IMMERSIVE 3D GEOVISUALIZATIONS OF GEOSITES IN DIFFERENT SCALES. COMBINING HIGH-RESOLUTION UAV DATA WITH A VIRTUAL REALITY ENVIRONMENT

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Abstract
Immersive 3D geovisualizations offer unprecedented opportunities for experiencing and exploring geosites, providing a powerful tool for conveying a geoheritage site's history and significance to diverse audiences. This study explores the integration of high-resolution unmanned aerial vehicle data with virtual reality environments to create immersive experiences in geosites and, more specifically, at Plaka's park in Sigrion on Lesvos Island, Greece. UAV scale-variant flight planning techniques were used to ensure that drone data acquisition has the correct spatial resolution based on a 1:50 cartographic scale. Additionally, terrestrial image acquisition was implemented to map the fossil sites on a cartographic scale of 1:5. Furthermore, terrestrial 360 panoramas were captured to enhance the immersive environment and the user experience. The data were processed to generate detailed 3D models of the sites and the fossilized tree trunks. The produced 3D models are integrated into a VR environment to create immersive user experiences. Through VR, users can explore the geosites fully interactively, gaining insights into their significance, unique placement, and fossil details. Integrating high-resolution UAVs with terrestrial data enhances the visual fidelity and realism of the VR experience, allowing users to navigate to the geosites with unprecedented detail and accuracy.

Keywords: *3D geovisualizations, UAV, Virtual Reality (VR), Geosites, Immersive environment*

INTRODUCTION

Geoparks encompass areas of profound geological significance, housing diverse geological formations distinguished by their scientific importance, rarity, and aesthetic appeal (Zouros, 2004). These regions often include globally significant geological heritage sites, reflecting the intricate geological history and formative events that have shaped their landscapes (Zouros, 2017). Geopark boundaries are carefully defined to include extensive areas containing internationally acclaimed geoheritage sites. Geoheritage, spanning global, national, regional, and local scales, serves as a repository of invaluable information about Earth's geological history, showcasing the myriad biotic and abiotic factors that have influenced its evolution (Gordon, 2018; Zafeiropoulos et al., 2021). Moreover, geoheritage sites serve as repositories of significant geological components such as rocks, minerals, and fossils, offering insights into the processes that have molded the Earth's surface over time (Joyce et al., 2018)

Geoheritage mapping is an essential procedure vital for managing and documenting geodiversity in support of the formulation and execution of geoconservation strategies (Bouzekraoui et al., 2018; Comănescu et al., 2012; Coratza et al., 2021; Fuertes-Gutiérrez & Fernández-Martínez, 2010; Gordon, 2019; Pál & Albert, 2019). The recent advancements in geographic information systems alongside geological, geographical, and geomorphological databases facilitate diverse cartographic applications in geoheritage (Cayla et al., 2014a; E. Papadopoulou et al., 2021; E. E. Papadopoulou et al., 2020). These systems contribute significantly to identifying, assessing, monitoring, and disseminating spatial data, thereby aiding in the comprehension, preservation, and promotion of geoheritage (Cayla et al., 2014b).

The extent of the geographical area occupied by a geosite significantly influences its mapping process, determining the appropriate geographic scale. This spatial coverage directly impacts the level of detail of geovisualization. Cartographic scale is also a crucial factor for both two-dimensional representations of geological features and three-dimensional depictions (Martin et al., 2014). Currently, there is ongoing research into scale considerations in the three-dimensional mapping of geosites and broader geological heritage (Chiabrando et al., 2017; E. Papadopoulou et al., 2021; E. E. Papadopoulou et al., 2020)

