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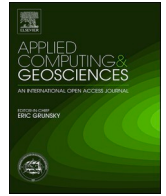
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GeaVR: An open-source tools package for geological-structural exploration and data collection using immersive virtual reality

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ABSTRACT

We introduce GeaVR, an open-source package containing tools for geological-structural exploration and mapping in Immersive Virtual Reality (VR). GeaVR also makes it possible to carry out quantitative data collection on 3D realistic, referenced and scaled Virtual Reality scenarios. Making use of Immersive Virtual Reality technology through the Unity game engine, GeaVR works with commercially available VR equipment. This allows VR to be accessible to a broad audience, resulting in a revolutionary tool package for Earth Sciences. Users can explore various 3D datasets, spanning from freely available Digital Surface Models and Bathymetric data to ad-hoc 3D high-resolution models from photogrammetry processing. The user can navigate the 3D model in first person, walking or flying above the surrounding environment, mapping the main geological features such as points, lines and polygons, and collecting quantitative data using the provided field survey tools. Such data, including geographic coordinates, can be exported for further spatial analyses. Here we describe three different case studies aimed at showing the potential of our tools. GeaVR is revolutionary as it can be used worldwide, with no spatial limitations, both for geo-education and Earth Science popularization, as well as for research purposes. Secondly, it makes it possible to safely access dangerous areas, such as vertical cliffs or volcanic terrains, virtually from a computer screen or Virtual Reality headset. Furthermore, it can help to reduce carbon emissions by avoiding the use of flights and vehicles to conduct field trips.

1. Introduction

Virtual Reality (VR) technology has been increasingly considered as a modern approach for education, geoheritage communication and scientific research in Earth Sciences (Trinks et al., 2005; Edler et al., 2019; Tibaldi et al., 2020a; Pasquaré Mariotto and Bonali, 2021; Pasquaré Mariotto et al., 2021; Harknett et al., 2022), as well as in medical imaging and astrophysics (e.g. Jarrett et al., 2021; Di Guardo, 2022). The use of so-called non-Immersive VR in Earth Sciences, where relevant 3D outcrops are provided on a 2D screen (Choi et al., 2016), dates back to the early 1990s, when Hilde et al. (1991) and Anderson (1992) made visible in 3D the topography on the Earth – ocean seafloor – and on the Elysium Region on Mars using non-immersive approaches.

Non-Immersive VR has been widely applied for educational purposes, including ‘virtual tours’ of geological sites of great interest, which

can be provided through a GIS platform. These sites can be visualized by users, e.g. both teachers and students, who can observe and study relevant 2D pictures and 3D Digital Outcrop Models (DOMs) directly on a laptop (Hurst, 1998; Warne et al., 2004; Martinez-Grana et al., 2015; Deng et al., 2016). Virtual tours are nowadays commonly used as teaching material in Earth Sciences and are considered a useful tool to cut travel expenses and to improve students’ learning processes (Deng et al., 2016). Recently, virtual tours are also made available using the most common electronic devices, such as tablets and smartphones, thereby reaching a broader audience (e.g., McCaffrey et al., 2010; Pasquaré Mariotto et al., 2021, 2022).

With regard to Immersive Virtual Reality, it has been demonstrated to enhance student engagement and improve their academic success (Liu et al., 2020). Its instructional effectiveness for science, as evaluated versus a 2D slideshow has also been demonstrated, and it has been

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showed that it can increase student interest and motivation (Parong and Mayer 2018). Despite the demonstrable benefits for research and education, the use of Immersive VR in Earth Sciences to actively explore 3D key geological areas in first person through a VR headset (Choi et al., 2016), is an approach that is not fully established yet. This is due to a paucity of available applications designed to simulate geological fieldwork (e.g. Lütjens et al., 2019; Tibaldi et al., 2020a; Seers et al., 2022). Furthermore, a very limited number of papers focuses on providing a detailed methodology and description of tools for 3D model creation and exploration (Gerloni et al., 2018; Tibaldi et al., 2020a; Seers et al., 2022), despite the increasing applications of 3D remote sensing techniques for data collection and analyses (see Hodgetts, 2013; Biber et al., 2018; Barnes et al., 2018; Tavani et al., 2019; Seers et al., 2022).

In view of this, GeaVR could be a great instrument to promote the use of Immersive VR and studies about its application for teaching, outreach and research activity, as recently suggested by Bonali et al. (2022) and Wright et al. (2022).

Additionally, Zhang, 2017 applied VR to the mining industry through a head-mounted device: their approach played an important role in terms of training and safety. Caravaca et al. (2020) applied Immersive VR to the characterization of an outcrop on Mars, derived from photogrammetry processing. Harknett et al. (2022) and Tibaldi et al. (2020a) applied this approach for data collection using GeaVR in volcanic areas affected by recent faulting, especially focusing on remote and dangerous ones.

However, one downside of Virtual Reality is that users can suffer from sickness effects (e.g., Munafa et al., 2017; Tyrrell et al., 2018; Chessa et al., 2019; Bonali et al., 2019a), generally suggesting that further improvements are needed for a wider engagement of this technology, especially to promote its use.

Bonali et al., 2021 involved users to navigate two Virtual Scenarios with GeaVR for a shorter period of time (a total of 10 min), and the percentage of users affected by motion sickness was not relevant. Furthermore, no user wanted to stop the experience and only 8% did not show any interest in trying again the experience, 9 out of 459 participants, testifying to the validity of the use of Immersive VR for educational and outreach applications. Thus, the problems associated with VR from motion sickness can be mitigated with proper planning, and control of its use. In view of the benefits of VR, in order to provide a generally useable and user friendly immersive VR system, we introduce GeaVR, an open-source package for geological survey and quantitative data collection. Sites can be explored in first person using a VR headset and the corresponding controllers, engaging the user in a fully immersive experience that simulates actual geological surveys. Additionally, a series of tools has been designed to simulate classical field activity like mapping and data collection. Another breakthrough innovation is that 3D models that can be used as a Virtual Scenario, as it is possible to use both Digital Elevation Model surfaces, or seabed bathymetric models, and, more importantly, photogrammetry-derived 3D high-resolution models. The latter especially enables the user to explore a photo-realistic environment, enhancing the realism and the immersivity of the experience. Considering also the increasing use of photogrammetry approaches applied to UAV (Unmanned Aerial Vehicle)-collected pictures (Thiele et al., 2017; Corradetti et al., 2017; Bonali et al., 2018; Priddy et al., 2019; Wakeford et al., 2019; Caravaca et al., 2020; Tavani et al. 2020a, 2020b), GeaVR could be an innovative software for a wider and wider audience that may build ad-hoc VR input scenarios for research, teaching and communication purposes. Outreach and education purposes have already been tested among students, academics and non-academics, resulting in an excellent approach and tool package (Bonali et al., 2021; Wright et al., 2022; Harknett et al., 2022).

