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Towards Enhanced Understanding and Experience of Landforms, Geohazards, and Geoheritage through Virtual Reality Technologies in Education: Lessons from the GeoVT Project

Vittoria Vandelli [1], Piotr Migoń [2], Ylva Palmgren [3], Evangelos Spyrou [4], Giannis Saitis [4], Maria Eleni Andrikopoulou [5], Paola Coratza [1], Mohand Medjkane [6], Carmen Prieto [3], Konstantinos Kalovrektis [5], Candide Lissak [7], Alexandros Papadopoulos [8], Nikos Papastamatiou [8], Niki Evelpidou [4], Olivier Maquaire [6], Sarantos Psycharis [5], Arjen P. Stroeven [3,*] and Mauro Soldati [1]

[1] Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, Via Campi 103, 41125 Modena, Italy; vittoria.vandelli@unimore.it (V.V.); paola.coratza@unimore.it (P.C.); mauro.soldati@unimore.it (M.S.)

[2] Institute of Geography and Regional Development, University of Wrocław, Pl. Uniwersytecki 1, 50137 Wrocław, Poland; piotr.migon@uwr.edu.pl

[3] Bolin Centre for Climate Research, Department of Physical Geography, Stockholm University, Svante Arrhenius väg 8, 10691 Stockholm, Sweden; ylva.palmgren@nrm.se (Y.P.); carmen.prieto@natgeo.su.se (C.P.)

[4] Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, 15784 Athens, Greece; evspyrou@geol.uoa.gr (E.S.); saitij@geol.uoa.gr (G.S.); evelpidou@geol.uoa.gr (N.E.)

[5] School of Pedagogical and Technological Education (ASPETE), Irini Station ISAP, 15122 Marousi, Athens, Greece; marilena.andri000@gmail.com (M.E.A.); kkalovr@gmail.com (K.K.); spsycharis@gmail.com (S.P.)

[6] Department of Geography, Joint Research Unit CNRS 6266, University of Caen Normandy, Esplanade de la Paix, 14000 Caen, France; mohand.medjkane@unicaen.fr (M.M.); olivier.maquaire@unicaen.fr (O.M.)

[7] Institut de Recherche en Santé, Environnement et Travail (Irset), UMR_S 1085, University of Rennes, Avenue du Prof. Léon Bernard 9, 35000 Rennes, France; candide.lissak@univ-rennes.fr

[8] Omega Technology, El. Venizelou Av. 4, 17676 Kallithea, Athens, Greece; alexandros@omegatech.gr (A.P.); papastamatiou.nikos@gmail.com (N.P.)

* Correspondence: arjen.stroeven@natgeo.su.se

Abstract: Virtual reality is a technological development that, among others, has revolutionized Earth sciences. Its advantages include an opportunity to examine places otherwise difficult or impossible to access and it may also become an important component of education, fostering a better understanding of processes and landforms, geohazard awareness, and an appreciation of geoheritage. This paper reports on the GeoVT project, which aims to create a platform to build and disseminate Virtual Field Trips (VFTs) focused on geomorphology, natural hazards associated with geomorphological processes, and geoheritage sites. To put the GeoVT project in context, an overview of applications of VR in geosciences is provided. This paper subsequently proceeds with a presentation of the project and the GeoVT Authoring application, which is an innovative platform designed to help teachers and students, followed by brief presentations of a number of VFTs developed within the project. They address themes such as fluvial landforms and valley development, coastal landforms, evidence of past glaciation, coastal erosion, wildfire effects, mud volcanoes, and landslides.

Keywords: virtual reality; geo-education; virtual field trips; coastal geomorphology; landslides; palaeoglaciology; geosites

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1. Introduction

Education in geosciences, whether formally in schools at different levels, including academic education at universities, or informally, aimed at popularizing various geoscience themes or informing decision-makers about phenomena potentially hazardous for society, has long been based on classroom teaching supported by field trips. Technological developments in the last three decades have revolutionized the educational sphere, adding

Extended Reality (XR) to the range of tools available to teachers, instructors, educators, and tour guides. XR is understood as a broad term, which includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), all enabling users, albeit in different ways, to engage with computer-generated elements in both real and virtual settings. The distinction between VR and AR resides in differences in the degree of immersion in the virtual world [1,2]. Thus, VR immerses users in a fully simulated environment, while AR overlays virtual elements onto the real world, creating an interactive experience that enhances the perception of the physical environment. Although it may be argued that VR may lead to a feeling of being disconnected from the natural world, whereas AR is more interactive and perceived as closer to reality, they actually serve different needs and are preferred in specific circumstances. Therefore, neither can be claimed to be better than the other.

Virtual reality, capable of simulating real landscapes, has proven particularly useful in geomorphology and related subjects, in research, teaching, and professional training. Obvious targets are inaccessible or poorly accessible localities, such as submarine landscapes [3,4], planetary surfaces [5], high mountain environments [6], and places too dangerous to visit in person, such as sites of active volcanism [7,8]. The use of VR in education shows considerable growth in general [9,10], and teaching geomorphology is not an exception. VR allows for students to observe processes shaping the surface of the Earth, even those occurring over large spatial and temporal scales, and experience landscapes as if they were outside the classroom [11]. Various contexts and process domains have been explored, such as landslide terrains [12], coastal cliffs [13], volcanoes [14,15], and even extraterrestrial settings such as Mars [16]. VR is also increasingly used to explore geoheritage sites [17], allowing for virtual contact with both localities too far or too complicated to reach [18–20], or unsuitable to be developed for large groups of visitors for conservation purposes [21]. In the last few years, a new unforeseen application field for VR in teaching and outreach emerged related to the global spread of the COVID-19 pandemic and related closure of field sites and transformation of teaching and outdoor education into online experiences [22]. Admittedly, using VR technologies to build learning environments has enormous potential, but it also comes with important challenges. Among the most critical ones is ensuring the virtual world is truthful to reality and that students can interact with it in a meaningful way [23]. This "sense of presence" is pivotal for building effective VR learning experiences [23,24].

This paper contributes to this increasingly explored interface of geosciences and technology, presenting selected results of the EU-funded Erasmus+ project GeoVT "Training new generations in geomorphology, geohazards, and geoheritage using Virtual Reality technologies". This project intends to deliver uniform and integrated teaching guidelines to facilitate distance education, taking advantage of recent technological developments. An overarching idea is to offer complementary educational tools, and to give students the opportunity to experience various geomorphological sites that are otherwise beyond their reach. To place the results of GeoVT in a proper context, the first part of this paper provides a brief overview of applications of VR in geosciences. The second part describes the approach, methods, and tools used in GeoVT, followed in the third part by presentation of the virtual field trips (VFTs), which are among the key outputs of the project. Experience gained and lessons learnt are then presented in the Section 5.