In recent years, significant advancements in cartographic science have been propelled by the emergence of novel geospatial data-collection instruments (Pavlis & Mason, 2017; Singh et al., 2018). Notably, the unmanned aerial vehicle (UAV) has revolutionized the acquisition of high-resolution imagery, offering a time-efficient, repetitive, and safe method for surveying challenging terrains (Jiménez-Jiménez et al., 2021; Nordin & Salleh, 2022; Papakonstantinou et al., 2016). Recent literature elucidates methodologies for 3D mapping spatiotemporal phenomena using UAVs, highlighting their utility across various domains. UAVs facilitate the transition from localized observations to regional mapping through earth-observation (EO) data, enabling high-quality, cost-effective monitoring at a local scale (Papakonstantinou et al., 2016). Advancements in data processing algorithms, such as structure-from-motion (SFM) and multi-view stereo (MVS), streamline the automated generation of 3D information from UAV imagery (Berra & Peppa, 2020; Franco & Naime, 2021). Furthermore, recent years have witnessed the emergence of augmented and virtual reality techniques for the 3D geovisualization of geographic data. Augmented reality (AR) supplements real-world environments with additional information, while virtual reality (VR) simulates immersive three-dimensional experiences (Billinghurst et al., 2014; Van Krevelen & Poelman, 2010; Vargas et al., 2020). These techniques find increasing application in geospatial analysis and land management, allowing users to explore geological formations remotely (Werner, 2018).

This study explores the integration of high-resolution unmanned aerial vehicle (UAV) data with virtual reality (VR) environments to create immersive experiences of geosites and, more specifically, Plaka's park in Sigrion on Lesvos Island, Greece. The combination of a) Very High-Resolution UAV data appropriate for a 1:50 cartographic scale mapping of the geopark, b)terrestrial images acquired to capture the fossil sites on a cartographic scale of 1:5, and c) terrestrial 360 panoramas were used to create and enhance a VR immersive environment. The produced 3D models are integrated into VR environments to create immersive user experiences. Thus, users can interactively explore the geosites, gaining insights into their significance, unique placement, and fossil details. The integration of high-resolution UAV data enhances the visual fidelity and realism of the VR experience, allowing users to navigate to the geosites with unprecedented detail and accuracy.

MATERIALS AND METHODS

Study area

The geosite selected is Plaka's park in Sigri, located in the western part of Lesvos island Aegean Region, Greece (Figure 1). It is an area of geological significance containing rare fossil deposits. Accessible via the coastal road linking Sigri and Eresos villages. Research has confirmed the presence of a substantial quantity of well-preserved plant fossils. The Park, inaugurated in July 2005, encompasses a 70-acre expanse bisected by the Sigri-Eresos rural road into western coastal and eastern inland sections. Within these two parts, significant fossils, primarily comprising root systems and tree trunks, constitute a geotope of exceptional rarity. The Park features 37 excavation sites showcasing fossilized trees preserving their original growth orientation. The Plaka Park in Sigri combines significant scientific and educational value with its natural landscape's unique beauty, allowing visitors to observe various geological formations and fossilized tree specimens. The study area was selected due to its impressive geomorphology and the combination of coastal and inland petrified formations.