We consider our software to be a major contribution to the field of Earth Sciences, as it allows students and scientists, as well as non-academics, to explore geological sites in first person, directly in a laboratory, office or even from home. Additionally, a series of benefits can be summed up as follows, considering the availability of high-resolution

3D models: *i*) potential access to dangerous sites; *ii*) no travel expenses and carbon-footprint reduction; *iii*) worldwide exploration thanks to freely available scenarios, including areas with limited access, e.g. as can be found in geosites in many protected areas, such as UNESCO global geoparks and World Heritage, where physical visitation can be a problem.

GeaVR has been firstly tailored in the framework of Argo3D project and fully developed in the framework of the EU Erasmus+ (3DTeLC) project (<https://erasmus-plus.ec.europa.eu/projects/search/details/2017-1-UK01-KA203-036719> and <https://www.3dtelc.com/>). It is available as a compiled software on <https://www.geavr.eu/> and as an open-source code on <https://github.com/GeaVR/>. A first set of Virtual Scenario & Teaching guides is available at <https://www.geavr.eu/get-started/demonstrator-vr-landscape/> where outcomes from EU Erasmus+ (3DTeLC) project are included.

2. Materials and methods

2.1. Overall software design and requirements for hardware environment

GeaVR is a Unity3D-based open-source package, and it is designed to work as an off-line desktop application, the current compiled version of GeaVR works on Microsoft Windows OS; the game engine version we used for the development is the v.2017 (<https://unity.com>). Requirements for hardware environment are listed below. GeaVR works with a consumer grade IVR headset (we tested Oculus Rift, Oculus Rift S and Oculus Meta Quest 2) (Fig. 1A) plugged in a consumer grade gaming computer. The above cited IVR headset is furnished with a couple of controllers designed to fully interact with the virtual scenario. With regard to the gaming computer, the lowest configuration we tested using GeaVR is a PC with at least Intel Core i5.8300H CPU @ 2.30 GHz, 16 GB of RAM and a GPU VR ready Video Graphic card with at least 6 GB of VRAM (Fig. 1B). The available and compiled file package consists of the GeaVR converter and the GeaVR viewer. A typical workflow involves the conversion of the 3D input model before loading it directly into the latter (Fig. 2), which enables the user to navigate the scene, and to collect geological data in a quantitative way as a next step.

2.2. Software design and implementation

Generally speaking, GeaVR is designed to use a photogrammetry-derived 3D model as VR scene to allow users to navigate this environment in first person and to map and collect data through ad-hoc designed tools; it also works with Digital Surface Models (DSMs) and Bathymetric Models (BMs). The input model uses the geographic coordinate system (WGS84) that are held in GeaVR to provide true horizontal and vertical scaling, thus providing the user (a) with a proper-scaled interaction with the environment and ensuring (b) that any mapped or collected data is scaled and georeferenced.

GeaVR has been designed using Unity, a game engine consisting of a software framework that implements features required to create virtual simulations of reality that can be explored and interacted with in real-time. Features maintain an internal simulation that handles sophisticated physics, graphics rendering and sound systems to provide the user with a presentation they can experience. To facilitate this simulation, technical systems such as data streaming, asset and memory management and networking are required. Game engines also maintain an internal scene-graph, a representation of the virtual world and the relationships between objects in that world. The specific implementation of each of these systems can have quite profound effects on how a game or interior of software are produced and must be considered during the design process. The main aspects upon which we based the software architecture are.

- **Scalability**, the scale of the scenario is only limited by the power and memory of the PC running the software.

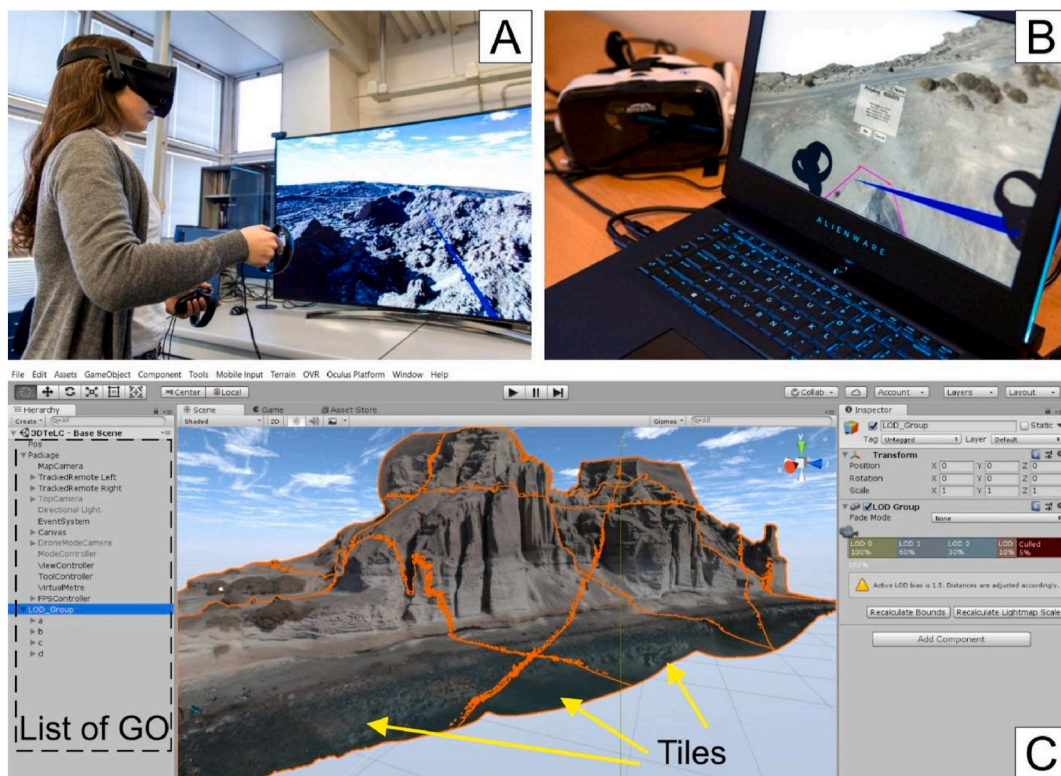


Fig. 1. (A) User surveying the Krafla Fissure Swarm (Northern Volcanic Zone, Iceland) using GeaVR tools package. (B) Gaming laptop running GeaVR during the exploration of the Metaxa Mine, Santorini Volcanic Complex (Greece). (C) Unity project related to GeaVR. On the left hand side some of the GameObjects (GO) are shown, which are also present in the “Scene”, like the 3D model as tiles, the sky, the clouds etc.

