

Geoscience popularisation in Geoparks: A common workflow for digital outcrop modelling

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ABSTRACT

Geodiversity has gained increasing attention, prompting geoscientists to advocate for its recognition to promote holistic nature conservation. UNESCO Global Geoparks (UGGps) have expanded globally, promoting geoheritage and contributing to geoconservation and sustainable tourism. In this framework, the IGCP 714 project, "3GEO – Geoclimbing & Geotrekking in Geoparks," launched in 2021, aims to use Geographical Information Technologies (GIT) – including GIS, remote sensing, Unmanned Aerial Vehicles (UAVs), and other geospatial tools - to enhance geoscience communication within UGGps. However, there is still a significant need for a repeatable, accessible, low-cost, and effective workflow to integrate these digital technologies into geoscience communication effectively. This study developed a workflow for creating Digital Outcrop Models (DOMs) of geosites and geodiversity sites used for recreational climbing and trekking. Using technologies such as UAVs and Smartphones equipped with LiDAR sensors, the workflow generates DOMs that can be integrated into web-GIS applications and Virtual Reality experiences, offering interactive educational content. Four examples are described, illustrating the implementation of the DOM workflow from the outcrop scale (La Pedriza Granitic Batholith, Spain, and Etna Volcano Lava Tube, Italy) to the terrane scale (Organ Pipes Columnar Jointing, Australia, and Baceno Tectonic Window, Italy). The workflow is designed to produce DOMs for public and student engagement, demonstrating their potential for broader educational and geoconservation applications. Moreover, the workflow aims to build capacity among Geopark practitioners and researchers by improving techniques for creating content on geoheritage features and enhancing geoscience communication. For this, the workflow is designed to be repeatable by employing common and relatively low-cost GIT tools. We discuss the need for investment in capability, software, and hardware to equip Geopark practitioners with the skills required to implement this workflow. By applying this workflow to create DOMs of geoheritage features, we demonstrate its potential to enhance the appreciation of geodiversity, support education and research, and promote sustainable geotourism within UGGps.

1. Introduction

Since the mid-1990s, the concept of geodiversity has gained increasing attention among geoscientists, with many advocating for the recognition of geodiversity, to foster a more holistic approach to nature conservation (Boothroyd and Henry, 2019; Brilha and Reynard, 2018; Gray, 2021; Monge-Ganuzas et al., 2024; Williams et al., 2020). This advocacy supports the establishment of specific laws to protect and

manage geoheritage and geodiversity sites (sensu Brilha et al., 2018), addressing legislative gaps in geoheritage site protection. Concurrently, the Geoparks concept, introduced to protect and promote geoheritage, has seen rapid global expansion now encompassing 213 UNESCO Global Geoparks (UGGps) in 48 countries. While UGGps have been successful, their establishment alone does not ensure protection unless there is complete overlap with designated protected areas and the geoheritage within is managed according to best practice principles (Crofts et al.,

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2020). This ongoing need in geoconservation highlights the necessity in geoscience popularisation among the general public, stakeholders and practitioners in charge for geoheritage protection and sustainable promotion.

UGGs, in particular, are ideal locations for geoscience popularisation and education activities, contributing to geoconservation and sustainable promotion of geoheritage. Catana & Brilha (2020) analysed how UGGs can address many of the UN's 17 Sustainable Development Goals (SDGs), prompting a 2019 initiative to develop new geoscience promotion guidelines within UGGs. Recent strategies have involved integrating new technologies into outdoor activities, enhancing geoscience popularisation (Bollati et al., 2024a; Dong et al., 2024; Quesada-Valverde and Quesada-Román, 2023). These digital experiences, enhanced with annotations on multimedia products that link geological and geomorphological features with climbing routes, not only help users understand the significance of the geoheritage but also highlight the cultural ecosystem services offered by geodiversity to society (Gray et al., 2013). This approach broadens access to outdoor recreation sites for people with disabilities or limited access, as well as the general public under pandemic restrictions (Fassoulas et al., 2022).

The use of innovative technologies is increasingly being used in geoscience education, with tools such as Unmanned Aerial Vehicles (UAVs), LiDAR scanners, Smartphones and Tablets, being used to create 3D multimedia products that enhance geoheritage sites at different scales (Papadopoulou et al., 2022). These products are being customised to create user-led activities based on immersive technologies, including virtual, augmented and mixed reality (Aldighieri et al., 2016; Bollati et al., 2024b; Cayla et al., 2014; Fassoulas et al., 2022; Goyanes et al., 2021; Hincapié et al., 2023; Martínez-Graña et al., 2019; Papadopoulou et al., 2021; Pasquaré Mariotto et al., 2023; Pasquaré Mariotto and Bonali, 2020; Perotti et al., 2020; Vandelli et al., 2024; Williams and McHenry, 2020). These technologies, grouped under the nomenclature of Geographical Information Technologies (GIT) (Williams and McHenry, 2020), offer the potential of revolutionising UGG operations, changing how geoheritage and geodiversity sites are experienced and promoted, and are crucial for deepening the appreciation of the geodiversity and cultural heritage.

Photogrammetry and LiDAR, in particular, have important roles in Earth Science due to their distinct technological strengths. LiDAR is effective for generating high-resolution data and excels in mapping surfaces irrespective of light conditions, making it ideal for documenting small to medium-scale geological and geomorphological features using a portable scanner, especially on a smartphone equipped with a built-in LiDAR scanner (Corradetti et al., 2022; Luetzenburg et al., 2021; Tavani et al., 2022). Photogrammetry, although limited in low-light conditions, performs well in brightly lit environments and is highly effective when combined with UAVs for accessing and documenting large or remote geological outcrops (Campos et al., 2022; Fazio et al., 2024; Granados-Bolaños et al., 2021; Jordan, 2019). As these technologies become more accessible, they offer extensive opportunities for detailed geological mapping and reconstructing geoheritage sites.