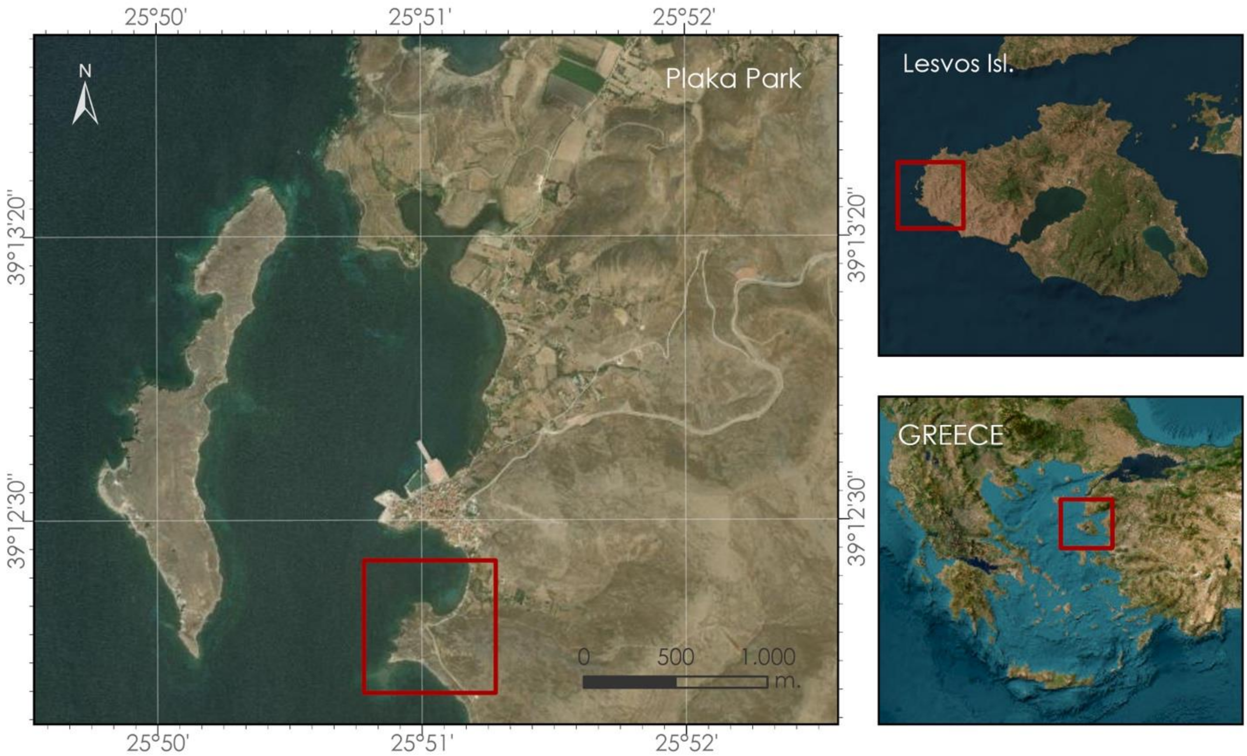

Figure 1. Map of the study area: Plakas geosite on Lesvos Island, Northeastern Aegean region, Greece.

Methodology

This research investigates the fusion of high-resolution unmanned aerial vehicle (UAV) data with terrestrial photos and 360 panoramas combined with virtual reality (VR) environments to establish immersive experiences of Plaka's park in Sigrion, Lesvos Island, Greece. Plaka's park is hosting over thirty fossilized points of interest. UAVs are utilized to capture high-resolution aerial imagery of the geopark. Scale-variant flight planning methodologies are employed to ensure drone data acquisition meets the desired spatial resolution at a 1:50 cartographic scale (E. Papadopoulou et al., 2021). Additionally, terrestrial image acquisition is conducted to document the fossil sites at a 1:5 cartographic scale.

Furthermore, terrestrial 360-degree panoramas are captured to enrich the immersive environment and user engagement. The obtained aerial and terrestrial images are subsequently processed using the SFM algorithm to produce detailed 3D models at both fossil and geosite scales. The 3D models generated were projected using the WGS84 geographic coordinate system. The Park areas were mapped at a resolution of 0.5 cm, and fossils and fossil-bearing sites at a resolution of 0.1 cm. The produced 3D models are integrated into VR environments to create immersive user experiences. Through the use of a cutting-edge VR immersive environment, users can fully and interactively explore the geosites. This enables them to gain valuable insights into each site's unique placement, fossil details, and overall significance. By seamlessly integrating high-resolution UAV data, the visual fidelity and realism of the VR experience are significantly enhanced. This level of detail and accuracy empowers users to navigate the geosites in an unparalleled way.

