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Review

Advanced Technologies for Geosite Visualization and Valorization: A Review

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Abstract: This review attempts to summarize contributions by authors who, in the last decade, have dedicated their efforts to making geoheritage accessible to the public. Geoheritage is composed of geosites, which are, nowadays, real milestones on which field-based geological education can be conducted. However, the COVID-19 pandemic in particular has made it clear that a new paradigm is needed; a series of tools must be introduced and increasingly used to make it possible for potential users, be they academics, students, or the lay public, to experience geosites from locations that can be thousands of kilometers away. All these have been achieved over time by a wide range of evolving techniques and advanced technologies such as GIS tools, virtual reality applications and further innovative technologies such as WebGIS platforms accompanied by appropriate navigation tools (VR headsets and thumbsticks). The viewers, in this way, are provided with a complete view of a virtual geosite, which enables visualizing its characteristics at different scales. VR technologies, especially, have revealed a high degree of satisfaction, based on feedback collected from VR geosite visualization events, both by scientists, students and the general public, and could be the forefront of geosite visualization and valorization in the near future.

Keywords: geosites; geoheritage; technologies; virtual reality; questionnaires

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1. Introduction

1.1. Geodiversity, Geoheritage, Geosites

Geodiversity involves elements which have geological, geomorphological, paleontological [1], petrological, volcanic [2–4], tectonic [5,6] mineralogical [7], stratigraphic, igneous [8], climate-related, and sedimentary relevance. Geoheritage, which involves elements of geodiversity, has been subject to discussion in several papers during the last 20 years e.g., [9–17] and has major scientific, cultural, and educational value, which makes it useful for popularization in Earth Science museums [18–21], and for protection in geoparks [22–31]; moreover, geoheritage can be instrumental for geotourism purposes [32–44]. Protecting geoheritage implies preserving peculiar geomorphological and geological elements that are called geosites, i.e., natural features that express the geological heritage of a locality [15,45–48] and are distinguished by a great deal of values, as highlighted hereon. Geosites can also be non-natural features, such as quarries, road cuttings, and museum collections. In a fairly recent paper [49] it has been pointed out that "the definition of a geosite should be interpreted as an outstanding outreach activity based on a deep knowledge of the general and local geological significance of the proposed site". Needless to say, geosites can correspond to geomorphological objects that compose geomorphodiversity [50] and, hence, are called geomorphosites [51].

1.2. Geosite Assessment

During the last decades, several authors have tried to quantitatively and qualitatively determine and define geosite quality by applying different criteria. Most efforts of this kind have used the scientific value [15,16,52], which consists of four sub-criteria, namely representativeness, integrity, rarity [15,16,53,54] as well as the degree to which a geosite has been the focus of scientific publications. In regard to representativeness, this reflects how exemplary a geosite is in terms of the natural events that have taken place there. Rarity reflects to which degree a geosite is uncommon [54].

Besides the scientific value, other, so-called additional values [15,16,55,56] can be determined and become subject to assessment. Such additional values are of the aesthetic, ecological, economic, educational, and cultural type. The latter consists of religious, artistic, literary, historical, and geohistorical sub-criteria [54]. The educational value [14,57] expresses the combination of the didactic potential of the geosite (which is related to how easily the general public can understand its characteristics), its accessibility, safety, as well as its possible "use" for educational goals—for instance in the form of guided tours.

1.3. COVID-19 and the Earth Sciences

During the COVID-19 pandemic, the closure of educational institutions all over the globe especially impacted the teaching of geosciences, which usually involves excursions in which numerous student groups participate. Furthermore, geologists often need to conduct field surveys in foreign countries for research purposes. Moreover, just like scientists from other fields, geologists also need to take part in meetings and conferences. With the purpose of coping with COVID-19-related circumstances, the possibility of sharing research and teaching resources on the web became paramount, and is becoming increasingly important also nowadays, even though the peak of the pandemic has passed. Given the above, virtual reality techniques can play a special role, as they are devoted to facilitating 3D visualization of Earth Sciences [58]; virtual landscapes are based on open geospatial datasets [59], and digital terrain/surface models along with bathymetric data [60].