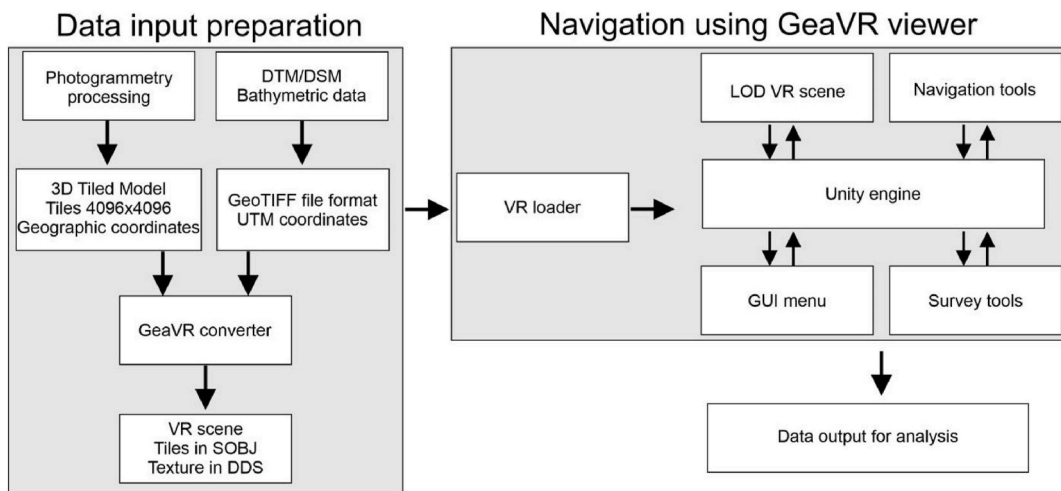


Fig. 2. GeaVR workflow, including data conversion and loading.

- **Effectiveness**, to allow the building of mechanisms aimed at performing measurements with correct scaling and providing geographic coordinates (datum WGS84) of any data supplied to it.
- **Interoperability**, the output of GeaVR is directly compatible with existing Earth Sciences user formats, and provides accurate data that can be used in lieu of, or compared to, data obtained from the field.

Each element that is imported (e.g. input models) or created (e.g. tools for navigation, mapping and data collection) in Unity is known as a GameObject (e.g. Fig. 1C). Similarly, each tool or action running in a Unity application, in fact, exists in the scene as a GameObject populating the 3D virtual scenario, such as the avatar, the VR scene, the lightning,

clouds, sky, etc. (Fig. 1C). According to Gerloni et al. (2018), Game-Objects consist of various components including the “Transform” component, which provides details about the object’s location, rotation and the scaling within the scene. Additionally, the visibility of an object requires the presence of a “Renderer” component, which can be either 2D or 3D, based on the object’s intended purposes and design. Furthermore, the “Collider” component plays a crucial role in determining collision occurrences between objects and collecting related information, while the “rigid body” component simulates the behavior of objects in accordance with kinematic and dynamic principles. Object-oriented C# scripts are used to implement the specific behaviors for each single GameObject within the 3D scene. These scripts are

responsible for controlling and coordinating individual components in the environment, like how the user moves. The GeaVR viewer is implemented within the Model-View-Controller design pattern and is composed of a series of Game Objects and a total of 360 scripts. The most important Game Objects are related to.

- Graphical user interface (GUI): this includes scripts that regulate the menus and the behavior of the graphical objects with which the user can interact; it includes also game objects for *oculus touch joypads (Left & Right)*.
- Scene Loading: this includes scripts to manage the loading of 3D scene models into the application; it includes also game objects dynamically created to represent the scene model.
- Navigation Tools: this includes scripts that manage the three modes of navigation - walking, drone and flight modes; it includes also game objects for *walking player, flying player and drone player*.
- Survey Tools: this includes the scripts that manage the behavior of each single tool designed for data collection and GIS mapping.

A diagram of the architecture has been added in the repository to facilitate efficient use and secondary development for users: <https://github.com/GeaVR/GeaVR/tree/main/UML>.

2.3. Input scenario

GeaVR works with two main categories of 3D Virtual Scenarios, which can be obtained by the conversion of a photogrammetry-derived 3D Tiled Model and from onshore DSMs & BMs; each user can create his own scenario; further details are found below and at <https://www.geavr.eu/get-started/documentation/>.

The 3D Tiled Model we tested is obtained by way of photogrammetry processing of imagery using Agisoft Metashape and must be exported in a Wavefront OBJ file format, with tile size of 4096 x 4096 pixel and attached geographic coordinates (WGS84) (e.g. [Tibaldi et al., 2020a](#); [Antoniou et al., 2020](#)). This kind of data input allows the user to obtain an improved and realistic representation of the terrain and the geological objects, with particular regard to the objects with vertical or oblique features; the texture is taken from the imagery and is extremely detailed and realistic ([Krokos et al., 2019](#)).

Differently, DSMs/BMs must be in GeoTIFF file format and set up in UTM coordinate system (WGS84) (details at <https://www.geavr.eu/> and <https://www.3dtelec.com/>). In both cases, once the 3D surface models and image texture have been created, they must be converted to scene files that are compatible with Unity engine. This is necessary to improve the performance of the IVR system, with regard to both the scene loading and reduced refresh rate, which, if not addressed, can result in an uncomfortable user experience. As a consequence, a pre-processing step to convert input files into a format that can be directly loaded into Unity is necessary and can be done using the GeaVR converter. The 3D Tiled Model is composed of a series of OBJ files (mesh), with a different level of resolution. These are converted into serialized.obj (SOBJ) format, which contain multiple meshes for visual display. In addition, associated metadata files are created that store vertex counts and byte offsets into the file for each mesh. Surface texturing files are converted from JPG to direct draw surface files (DDS), an image format that is able to remain compressed on the GPU, which reduces video memory usage. In addition, extra files are created to store the coordinate data necessary for measuring horizontal and vertical geographic coordinates in VR (such as Latitude and Longitude) for the boundaries of the converted area. DSMs/BMs in GeoTIFF file format can be converted too, resulting in a series of SOBJ and DDS files, as well as in extra files to store the coordinate data. A series of Input scenarios, already converted, are available at <https://www.geavr.eu/get-started/demonstrator-vr-landscape/>, including the three case studies from the present work and twelve more as outcomes from 3DTELC Erasmus + Project.