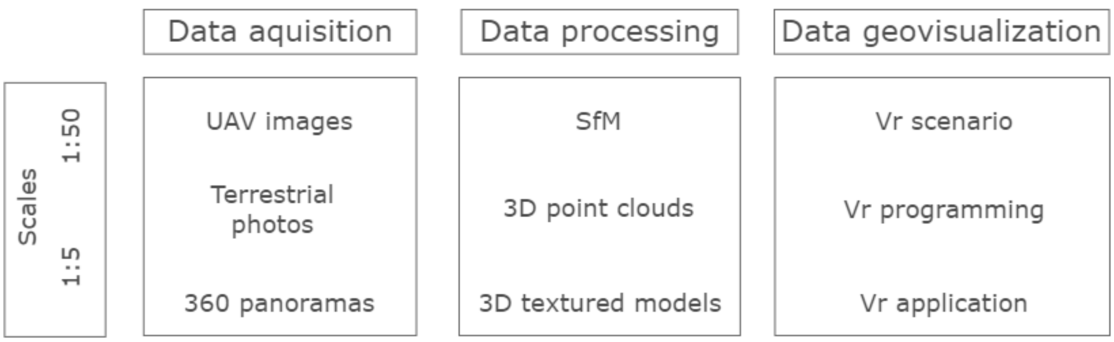

Figure 2. Methodology flow chart: data acquisition, data processing, 3D geovisualization (VR)

Equipment

The equipment used in this study comprises a UAV, a terrestrial camera, and a 360 camera. The UAV Matrice 300, manufactured by DJI, has been utilized for the mapping of Plakas Park on a geopark scale (1:50). The Matrice M300, equipped with the P1 optical camera, was used to collect the photos to create the orthomosaic. DJI Matrice 300 RTK offers up to 55 minutes of flight time. The quadcopter airframe design of the Matrice 300 RTK gives the system an Ingress Protection (IP) rating of IP45. In contrast, its mechanical design with quick-release landing gear and folding arms makes the platform easy to transport, store, and prepare for flight. (Da-Jiang Innovations, n.d.). The DJI P1 camera used is a professional-grade camera designed for aerial mapping and surveying applications. It features a large, high-resolution sensor with a 45-megapixel full-frame resolution and a global mechanical shutter, ensuring accurate and detailed image capture. The sensor has a three-axis stabilized gimbal for smooth and stable footage and is synchronized with the GPS and IMU (Inertial Measurement Unit). This synchronization enhances the accuracy of mapping and surveying data, making the P1 suitable for high-precision applications (Da-Jiang Innovations, n.d.).

The following cameras were used to realize terrestrial data acquisition of fossils, to achieve better spatial accuracy and visual fidelity, and to create 360° panoramas. The Nikon D3400 is a compact DSLR camera designed for entry-level photographers. It features a 24.2-megapixel DX-format CMOS sensor and an EXPEED 4 image processor, enabling high-quality images with low noise. It offers an ISO range of 100-25600, 5 fps continuous shooting, and full HD 1080p video recording at 60 fps (*Nikon*, n.d.). The GoPro Hero Max 360° is a versatile action camera capable of capturing immersive 360° footage. It features dual lenses that combine to create seamless 360° videos and photos, offering an immersive viewing experience (*GoPro MAX 360 Action Camera (Waterproof + Stabilization)*, n.d.). With its rugged and waterproof design, the GoPro Hero Max is suitable for capturing panoramas in any environment. It also offers advanced features such as in-camera stitching, horizon leveling, and six-microphone audio capture for high-quality sound. Additionally, it provides various shooting modes and stabilization options to ensure smooth and clear footage.

Data Acquisition

The aerial data collection was carried out with the UAV- DJI Matrice 300, realizing an automated mission on 17/09/2022. The flight was realized at a height of 40 meters, with 80% front and side lap, achieving very high-resolution images at a ground sample distance (GSD) of 0,5 cm/pixel. The GSD of 0,5 cm/pixel was appropriate for the 1:50 cartographic scale of the final visualizations. Finally, the total flight time was 35 minutes (air time). The UAV, DJI Matrice M300, employed for aerial photography acquisition was coupled with HxGN SmartNet, a GNSS correction service leveraging a proprietary network of reference stations (Hexagon, n.d.). HxGN SmartNet facilitates expedited determination of positions with a precision ranging between 1 to 2 centimeters. A total of 995 aerial images were collected during the data acquisition flight.