The use of GIT in geoscience education can significantly advance multiple Sustainable Development Goals (SDGs), such as SDG 4 - Quality Education and SDG 11 - Sustainable Cities and Communities, by enhancing awareness of natural resources. Albers et al. (2017) demonstrated this through a citizen science activity using smartphone-based augmented reality for environmental monitoring that also served to raise awareness in the public and schools. Bollati et al., (2024a) illustrated how geosites at high risk of degradation can be preserved and explored virtually through 3D models, fostering geoconservation and enhancing educational outcomes. Additionally, UGGs often include geosites that offer recreational activities like climbing and trekking, which not only promote visitor health and well-being (SDG 3) but also support local economic growth (SDG 8) when conducted alongside experts and guides. These activities, coupled with digital educational content such as 3D models of geoheritage sites (Bollati et al., 2024b),

increase engagement with geodiversity, furthering educational objectives (SDG 4).

Utilising GIT at popular outdoor recreation sites can enhance awareness of geodiversity, promoting both education and geoconservation. *Geoclimbing*, which combines outdoor climbing with the study of geological and geomorphological features of rock outcrops, serves as an example of how outdoor activities can popularise geoscience. From an educational and scientific point of view, climbing routes are ideal locations for studying the geomorphology of areas where it would be very difficult to do so without these climbing activities (García-Rodríguez, 2015). Geoclimbing also helps to explain the influence of geology and geomorphology on climbing styles and difficulty (Bollati et al., 2014, 2016, 2018, 2024b; García-Rodríguez and Fernández-Escalante, 2017; Garlick, 2009; Williams and McHenry, 2020). This understanding of the geology helps climbers understand how best to climb these formations, avoid unstable rock bands, and select the appropriate gear for protection (Garlick, 2009). Similarly, geotrekking and georafting also promote geoheritage appreciation through outdoor activities (Bollati et al., 2024a). The IGCP 714 project, "3GEO – Geoclimbing & Geotrekking in Geoparks: methods and tools for enhancement, sustainable fruition and educational projects" launched in 2021, aims to enhance geoscience communication within Geoparks focusing on geodiversity and geoheritage sites equipped for climbing or located along trekking routes, taking advantages of both outdoor activities and GIT. However, there is still a significant need for a repeatable, accessible, low-cost, and effective workflow to integrate GIT into geoscience communication strategies. Bollati et al. (2024a) described the methodology through which the most suitable geoheritage and geodiversity sites equipped for climbing or located along trekking routes have been selected in the framework of the IGCP 714 project. These sites will be the object of a 3D modelling strategy. Additionally, they demonstrated the preliminary 3D models realised using different kind of tools and methodological strategies by different IGCP 714 project partners. The aim of this work is to proceed further by documenting a common workflow, developed by some of the IGCP 714 project partners, for creating 3D models using accessible GITs. Hence, this study focuses on a workflow expressly set to create Digital Outcrop Models (DOMs) of geoheritage and geodiversity sites used for recreational climbing and those located on trekking routes. The investigation highlights the potential for geoscience communication through a web-GIS digital platform, which serves as a repository for DOMs stored online on SketchFab, showcasing iconic climbing cliffs and trekking routes. Additionally, emerging technologies such as virtual reality have been employed to enhance the DOMs, transforming them into an engaging educational experience that promotes and raises awareness of geodiversity in UGGs.

2. Digital outcrop modelling workflow

A multifaceted approach was employed using a variety of 3D data capture devices, selected for their suitability based on the scale, accessibility, and geometry of the geoheritage feature. Advanced techniques in digital modelling and remote sensing, based on LiDAR-enabled smartphones and Structure from Motion (SfM) photogrammetric techniques employing smartphone, UAV-mounted cameras, and Digital Single-Lens Reflex cameras (DSLR) are considered. These technologies are used to construct comprehensive and accurate DOMs of geoheritage features used for climbing and located along trekking routes, enabling a cost-effective and versatile data collection process, accommodating the unique characteristics and challenges presented by different geoheritage sites and geodiversity sites.

2.1. DOM classification and 3D data capture technology

The geological and geomorphological features of interest within the IGCP 714 project may span a range of spatial scales and vary in

geometric complexity. These parameters determine the appropriate selection of a 3D data capture technology used to produce a DOM (Fig. 1). For feature classification based on scale, we adopt the guidelines from the Geoheritage Tool-Kit (Brocx and Semeniuk, 2011).

- i) crystal (e.g. minerals, fossil, and pebbles at small scales);
- ii) outcrop/bed (e.g. cliff, bed, or rock at meso-scales);
- iii) terrane (e.g. cliff or landscape at large to regional scales).

To ensure that the process of collecting data was cost-effective and versatile, four 3D data capture technologies were identified as suitable for acquiring 3D geospatial information based on the feature scale, accessibility, lighting conditions, and feature geometry. (Fig. 2).

- i) Smartphones (Photogrammetry): this ground-based technology becomes the preferred choice due to its widespread availability,

when the feature scale ranges from crystal to outcrop/bed, and the geometry is simple i.e. a single dimension. Favourable lighting conditions and easy accessibility are required, which allow for complete coverage of the feature dimensions.