The present work shows several examples of geosite visualization and promotion by means of cutting-edge, innovative techniques, among which the creation of virtual geosites, which can be put at disposal of the public owing to advanced methods involving Unmanned Aerial Vehicles (UAVs) as well as Structure for Motion (SfM) methodologies.

2. Innovative Technologies for Geoheritage Visualization

2.1. Virtual Outcrops and Virtual Geosites Building

In order to pursue the objective of virtual outcrop and virtual geosite building, many authors in the past have employed Structure from Motion photogrammetry [61,62]. This method is particularly useful, as it produces photorealistic 3D models [63,64]. The creation of 3D models of outcrops consists in two main phases: (i) image collection by Unmanned Aerial Vehicles (UAVs); (ii) processing of photogrammetry and building of a 3D model.

The first phase comprises the use of UAVs, which have been used, during the last two decades, to improve understanding of several kinds of phenomena, from earthquakes [65,66] to volcanic activity [67–70], gravity-related mass movements [71–75] and flood hazards [76,77]. As highlighted above, the use of drones has been complemented by Structure-from-Motion (SfM) photogrammetry [64,78,79], a very helpful method to improve the traditional techniques employed to collect field data in Earth Sciences. Tibaldi et al. [80] showcased a new approach that makes use of Virtual Reality (VR) on the basis of 3D Digital Outcrop Models (DOMs). The latter are constructed by photogrammetry techniques, and, lastly, game engine technologies are used to create a VR scene. The above techniques can be used for gathering images of geosites, and for building "Virtual Outcrops (VOs)" [81,82], that may also be called "Virtual Geosites" (VGs) [83]. This advanced technique can be employed for promoting local geoheritage by (i) illustrating geosites, assessing their value; (ii) communicating geoscience topics highlighting active geological processes and (iii) engaging youths who are keen on experimenting with interactive communication techniques.

2.2. GIS Tools

Since the 2000s, GIS tools have been instrumental in improving data access and dissemination, enabling spatial data exploration, and providing new options for processing, analyzing, and modeling data [84]. Several initiatives in the recent past have employed GIS features to enable promoting areas of interest and enhancing their tourism attractiveness. Just to mention two of the numerous, relevant applications, it is worth highlighting the use of interactive and dynamic web-based maps to promote the value of touristic areas [85] and the use of WebGIS platforms to foster valorization of city centers with historical value [86]. Moreover, Kiss et al. [87] have evaluated the strategies employed by countries at the global level and underscored the usefulness of visualizing topics such as the above by means of open-access WebGIS tools. Another study [88] has been centered on showing how spatial environmental databases can be visualized by way of open-source WebGIS systems and Google application programming interfaces (APIs).

2.3. Virtual Reality (VR)

Thanks to the recent developments in VR technology and functionalities, scientists have at their disposal additional options for visualizing spatial information. VR functionalities represent a way by which the viewer is immersed in a study area [89]. Digital viewers can navigate through an area through their smartphones or by means of VR ad-hoc equipment [90]. Fostering the development of VR technologies can provide added value with the goal of fostering touristic activities [91], and also as a way to create added educational value for geoplatforms. Antoniou et al. [92] have used VR for data collection, complemented with analyses performed in Metaxa Mine, a renowned volcanological area in Santorini, Greece. They have come up with new maps in a GIS environment through data derived from the VR experience; finally, they have presented new results that highlight the role of Metaxa Mine as a crucial volcanic geosite particularly suitable for geotourism.