2.4. VR loader

The next stage of the workflow involves loading the SOBJ (mesh) and DDS (texture) files into the GeaVR viewer using the VR loader software, taking into account the different level of details related to the 3D Tiled Model. We have attempted to decrease the amount of time that is necessary to load these data files by performing the files loading at runtime. The Terrain Loader is an entity that encompasses a collection of Object Loader components, tasked with loading each SOBJ file, and it is associated with mesh and texture information. Each loader is independent, so we have been able to leverage multi-threading to perform the loading of files simultaneously. Even though GeaVR has been developed using Unity game engine and only one VR headset, we designed a series of procedures for setting such tool packages, including the hardware, abstracting to the max from ad-hoc realisations. In this way, we are capable of supporting other technological solutions and ensuring long-term sustainability.

3. Tool package for user experience

GeaVR viewer includes two main components that can be used during the immersive exploration: a first set of tools that controls the navigation of scenes in either walking, drone or flying modes ([Fig. 3A](#)) plus a second set that allows the user to collect data and perform mapping activities ([Fig. 4A](#)). The early development of these tools is available in [Gerloni et al. \(2018\)](#) and [Tibaldi et al. \(2020a\)](#), whereas here the tools are described in their final stage.

3.1. Navigation modes

Three navigation modes have been designed. When the virtual exploration starts, users observe the VR scenario as if they were walking on a solid ground surface ([Fig. 3B](#)): this is the “Walk Mode”, which is shown in the video included on the Erasmus + Project website ‘Moving in VR’ (<https://www.geavr.eu/get-started/documentation/>). The other two navigation modes are: “Drone Mode” and “Flight Mode”. The system allows the user to switch between either of those ([Fig. 3A](#)). In the “Drone Mode”, users have the ability to fly freely above ground without being affected by gravity ([Fig. 3C](#)), as if they were a drone (including moving forward, backwards, rolling, yawing and pitching using the hand controllers). In “Flight Mode”, the users observe the terrain orthogonally from the above, enlarging the aerial extent of the scenery ([Fig. 3D](#)), as well as covering long distances faster.

3.2. Tools for mapping and data collection

GeaVR includes tools that allow the user to take quantitative measurements and collect data, showcased in the application sites and [Figs. 4 and 5](#). These tools are grouped in three main categories: Mapping (1-4), Field survey (5-8) and GPS tools (9-12) ([Fig. 4A](#)). The Mapping tools allow users to add Points (1), to trace as many lines or polygons (2-3) as needed (similarly to GIS systems), as well as to obtain topographic profiles (4) ([Fig. 4B](#)). These elements can be exported in a CSV or KML format, including geographic coordinates, for further analyses and visualization.

The Field Survey toolkit allows the user to quantify the orientation (both dip direction and dip angle) of a surface (5) ([Fig. 6B and C](#)), to measure the distance between two selected points (6) together with the geographic direction of the line and its inclination ([Fig. 4C](#)), to take notes on the virtual field notebook (7) ([Fig. 4D](#)), and to capture photographs (8) ([Fig. 4E](#)).

All the data collected, including geographic coordinates, from the Field Survey toolkit can be exported as a CSV or KML file for further analyses and visualization; further details on the exporting procedure are available at <https://www.geavr.eu/get-started/documentation/>.

The GPS-based group of tools use real geographic coordinates in

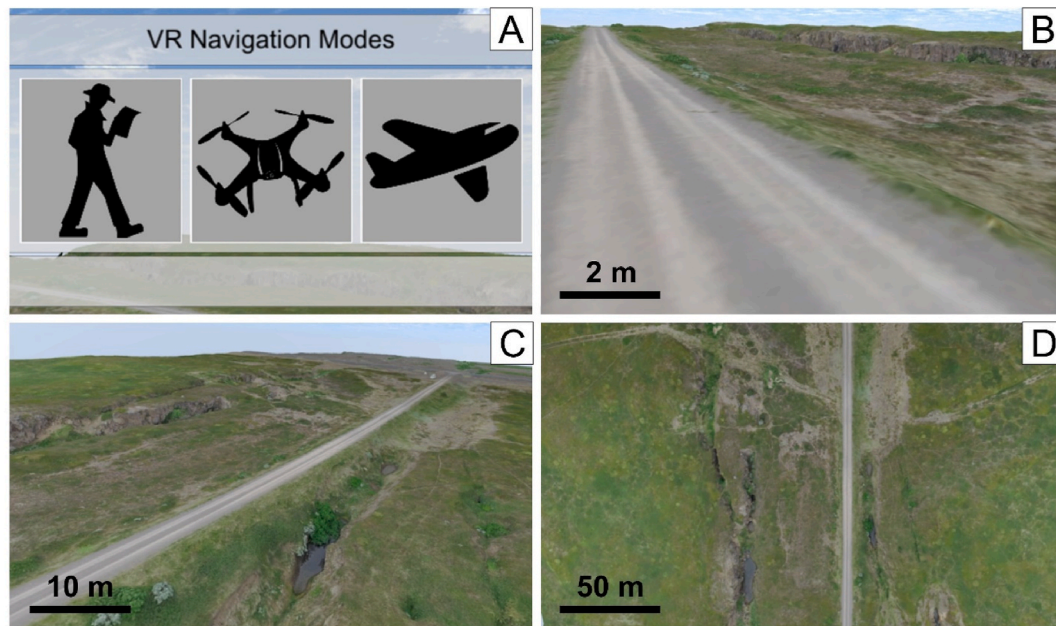


Fig. 3. (A) Navigation Modes menu as visualized during immersive VR exploration. View of the three surveying modalities: (B) Moving on foot, (C) UAV-flight and (D) Airplane-flight modes.

order to.

- i) show the location of the user in geographic coordinates, the elevation and the heading azimuth value (9) (Fig. 4F);
- ii) show the location of the user in the scene through a virtual map (10) (Fig. 4G);
- iii) add a waypoint including notes and photographs (11) (Fig. 4H);
- iv) record a GPS track including the geographic coordinates and the elevation (12).

Waypoints and GPS tracks can also be exported.

4. Application to key geological sites with different extent and resolution

We applied GeaVR to test the collection of data in three virtual key geological sites reconstructed in 3D through photogrammetry processing using.

- i) photos from a ground-based camera typically used by field geologists;
- ii) photos collected during UAV surveys;
- iii) historical aerial photos.

The aim is to demonstrate the suitability of our approach by analyzing and collecting quantitative geological measurements in 3D Virtual Scenarios with different aerial extent and resolution.

The selected sites are.

- i) the 1809 CE volcanic system along the NE rift on Mt Etna, Italy;
- ii) dykes affecting Tertiary lava units in Eastern Iceland;
- iii) rift faults belonging to the emerging portion of the mid-Atlantic ridge in Northern Iceland.

The first and second Virtual Scenarios cover a small to medium area with centimetric resolution, while the third covers a larger area but with a decimetric resolution.