- ii) Smartphones (LiDAR): an alternative to ground-based photogrammetry, this technology offers high-resolution modelling with precise depth accuracy, and it is appropriate for features from crystal to outcrop/bed scale. It is the preferred technology when lighting conditions are variable, and the feature has complex geometry i.e. multiple dimensions.
- iii) UAVs (Photogrammetry): an aerial survey approach using a UAV is ideal for capturing data across outcrop to terrane scale features that are difficult to access and are generally with favourable lighting conditions.
- iv) Combination of UAVs, Smartphones, and DSLR (LiDAR and Photogrammetry): this hybrid approach achieves multiple levels

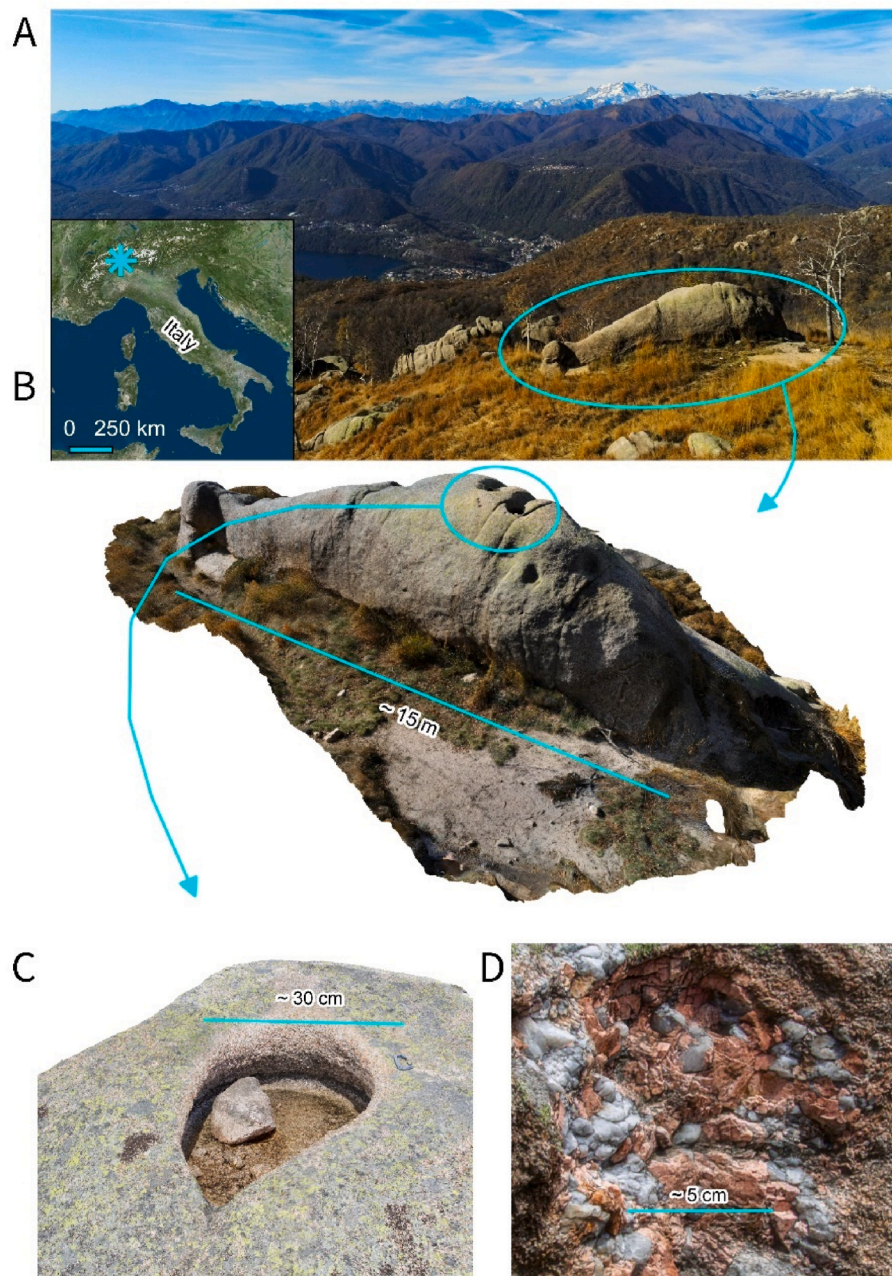


Fig. 1. (A) Scale variation examples: from the large terrane scale (B, C) through to outcrop/bed of meso-scale (D) to the small scale of crystals (D).