2. Virtual Reality in Geoscience–Education and Interpretation

2.1. Virtual Reality in Education

2.1.1. The Role of Virtual Field Trips

A typical geoscience classroom includes the usage of written materials such as textbooks. However, traditional teaching methods are not adequate for geosciences without direct contact with our surroundings [25–28]. In fact, places serve as our lens for perceiving and understanding the world, and exploration and education about Earth and planetary systems usually occur through the appreciation of specific locations [29]. Field activities are often essential for collecting data and making new original findings. Therefore, excursions are a necessary component of geoscience education [30–40]. The time spent on field trips, however, has decreased in geoscience education, for reasons that are complex. They include financial constraints [41–44], potential mobility issues, and practical inaccessibility [45–47]. Moreover, during field trips, participants may also be exposed to negative experiences, as illustrated by Marín-Spiotta et al. [48]. Realizing the reality of such contemporary constraints and educational benefits has fueled the exploration of virtual field experiences (Figure 1).

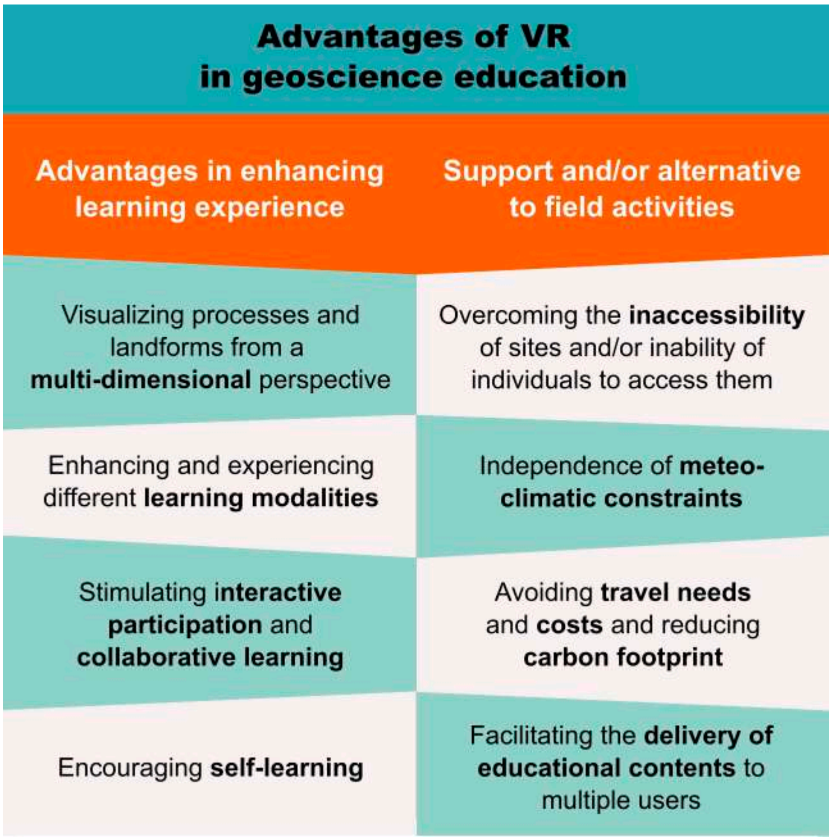


Figure 1. Overview of the advantages of VR in geoscience education.

According to Bonali et al. [15], the earliest applications of VR for investigating geomorphological processes were developed by Hilde et al. [3] and Anderson [49], who utilized 3D visualization methods to reconstruct the topography of the ocean floor by implementing 3D scenarios and virtual tours. However, applications in teaching practice did not lag much behind. Already in the 1990s, the potential of VFTs as teaching tools was recognized [45], and now, the application of VR in geoscience classrooms is considered a fundamental issue for the engagement of students in geological phenomena [11]. VFTs include components of pedagogical importance such as examination of the field area to be studied, gathering of data (analogous to data collection in real field work), formulation of hypotheses (an essential tool in inquiry-based learning and teaching approaches), and reporting of results [45,50]. Since the 2000s, VFTs have emerged as a compelling alternative to traditional field trips, offering a convenient and accessible way to engage with geographical concepts. At their core is the visualization of geographical phenomena through the use of 360-degree technology (e.g., spheric photos and videos), which enhances the immersive nature of VFTs, allowing for students to virtually step into different geographical settings as if they were physically present. VFTs are a money-saving solution, possible to apply in almost all cases as an alternative to physical field trips [45,51–55]. This is particularly the case for VR, as it is cheap in use [11] and can be visualized on both computers and mobile phones [11,56–58]. It was also argued that consistent use of easily available tools would help to overcome a problem recognized, that some students attend geoscience courses only in order to fulfill the requirements necessary to complete their bachelor's studies rather than a genuine inquisitive attitude [59–61]. Under such circumstances, raising their interest in geoscience is of primary significance [56,60,62,63]. On the other hand, many geoscience students are rather unlikely to prefer VFTs over physical field experience [39,40,64] and it is clear that, at present, despite numerous benefits of VFTs, they cannot exactly replicate the authentic experience involved in real-world fieldwork [11,65]. They can, however, provide students with experiences that cannot be achieved on real field trips, including an ability to experience a bird's eye view, and comparing sites over time and space [66]. In fact, Jitmahantakul and Chenrai [11] assessed the efficacy of VR environments in high school-level geoscience classrooms, revealing a learning improvement of 22–28%. Similarly, immersive experiences based on a virtual inspection of geosites, implemented by Bonali et al. [15], received general appreciation, especially among academics and school students.

2.1.2. Virtual Reality and Geohazards

Among various themes addressed using VR, the ones related to geohazards are of particular significance [67,68]. Havenith et al. [69] argued that a thorough assessment of geohazards necessitates the use of a novel geoscientific and technological environment that is multi-dimensional, spatiotemporal, integrated, interactive, and collaborative. They concluded that VR fulfils the requirements and offers a promising solution to overcome various challenges associated with awareness raising, not only among decision-makers but also among the general public. In fact, modelling of a virtual scene is a very important component of the application of VR technology in geohazard studies and education [67]. Thus, digital 3D models were used to reproduce landscapes vulnerable to geohazards such as landsliding [70–72], volcanic eruptions [7,8], and flooding [73,74], but also subject to technological hazards such as dam failing [75].