4.1. 1809 CE volcanic system, Mt Etna

The 3D visualization in Fig. 5A shows two N20°E-aligned craters related to the historical eruption that occurred in 1809 CE along the NE rift of Mt Etna; it has an aerial extent of about 250 × 150 m with a resolution of 0.6 cm/pixel. In the southernmost crater, it is possible to observe and study by means of quantitative measurements both the feeder dyke system and the host rock (Fig. 5B), which have been previously characterized through standard field surveys by Geshi and Neri (2014). The model has been reconstructed by field-camera collected pictures through photogrammetry processing (e.g. Micheletti et al., 2015; Tavani et al., 2020; Bonali et al., 2021).

An example of application of GeaVR to this area is shown in Fig. 5A, where, by navigating in “Drone mode”, it has been possible to capture an image of the birds-eye view, clearly showing the two craters aligned along an NNE-SSW direction. It has then been possible to identify the best view of the outcrop, shown in Fig. 5B, that could be used for further analysis to identify all the volcanic layers and the feeder dyke described by Geshi and Neri (2014); also, by using the ruler tool (6), we have been able to measure the thickness of the dyke as well as the lava and spatter deposits, representing the host rock, as shown in Fig. 5C-D-E.

4.2. Dykes affecting Tertiary lava units in eastern Iceland

GeaVR has also been used to study Tertiary volcanism in Eastern Iceland. Here, the 3D model shows a portion of the easternmost and oldest rift in Iceland, where dykes affect Tertiary lava units (Walker, 1974; Gudmundsson, 1995): it has an aerial extent of 270 × 220 m and a resolution of 1.05 cm/pixel. This area is significant as it provides exposures of dykes that have reached the surface or have been arrested in active rift zones (Gudmundsson, 1990; Paquet et al., 2007). The area shown in Fig. 6A is affected by two main dyke systems, striking about NE, which affect a lava succession to a height of 45 m. Using the “Drone Mode”, it has been possible to capture relevant pictures showing the dyke dimensions and the relationships with the host rock (Fig. 6A-B-C). By using the surface tool (5), it has been possible to measure the attitude of both dykes by collecting five and seven attitude values on the dyke walls, which would have been impossible and unsafe to collect by standard field activity, as they are located several meters above the

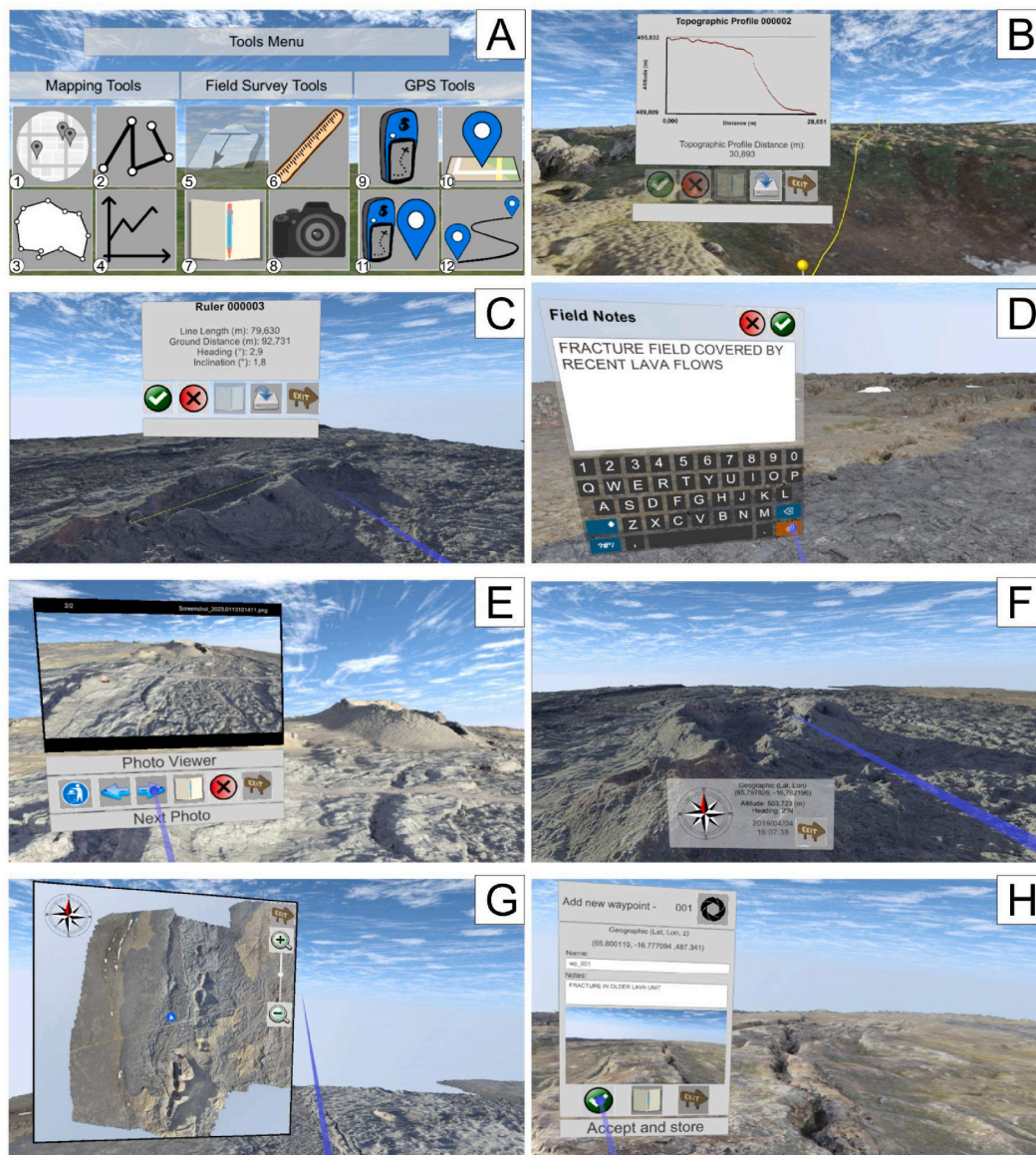


Fig. 4. (A) Tools menu as visualized during IVR exploration, classified in three main groups: Mapping, Field Survey and GPS tools; numbers from 1 to 12 are used in the text describing each tool. In figures (B–H) the Topographic profile (4), the Ruler (6), the Field notebook (7), the Camera (8), the GPS (9), the Location on map (10) and the Waypoint (11) tools are shown in action.

ground. The average attitudes are $N131^{\circ}/81^{\circ}$ and $N123^{\circ}/80^{\circ}$.