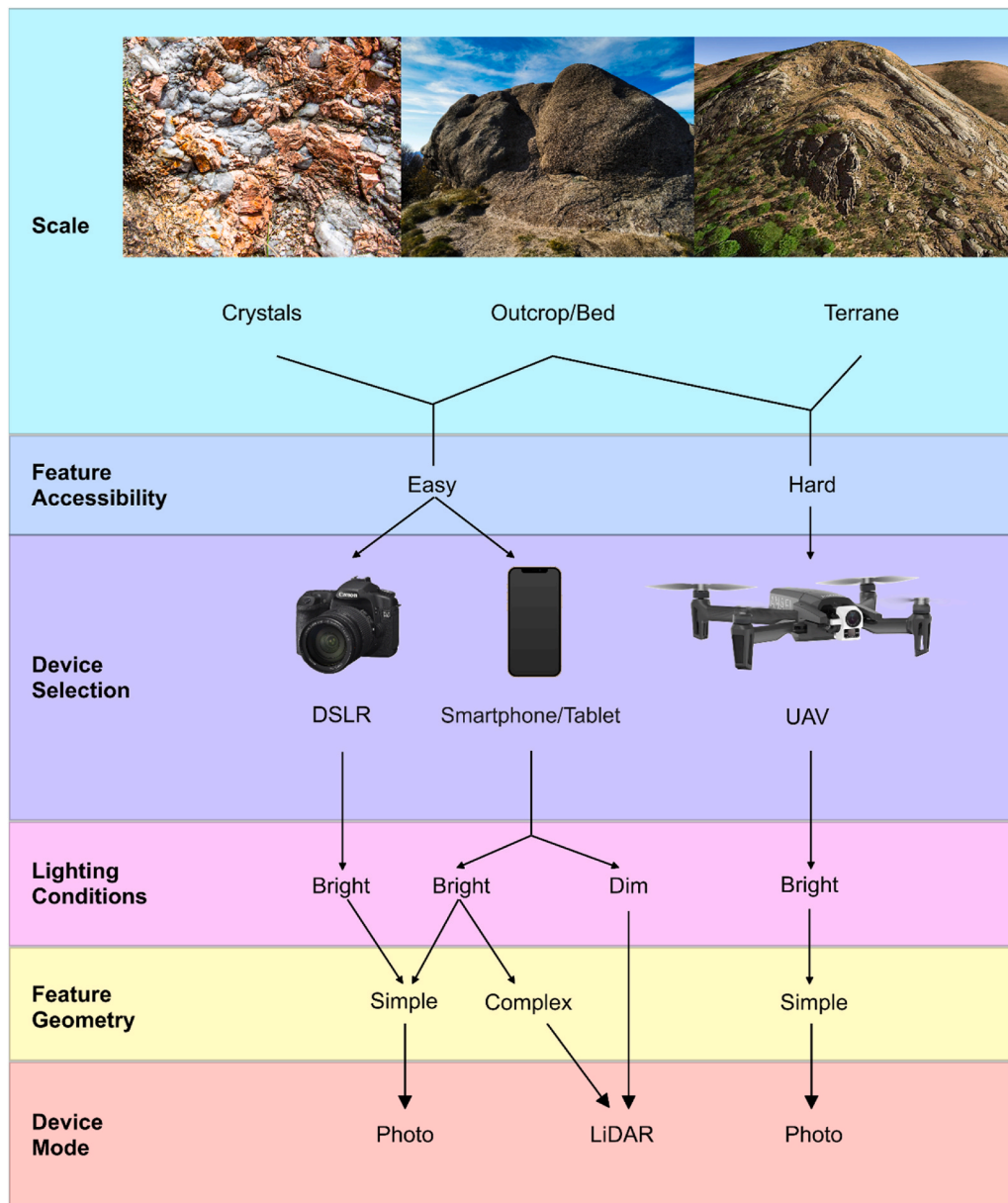


Fig. 2. 3GEO Workflow for determining the most appropriate 3D capture technology based on DOM parameters of size, access, lighting and geometry.

of resolution over terrane scale areas by creating sub-DOMs for specific features. The choice of technology for each sub-DOM is determined based on access, lighting, and geometry of the feature. These sub-DOMs are then integrated into larger, multi-scale DOM.

2.2. Data capture and processing procedures

The subsequent sections outline the data capture and processing strategies implemented by IGCP 714 for each technology to ensure the effectiveness of DOM reconstruction and complete surface coverage of the feature. The mission plan and processing approach are tailored based on the geometry of the feature, and the strategies vary according to scale of the feature and the chosen technology.

2.2.1. UAVs (photogrammetry)

The scanning process for the aerial-based photogrammetry approach utilised consumer level UAVs (e.g. DJI Phantom 4) with various mission planning applications, (e.g. Pix4Dcapture Pro). For features with

simpler geometry dominated by one dimension, vertical or horizontal missions should be employed, while a circular mission is recommended for features with multiple dimensions (Fig. 3). For multidimensional features at very large scales i.e., terrane, multiple mission plans covering each dimension are recommended. In such cases, a mixed mission plan is employed and, additional data should be capture at 45° to connect data from the previous missions.

These aerial surveys can be conducted in both automatic and manual data configurations, providing versatility for different features. Manual surveys, for instance, can mitigate the impact of signal interference stemming from mineralogy/morphology and vegetation. However, in both types of missions, it is recommended to maintain an overlap of approximately 70–80 % among captured images. This overlap is typically achieved by executing successive strips aligned parallel to the primary dimension of the feature being surveyed (Deliry and Avdan, 2021) (Fig. 4A).

Effective data capture for features involves maintaining specific flight altitudes - 1 and 10 m for outcrop/bed scale, and 10–80 m for terrane scale. The camera angle should ideally be fixed at 90°, parallel to

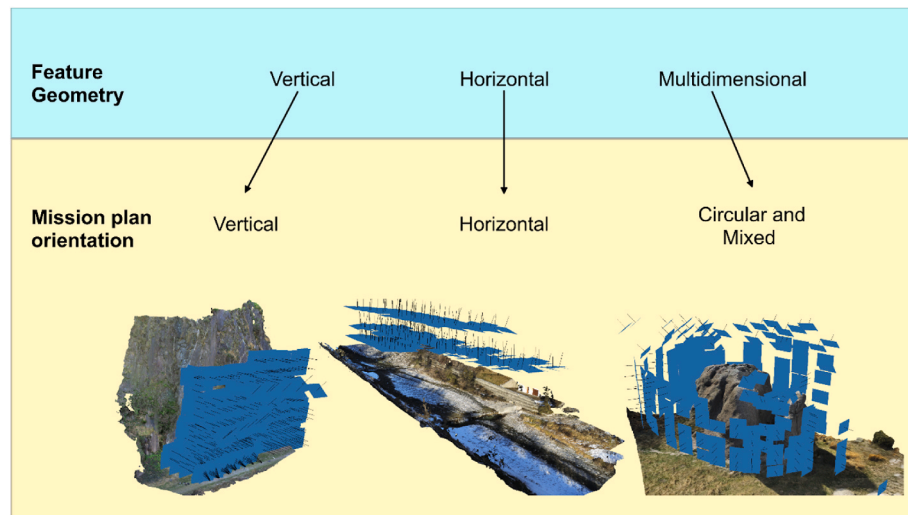


Fig. 3. UAV mission plan based on feature geometry.