Tools that immerse users in realistic experiences have been instrumental in hazard and emergency management, encompassing hazard identification, prevention, and safety training [76]. Emergency management has several components: (i) how to avoid hazards; (ii) how to prepare for emergencies (safety rules); (iii) how to react during emergencies (evacuation and rescue); and (iv) how to recover from disasters and restore fundamental infrastructure [76,77]. It is important not only for helping saving lives and the environment but also for pedagogical aspects. Through emergency management exercises, students are involved in modelling, select different variables, and can create a simulation that accepts different values for physical parameters and shows the response of the system under these changes [78–80]. This in turn can engage students in the study of a contemporary problem—sometimes called "ill-defined"—in an interdisciplinary, holistic way, which is at the core of the STEM approach [81,82]. Thus, students have to decide on the parameters critical to a natural phenomenon and determine their ranges to face a realistic situation. They act like scientists and engineers, formulating hypotheses, checking them, and sometimes changing the model of simulation to arrive at a final decision.

The REVE Cot project is a relevant example in this context [83]. It shows how VR simulations can be used not only to improve scientific research but also to engage decision-makers and planners. In particular, simulations of flooding in Normandy due to sea-level rise were displayed in an immersive room. Nearly 150 elected representatives from various local authorities in Normandy were introduced to VR simulations depicting future transgression scenarios. A significant 95% of them expressed enthusiasm and a desire for wider distribution of these simulations [84]. The positive response from participants highlighted the potential of VR simulations as tools to bridge the gap between scientific understanding, public engagement, and informed decision-making in the frame of sustainable development under conditions of a changing climate. In this regard, some pivotal studies suggested that utilizing immersive VR simulating long-term hazardous processes (e.g., sea level rise) that are often overlooked by the general public could provide an alternative approach to increase public awareness concerning the impacts of climate change [85–87].

2.2. Virtual Reality in Geoheritage-Oriented Tourism

Within the domain of geomorphological studies, conservation and promotion of geoheritage is crucial in fostering the establishment and growth of sustainable communities [88–91]. Geoheritage is a fundamental component of global natural heritage. Geoheritage consists of places and objects that have a key role in the understanding of the history of the Earth including rocks, minerals, fossils, landscapes, and landforms [92]. Growing international interest in this topic is witnessed, among others, by the UNESCO IGCP project on "Geological Heritage Sites" managed by the International Union of Geological Sciences (IUGS) [93], but mainly by a rapidly rising number of individual publications published in journals, conference proceedings, book chapters, and as books, e.g., [94,95].

Although geoheritage issues have been discussed since at least early 1990s [96], a notable trend of the last decade is an increasing popularity of VR technologies to promote geoheritage, to make it more accessible, and to facilitate understanding of complex geological and geomorphological evolution of a site or area. It is obviously related to ongoing digital advancements and is spurred by the necessity to explore innovative approaches allowing for more effective communication with the general public, better appreciation of geoheritage, and a need for conservation [17,91,97]. Introduction of modern technologies can also help overcome problems associated with the use of technical, specialist language that may not be easy to comprehend by non-specialists [98]. The most used technologies are 3D visualizations in VR and AR tools, which are usually implemented through mobile apps and/or web platforms. For instance, 3D models have been used in geoheritage visualization including the implementation of virtual models of geosites, so-called virtual geosites [99]. Examples of these applications are virtual geosites presented for Lesvos island [100,101] and Santorini [19], both in Greece, as well as remote geosites in the east of Iceland [18]. Underground spaces are another target, as demonstrated by Melelli et al. [21], who virtually reproduced geological and archaeological features of Etruscan subterranean remains in Central Italy, also highlighting linkages between cultural heritage and geoheritage. Various tools offered by modern technologies and resources based upon them may also help to better understand the main features of relief and the sequence of events poorly captured by "classic" geosites such as rock outcrops, typically much older than the evolution of topography, and minor landforms, which document the most recent stages of landscape evolution [102]. At the scale of individual outcrops of volcanic rocks witnessing ancient volcanism, animated reconstructions of emplacement and eruptive histories are powerful tools to increase geosite attractiveness [57]. AR has been extensively used by Martínez-Graña et al. [103–105] in the context of geoheritage localities in Spain and Portugal. Promotion of geoheritage usually proceeds via geotourism, which increasingly incorporates virtual tours [6,106–109]. Some of the early applications of virtual tours aiming to promote geoheritage and geoconservation awareness were developed by Martínez-Graña et al. [37,103], who implemented 3D virtual itineraries using Google Earth.

3. Approach, Materials, and Methods

3.1. Rationale

The GeoVT project is characterized by a comprehensive approach to enhance distance learning, by employing methods, tools, and platforms that tailor to education facing new challenges. It is focused on expanding educational capabilities at an international level and adapting education to the evolving global landscape by integrating virtual experience with immersive education. Collaboration among scientists from different partner institutions has resulted in the implementation of an educational platform designed to be interactive and dynamic, offering new opportunities for students who access and interact with educational contents. The requirements were that the GeoVT platform can be easily used by newcomers in the field of virtual technologies to stimulate the creation of customized VR-based lessons (e.g., VFTs) by including multimedia elements such as VR images, maps, animations, and VR videos and to convey concepts related to geomorphology, geohazards, and geoheritage. Thus, the platform leverages the dynamic capabilities of VR and seamlessly integrates content sourced from a backend web platform, offering an immersive and personalized learning experience. The GeoVT Authoring application works via 360° images and videos, which form a scene ("sphere") that can be viewed and virtually experienced in a full 360° perspective. It makes these immersive VR-based lessons accessible to learners via the GeoVT VR Player, compatible with Meta Quest VR headsets, enabling students to experience 360° VR exploration. This experience is not limited to those having access to VR headsets; they can also be viewed on a personal computer. The rationale driving the approach of the GeoVT project is rooted in the established principles that advocate for active participation over passive learning, as demonstrated by Mayer [110], and the utilization of immersive media, as articulated by Makransky and Mayer [111].

3.2. The GeoVT Platform

The GeoVT platform can be used for the creation of VFTs that explore themes related to geosciences, geohazards, and geoheritage, but they may also serve other purposes. In order to create a VFT through this platform, 360° photos and/or videos are required from the field, and these were collected using the Insta360 ONE X2 camera, prepared and exported into usable formats (.jpg, .png, .mp4) using the Insta360 STUDIO 2023 program, and uploaded onto a webpage created alongside the GeoVT platform. On the same webpage, one can also upload regular image files (.jpg or .png) or videos (.mp4) as supplementary material. Besides landscapes, these can be any symbol or feature, for example, arrows indicating the next or the previous site of the VFT. Finally, one can upload audio material (.mp3), which could be a narration, serving as a guide to the structures and landscapes that the users experience, or a song/soundtrack serving as background music (Figure 2).