3. Examples of Geoheritage Visualization and Valorization through Innovative Technologies

We provide hereunder a selection of the works that, in the last decade, have illustrated the use of innovative technologies for geosite visualization, for both educational and geotouristic purposes. Starting with a pioneering work [93], Martínez-Graña et al. have set up a VR-based tour focused on the Province of Salamanca, in the Las Quilamas Natural Park. They have made use of topographic and digital terrain models and geological layers, which can be included in a 3D model. They have used Google Earth to import placemarks of the geosites. For each one, the authors created a tab that showcases an illustration of the geological characteristics, integrated with photos and diagrams that allow to define the educational, scientific, and touristic value of each site. The authors have also proposed the use of augmented reality, enabling viewers to access the georeferenced thematic layers on their mobile devices. Again, Martínez-Graña et al. [94] have set up a virtual geological itinerary at the "Las Batuecas Valley" (Spain), identifying and evaluating ten geosites of major geological importance and scientific, educational and touristic significance. The virtual tour was made possible by using Google Earth so as to make the most of cutting-edge, innovative educational resources, i.e., 3D virtual flights, educational materials, digitized routes, georeferenced and linked to tables, sheets, photos, and QR codes. In an editorial by Cayla et al. [95], the authors introduced a Special Issue dedicated to the different digital technologies employed for the assessment, monitoring and promotion of geosites. Particularly worthy of mention is the work by Cayla [96], who reviewed the existing and emerging technologies for the characterization and interpretation of geosites. The author analyzes three main topics: georeferencing and mapping of geoheritage, 3D digital imaging (including photogrammetry and laser scanning) and experiments in the promotion of geoheritage using augmented reality. In the same Special Issue, particularly interesting is the work proposed by Lansigu et al. [97], who have founded a small private company that develops graphic communication tools to promote geoheritage projects. They present several examples of projects carried out for different public audiences, using different types of presentation. To point out how useful their approach to the communication of geosites and geoheritage can be, they illustrated the work they implemented for the Lubéron Natural Park (France). Among the various products, a special mention needs to be made of the production of a short movie that illustrates alpine geology (in four languages) and the creation of a 14-min cartoon that showcases the several geosites and features that compose the park's geoheritage. A paper by Ghiraldi et al. [98] presents the case study of the Seguret Valley (Piedmont, NW Italy). The use of geomatic tools, such as digital photogrammetry and a global navigation satellite system, have enabled the authors to produce a geomorphological map of the study area and the identification and selection of the most representative and relevant sites. Web Mapping tools based on GoogleMaps© have also been set up for the online dissemination of geoscience-related information, to be able to reach the broadest possible audience. Another paper by Cayla and Martin [99] has been focused on cutting-edge geovisualization techniques by way of high-resolution images or 3D representation, which allow for the acquisition of accurate digital models. These virtual models of natural environment can be used to prevent and mitigate natural hazards in touristic places such as the Yosemite National Park, to keep a digital archive of vulnerable sites such as in the Valley of Geysers in Kamchatka, to create cave replicas, such as of the Chauvet cave in France, or to use augmented reality for tourists such as in the GeoGuide project.

Martin [100] illustrates the application of specific techniques for the interpretation of geomorphological features by interactive visual media. His paper focuses on the use of interactive functionalities that enable to go beyond the cartographic limits of classic visual media, by means of multimedia, interactivity and animation. The impacts of these innovative technologies on learning are discussed according to recent results in media and cognitive psychology.