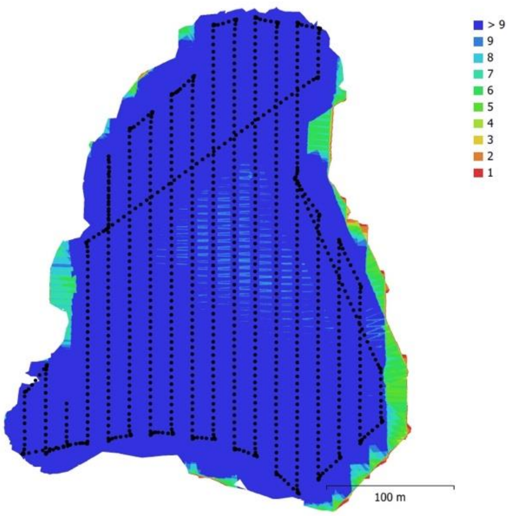

Figure 3. UAV aerial data positions and overlap from Plakas Park data acquisition on 17/09/2022.

Additionally to the aerial data, terrestrial data acquisition was realized on 18/09/2022 using the Nikon D3400 camera for all fossil places. The 16 fossil places were captured at 1:5 scale, thus with a resolution of 0,1 cm/pixel. A total of 576 photos were collected from terrestrial data acquisition. On the same day, 360-degree panoramas were captured to enrich the environment of the virtual reality (VR) space. More specifically, a 360° panoramic photo was captured outside the entrance of Plakas Park and from the center of the west part of Plakas Park to capture the surrounding environment, thus using it as an environment enhancement of the 3D model and the overall realistic impression. The panoramic photographs were captured using the GoPro Hero Max 360° camera, with a 16.6MP resolution and a 270° wide-angle lens. Additionally, they were taken from various distances outside the entrance to the Park, in front of the information sign. The camera's height was placed close to the eye level of an average person (about 170cm) using a tripod.

Figure 4. 360° panorama acquisition a) at the entrance and b) at the center of the west part of Plakas Park.

Data Processing

UAV spatial data acquisition and the SfM photogrammetric pipeline were implemented. The SfM pipeline is based on computer vision image processing algorithms (Micheletti et al., 2015). Using overlapping sequences of UAV images produce 3D textured meshes. All terrestrial and drone images were processed with Agisoft Metashape 3 (Agisoft, n.d.). The following table presents the details of all 3D meshes that were processed.

Table 1. Fossil Sites 3D reconstruction details.

Fossil Site	Mapping Scale	Processing Quality	3D Model faces	3D Model Vertices	Texture Mapping Mode	Texture Blending Mode
Plaka Park	1:50	Medium	12,310,154	6,155,668	Generic	Mosaic
1	1:5	Medium	6,579,267	3,339,608	Generic	Mosaic
2-3	1:5	High	260,507	131,136	Generic	Mosaic
4	1:5	High	168,707	85,004	Generic	Mosaic
5-6	1:5	High	125,395	63,992	Generic	Mosaic
7-8	1:5	High	220,114	110,804	Generic	Mosaic
12	1:5	High	859,097	432,228	Generic	Mosaic
13	1:5	High	812,243	408,655	Generic	Mosaic
14	1:5	High	686,401	345,737	Generic	Mosaic

16	1:5	High	4,678,251	2,345,801	Generic	Mosaic
17	1:5	High	499,076	251,943	Generic	Mosaic
19	1:5	High	1,618,229	819,235	Generic	Mosaic
20	1:5	High	1,008,849	508,349	Generic	Mosaic
Standing Fossil tree trunk	1:5	High	365,638	184,159	Generic	Mosaic
Decumbent Fossil tree trunk	1:5	High	394,494	198,289	Generic	Mosaic

