewing and plotting in Microsoft.

The DOM of the Husavik Triple formed the basis for development of virtual teaching and learning activities as a deliverable from the Erasmus funded project (Erasmus+ 3DTeLC Project Summary, 2021). This model has been used for structural and geomorphological mapping using VR, replicating a walkover survey of the site on foot, whilst also taking advantage of the birds eye view afforded by the drone flight mode.

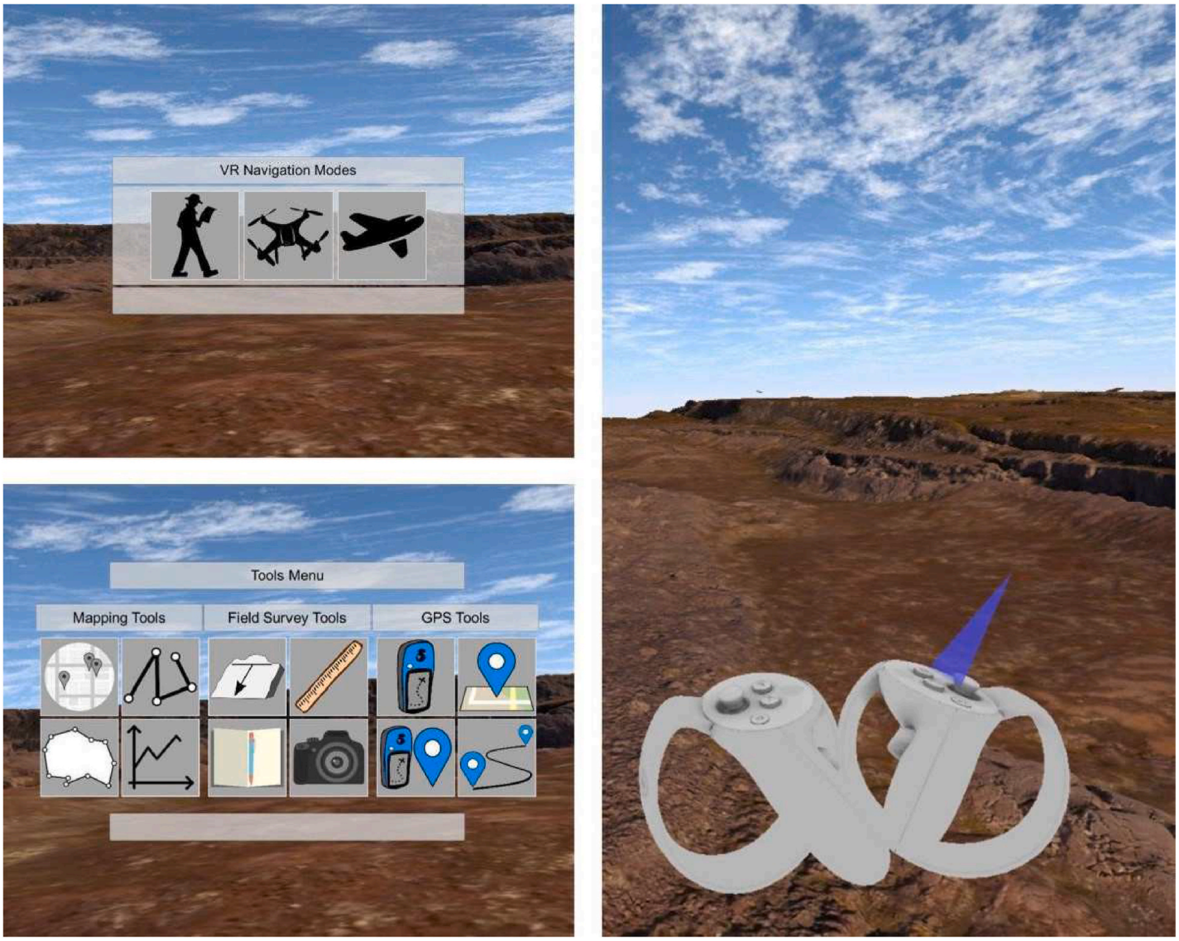

Fig. 6. Overview of the options available within GeaVR. (top left) three transversal modes available in virtual reality: walking, drone and aircraft flight modes. (bottom left) Mapping, survey and GPS tools available within the virtual reality, and (right) example viewpoint seen by the user when in virtual reality, showing the Oculus Rift controllers and pointer used to interact with the environment.

3.5. *Virtual reality walkover survey*

The virtual reality (VR) walkover survey, mapping and the observations that are described in this paper were undertaken by the lead author, who had no prior field experience of the site, during the development of VR based teaching materials (later detailed in section x) using the 3D model of the Husavik site. This in effect allowed a traditional field survey of the Husavik site in VR to be completed using the mapping tools, without prior field knowledge or observational bias. The methodology developed during these virtual tours of Husavik, formed the basis for the student activities and allowed a step-by-step workflow to be developed and documented, while identifying factors affected the student experience of VR. These observations helped form the basis of our proposed curriculum design based on this unique geological site. Whilst the DOM must be viewed in VR to be fully appreciated, Fig. 7 through 10 show the innumerable fault features on display at this site. Identifying what features are distinguishable using the DOM in VR is key to providing a framework for how 3D structural geology models such as this can be used in an educational setting.