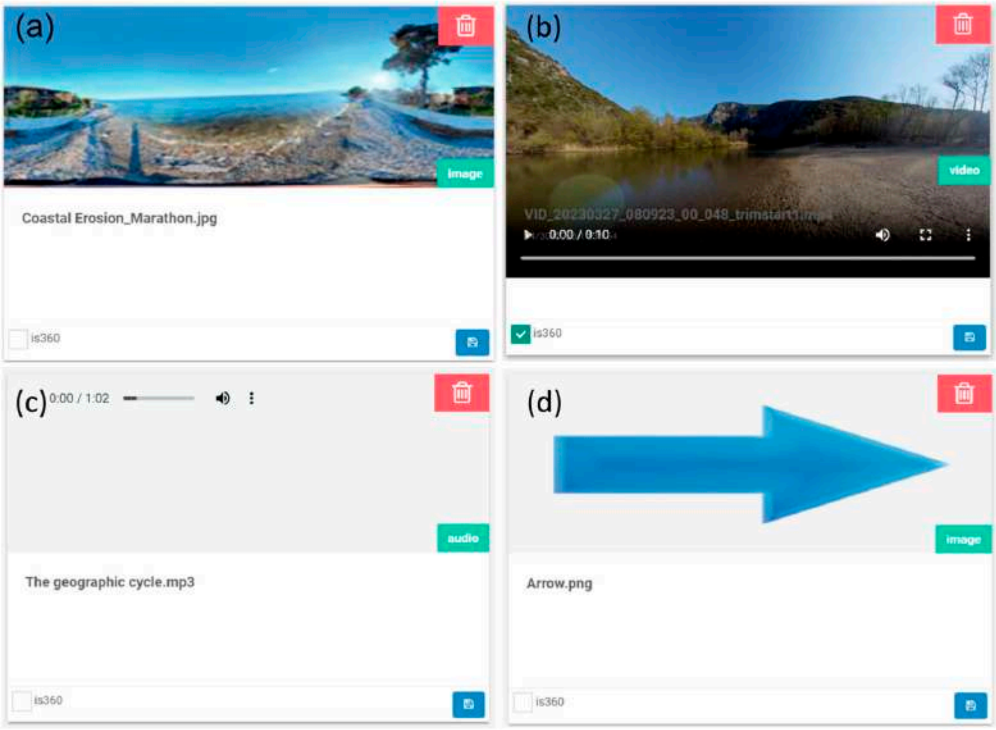


Figure 2. GeoVT online content repository: (**a**) 360° photos used for VR spheres; (**b**) 360° and simple videos used for VR spheres or additional material; (**c**) audio files incorporated in the VR field trips; (**d**) graphics used in the VR field trips.

Starting the creation of the VFT, the user can produce different "spheres", each sphere corresponding to one 360° photo or video out of those uploaded in the webpage. In each sphere, one can import an image, video, or audio file from those uploaded to the webpage. Each file can be used in more than one sphere. All of them can be set to begin and/or end at a specific time and/or have a specific duration. Alternatively, they can be set to remain in the sphere for as long as it is active. Regarding images and videos, the user can define their exact location, dimensions, orientation, and rotation. Finally, one can insert texts, which can be customized regarding font color, size, style, and frame. For each of these elements (files, texts), transfer to another sphere may be determined, not necessarily to the sphere created next. When the users complete and save the VFT, they can start to play and observe it as if they were actually there.

The GeoVT platform consists of three subsystems [112]:

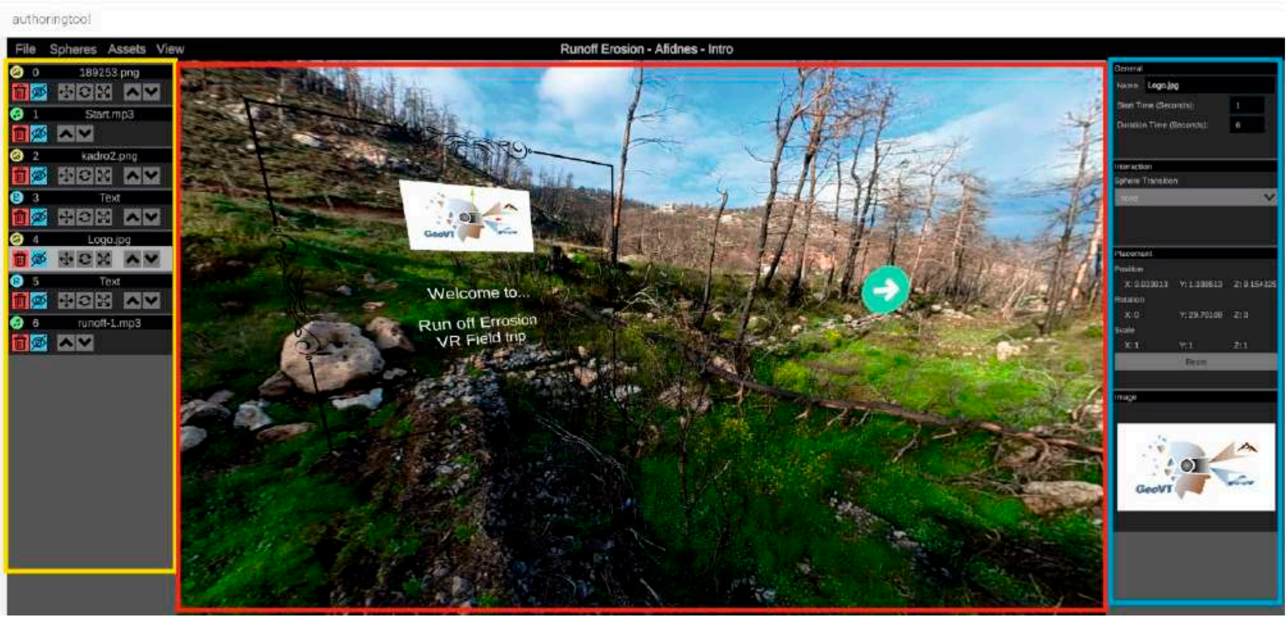
- An online content repository accessible from any web browser [113];
- GeoVT authoring applications for Windows and Mac devices;
- GeoVT player for Meta Quest VR headsets.

Within the digital repository, instructors have the capability to incorporate 360° imagery or video for their virtual presentations. Multiple 360° images or videos can be uploaded for each presentation (Figure 2). Furthermore, it is possible to supplement these immersive landscapes with supplementary multimedia elements such as images, audio files, and even three-dimensional objects. Additionally, there exists a complementary resource library containing valuable assets—including, but not limited to, arrows and informational icons—that can enhance the content of a presentation.