4.3. Rift faults in the Northern Volcanic Zone of Iceland

We have considered a virtual scenario in the western portion of the emerging mid-ocean ridge in Northern Iceland, especially in the so-called Theistareykir Fissure Swarm (Pasquaré Mariotto et al., 2015; Hjartardóttir et al., 2016; Rust and Whitworth, 2019; Bonali et al., 2019a; Tibaldi et al., 2020b; Einarsson et al., 2021). The site has an aerial extent of 12.6×10.2 km and a resolution of 67.4 cm/pixel (Fig. 7A). This part of the rift is of significant interest to study the volcano-tectonic evolution of active rifts, as highlighted by Tibaldi et al. (2019). In fact, a series of dip-slip faults are clearly visible and dislocate the surface (Fig. 7B and C). Their strike is N to NNE and they affect units of different ages, ranging from the Miocene to the post-Late Glacial Maximum (Saemundsson et al., 2012). In this case, the 3D model has been derived from photogrammetry processing of 42 historical aerial photos (e.g. Micheletti et al., 2015; Tavani et al., 2020; Bonali et al., 2021), downloaded from the Icelandic National repository

(<https://www.lmi.is/>). For this study, we used a set acquired in 1982, which has been recently digitalized in a TIFF format with a resolution of 1270 DPI. The model has been georeferenced using elevation points available on the same website.

Using the “Drone Mode” (Fig. 7A and B), it has been possible to capture relevant pictures that highlight the presence of major fault scarps facing East, with a vertical offset of the order of 150–200 m, as well as East-facing, minor fault scarps (Fig. 7C) with a vertical offset in the order of 10 m, and tension fractures. Vertical offset values have been measured using the topographic profile tool (4) crossing the fault system in an E-W direction over a length of about 6 km, as shown in Fig. 7A–D, and collecting the elevation values at the top and the base of a fault scarp. Finally, by collecting vertical offsets at different sites along a minor fault scarp, we calculated the slip profile (Fig. 7E), which is relevant when studying rift evolution (Manighetti et al., 2001, 2007; Tibaldi et al., 2016a, 2016b, 2020c; Pedicini et al., 2023).

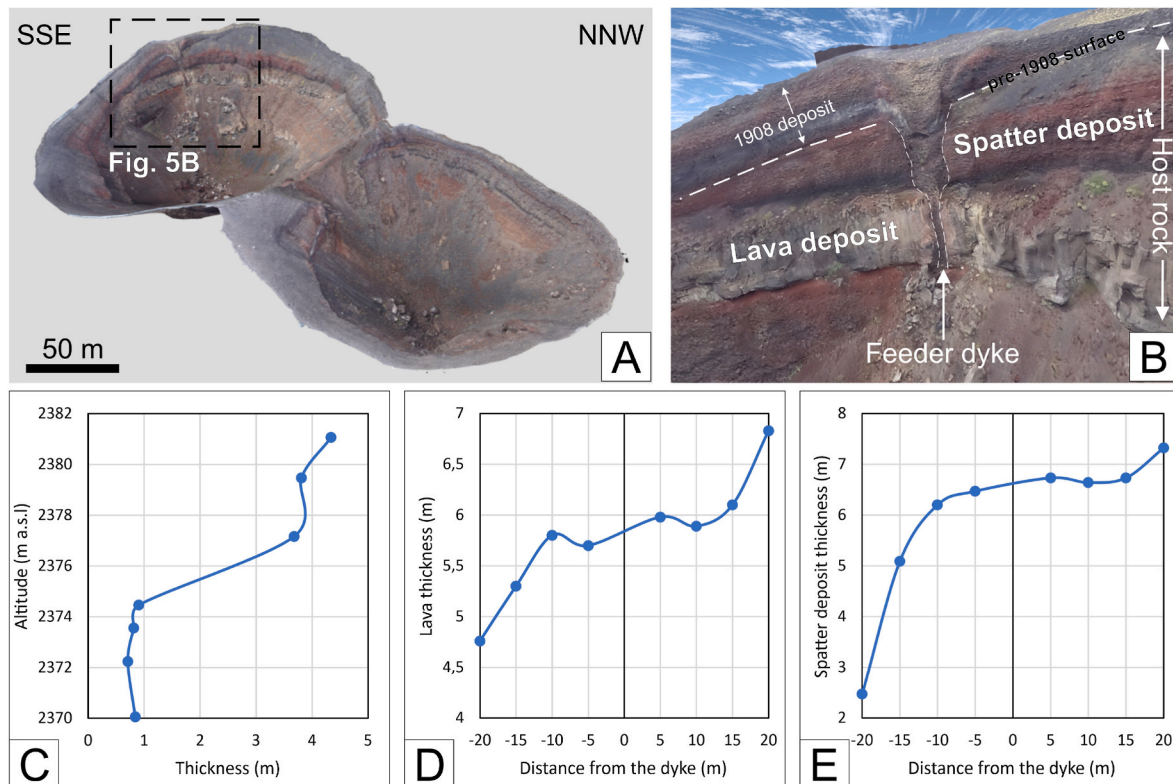


Fig. 5. (A) 3D visualization of the reconstructed 1809 CE craters on Mt Etna. (B) Picture collected using GeaVR, the main geological features that have been mapped are highlighted. (C) Dyke thickness, (D–E) thickness of the lava flow and the spatter deposits; all have been measured using the ruler tool (6) with respect to the altitude and the distance from the dyke walls.

5. Discussion

5.1. Novelty of GeaVR

We have introduced, described and explained GeaVR, which is the first open-source package containing a complete set of tools for geological survey and data collection using Immersive Virtual Reality.

GeaVR is designed to work with commercially available VR equipment (consisting in a VR headset and a PC/laptop with a VR ready GPU/graphics card), making it accessible to a broad selection of users and a wide audience. The system has been created to allow the users to build and navigate their own immersive Virtual Scenarios starting from their own different models, of many different scales and environments. They span from lab-scale (e.g., Tortini et al., 2014; Bonali et al., 2018) to hundreds of meters-scaled DSMs (e.g., Takaku et al., 2020) and bathymetric dataset with various pixel size (e.g., Savini et al., 2014), as well as 3D DOMs derived from photogrammetry processing (e.g. Tibaldi et al., 2020a; Antoniou et al., 2020) with a tested resolution up to 1 mm/pixel.

Immersive VR approach can provide equal opportunities to everyone for geological fieldwork-based teaching and research activities, as well as a greater user involvement with respect to non-immersive VR (Bonali et al., 2021). As a consequence, we consider GeaVR to be a revolutionary tool for Earth Sciences for the following reasons.