Fig. 7 presents comparison between a real world and a VR view of the site looking west-north-west over the Husavik Flatey Fault (HFF) from the main escarpment. Images within the 3D VR model were captured using the built-in camera tool. GPS coordinates were recorded for photographs taken during the 2016 field survey of the HFF allowing for an accurate comparison from the same vantage points in VR. It is clear from this snapshot captured in VR that large features viewed from distance are clearly distinguishable in the DOM when viewed with an HMD. The faulting in this area is developed in the 12.5ka pahoehoe lava flow field, the surface of which has been vertically separated by the Theistareykir escarpment from which both images have been taken. The dip-slip component of the faulting along the HFF can be easily identified in VR from the tilted slabs in the lavas running centrally through both images, as well as the 2.4ka lava front, which can be seen encroaching on the 12.5ka lava field from the far-middle-left of both images. The collapsed columnar jointing of the 12.5ka lavas can be identified in the fissures of the real-world photograph in Fig. 7a, but due to distortion of the images over the DEM these are visually less clear in VR (Fig. 7b). Similarly, the riedel shears to the middle-left of the real-world image are harder to distinguish in VR from this distance. The pahoehoe lavas in the foreground of both images Fig. 7a and b provide the clearest example of the degradation of image quality in VR when viewed closeup, compared to at a distance. This is further highlighted in Fig. 8 when viewing fault scarps and depressions in the model where the image is distorted when stretched over the DEM.

Fig. 9 presents examples of landforms that were identified during the virtual walkover survey. These features result from the kind of structural complexity that result from the intersection between an extensional rift zone and transform fault system. Although six features are shown in this figure, the site is covered by varied structural features of equal quality, and it is this that makes the site such a unique structural geology experience in VR. Fig. 9a shows an example of a circular depression that results from lava deflation and collapse structures. Fault mapping in this area, both in real-world and VR experiences, is complicated by the presence of these types of deflation structures in the pahoehoe flows.

Fig. 7. Comparison between a real world and virtual reality view of the Husavik-Flatey Fault zone from the main escarpment. a) Field photograph from 2016 survey taken from location (65.944963, −16.992048 looking west north west) and b) view from the same location in virtual reality using the GeaVR software in walking mode with the virtual user height set to 1.8m. The edge of the virtual reality model can be observed in the lower figure reflecting the limit of the drone imagery acquired in the field.

Fig. 9b shows the northern boundary of the younger 2.4ka lava flows from the Theistareykir volcanic centre, covering the southern edge of the DOM. These flows stop short of covering the en-echelon fault complexes trending north-west through south-east throughout the model (Fig. 9d), before buttressing against the rift zone. The eastern section of the DOM is dominated by normal faults in the Theistareykir rift zone; these form steep fault escarpments that are clearly visible in the VR (Fig. 9c and e). The model highlights the vertical displacement along the rift through the escarpment running north-south through the model. Fig. 9f shows piercing points identified in the DOM and are a key indicator of structural movement along the faults.

The columnar jointing that is pervasive throughout the pahoehoe flows complicated data collection in the field, obscuring piercing points and exaggerating opening amounts. (Rust and Whitworth., 2019). This is exacerbated further in VR due to issues with the resolution of the imagery used to create the 3D mode and distortion caused by the image being stretched over vertical surfaces not visible to the drone, as highlighted in Fig. 8. This makes reliable identification and measurements of these features in VR difficult and subject to greater inaccuracy than was encountered in the original field survey.

Fig. 10 displays the results of structural mapping undertaken by the authors using the DOM, completed in VR using the GeaVR mapping toolkit with Oculus HMD and Oculus Rift controllers. For comparison, detailed structural observations from the study area and original field survey can be found in Rust and Whitworth (2019).

Primary lava features such as the 2.4ka lava front encroaching from the southwest and lava deflation features within the pahoehoe lavas were mapped using the polygon tools. Faults were mapped systematically across the Husavik DOM using the line tool. Three distinct areas can be distinguished from the completed mapping, as highlighted in Fig. 10. The two main fault systems, the NW-SE transform-affinity en-echelon fault complexes of the HFF and the N–S normal faults from

Fig. 8. Comparison of real-world vs VR view of transform affinity faulting. Surface features such as the fractures in the columnar jointing in the pahoehoe lava and tilting of the lava surface are clearly visible, but image distortion is apparent inside the faults. This poor image quality results from image stretching over vertical surfaces not visible to the drone.

the Theistareykir rifting, continuous with the well-developed fault scarp marking its western margin, are all clear from their consistent trend. The transform zone shows a series of left-stepping transform-affinity en-echelon fault complexes before curving into alignment with the Theistareykir rifting, highlighted in the centre of Fig. 10. Larger features from the model are easily identifiable and viewing the model in 3D helps to distinguish some features based on their topography in a way that viewing the orthomosaic in 2D cannot. It was noted in the original field study that the detailed birds eye view offered by the drone imagery proved a useful tool for mapping the spatial relationships of the tectonic deformation taking place at the triple junction, observations that at ground level were difficult to reliably differentiate from smaller faults. (Rust and Whitworth, 2019). This also translated well when viewing the Husavik DOM in VR. The drone traversal modality proved most useful to navigate and map the features across the site. The oblique view afforded by this traversal mode, as well as the ability to pan and adjust the virtual height of the observer whilst utilising the field toolkit made it the preferred choice over the fixed height or viewpoint of the other two traversal options when mapping and identifying features.