VR Geovisualization

VR application design is based on a scenario formulated to thoroughly cover the information that needs to be transferred through virtual navigation (Gavalas et al., 2015; Kasapakis & Gavalas, 2015). The scenario's objective is to facilitate information dissemination through interactive and visual means to create a unified user experience in direct engagement with geological exhibits, particularly fossilized trees and root systems, within a virtual setting. The spatial narrative unfolds across Plakas Park, allowing users to select any park location with a fossil site utilizing a virtual map guide. The Lesvos Geopark provided this map, which depicts the area of the established Geopark on Lesvos island (Figure 5).

Figure 5. 3D geovisualization on VR environment of Lesvos Geopark Map. At the center, with the 3D symbol, Plakas Park is depicted. (Symbol annotation and Legend are in Greek)

The VR geovisualization created in this study primarily focuses on the Park of Plaka, wherein two distinct walking routes, delineated as the western and eastern segments, are made available for exploration. Within these routes, emphasis is placed on ten pivotal sites situated in the west section of the Park, showcasing excavated fossil locales. Users can interact through designated icons integrated within the user interface. Employing audiovisual media such as three-dimensional environments, photographs, and textual content, excavation findings are elucidated to the user. The application was implemented utilizing the Unity3d cross-platform game engine, developed by Unity Technologies, facilitating the creation of applications across diverse operating systems, including Android, iOS, and virtual reality platforms (*Unity Real-Time Development Platform | 3D, 2D, VR & AR Engine*, n.d.). To facilitate the development process, integration with the HTC Vive Pro VR was implemented (*VIVE Pro 2 Headset - High-Resolution Virtual Reality for PC*, n.d.). The Unity version employed was 2020.3.26f1 (64-bit).

The developed VR application contains three scenes, thus three different virtual spaces. The user starts the VR journey within the application at the initial scene, serving as an introductory point. Within this scene, the used select their desired place within the Lesvos Geopark Park (Figure 5). In this application, Plakas Park is the only available area. Progressing to the subsequent scene, situated at the core of Plaka Park, users can select their preferred walking route, limited to the western section pathway. Transitioning to the third scene initiates the VR tour unfolding within the western part of the Park. Users may explore the virtual environment in the first two scenes through headset movements supplemented by interactive icons (UI elements).

Conversely, within the third scene, users can teleport along a predefined trajectory spanning the upper to lower extents of the western part of Plakas Park. Furthermore, users can select specific excavation sites from the area map for instantaneous teleportation(Figure 6 b). Throughout the tour route, users may visit on a scale 1:1 the fossil sites, each rendered with spatial precision and visual fidelity to showcase excavation findings from data acquired from terrestrial acquisition at a 1:5 scale (Figure 6 d).