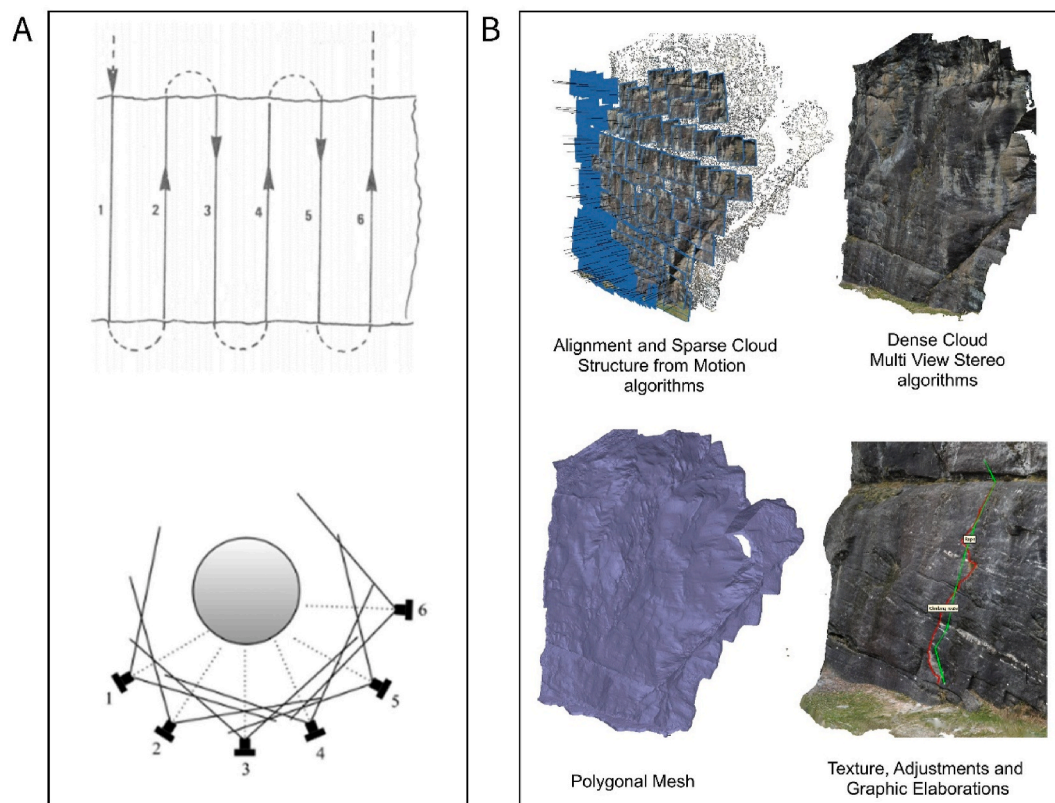


Fig. 4. (A) UAV data capture (B) and processing workflow.

the feature's primary surface, though in practice it may vary between 70° and 90° (Fig. 4A). To minimise blur effects, it is advisable to capture imagery at 3-s intervals at low flight speeds in calm wind conditions. For best image quality, captures should be scheduled for midday hours during the summer, when sunlight is most direct, avoiding cloudy days.

The data processing of UAV data is best performed using common photogrammetry software (e.g. Agisoft Metashape or Pix4Dmapper). These software packages leverage feature detection and matching algorithms for tie point identification and SfM Multi View Stereo (MVS) algorithms to reconstruct the feature into a DOM. The initial processing stage involves alignment and sparse cloud construction, which requires

selecting a quality level from high to highest, based on the dataset size and processor capabilities (Fig. 4B). Dense cloud construction entails applying the same quality settings along with depth filtering and point colour adjustments for quality assurance. Polygon mesh construction includes aesthetic adjustments such as removing unwanted objects or filling gaps. Lastly, texture building involves enhancing contrast and brightness to finalise the appearance of the DOM. Some photogrammetry software, such as Agisoft Metashape, supports annotating the DOM with lines, which is useful for interpretation of geological/geomorphological features or providing sport information such as climbing routes.

2.2.2. Smartphones (photogrammetry and LiDAR)

The scanning process for the ground-based photogrammetry approach utilised a common Tablet or Smartphone, such as an iPhone with a 1.0 m selfie stick, using the 3D Scanner App (<https://m.3dscannerapp.com/m?id=GZw75hT>) in the Photos mode. The mission planning adheres to the general guidelines used in aerial photogrammetry approach (complete coverage, perpendicular trajectory, guaranteed overlap of at least 70 %, parallel strips coverage, a constant and slow speed, and good lightning conditions) (Fig. 5A). Similar to UAV surveys, there is an option between automatic and manual data capture, which can be used interchangeably during a mission. In automatic mode, the application captures images about every 0.8 s.

Currently, LiDAR scanners are only available on iPhones and iPads, although the smartphone LiDAR market is expected to grow as the technology becomes more cost effective (Jha, 2022). The LiDAR scanning utilised the LiDAR Advanced mode of the 3D Scanner App, and the data capture process is similar to that used in Photos mode but with the advantage of real-time feedback during scanning, allowing users to make immediate adjustments for high quality data (Fig. 5B). Additionally, the scan can be resumed using an extend scan function, which allows for repositioning or covering areas of the feature that were missed in the initial scan.

While LiDAR and Photos data capture modes use distinct sensors, both employ surface reconstruction algorithms to generate a seamless surface representation from dense point clouds. The 3D Scanner App offers three processing quality options: High Definition, Medium, and Fast. These options vary in texture quality, and the processing speed is based on the quality option chosen and the mode of data capture. In Photos mode, the photos are used to generate a surface by matching features across images, whereas the LiDAR mode employs real-time surface reconstruction with minimal post-processing required. Upon completion of the of the initial DOM, the application allows for further post-processing options, including adding textures; automatically filling in gaps or holes in the mesh; measuring dimensions, distances, or angles; and integration with other software tools or platforms to add annotations. In the case of the ICGP 714 project, annotations include geological or geomorphological features and sport-related information such as climbing routes.