Despite the benefits described, there were limitations that became apparent while using the DOM in VR. Firstly, as highlighted in Fig. 8, the resolution of the UAV-SfM imagery and the distortion created by the photogrammetric process over fault scarps and blockier lava features, for example, can make detailed VR field observations and measurement in these areas difficult. Therefore, it is essential that very high-resolution drone imagery is acquired, where the intention is to use this data to create a VR model. Care must be taken during the photogrammetric process used to convert the individual drone photos onto an elevation model and orthophoto mosaic. Photogrammetry and UAV-SfM surveys depend on feature matching algorithms and complex, repeating patterns (often found in complex terrains) can introduce uncertainty during this process, leading to incomplete reconstruction and or repetition of features in the final orthomosaic (Lane et al., 2000; Iglhaut et al., 2019). This can be reduced by increasing the overlap of images taken by the drone during the UAV-SfM survey and introducing more ground control points increasing location accuracy. (Westoby et al., 2012; James and Robson., 2014). Manual selection of user identified tie-points (matching areas/features) within the imagery with high confidence will also reduce errors in the final model. Image distortion over vertical surfaces is reduced with the implementation of oblique imagery throughout the

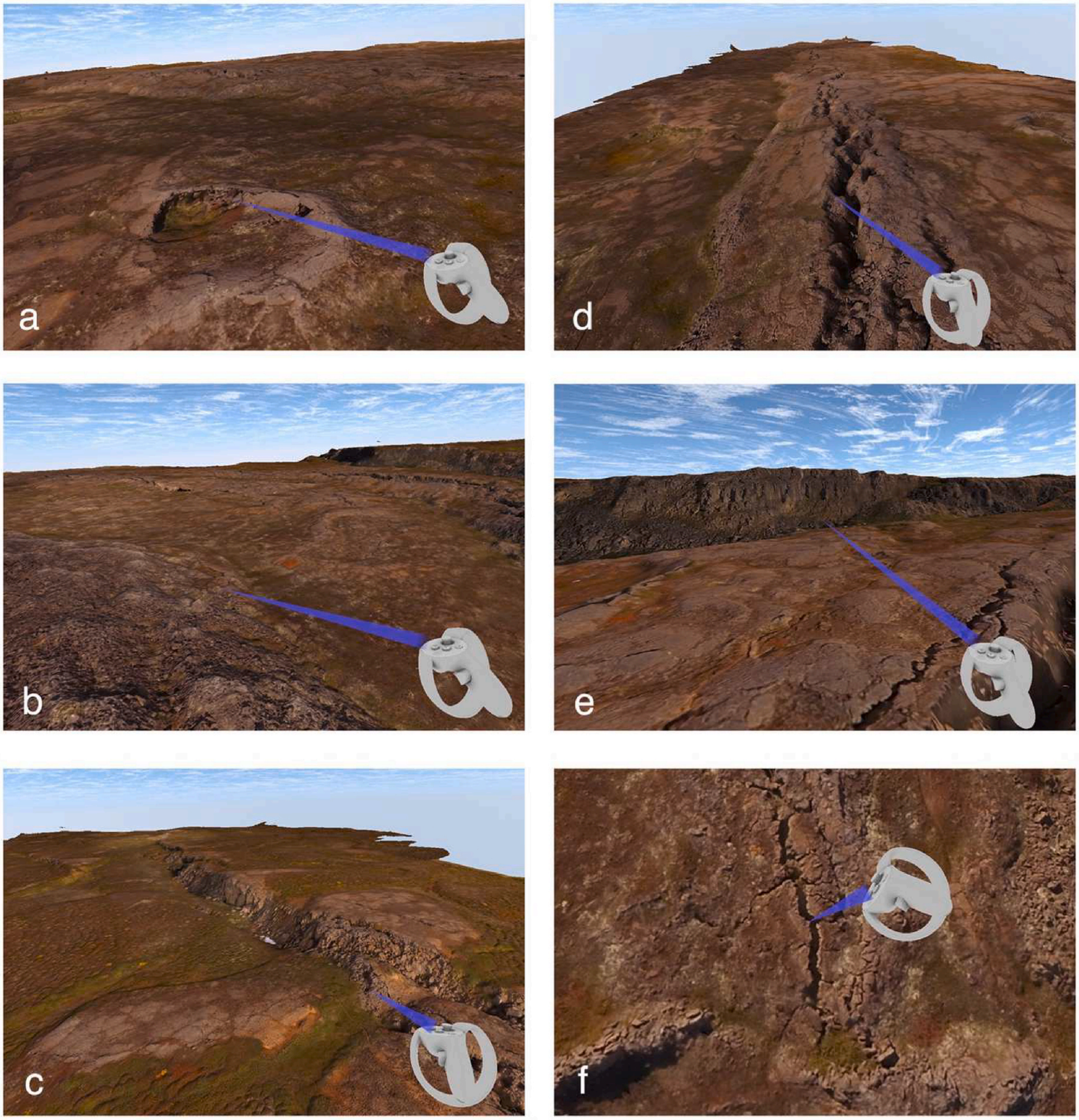

Fig. 9. Example views of terrain and structural features from the Husavik model in a virtual field survey, with blue marker from Oculus Rift controller identifying their location. a) Deflation in pahoehoe lava flow deposits. b) Encroachment of younger 2.4ka blocky lavas. c) Normal faulting with vertical offset developed in the Theistareykir rift zone. d) Oblique normal en-echelon fault complex along the Husavik-Flatey fault. e) View eastward toward the Theistareykir escarpment. f) Piercing points identified in oblique normal faulting. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