To ensure proper user interaction within the GeoVT platform, we have implemented several control mechanisms. Firstly, users are required to create a GeoVT account (username and password) to access and utilize the platform. The activities of the accounts can be scrutinized by the platform administrators. They possess the authority to review and verify the materials uploaded by users, thereby maintaining quality standards. VFTs created by users undergo an approval process by the GeoVT platform administrators before they are published online. This additional layer of validation ensures that only suitable and relevant content is made available to users.

In the GeoVT Authoring application (Figure 3), instructors or students have the capability to construct their VR presentations by generating spheres using the resources available in the online repository. Within each sphere, they have an option to designate a 360° image or video as the background and, subsequently, they can insert supplementary assets, while also establishing a chronological timeline for the sequence of events. Furthermore, instructors or students can interconnect these spheres to form educational pathways. They have the flexibility to save their work as a work-in-progress until they complete it, at which point they can proceed to publish their VR presentation.

The GeoVT Player (Figure 4) provides students with an immersive virtual reality experience that enables them to engage with the content and move from one sphere to another, simulating a realistic exploration of these landmarks while facilitating their learning process. The VR player is made with Unity, which is a versatile and widely used development platform that empowers creators to build interactive and visually engaging 3D applications across various platforms. Its robust features and cross-platform compatibility make it a popular choice for a wide range of interactive experiences. The seamless communication between the VR front-end interface and the back-end system is facilitated by means of a well-structured application programming interface (API) that implements OAuth2 authentication protocols. This robust and secure framework ensures the authentication and authorization of data transactions, enhancing the overall reliability and confidentiality of the system's operations.



Name: Logo.jpg
Start Time (Seconds): 1
Duration Time (Seconds): 6
Rotation X: 0 Y: 29.70108 Z: 0
Scale X: 1 Y: 1 Z: 1

Figure 3. The GeoVT Authoring application environment: the yellow area (**left**) corresponds to the uploaded assets of a specific VR sphere; the red area (**middle**) corresponds to the VR sphere and asset positioning management; the blue area (**right**) corresponds to the asset settings.

Figure 4. The GeoVT VR player environment. The user is hearing the audio and according to the settings will observe assets appearing and disappearing in a specific sphere. The user can interact with the assets in order to "jump" from one sphere to another according to the author's settings.

4. Results—Virtual Field Trips in Practice

4.1. Fundamentals of Geomorphology

4.1.1. Fluvial Geomorphology

The Nestos is a major river in the Balkan peninsula, with a total length of 243 km. It has its spring in the Rila Mountains (Bulgaria) and flows across the Rhodope Mountains into the Aegean Sea, in Kavala Prefecture (Macedonia, Greece). As the river shows complex geomorphological evolution, it has become a perfect area for education regarding fluvial geomorphology. In the Greek part of its course, it forms a deep canyon, but at the same time shows a sinuous pattern, with deeply entrenched meanders [114–116]. As meandering is typical for wide floodplains, e.g., [117], it is assumed that the predecessor of the contemporary Nestos River flowed across a flatland, developing its meandering course, and, only subsequently, in response to late Cenozoic tectonic uplift of the Rhodope Mountains, the river incised into its floodplain and then into bedrock. Thus, the VFT along the Nestos River addresses the main principles of geomorphology of fluvial systems, beginning with the processes of weathering within the drainage basin, through erosion, transportation, and finally, deposition. The field trip points out consecutive evolutionary stages that a drainage basin typically follows (youthful, maturity, old stage, and rejuvenation in response to tectonic uplift). In addition, human interference with river morphology is considered by looking at various anthropic features inserted into the channel and valley floor.

4.1.2. Coastal Landforms

The VFTs in Mikri Vigla, Airport Lagouna, Plaka, and Glyfada, all sites located on Naxos island (Cyclades, Greece), focus on relative sea-level changes and sea-level indicators, but address other landforms found on the western coast of the island too. Landforms such as beachrocks, lagoons, sand dunes, and tafoni, and their evolution through time are discussed, as well as their interactions with the local geomorphological regime (e.g., streams and sediment yield, winds and waves) [118–121]. Contrary to its northern, southern, and eastern coasts, which are rocky, the coasts of western Naxos are more diverse, ranging from hardrock cliffs to vast coastal plains, and are hence particularly suitable for teaching coastal geomorphology. One can also address an important controlling role of bedrock geology. The presence of granodiorite along most of the western shorelines of the island creates an abundant source of very fine sand, which then supplies the littoral transport system. This in turn has led to an abundance of well-developed coastal depositional landforms, from sand spits through beachrock to sand dunes [118–121].

Coastal geomorphology is also the subject of a VFT set up in Laconis, in the southern Peloponnese (Greece). Within the peninsulas of Mani and Monemvasia, there occurs a sequence of marine terraces and abrasion platforms, providing an opportunity to present both landforms and their controlling factors, as well as processes involved in their origin. Both peninsulas have had a complex geological evolution, with differential tectonic movements as the main controls, accounting for subsidence in some areas and uplift, non-uniform itself, in other areas [122–130]. At the same time, the peninsulas are lithologically diverse. Hard carbonate rocks occur alongside more recent and softer rocks such as marls. These circumstances have led to the development of flights of marine terraces, whose dimensions and clarity reflect a combination of many factors, including uplift rate, lithological controls, and eustatic sea-level fluctuations. Active abrasion platforms are common along the peninsulas, and given ongoing regional uplift, they will turn into raised marine terraces in the geological future.

4.1.3. Palaeoglaciology and Glacial Landscapes

A topic well-suited for VFTs is that of the impact of ephemeral ice sheets on landscapes, presented here with an example of a virtual excursion to the southern Swedish Mountains in central Scandinavia. This area showcases some of the classical landforms formed by warm-based ice sheets, such as lineations and meltwater features [131], and formed by, or preserved underneath, cold-based ice. This highly diverse set of landforms also derives from this area's unique setting close to the location where, during deglaciation, a separation of the Fennoscandian Ice Sheet into its southern and northern domes occurred [132]. Indeed, this has therefore been a focus area of both research [133–135] and education at Stockholm University (SU). The presented GeoVT excursion is based on a master's-level course in palaeoglaciology at SU.