2.2.3. Digital Single-Lens Reflex (DSLR) camera

High-quality digital cameras, including DSLRs and mirrorless models, are often superior to smartphone cameras due to their higher-quality optics and sensors. These advantages contribute to improved survey quality and the successful creation of photogrammetric 3D models. As with previous techniques, survey guidelines follow general photogrammetric principles, requiring complete coverage of the object, a generally consistent and perpendicular trajectory between the sensor

and the object, and an image overlap of approximately 70 %.

The main limitations of digital cameras are their size, weight, and difficulty in capturing objects with significant vertical components. A DSLR camera can be used alongside a UAV camera to enhance model resolution. Higher-resolution detail can be captured in lower portions accessible through DSLR surveys, while upper portions are captured at a lower resolution using UAV surveys. Despite their limitations, DSLRs remain a reliable alternative, demonstrating their full potential when used for surveying objects with low vertical dimensions. Additionally, extension poles or high-capability drones can help overcome challenges in capturing tall vertical structures.

3. Limitations of digital outcrop modelling workflow

Although the 3D capture technologies used in the workflow are common and easy to employ in collecting and processing data for DOM reconstruction, it is important to consider and overcome their various limitations to optimise data collection and ensure satisfactory DOMs.

UAV operation is regulated by country-specific regulations, often requiring permits, leading to long waiting periods to collect data and, in some cases, making data collection impossible. Additionally, piloting UAVs demands specialised professionals with expertise and experience in aerial data collection methods. While consumer-level UAVs are economical, the data processing procedures necessitate specific software of a certain complexity, incurring additional expenses.

Although smartphones are highly accessible, LiDAR mode is only available on certain iPhones or iPads, which can be more expensive than other smartphone or tablet options. Beyond the costs, primary limitations of using smartphones include challenges with surface properties, where highly reflective surfaces, intense light, and shadows can disrupt the construction of the point cloud, thereby impacting DOM quality. In LiDAR mode, areas with dense vegetation containing complex structures, such as grass and bushes, cannot be effectively scanned. Additionally, issues arise with feature dimensions; Photos mode generally produces better DOMs of crystal-scale features (Fig. 6A), whereas LiDAR mode often leads to meshing problems if their dimensions are insufficiently prominent (Fig. 6B). At the outcrop scale in LiDAR mode, angular objects with sharp peaks and edges can produce distortions, producing holes in the mesh and incomplete DOMs (Fig. 6C).

Furthermore, the 3D Scanner App used in this workflow restricts image storage capacity to 250 images per scanned feature when used in Photos mode. This constraint may be overcome by using an alternative commercial scanning application. Additionally, processing times in Photos mode is longer than in LiDAR mode due to the need to construct a point cloud using SfM techniques, and the absence of a real-time mesh preview in Photos mode introduces more errors into the scanning, making it difficult to ensure complete coverage of the feature.

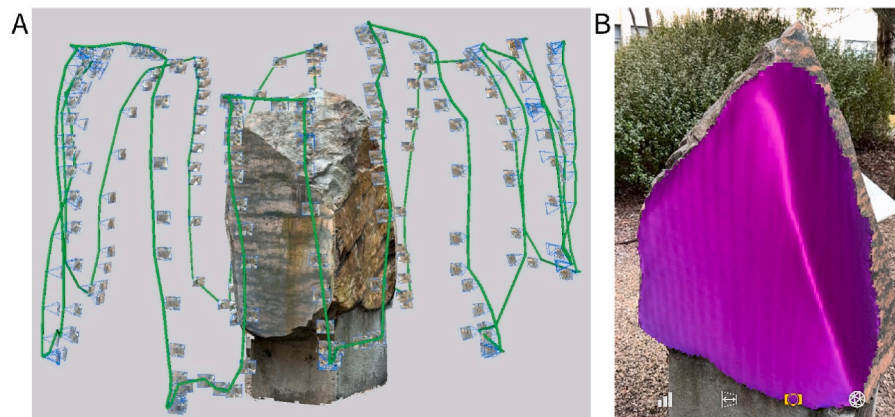


Fig. 5. (A) Camera position showing parallel strips coverage. (B) Real-time feedback scanning method in LiDAR Advanced mode.

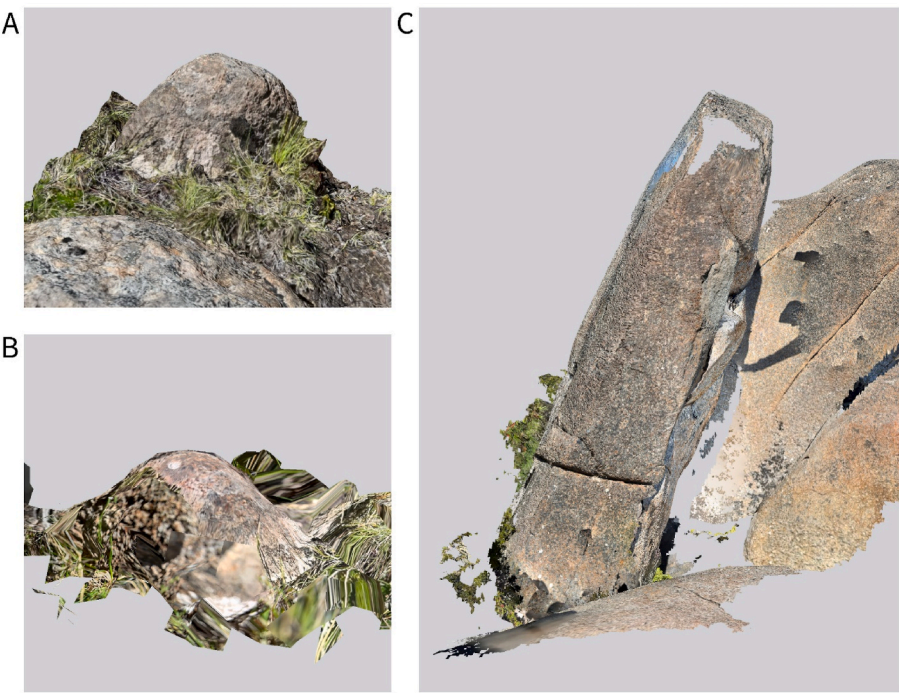


Fig. 6. (A) DOMs of a crystal-scale feature using Photo mode (B) compared with LiDAR mode, (C) and an outcrop scale feature with incomplete mesh due to modelling errors.