survey (Cecchi et al., 2011). These steps can be taken to reduce inaccuracies but can prove inefficient over large study areas such as this site. The original walkover study yielded 120 measurements of fault displacement between piercing points. This was supplemented by a further 80 measurements taken from the drone imagery. It was noted from the original field study (Rust and Whitworth., 2019) that due to the resolution of the imagery, the measurements taken from the orthomosaic proved to be significantly lower in quality than those taken in the field. It is then apparent that the added distortion introduced in the DOM and VR would further degrade the accuracy of any data collected.

From a research point of view these limitations can affect the quality and reliability of any meaningful data collection using the DOM and are important to consider, especially for researchers intending to study these sites further in VR. However, with regard to using the Husavik DOM as a teaching tool, this does not detract from benefits previously discussed. The ability to view this complex site in VR is an immersive experience, allowing the user to clearly identify important geological structures across the site and affording the user a greater understanding of the spatial scale of these structures. This has the potential to resolve conceptual difficulties that are often encountered by students during field experiences, such as interpreting 3D structures from 2D imagery, and affords a greater understanding of the geologic relationships on display at this site (Whitmeyer et al., 2009). The addition of mapping tools such as the line, polygon and topographical cross section tool are spatially accurate and could provide an excellent introduction to mapping the area as a case study or in preparation for a real-world field trip (Paz-Álvarez et al., 2022). Academic staff will often visit the same field location year on year and, with the correct training and equipment, UAV-SfM surveys can be conducted to generate DOM's that can support pre and post field work activities using these tools.