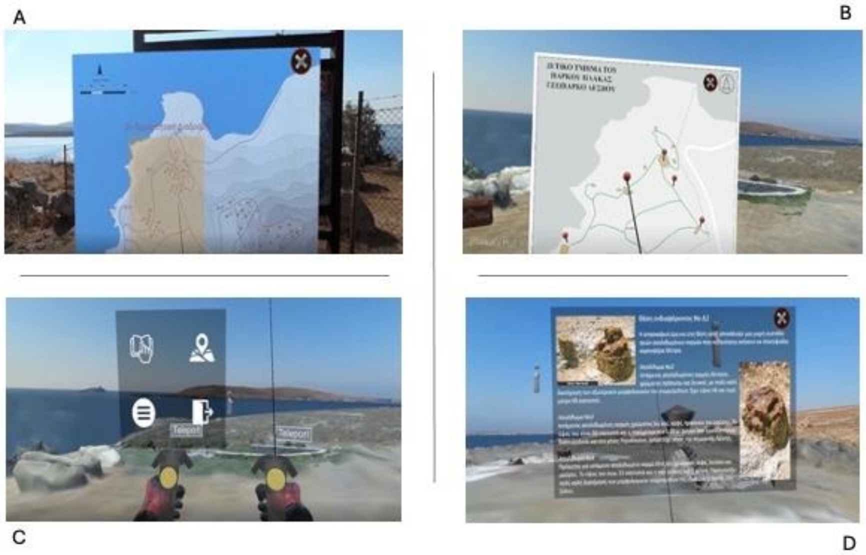

Figure 6. Depictions from Virtual reality environment a) Entrance to Plakas Park with virtual maps presenting the geopark. B) The virtual map is a tool of navigation that provides teleport to the used c)graphical icons acting as application aids (UI elements) d) thematic info for a fossilized place selected by the used. The info is used triggered when within the fossil place.

Users retain the ability to navigate between scenes and opt for alternative browsing options via the interface menu accessible from each scene (Figure 6 c). Throughout the app, thematic information and visual aids such as various elements, including scenes, images, backgrounds, slides, and icons, were created to achieve the best visual communication before their integration into Unity.

Figure 7. The symbology used in the VR environment to facilitate virtual exploration (Symbols are in Greek – English translations are as follows: Instructions / Exit / Location map / Menu / Bag / Close app).

CONCLUSIONS

The main conclusion from the proposed Immersive 3D geovisualizations of geosites in different scales is that combining high-resolution UAV data with a Virtual Reality environment underscores the pivotal role of cartographic scale and UAV-based data acquisition in facilitating the effective visualization of geospatial information within virtual reality (VR) environments. The cartographic outputs derived from UAV data exhibited successful geovisualization potential when presented at appropriate scales in VR settings. In the context of virtual tours of fossiliferous sites, VR geovisualization offers several advantages, including the ability to observe sites across different scales simultaneously, exploit the high resolution inherent in cartographic outputs, and facilitate interactive communication of inferred insights.

By providing immersive experiences that transcend physical boundaries, these technologies have the potential to democratize access to geosites and foster greater appreciation and understanding among diverse audiences. Integrating high-resolution UAV data with VR environments is a promising approach to creating immersive 3D visualizations of geosites. Through a combination of advanced technologies and innovative methodologies, these immersive experiences offer new ways for exploring, interpreting, and experiencing geoheritage in the digital age.

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BIOGRAPHY

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Dr Ermioni Eirini Papadopoulou earned her BSc, MSc & PhD in Geography from the University of the Aegean, focusing on cartography and geoinformation. During her PhD, completed in 2023, she actively contributed to numerous research projects, including 3D mapping and representation of archaeological work, documentation, and monitoring through 3D mapping methods for the management of geological monuments and utilization of UAV with LiDAR technology for the 3D mapping of the area Vrisa and Vatera, affected after the fire on 12/7/22. Notably, she is a licensed drone operator. Her PhD thesis investigates issues related to the 3D mapping of geological heritage monuments, employing contemporary methods and tools such as UAVs. Additionally, it studies themes in the geovisualization of cartographic results using virtual and augmented reality techniques. Dr. Papadopoulou (Scopus Author ID: 57214571352, ORCID ID: 0000-0003-4122-8450) has published more than 13 papers in peer-reviewed journals and conference proceedings, has a Scopus h-index of 5, and has more than 60 citations in Scopus.

Elefterios Karaelefteriou holds a Bachelor's degree in Computer Science and Cultural Informatics and an MSc in Cultural Informatics and Communication, specializing in VR environments. With expertise in 3D/VR technologies, he has a strong foundation in computer science and cultural studies. His academic background is complemented by practical experience in integrating high-resolution UAV data with VR environments for immersive geospatial experiences. Passionate about leveraging technology to enhance cultural heritage, he brings a unique blend of technical skills and cultural insights to VR and cultural informatics.