Aldighieri et al. [101] illustrate the technological platform developed in the framework of the 2-year long Openalp 3D project. This cutting-edge tool, devoted to explaining the geology and geomorphology of the Dolomites (Italy), can be used both online and offline and features a 3D cartographic background with embedded elements (lines, points, polygons), which are helpful in assisting tourists in the choice of suitable itineraries. The Openalp platform also allows for the production of 3D motion pictures, with dynamic descriptions of sites and itineraries. The paper by Santos et al. [102] had the purpose of integrating information collected by way of unmanned aerial vehicles, georeferenced information processed in GIS, photogrammetry techniques, and multimedia technologies to provide a better visualization of the geoheritage of a territory. Martínez-Graña et al. [103] have introduced and described eight sites marked by geomorphological and geological interest (geosites), belonging to Lower and Mid-Miocene carbonate sedimentary strata close to Albufeira in the central Algarve (Portugal). Over a 1-day field trip, these sites can be visited in person. The authors have implemented a virtual, 3D tour of the sites, also making use of augmented reality methods and geoinformatic tools that integrate digital layers such as geological maps and orthophotos. Each part of the tour features graphic and descriptive elements, which can be observed in Google Earth, integrated by photographs, diagrams and information files that describe the educational, cultural, touristic, and scientific values of the geosites. A paper focused on Iceland [104] has taken into account some selected volcano-tectonic geosites and described them through UAV-captured images, 3-D models, and field photographs. Furthermore, the authors have illustrated the pros and cons of each visualization method; finally, they have proposed a brand-new approach to geoheritage popularization, which uses interactive, VOs that are made available and can be accessed and navigated online. Pasquaré Mariotto and Bonali [83] have showcased the technique employed for creating VOs and have presented, for the first time, the concept of "VGs"; these may be key to popularizing and illustrating geological phenomena to viewers that may navigate through the different outcrops, in a way that resembles an actual field survey conducted in person. In order to highlight the originality of this technique, they have selected and described VGs, which can be observed at volcanic areas situated in East Iceland and which are no longer active (Figure 1).

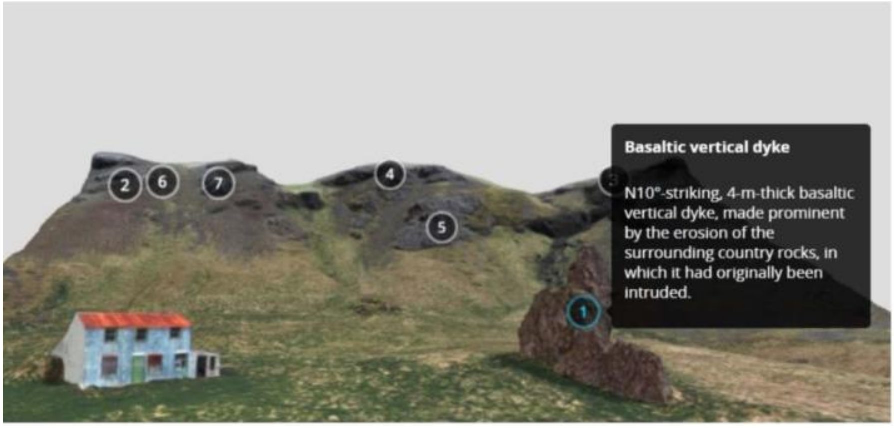

Figure 1. Example of a Virtual Geosite showing a series of subvolcanic units in East Iceland. Observe annotations that help the virtual observer to gain insight into the features of the Virtual Geosite. 1: Vertical basaltic dyke. 2. Basaltic lavas. 3. Vertical basaltic dyke. 4. Inclinded sheet. 5. Vertical basaltic dyke. 6. Vertical basaltic dyke. 7. Vertical basaltic dyke. Modified after Pasquaré Mariotto and Bonali [83].

Pasquaré Mariotto et al. [105] have shown a geotrail that can be virtually walked along, across the East flank of Mt. Etna (Italy). The elements that compose the virtual geotrail derive from a major eruption that took place in 1928. The geostops in which the geotrail is articulated have been produced by means of the SfM photogrammetry technique, applied to a great number of images gathered by operating UAVs.