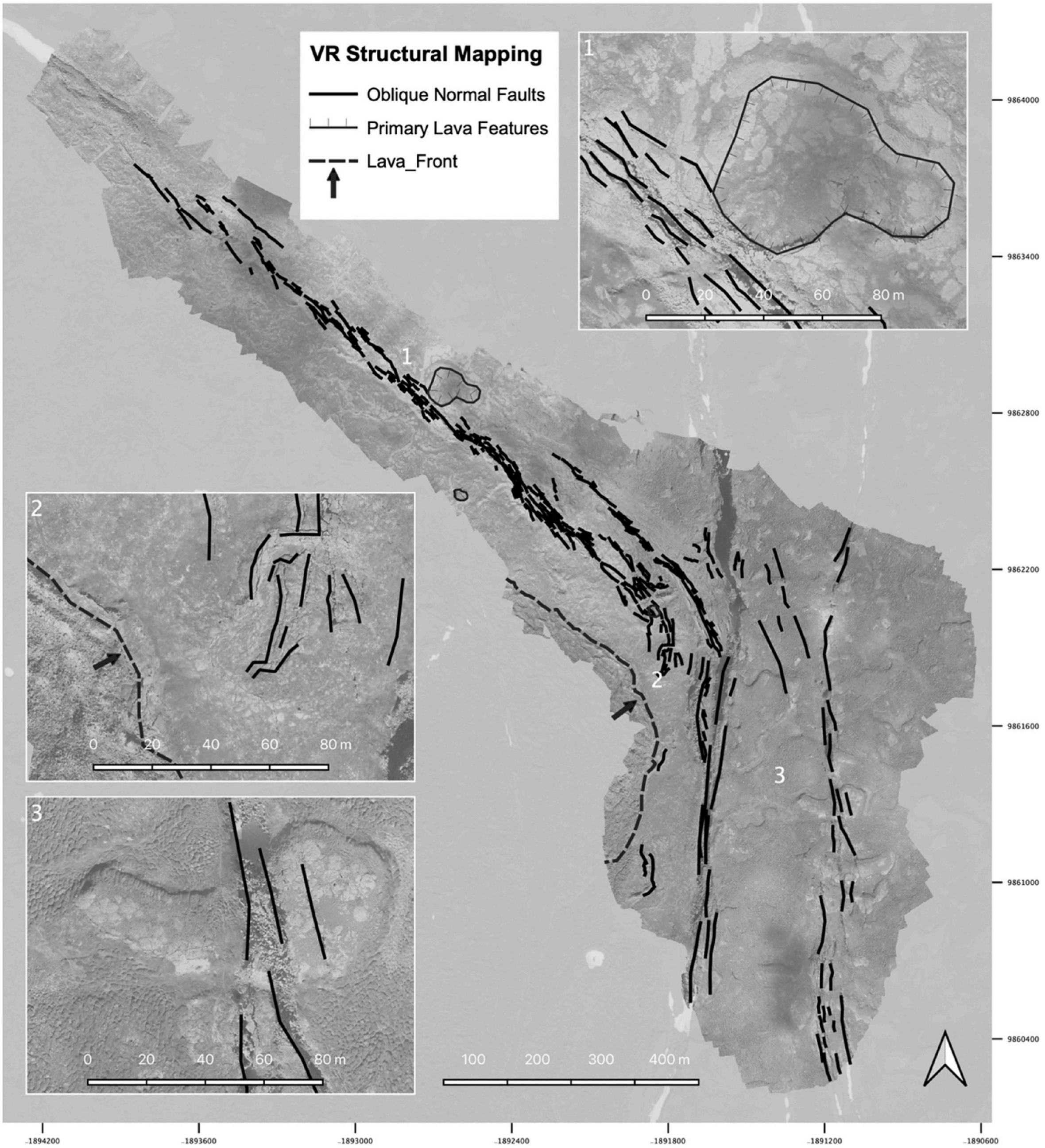

Fig. 10. Structural mapping of the Husavik Triple Junction area. Mapping completed using the GeaVR toolkit in VR, exported and then processed in QGIS. Insets 1–3 show features corresponding to those highlighted in Fig. 3.

3.6. Implementation for teaching

Based on these observations we have designed a series of student activities based around use of the Husavik Triple Junction DOM in VR. Students are first asked to navigate to the top of the escarpment along the Theistareykir rift using the drone or flight traversal mode, affording them a similar view to that shown in Fig. 7 and familiarising them with the flight traversal option. The guided nature of this task and the singular location means that it can be delivered first by the lecturer, explaining the key features that are on view before the students enter the VR HMD to experience it themselves. Tasks are then introduced with each one utilising one of the key mapping tools (Fig. 6) to create a structural model containing faults and primary lava features across the site (Fig. 9). One such exercise breaks the site down into three sections examining the en-echelon fault complexes, the transform zone and the rift as outlined in Fig. 10 and utilising the line tool to measure and record faults in each area. The KML files for each session on the task are saved separately but can be merged later using GIS. Between each task regular intervals encourage breaks from using the HMD to reduce concerns surrounding motion sickness raised in 5.1.2. Likewise, each task builds upon the last, gradually increasing the students' familiarity with both the traversal modes and the toolkit, assuming a beginner level at the outset. The final task utilises the data collected in VR to help students produce their own structural map for the study site, as is shown in Fig. 10. Incorporating VR in this manner, alongside traditional GIS skills based practical sessions, provides an enhanced learning outcome and supports wider skill development.

3.7. Curriculum design

One of the principal outputs from the Erasmus + project involved creating a series of specific learning activities for each of the sites where imagery was collected to create DOM's for use in VR. Each site surveyed was chosen for the varied geomorphological features and structural landforms that characterized that chosen landscape.

In our experience, when implementing VR as part of a teaching curriculum and fieldwork activities, it is important to include the following:

- Clearly articulated learning objectives that aligned with the course module in which the activities would sit. Here we chose a post-graduate module on a geological and environmental hazards course where natural hazard processes, structural geology, fieldwork, mapping and spatial analysis form integral components of the course activities and learning outcomes.
- Overview of the study area and surrounding region that provides the student with a summary of the geological setting and recent historical activity with links to published research. In our case the IVR session is preceded by an induction talk or presentation which provides context for the site. The teaching resources provides links to published research to allow for more self-directed reading and in-depth investigation to be undertaken by the students, important especially for those studying at postgraduate level.
- Summary of how the DOM was created. This was an important part of the Erasmus + project and expands upon the overall learning outcomes from the exercise, providing insight into a growing field of study. To this end, each learning resource included a summary of the methods involving the UAV-SfM surveys, and processing of the imagery for further use in VR.
- Step by step instruction on how to load, visualise and navigate the model in VR. This is described in the learning materials but could also form part of the induction session to allow students to become familiar with navigation and the use of the mapping tools available. This is to be completed before beginning the learning activities in VR.
- Mapping and measurement tasks. Students undertake a set of tasks specifically designed for the 3D terrain under investigation. This involves relevant use of mapping tools (point, line and polygon) and measurement tools (topographic profile, virtual camera, GPS waypoints and compass clinometer), depending on the study area and proposed learning outcomes from the chosen site. Using the Husavik Triple Junction as an example, the teaching materials principally follow the walkover survey presented in section x. Step by step students are tasked with building a structural model of the site, mapping easily identifiable features such as the 2.4ka lava front using the polygon tool and then mapping faults using the line and measurement tools. Students are directed between individual tasks to take breaks to minimise any effects of VR induced motion sickness.
- Instructions for exporting data collection in VR for further analysis in a Geographic Information System (GIS). The measurements and mapped features collected in VR are exported with real-world coordinates as comma separated values (CSV) for use in a spreadsheet or data processing tool, or as KML spatial files allowing students to export these measurements into GIS software. This is an important part of the overall task as it reinforces other learning outcomes relevant geoscience courses. In the case of our Husavik teaching materials the user is tasked with building a complete structural model of the site using measurements collected in VR and preparing this data as a figure to be presented using GIS software.