Within the virtual excursion, different glacial landforms are shown in a 360° environment and full-sphere imagery of individual landforms become natural stops along the excursion path. At each stop, participants can educate themselves by means of pre-recorded lectures informing about landform type, formation processes, and their palaeoglaciological context. The environment is enhanced with maps derived from orthophotographs and LiDAR data from the Swedish Land Survey and the Norwegian Mapping Agency. Through this connection between landform appearance in the field and in remotely sensed imagery, students learn how to recognize glacial landforms and how to interpret them in terms of (sub)glacial conditions and glacial history. The excursion includes three main sites in Sweden and Norway. Topics discussed are, amongst others, relict glacial landforms at higher elevations formed under cold-based ice conditions (relict moraine), the development and successive drainage of ice-dammed lakes during ice-sheet retreat (shorelines, outlet channels), and the effects of a sudden release of meltwater from the glacial lakes (downstream perched delta, drainage channels) (Figure 5).

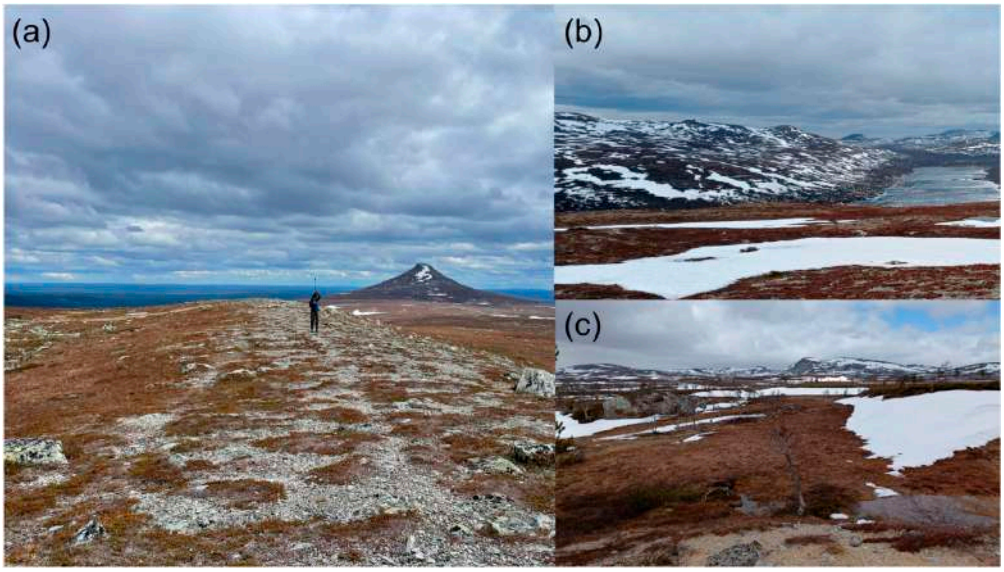


Figure 5. Elements of the glacial landscape in the southern Swedish mountains. (**a**) Ylva Palmgren taking a 360° image of a relict end moraine; (**b**) Lake Grövelsjön with raised shorelines indicating it was once dammed to much higher levels; (**c**) lake outburst drainage channel, the level of which relates to the level of one of the former lake shorelines, and the direction of which was guided by the retreating ice sheet margin.

4.2. Geohazards

4.2.1. Coastal Instability

The VFT is focused on a highly dynamic coastal cliffs in Normandy, northern France, themselves a part of the French observatory of coastline erosion [136]. At the site known as the "Falaises des Vaches-Noires", five watersheds have been monitored for many years to understand the complex morphogenetic processes at work [137,138]. The cliffs (Figure 6), supported by clayey marl formations (Callovo–Oxfordian) and topped by a sandy chalky series from the Albian–Cenomanian, present a badland landscape with a ruiniform appearance, which is unique on the French coast, but difficult to access.

The VFT offers a journey that starts with the general appearance of the cliffs and the coastline and is followed by a detailed look at gullies that successively shape this landscape from east to west (Figure 7). Throughout the tour, attention is drawn to structural and morphological underpinnings of the badland landscape, starting with the basal scarp, which is broadly rectilinear but has a succession of small coves and headlands. Beyond this, a hummocky morphology with numerous escarpments associated with nested rotational and/or translational landslides occurs. The trip concludes next to the gullies, whose seasonal activity, characterized by incision and the evacuation of debris, is constantly shaping this chaotic landscape and reveals structural features that explain the landform.

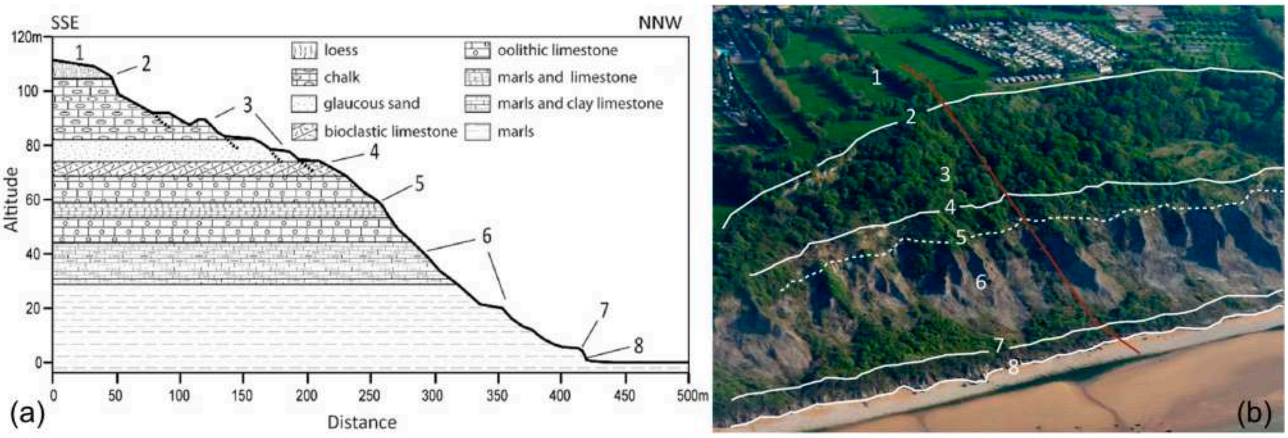


Figure 6. Main morphological units of the Vaches Noires cliffs. (**a**) Geological section. (**b**) Aerial photograph; red line: trace of the profile in (**a**) with the limit of the main features. Legend: (1) plateau; (2) main scarp; (3) hummocky, chaotic morphology; (4) second scarp; (5) third scarp; (6) badlands (V-shaped gullies); (7) edge of basal scarp; (8) bottom of basal scarp.