As regards GIS tools, Mango et al. [85] produced a Web-based, GIS model integrated with interactive and dynamic maps suitable for promoting and managing tourism resources in Tanzania. Antoniou et al. [106] presented an effort aimed at describing a web application with which they came up, by using a GIS tool, Story Maps, made available by ESRI's online platform. Their purpose has been to present to broad audiences and describe Nisyros Volcano's geo-cultural environment, which represents a complex volcanic and cultural site in eastern Greece. Moreover, Antoniou et al. [107] created a trip to the Greek island of Salamis by using an interactive, GIS-tailored, story map application. Pasquaré Mariotto et al. [108] created nine VGs in Santorini Island (Greece) through photogrammetry based on UAV-collected images, followed by 3D modeling. Subsequently, VGs have been put into a WebGIS environment, available online and thus suitable for geoscience communication and teaching. The Virtual Geosites can be accessed by way of a smartphone, a PC, or a tablet. Each VG is described in detail and contains a lot of annotations, which the users can access during 3D navigation (Figure 2).

VR is a cutting-edge method that enables conducting 3D analyses in Earth Sciences, geoinformation for data gathering and dissemination, and, of course, an immersive experience for the users. Today, VR scenarios can be based on appositely produced geospatial datasets that include digitalized terrains and photogrammetry-created 3D models. The latter, as seen above, can be offered as virtual outcrops and geosites, and can be considered a crucial tool for solving typical difficulties experienced by students, enabling the viewing of 3D concepts on a 2D arrangement, or a virtual tour composed of images [109–111]. In 2010, a novel approach was proposed, represented by a series of 3D models that can be viewed in a similar way to a virtual tour, through a PC, a tablet or a smartphone; for instance, McCaffrey et al. [112] used this method, applying it to petroleum geoscience.

Figure 2. 3D model of the volcanic crater formed on Nea Kameni volcano in 1570–1573 AD within Santorini Caldera, Greece. Annnotations are as follows: 1. Cone flank. 2. Eruptive fissure. 3. Cone crater. Modified after Pasquaré Mariotto et al. [108].

Choi et al. [113] have pointed out that VR applications can be regarded either as non-immersive, or fully immersive experiences. Non-immersive VR entails 3D visualization, in which the models are displayed on a PC screen and/or smartphone, without using any head-mounted devices. On the contrary, immersive VR is being increasingly used on occasions such as dissemination events and offers to the viewers a number of virtual ways to navigate through geosites, flying over appositely created scenarios, with the aid of VR thumbsticks and headsets. The viewers, in this way, can have an overall experience of a virtual geosite, which enables them to identify and observe various elements of a geological landscape or a geosite at different scales [114,115]. During the last ten years or so, many cheap options have been offered so as to allow for an easy, immersive VR experience. Such new options are represented by both hardware and software solutions, and this has offered professors, students, and scientists a number of cutting-edge tools that can be applied to geosciences [116,117].

As illustrated by Bonali et al. [118], at nine VR-based activities which took place in 2018 and 2019 at several sites (in Austria, Italy, and Greece), a great amount of participants had a chance to experience immersive VR across scenarios built through innovative, UAV-based photogrammetry methods. The VGs picked for organizing the events are stunning volcano–tectonic environments, with great historical, cultural, educational and scientific value. These are as follows: an awesome on-land triple-junction [119] and the 1984 Krafla eruptive zone [104], both situated in the Icelandic North Volcanic Zone (NVZ); Mt Pizzillo, located in the NE rift of Mt Etna [120] and the Metaxa Mine (Figure 3), a major touristic site on the island of Santorini [92].

The immersive VR application by Bonali et al. [118] featured scenarios that were built through UAV-based photogrammetry techniques, which result in virtual landscapes (3D models), which have centimetric, pixel size resolution. Such a methodology has been used for models with diverse ranges of aerial extents and resolutions, from 50 to 1000 m (the longest), and from 0.8 to 4 cm/pixel.