Sessions using VR must be carefully planned with clear sight of how the activities align with the learning outcomes for the module. VR should only be included if there is a reasonable expectation it could enhance student learning and engagement (Detyna and Kadiri., 2019; Stojšić et al., 2017). Use of VR for virtual field activities requires significant preparation, including allowing time for students to become familiar with VR and providing clear instructions that set out the aims and objectives of the session. Students have shown that without specific guidance virtual experiences can prove daunting (Dolphin et al., 2019). Task design is therefore, one of the most important considerations when developing course content using VR (Hafner et al., 2013). VR based activities should be planned as part of a broader range of activities that enhance students' skills. For example, allowing the user to export mapping and other data from VR for use in other software such as Geographical Information Systems (GIS) to generate new products and outputs. These initiatives can help embed interactive digital learning activities to reinforce classroom-based learning and support specific digital skill development (McGuinness and Fulton., 2019).

3.8. Two-dimensional alternatives

It is important to consider how to provide access to the DOM's in situations where VR equipment is not available. It therefore may be necessary to provide a version of the DOM that does not require use of an HMD and controller, but only requires access to a standard computer and monitor and allows simple navigation, allowing the students to walk and fly over the site using their keyboard and mouse. This approach can be used for face-to-face teaching to large student groups in computing facilities without access to VR equipment or for remote teaching, where students are studying away from university and using their own computers in the UK or overseas. In each case the two-dimensional package can be downloaded and installed on the host computer and operated using the keyboard and mouse, allowing students to traverse the virtual terrain without the need for use of full VR equipment. This was trialed successfully using the Husavik model during a virtual conference held as part of the Erasmus + project. A Learning, Teaching and Training (LTT) event was held remotely as part of the 3DTeLC project during the May Covid-19 2020 global lockdowns. Students attending remotely using their own computers (at home throughout Europe), were able to download a 2D Husavik terrain model for use on both Windows and Mac and undertake a series of individual and group learning activities.

3.9. Learning materials

This teaching plan described for the Husavik site has been replicated for DOM's of geomorphological sites for other hazard landscapes, including landslides (Black Ven & Chale, UK), lava flows (Mt Etna) and coastal spits (East Head, UK). The outputs from the Erasmus+ funded project are available to download from the EU project portal (Erasmus+ 3DTeLC Project Summary, 2021) and http://www.3dtelc.com, while the GeaVR software is available at https://geavr.eu.

These resources include the drone-to-VR scene converter and VR viewing software, raw drone imagery, Oculus VR ready scene files created from the drone imagery and teaching materials describing learning activities for each of the virtual reality sites (including the Husavik Triple Junction site discussed herein). For each of the chosen geological sites, for which drone imagery was acquired and DOM's created, detailed learning activities were devised. These included (1) a detailed background to the site with relevant literature and maps and figures; (2) a short exploratory exercise to familiarize the student with the VR controls and the DOM; (3) a series of more detailed mapping tasks to be completed in VR using the GeaVR toolkit, and (4) data processing outside VR using data exported from the model in GIS or Microsoft Excel to present and visualise the data.

3.10. Limitations

Throughout our walkover surveys in VR and preparation of teaching materials it became apparent that while IVR holds much promise there are barriers that need to be overcome if it is to be successfully implemented onto curriculum. Fully understanding these limitations is crucial for the development of effective VR based teaching materials that can be integrated onto geoscience curricula.

3.11. Teaching and implementation onto curriculum

3.11.1. Hardware

Investment in hardware, upgrading computing requirements and associated cost, can be seen as the biggest initial barrier to fully implementing VR. Whilst popular consumer headsets now start from around £300 (in the case of the new Oculus Quest), outfitting a computer laboratory with enough headsets for a large class can prove prohibitively expensive. VR software is also often very graphic-intensive and requires dedicated on-board graphic cards and external onboard connections which are not always ubiquitous in campus computers, therefore utilising VR may also require upgrading existing PC hardware. Without dedicated VR laboratories, set up times mean that sessions require more preparation than normal computer based practical's and staff trained in both set-up and use of VR are needed to oversee lessons. Widespread implementation of VR onto the curriculum would require thorough planning, training and support of teaching staff (Stojšić et al., 2017; Detyna and Kadiri., 2019). The lack of standardisation amongst VR software and technologies must also be considered. For example, the VR software and associated VR models and teaching materials in this study have been designed for use with Oculus VR equipment and have not been tested on alternative headsets. Institutions who have previously invested in other devices would need to find bespoke solutions tailored to their hardware. Concerns persist that due to the rapid technological developments in the sector, future VR headsets and operating systems will require significant changes to existing software. For example, set up times are reduced for non-dedicated VR laboratories with newer wireless VR headsets though the closed app ecosystem utilised in hardware such as the Oculus Quest.

3.11.2. Usability

Implementation of VR can be viewed as positively removing preexisiting barriers to field exercises for those with physical disabilities or other difficulties with field-based training (Hall, 2004; Chiarella and Vurro., 2020; Bonali et al., 2019; Bonali., 2021). There are clear advantages in terms of equality and inclusivity that IVR experiences in geosciences can provide, including providing virtual access for those who physically cannot go to the field unless specific measures are implemented to enable access (Bond and Cawood., 2021). However the side effects of using VR introduces its own issues. VR has been shown to induce motion sickness in 25–40% of individuals (Fulvio et al., 2021) and this has also been shown to disproportionately affect gender, with women increasingly likely to experience VR motion induced sickness (Munafo et al., 2016). Beyond optimisation of software there are steps to reduce the likelihood of VR induced motion sickness, such as tailored VR personalisation and self-regulating movement and rotation when using HMD, methods that are difficult to control in a classroom environment. Care needs be taken when creating any assessment that relies upon use of VR, as this would negatively impact those who are unable to use VR effectively for these reasons.