1. It can be used worldwide, with no spatial limitations, for research, education and dissemination in Earth Sciences (e.g. Bonali et al., 2021; Wright et al., 2022).
2. It makes it possible to access sensitive, restricted and dangerous areas, virtually from any desktop (e.g. Tibaldi et al., 2020a). This is of paramount importance when field activities become difficult, or forbidden, as during the COVID-19 pandemic (Chinazzi et al., 2020), or when people cannot, for some permanent or temporary disability, go to the field (Bonali et al., 2021)

3. Our Immersive VR approach helps move towards net zero, by reducing travel, thereby reducing carbon emissions (Hansen et al., 2013).
4. The software introduces a novel way of visiting the field, which is to fly like a drone, a way preferred by most users (Bonali et al., 2021).

Additionally, to provide practical examples, a total of fifteen Virtual Scenarios have been made available (<https://www.geavr.eu/get-started/demonstrator-vr-landscape/>). Other users can prepare their own Virtual Scenarios to share on our website (or elsewhere). This can move towards a community of GeaVR composed of public and academic users. The steps for this are described on the website (<https://www.geavr.eu>). It is worth pointing out that the reliability of measurements collected in GeaVR is related to the quality and resolution of the 3D input scenario, (Vasuki et al., 2014; Vollgger and Cruden, 2016; Thiele et al., 2017; Bonali et al., 2019b), and to the operator's geological experience (Jaud et al., 2022).

5.2. Immersive virtual reality, improvements and impacts

Generally speaking, Immersive VR already represents a step further compared to non-Immersive VR (e.g., Pasquaré Mariotto et al., 2021, 2022), providing a chance to correctly picture, at a realistic scale and without spatial distortion, the Virtual Scenarios, thus providing a more reliable sense of the geometrical features of the outcrop than what the user could see on a 2D flat screen (e.g. Deng et al., 2016).

With regard of GeaVR, further versions might benefit from contributions from other developers. This can cover the following aspects: *i*) a more modern graphic interface; *ii*) speech-to-text feature for taking notes; *iii*) incorporating data references within the field notes; *iv*) object detection technologies to create field sketches; *v*) tools for image analysis; *vi*) compiled version for different VR headsets and OS.

Differently, possible future improvements for Immersive VR might

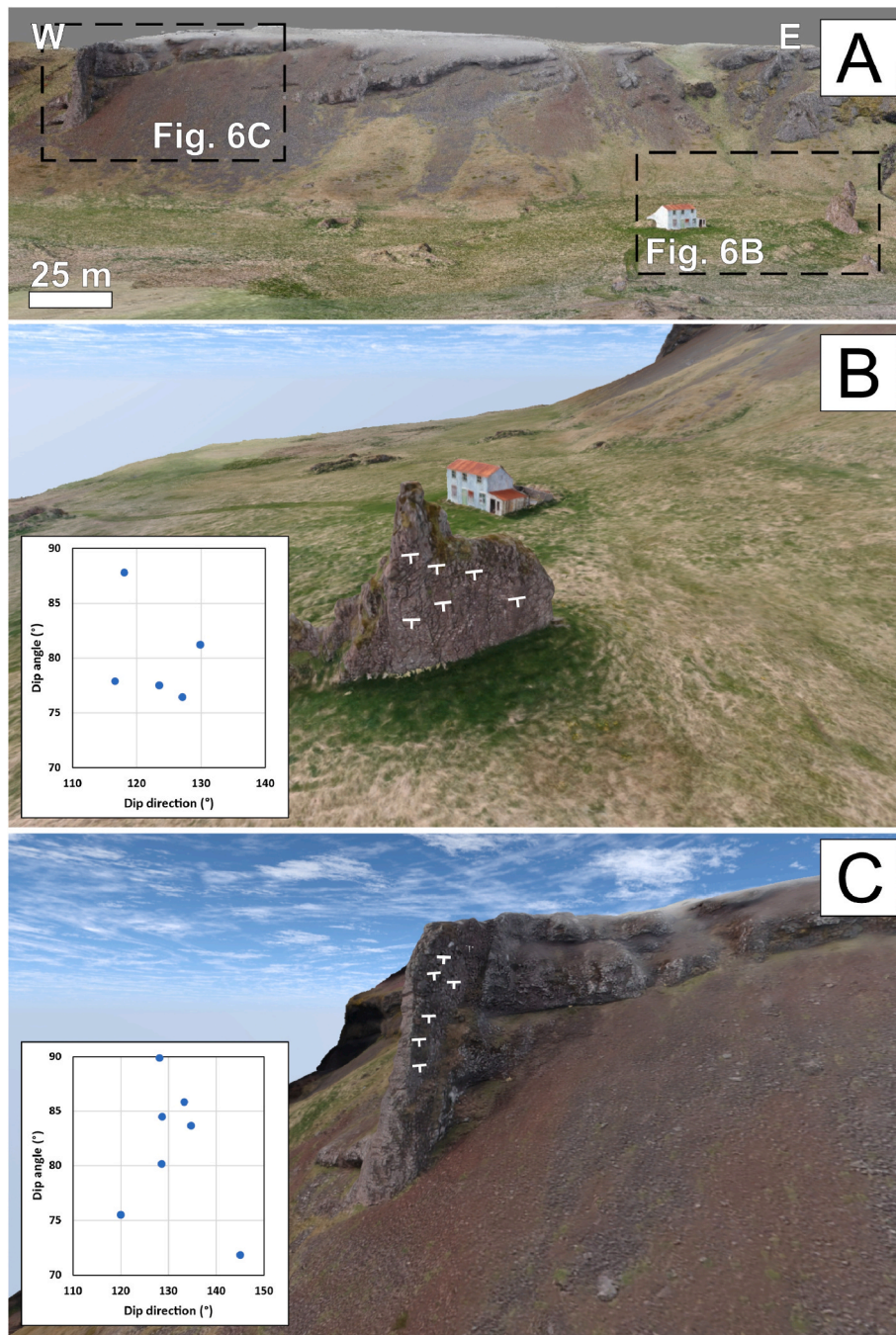


Fig. 6. (A) 3D visualization showing two main NE-striking dykes affecting Tertiary lava units. (B–C) Collection of dyke attitude values (points of measurement are shown by the white dip symbols) using the surface tool: results show that the two dikes are sub-vertical with a dip direction to the southeast.

include new commercial-grade headsets with a better performance in terms of frame rate (≥ 90), as suggested by Kersten et al., 2021 to reduce motion sickness.

In addition to that, improved training scenarios are advisable. Some training is needed to use this technology; for example, users can start using Immersive VR a few minutes each time, as has been tested during the development of GeaVR. Indeed, from the authors' experience, the more frequently Immersive VR systems are used, the more comfortable users become, especially for sessions devoted to data collection for research purposes.