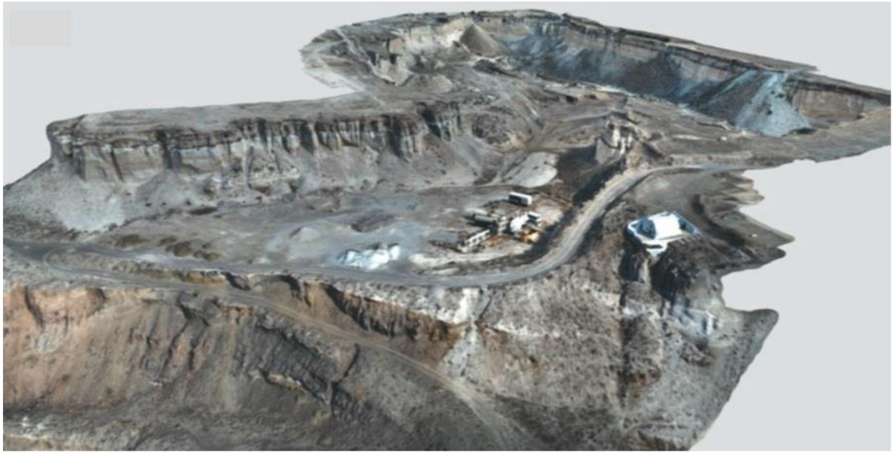

Figure 3. The 3D model of a major geosite in Greece, the Metaxa Mine on the Island of Santorini. Modified after Antoniou et al. [92].

During the nine events, Bonali et al. [118] quantitatively evaluated the perception of the virtual experience by a total of 459 respondents. The subsequent evaluation of the questionnaires, articulated in nine items, allowed the authors to gain major insights into the usefulness of this approach for educational aims. Most respondents showed major interest in the immersive activity. Especially appreciated was the chance to hover above the geosites in “drone mode”. By analyzing the results of the survey, the authors were also able to appreciate the participants’ satisfaction with the quality of the environments, reproduced through innovative, UAV-based photogrammetry methodologies.

As pertains to the educational potential of this method, the majority of respondents gave high marks to their experience (totaling 94%); the percentage peaked to 96% among geoscience academics. Thus, the paper by Bonali et al. [118] confirms that students and teachers perceive VR as a major strategy for geoscience-related education. Finally, a paramount work by Martínez-Graña et al. [121] was devoted to illustrating twelve geosites in the geopark called “Arribes del Duero” (Spain). The Authors created a 3D virtual geotrail based on Google Earth for educational purposes, integrated with georeferenced cartographic products, thematic maps, itineraries, didactic and interpretive panels. They also made a field guide and an app available to users. Users can access the field guide (in PDF format), through a QR code. The field guide and the geoapp helped make the georoute more entertaining and helpful for the users.

4. Conclusions

Especially in the last decade, there has been an increasing interest in geoheritage and its main expressions, geosites, which can have aesthetic, cultural, economic, touristic, educational and scientific relevance. Many papers have been dedicated to the assessment of geosites all over the world. Besides the assessment, there have been many efforts by authors to come up with interactive and multimedia tools aimed at the visualization and valorization of geosites. Such tools belong mainly to three categories: the building of Virtual Geosites (VGs), the Geographic Information System (GIS) environment, and Virtual Reality (VR). In our contribution, we have tried to shed light on the most relevant and cutting-edge papers dedicated to enabling the lay public, as well as Earth Science academics and students, to visualize geosites, almost always arranged in virtual geotours, so as to valorize the related geological heritage. It is also worth noting the importance and potential of a multidisciplinary and multicultural approach that the use of these technologies in a GIS environment supports, both in a geological and naturalistic context. In view of the above, VR plays a pivotal role: users have a chance to hover above ad-hoc created geological environments, by using ad-hoc devices that facilitate the overall experience. The viewers, in this way, experience an overall view of a VG, allowing them to examine particular elements of geosites at diverse aerial scales. In this regard, the pioneering paper by Bonali et al. [118] has attempted to obtain a statistically relevant evaluation of how scientists and students experienced immersive VR for geology-related education. Their results indicate that most participants would be keen on repeating the VR experience; most importantly, the majority of students and academics who participated in the experience confirmed the high value of this method for geo-education purposes.

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