3.11.3. Digital literacy

Students arriving at university have varying levels of digital literacy and often do not have the computing skills needed to solve scientific problems (Shopova, 2014). Those who struggle with standard geoscience computer applications will undoubtedly experience similar difficulties with VR due to the added complexity and physicality. VR use prior to higher education varies significantly amongst students and often, due to the lack of implementation in early education, depends on the personal experience of the user with VR, most commonly with computer gaming. There is a strong association between previous IT experience and gaming that informs how well students will perceive and engage with VR based activities (Wright., 2022; Bursztyn et al., 2022). These disparities can be overcome by embedding VR throughout the curriculum so students become proficient in their use. Through careful support and scaffolding at a module level, students need time with VR to allow for exploration and discovery to better embrace these experiences. (Wright et al., 2022; Detyna and Kadiri., 2019). As with all new technology, each of these issues may fade as time goes by and VR and HMD's become more commonly used in areas inside and outside pre-higher education (Pantelidis, 2010). As such and following recommendations regarding motion sickness in 5.1.2. VFT's using VR should be designed without assessment to remain broadly applicable (Barth et al., 2022).

4. Discussion

Field mapping experience is a critical part of any structural geological teaching, and learning can only take place where students are exposed to real world examples of different structural features and landforms. Fieldwork is typically planned to support classroom teaching and provide students with these opportunities. Students can sometimes find themselves struggling to identify features in the field due to a lack of spatial skills and the difficulty of conceptualizing space and scale (Kastens et al., 2009; Liben and Titus., 2012). Whilst there is an increasing trend of encouraging the use of mobile technology in the field, measurements and apps that replicate compass clinometers fail to solve this issue (Cawood et al., 2017). Similarly, this difficulty conceptualizing space and scale is not solved by traditional fieldwork preparation and reconnaissance using two-dimensional satellite imagery (Bursztyn et al., 2022). Visualising the three-dimensional nature of geological structures, the intersection of geological structures with topography and the extrapolation of small-scale features into larger scales are common issues faced when learning from traditional two-dimensional imagery (Whitmeyer et al., 2009). Studies show that users of IVR can more accurately perceive spatial properties than in non-immersive VR and that the understanding of spatial relationships is enhanced within this setting. (Schnabel and Kvan., 2003; Lukacevic et al., 2020). If implemented onto the curriculum correctly, IVR has the potential to reduce the performance gap between students with high and low spatial abilities (Simpson et al., 2017; Bursztyn et al., 2022).

The 3DTeLC Erasmus + project's Learning, Teaching and Training (LTT) events were impacted by the Covid-19 pandemic that took hold in March 2020 and led to significant disruption to classroom and field-based teaching activities. Norms for data collection, teaching, research and dissemination have all been challenged by the pandemic and resulting travel restrictions and limits on group activities have severely limited national and international fieldwork opportunities for students. So, any virtual technique that can help provide an alternative when fieldwork is curtailed in this manner will be beneficial as travel restrictions are often introduced with little notice and alternatives are required quickly in response. The impact of fieldwork on climate change is also now under greater scrutiny, yet many courses in geosciences involve an element of student field work that still requires air travel, one of the most carbon intensive forms of travel (Macintosh and Wallace., 2009). While universities actively aim to reduce emissions, few attempts have been made to limit the impact of long distance travel involved in international student mobility (Arsenault et al., 2019). There will be increasing pressure for the academic sector as a whole to reduce its own carbon footprint (Higham and Font., 2019). Increasing student numbers in higher education and stretching of departmental resources (Dolphin et al., 2019) puts pressure on geoscience curricula to find alternatives to international field work or to minimise time spent on overseas field visits. Overseas fieldwork while considered a key component of many geoscience courses, is often expensive and students are increasingly having to self-fund trips at undergraduate level (Giles et al., 2020).

Being able to transport students to field sites through VR, without ever having to leave the classroom would appear to solve many of these issues. However, while students are intrigued by the developments with the technology, they may be unlikely to fully accept IVR experiences as a replacement for actual field work (Cliffe, 2017; Paz- Álvarez et al., 2022; Wright., 2022). Younger users would appear to be less impressed by VR (Bonali., 2021), having had more exposure to its capabilities in other platforms such as gaming. Therefore it may be that VR applications need to be defined better to tailor towards younger audiences rather than researchers and academics. While the benefits of 3D learning are clear (Whitelock and Jelfs., 2005; Bond and Cawood., 2021), the desire still for hands on field experience would seem to warrant VR's place on geosciences curricula, not as a replacement for fieldwork in its current form, but as a tool to help students develop their spatial understanding and existing fieldwork skills, increase critical analytical skills and provide unique experience that can enhance graduate career prospects (Bos et al., 2021; Paz- Álvarez et al., 2022; Bursztyn et al., 2022). Advantages of using VR as a part of existing fieldwork plans include their use as part of pre-fieldwork site orientation, induction and health and safety overview; and post-fieldwork debriefing and subsequent formative and summative feedback.