4. Examples of application of the digital outcrop modelling workflow

Four example geoheritage or geodiversity sites are described below to illustrate the implementation of the DOM workflow at various scales and using the appropriate 3D capture technologies and processing strategies. In Table 1, the main features of the four example case studies are summarised. The first example is an outcrop/bed to terrane-scale granitic batholith, the second is an outcrop/bed-scale basaltic eruption system featuring a lava tube, the third is a terrane-scale doleritic intrusion featuring outcrop-scale features, and the fourth is a terrane-scale metamorphic exposure related to tectonic uplift. These examples of DOMs are aimed at communicating geoscience to climbers, trekkers, and students, and to demonstrate the repeatability, accessibility, and relatively low-cost of the workflow that can be employed by Geopark practitioners and educators. The 3D models have been uploaded to the IGCP 714 project collection named 3GEO on SketchFab (<https://skfb.ly/psJY0>).

[ly/psJY0](https://skfb.ly/psJY0)).

4.1. La Pedriza Granitic Batholith, Spain

La Pedriza, part of the Sierra de Guadarrama National Park, is one of the most emblematic natural areas in Spain, renowned for its granitic geomorphology that have attracted naturalists and climbers since the early 20th century. Several studies have identified this area as significant for understanding weathering and erosion processes on granite that give rise to climbing walls (de Pedraza et al., 2014; García-Rodríguez, 2015; García-Rodríguez and Fernández-Escalante, 2017). The fractures, dykes, mineralogical composition, and weathering processes that shape these climbing environments are of particular interest, highlighting the intricate interplay between geological formations and erosional dynamics.

Los Brezos, an easily accessible area in La Pedriza, has many slab climbs at outcrop to terrane scale between 10 and 60 m in length of

Table 1
Summary information on the case studies proposed by the IGCP 714 project.

Name	Location	Lithology	Landform	Scale (crystal; outcrop/bed; terrane)	Acquisition device(s)	Processing software(s)	SketchFab link (s)
La Pedriza Granitic Batholith	Sierra de Guadarrama, Spanish Central Range, Spain	Granite	Block faulted granitic domes and tors	Outcrop/bed to terrane	LiDAR	3d Scanner App	https://skfb.ly/psKpq ; https://skfb.ly/psKoY ; https://skfb.ly/psKoO
Etna Volcano Lava Tube System	Etna, Sicily, Italy	Basalt	Lava tunnel	Outcrop/bed to terrane	LiDAR	Scaniverse	https://skfb.ly/p9pHU
Organ Pipes Columnar Jointing	Wellington Range, Tasmania, Australia	Dolerite	Periglacial escarpment with blockfields	Outcrop/bed to terrane	UAV	Agisoft Metashape	https://skfb.ly/psJXp ; https://skfb.ly/6TvWX
Baceno Tectonic Window	Italian Alps, Verbano- Cusio-Ossola, Italy	Micaschist with garnet	Fluvio-glacial cliff	Terrane	UAV and DSLR Camera	Agisoft Metashape	https://skfb.ly/psJZt https://skfb.ly/psJZA

varying difficulty levels. The difficulty of the routes depends, in addition to the slope of the wall, on certain geomorphological features such as roughness, hardness, alteration of the rock, flaking, micro-reliefs, hardened surfaces, and polygonal cracks. A ground-based survey approach was employed using a iPhone 14 Pro equipped with a LiDAR sensor to capture some of the features in addition to access by rappelling down climbing routes (Fig. 7A). The data was processed through the 3D Scanner App using the Smartphone (LiDAR) workflow. Annotations can be added to these DOMs and shared with climbers (Fig. 7A), and detailed DOMs can be used to study the geomorphology of the climbing sites (Fig. 7B and C).

4.2. Etna Volcano Lava Tube system, Italy

Mount Etna in southern Italy is the highest active volcano in Europe. A geotrekking route, aimed at students and trekkers, has been proposed on the eastern slopes of Mount Etna visiting two geosites of national importance (Fig. 8A). The route starts at sea level near Aci Castello and Acitrezza, at two small villages 15 km north of Catania, where the earliest submarine eruptions of Etna took place 500 kya (Corsaro and Cristofolini, 2000). The submarine eruptions display a reddish aureole from contact with the clays forming the ancient marine seabed (Acitrezza seastacks), displaying some spectacular examples of prismatic columnar basalts (Fig. 8B). The route ends in the village of San Gregorio, where a lava tube is well preserved inside a nature reserve (access inside the cave is possible only for scientific purposes for small groups of visitors with the presence of the natural reserve staff). The protected natural area called 'Complesso grotte Immacolatelle-Micio Conti' located in San Gregorio (CT) consists of a system of volcanic caves inside a lava field of Hawaiian morphology. In Micio Conti Cave (Fig. 8C), the passage of lava has left striations on the walls, lava rolls at the base of the walls, lava ropes and small stalactites-like features due to partial melting of the dome. These syngenetic lava caves, formed during eruptions and lava flows, develop predominantly in a planar fashion, with a course roughly parallel to the outer surface of the flow as the lava exits the vent and begins to lose heat and cool.