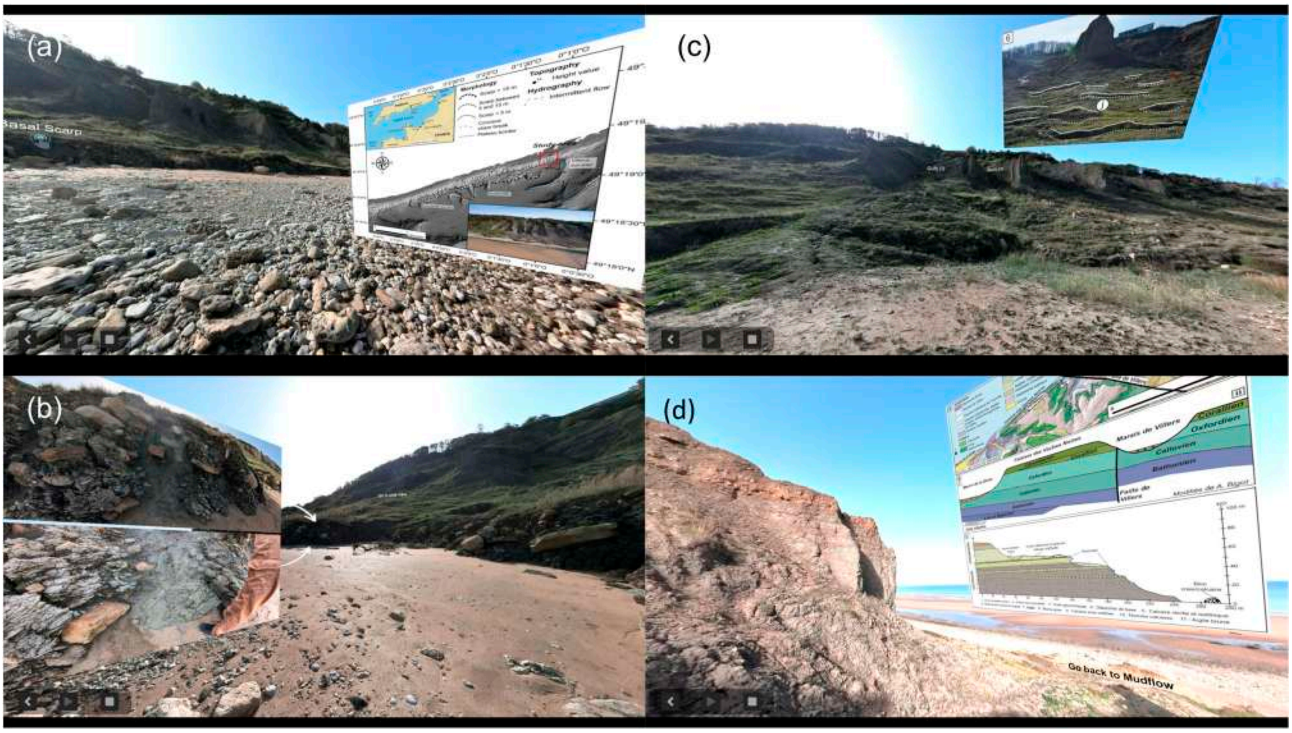


Figure 7. Example of viewpoints suggested during the virtual walk on the Vaches Noires cliffs: (**a**) general view of the cliff including a sketch map; (**b**) focus on the basal scarp with two close-up photos showing mudflow activity; (**c**) focus on nested rotational and/or translational landslides; (**d**) focus on a gully flank with an inlaid morphostructural diagrams.

The complex and chaotic morphology of the cliffs is gradually being exposed through the pedagogical virtual field trip medium in order to disseminate more effectively the knowledge that has long been produced on this experimental site [139].

4.2.2. Surface Runoff Effects

The VFT in Afidnes (Attica, Greece) addresses the problem of runoff erosion. Besides offering insights into the phenomenon in general, it focuses on the effects of the 2021 wildfires that struck the area [140], their impact on slope morphology and underlying soils, and the extent and pattern in which the runoff erosion hazard has increased due to the fires [141]. This is, among others, because the vegetation, and much less, forests, can protect the soil by restraining the particles, as well as reducing the surface runoff [142–145]. Through forest fires, this protection is destroyed. For the same reason, forest fires lead to an increase in flood risk as well [142–145], which is also the case in Afidnes [146]. Within the settlement of Afidnes, there is a confluence of two mountain streams draining a significant area of western Attica. Their drainage networks are well developed. Therefore, upon extreme weather conditions, they are capable of transporting huge amounts of water, leading to destructive flood events. Due to the 2021 wildfires, the vulnerability of the catchment has increased, and risks related to runoff erosion and floods have become even higher. Moreover, the presence of a ford within the village and right at the confluence of these two streams has deteriorated the village's situation. A ford (or "Irish junction") is actually a part of the road network that directly crosses the bed of a river or stream (instead of a bridge). Therefore, it will be among the first parts of the settlement to become inundated in case of a severe flood. In the case in Afidnes, this junction is located right outside a school, meaning that it serves daily as a passage to many students and parents, all of whom would be in severe danger in the case of a flood.

4.3. Geoheritage

4.3.1. Mud Volcanoes

The site featured in the VFT is the Salse di Nirano Natural Reserve, situated at the foothills of the Emilia Apennines (northern Italy), where spectacular mud volcanoes and scenic badlands contribute to the aesthetic value of the site. Apart from their aesthetic value, the Salse di Nirano is a prime example of a geosite presenting diverse values including, above all, a scientific one. The Nirano mud volcanoes are among the best-preserved examples in Europe, and they have been studied for a long time. Starting from the 17th century, the Salse di Nirano were the object of scientific investigations by renowned geoscientists [147,148]. Numerous subsequent studies have focused on geological, geomorphological, and biotic features of the area [149,150]. The volcanoes are the result of muddy emissions caused by the upward movement of saltwater mixed with mud and hydrocarbons along fractures in the ground, up to the topographic surface. The Salse di Nirano Natural Reserve was among the first protected areas of Italy for its ecological values due to the presence of peculiar plant species. The area also has socioeconomic value, being a popular geotourist destination due to the occurrence of bubbling mud volcanoes. Local communities also benefit from the tourism influx, as it fosters economic growth and opportunities for sustainable development. In addition to the socioeconomic value, the site has historical value. Many historical sources testify that since ancient times, the Nirano area has been a dwelling place of organized groups.

All these features lend the Salse di Nirano area a high educational potential that has been exploited for the development of a VFT aimed at illustrating diverse geoheritage values. The VFT was developed through a series of stops corresponding to points of interest exemplifying its aesthetic, scientific, ecological, socioeconomic, and historical value. Notable points of interest along the VFT include a panoramic viewpoint (Figure 8), a visitor center, and the mud volcanoes themselves. Each stop is accompanied by voice recordings, images, or diagrams that clarify key concepts associated with the site. Sound recordings capturing the bubbling of the mud volcanoes and the ambient sounds of the reserve are integrated to enhance the immersive experience during the VFT.