While interest in educational VR applications remains high (Bonali et al., 2021), they are often underutilised and research thoroughly describing how VR based teaching can be adopted into the curriculum is uncommon (Radianti et al., 2020; Klippel et al., 2019). This Erasmus+ funded project aimed to tackle this shortcoming by developing the software and workflows required to generate VR models from raw drone imagery, establish a database of VR models for different geological settings and develop a range of teaching materials, videos and learning activities to compliment these VR models that are aligned to learning outcomes of standard undergraduate and postgraduate geoscience modules.

There are significant advantages to teaching using IVR and sites that are impractical for student visitation become alive in a virtual space that traditional 2D teaching cannot replicate without field work. 3D learning provides enhanced learning outcomes over similar methods currently delivered in 2D, helping students contextualise space and further develops spatial skills (Bond and Cawood., 2021). Though it is unlikely that students would accept VR as a replacement for real world experiences, existing fieldwork preparation and case studies can be enhanced using VR if implemented in a way that complements the existing curriculum, either utilising the 3DTeLC database of field sites, converting existing orthomosaics or through the development of new models. Following the workflow presented in the case study, DOM's can be generated that can help develop teaching materials for future student year groups.

Implementation of IVR experiences requires careful planning of what students can reasonably be asked to achieve in the timeframe of typical 1–2 h practical sessions. In structuring tasks, the learning outcomes need to be clearly defined and met during these sessions to warrant VR's inclusion (Hafner et al., 2013; Detyna and Kadiri, 2019). IVR provides many exciting opportunities for new ways to observe and interact with 3D earth models created from high quality imagery. These novel techniques are providing researchers with exciting new tools to study geological sites and innovative ways to disseminate the information (Marshall and Higley, 2021; Mahan et al.,. 2021). However, the 'reality' of introducing VR as a core component of any taught curriculum is complex. Questions remain on how effectively it can be implemented onto geoscience courses due to the obstacles highlighted in this paper. No doubt as technology improves and becomes cheaper to implement, IVR will be a useful tool for academics and researchers to incorporate with pre-existing methods of learning and visualization.

5. Conclusions

Complex geological sites like the Husavik Triple Junction in remote locations such as northern Iceland are often too costly, too inaccessible, or simply dangerous for students to visit. Given the rising demand for online digital resources, blended learning in higher education, and rising costs of fieldwork in geosciences in particular (Giles et al., 2020), alternatives that can provide or support the learning outcomes of traditional fieldwork are more important than ever. Three-dimensional learning using VR can provide enhanced learning outcomes over similar classroom-based methods when devised carefully (Hafner et al., 2013), helping students contextualise space and further develop spatial skills (Bursztyn et al., 2022). It is unlikely that students would accept VR as a replacement for real world experiences (Bond and Cawood., 2021), but existing fieldwork preparation and case studies can be enhanced using IVR if implemented in a way that complements the existing curriculum, either by utilising an existing database of DOM's, or by converting DOM's for use in VR.

The Husavik Triple Junction DOM presented in this study shows that while the quality of these 3D models are currently not sufficient enough for researchers on a site of this scale for thorough data collection, their use as an educational tool, especially when paired with VR to create an immersive experience, has an important role to play on existing geoscience curricula. Implementation of IVR activities based on DOM's of geological sites, replicating traditional fieldwork techniques, requires careful planning and should include pre-sessional orientation and induction, while allowing time for students to become familiar with VR hardware and software (Wright,. 2022).

IVR provides many exciting opportunities for new ways for students to observe and interact with Earth. These novel techniques provide students with new tools to study geological sites and innovative ways for academics to disseminate information. Importantly, as more remote geological sites are surveyed and the DOM's made publicly available, VR provides an opportunity for students to visit these localities in a more immersive way than traditional VFT's. From this, remote geological sites will become increasingly accessible to students opening huge opportunities for increasing the range and quality of students' virtual field experiences and giving them the essential preparatory skills to conduct real world fieldwork.

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Author statement

Harknett: Writing - Original Draft, Investigation, Visualization Whitworth: Funding acquisition, Project administration, Writing - Original Draft, Conceptualization, Methodology, Validation Rust: Writing - Review & Editing, Validation, Resources Krokos: Resources, Investigation, Conceptualization, Methodology, Project administration Kearl: Software, Validation, Data Curation Tibaldi: Funding acquisition, Investigation, Conceptualization, Methodology, Supervision, Project administration, Writing - Review & Editing Bonali: Writing - Review & Editing, Investigation, Conceptualization, Methodology Validation, Visualization Van Wyk de Vries: Writing - Review & Editing, Investigation, Methodology, Conceptualization, Validation Antoniou: Investigation, Conceptualization, Methodology Validation Nomikou: Investigation, Conceptualization, Methodology, Validation Reitano: Resources, Investigation Falsaperla: Resources Investigation Vitello: Software, Conceptualization, Methodology, Data Curation Becciani: Software, Conceptualization, Methodology, Data Curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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