Even if Immersive VR is not able to substitute research field surveys (in places in which those are possible), it can be an important contribution to increasing the amount of quantitative data and better

preparing field trips beforehand. In fact, it has been demonstrated that Immersive VR is a powerful tool capable of enhancing student interest and improving the learning process, resulting in a pretty useful approach for teaching in Earth Sciences (Warne et al., 2004; Deng et al., 2016). As such, it should not be seen as a replacement, but a complement to classic student fieldwork-based teaching, during which they can actually collect measurements and study geological features from the scale of the outcrop down to rock structures, textures and minerals.

6. Conclusions

Immersive Virtual Reality has great potential to enhance learning outcomes and assist research in Earth Sciences. It allows users, of all

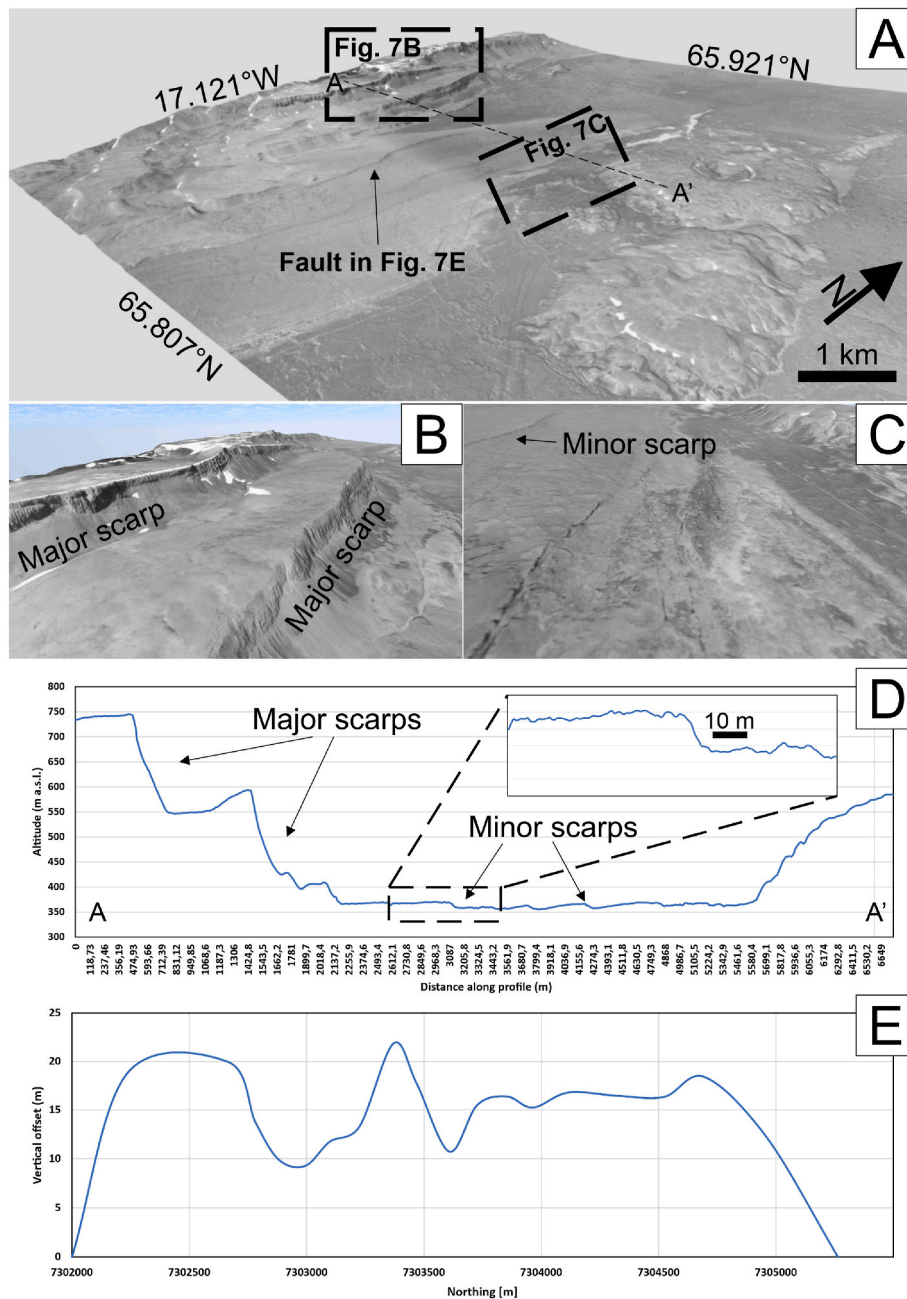


Fig. 7. (A) 3D visualization of part of the Theistareykir Fissure Swarm. (B–C) Photos collected using GeaVR where major and minor scarps related to normal dip-slip faults are shown. (D) About 6-km-long topographic profile made across both major and minor fault scarps, obtained during the survey in IVR; its location is indicated in (A). The inset shows the profile across a minor one. (E) Slip profile of the fault highlighted in Fig. 7A, obtained by data collection in IVR, showing an example of a mostly symmetrical fault.

types, to visit and work in environments that are otherwise out of reach, due to access, hazard, or the person’s condition. It also is useful in lessening the need for physical travel, with obvious effects on time taken, on convenience and on reducing travel. This has also significant environmental benefits.

GeaVR has been introduced, and we have shown that this software, and the methods to use it, are valuable additions to the Earth Science community. This is especially in terms of providing an easy to use, available, open-source software, backed up with a website and a developing set of examples for easy use.

Users can create and add their own examples, or use GeaVR for their own purposes.

GeaVR thus provides a step forward in all aspects of Virtual Reality

use in Earth Sciences, and sets up an opportunity for more accessible and community-supported Immersive Virtual Reality over a broad range of scales and scenarios.

Code availability

The compiled version of GeaVR is available on www.geavr.eu, the open-source code is available on GitHub¹ under the GPL-3.0 license: <https://github.com/GeaVR/GeaVR> ; <https://doi.org/10.5281/zenodo.7662284>.

¹ <https://github.com/GeaVR/GeaVR>.

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CRedit authorship contribution statement

Fabio Luca Bonali: Writing - original draft, Methodology, Conceptualization. **Fabio Vitello:** Writing - original draft, Software, Methodology. **Martin Kearnl:** Software. **Alessandro Tibaldi:** Writing - review & editing, Conceptualization. **Malcolm Whitworth:** Writing - review & editing, Funding acquisition. **Varvara Antoniou:** Writing - review & editing, Validation, Methodology. **Elena Russo:** Writing - review & editing. **Emmanuel Delage:** Validation. **Paraskevi Nomikou:** Writing - review & editing. **Ugo Becciani:** Writing - review & editing. **Benjamin van Wyk de Vries:** Writing - review & editing. **Mel Krokos:** Writing - review & editing.

Declaration of competing interest

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Data availability

Data will be made available on request.

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