Figure 8. Main features and points of interest of the virtual field trip to the Salse di Nirano Natural Reserve: (**a**,**b**) views of the mud volcanoes; (**c**) 360° spheric photograph taken at the initial viewpoint of the virtual field trip; (**d**) zoomed view, from the spheric image center perspective, at one of the edifices of the mud volcanoes and related explanatory sketch.

4.3.2. Coastal Cliffs and Coastal Landslides

Paradise Bay on the northwestern coast of Malta has been selected as another site for a geoheritage VFT. Again, it has considerable aesthetic value, as visitors can see clear sea waters bordering a white sandy beach backed by high limestone cliffs [151]. The cliffs are of primary interest from a geoheritage point of view, offering representative examples of slope instability processes including lateral spreading and rock toppling affecting the cliffs, evident in a sequence of landforms, from open cracks beyond the rim of the cliffs through vertical scars, downthrown blocks and minor grabens, to chaotic accumulations of huge bedrock blocks. This diversity and clarity of view due to sparse Mediterranean vegetation allows for the examination of landslides as valuable components of geoheritage, as recently highlighted by Morino et al. [152]. Adjacent to Paradise Bay is a sinkhole, probably formed during the Quaternary due to the roof collapse of a small cave [153]. The sinkhole has a diameter of 35 m at ground level and is surrounded by a rocky floor covered by soil. Large dimensions and its exemplarity as one of the few inland sinkholes in Malta make it an exceptional place to observe ongoing karst processes affecting limestones. Furthermore, the presence of thriving Mediterranean vegetation within the sinkhole gives it considerable ecological value. The VFT implemented in this area includes a stop at a panoramic viewpoint showcasing the geomorphological features due to slope instability processes mentioned above. The subsequent stops are placed at key points of interest, namely, the sandy beach and the sinkhole. To captivate learners, a 360° video allows for them to explore the bottom of the sinkhole. The comprehension of geomorphological features and processes is facilitated by textual explanations and annotated images.

5. Discussion

The deliverables of the GeoVT project are twofold. First, new tools have been developed, tested, and successfully implemented, allowing users to create and experience VFTs. Second, a collection of VFTs is presented, covering various themes related to geomorphological processes and landforms, hazardous surface processes, and geoheritage issues. They add to the growing number of virtual experiences made available in recent years due to rapid technological developments [7,8,15,18–21,100,101,154]. Moreover, all themes have practical applications for sustainable land management, understanding the effects of climate change at different temporal and spatial scales, and conservation of sites of considerable scientific value facing increasing pressure from tourism and related infrastructural development. Similar to some other VFTs reported in the literature, some of the field trips presented here have been designed to make various aspects of geomorphology more accessible, overcoming access limitations due to either conservation or safety reasons. An example is the palaeoglaciology excursion in Sweden, focused on areas quite challenging to reach. For most of the year, winter temperatures and snowy conditions are significant obstacles, while during spring and early summer visits, traditional reindeer herding may be exposed to disturbances. An additional factor is that students with mobility or financial issues cannot easily access the study area. Hence, a virtual excursion has the potential to make glacial geomorphology of Scandinavia more accessible, independent of the season.

Another benefit offered by the implemented VFTs is their ability to be attended in asynchronous mode, without synchronous guidance by an instructor, allowing for learners to educate themselves through recorded lectures and with the support of textual explanations, photographs, figures, and diagrams within a 360° environment.

The experience gained during the project implementation allows for us to evaluate the GeoVT tools as useful and user-friendly. Indeed, instructors from GeoVT partner institutions, many of whom are not VR developers, successfully implemented and integrated VFTs into their academic courses on physical geography and geomorphology. Additionally, the versatile tools within the GeoVT platform present an opportunity to customize field trips based on educational levels and empowers instructors to tailor VFTs according to specific teaching needs and lesson contents not only limited to geosciences, making them a valuable resource for disseminating the sciences beyond academic settings.

The GeoVT platform was presented to users and the public through multiple activities, including a series of online workshops and webinars. These virtual events attracted a substantial audience, averaging around one hundred participants each, comprising not only students and scholars but also educators and people involved in science outreach. Scientific dissemination events aimed at a non-specialist audience were also organized. During these events, attendees were able to immerse themselves in virtual field trips through the GeoVT player for Meta Quest VR headsets.

Furthermore, an intensive five-day online training course focused on geomorphology, geohazards, and geoheritage was offered to students from partner universities as part of the GeoVT project. The course was attended by 30 participants, who experienced the immersive virtual field trips developed within the project. These immersive experiences were complemented with detailed textual explanations, relevant bibliographical materials, and synchronous interactive lessons. The latter were intended to facilitate open debate, allowing students to ask for clarifications, delve deeper into topics of interest, and discuss the potential of VR in teaching and research. Positive feedback on the course contents and organization emerged from the questionnaire completed by the students at the end of the course. Around 90% of the students found the course interesting, that it met their expectations, and that it was helpful in understanding the main principles of geomorphology, geohazards, and geoheritage.

All these activities were an opportunity for us to identify improvement needs, especially regarding the GeoVT platform, the VFTs, and the related teaching material. These initiatives saw general enthusiastic participation, testimony to the success of the project.

It is also argued that VFTs are adequate responses to challenges recognized in the analysis of past Erasmus+ projects and associated recommendations [155]. One of the latter calls for making the Erasmus programme more inclusive, overcoming an obstacle of the lack of funding to support student mobility. VFTs that can be experienced freely and linked to free educational content certainly promote greater inclusivity. Crucially, de Castro and García-Peñalvo [156] propose that a measure of project success is the usefulness of its outcomes beyond the time of funding, and this too is clearly the case of VFTs developed during the project. Likewise, the emphasis on the application of innovative methodologies at various participating institutions is relevant and, in fact, the GeoVT project surpasses in this aspect, making the experience available online to everyone.

6. Conclusions

Virtual field trips are effective means of learning and communication in geoscience education at different levels, being more interactive than conventional teaching methods, while also helping develop digital skills and competences. The user-friendliness and interactivity of the tools presented in this paper allow for motivated students to both use them in their own careers, whether in education or research, and create their own VFTs. The VFT experience may encourage users to learn more about a given area and/or theme, and to visit the area, but an additional advantage is the opportunity to "visit" localities that are otherwise poorly accessible or inaccessible (temporarily or permanently), for a variety of reasons (e.g., from financial, mobility, or safety aspects). On the other hand, even if access restrictions do not apply, VFTs should be considered as auxiliary educational tools, not exclusively intending to replace actual field trips but integrated into them, providing new and effective learning opportunities within school or university curricula dealing with landform recognition, geohazards, and geoheritage.

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