To capture DOMs of both the coastal basalts and the lava tubes/caves

on the geotrekking route, multiple technologies were utilised using a ground survey approach. An iPad Pro 11", equipped with a LiDAR sensor, was used to capture DOMs of the prismatic columnar basalts with the Smartphone (LiDAR) approach. The Micio Conti lava tube system was surveyed by walking inside the lava cave using the same iPad device, adopting the Smartphone (Photogrammetry) approach. To produce the DOMs, the 3D Scanner App and Scaniverse applications were used following the Smartphone (LiDAR) and Smartphone (Photogrammetry) approaches, and the resulting DOMs were uploaded to a web repository (<https://skfb.ly/p9pHU>) for visualisation and geoscience education for the general public and students.

4.3. Organ Pipes Columnar Jointing, Australia

The Organ Pipes, a geosite of district significance in Tasmania, Australia, is a columnar jointed Jurassic dolerite cliff, part of a dolerite intrusion covering a large portion of the Wellington range. This formation represents the edge of a horst block related to rifting and the breakup of super-continent Gondwana. As a world class climbing destination, only 20 min away from the centre of Hobart, it features hundreds of climbing routes at all difficulty grades.

The Organ Pipes is a terrane-scale feature, it includes multiple outcrop-scale geomorphological features embedded into the main geosite. A DJI Phantom 4 Pro UAV was used to capture the extent of the 'Organ Pipes' using an automated horizontal mission, with additional vertical and circular missions, and several manual missions for outcrop-scale features that are embedded into the main cliff line. The data was processed through Agisoft Metashape 1.5.3 using the UAV (photogrammetry) workflow and the resulting DOMs have been made accessible on Sketchfab of the IGCP 714 project (<https://skfb.ly/psJXp>). An annotated version of the model, featuring geoscientific information (<https://skfb.ly/6TvWX>), is available to enhance the understanding of the area's geological evolution (Fig. 9A). Embedded DOMs of different scales are accessible via links within the main DOM (Fig. 9B and 9C).

Due to its proximity to Hobart and walking trails, it is frequented by trekkers and climbers and is often used as a site to teach university students about the geological history of the southern Tasmania. The

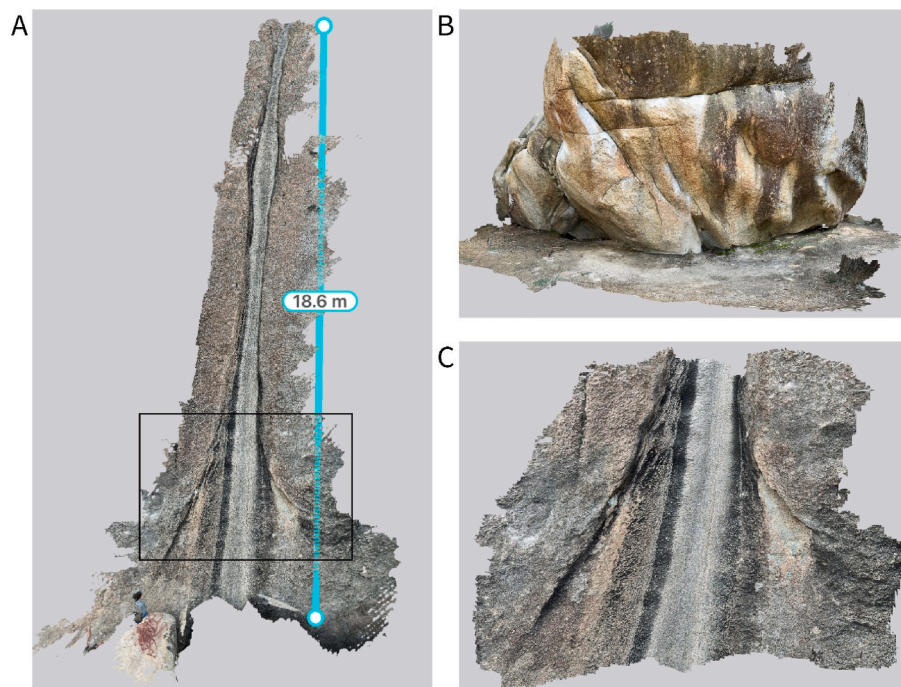


Fig. 7. (A) Annotated DOM of a climbing route in Los Brezcos using Smartphone (LiDAR) workflow (<https://skfb.ly/psKpq>). (B) Granite block where geoclimbing is practiced (<https://skfb.ly/psKoY>). (C) Detail of the lower part of the climbing route (<https://skfb.ly/psKoO>).



Fig. 8. (A) Geotrekking route on Etna Volcano. (B) Coastal prismatic columnar basalt. (C) DOM of Micio Conti Cave/lava tube system using Smartphone (LiDAR) workflow (<https://skfb.ly/p9pHU>).

DOMs of this geosite have been used to compliment an inventory for the Wellington Park reserve and as a teaching resource for university students (Williams and McHenry, 2021).

4.4. Baceno Tectonic Window, Italy

The Premia-Balmalfredda cliff, a geosite of national significance in Verbano-Cusio-Ossola, Italy, is a tectonic window where the deepest tectonic units of the European Alps outcrop due to tectonic uplift and fluvio-glacial erosion. The dominant lithology is micaschist, showing mica- and quartz-rich layering, with visible garnets, and amphibolitic boudins, shaped by glacial and fluvial geomorphological processes (Fig. 10). The cliff exposure is 80 m high and is a historical climbing destination in the Ossola Valley with more than 60 climbing routes at various difficulty grades. Moreover, the site is an ideal spot to host climbers with families or large groups of school students for both recreation and school excursions.

A combined aerial survey approach using an Anafi Parrot UAV was chosen considering the terrane-scale features that are difficult to access from the ground, while a DSLR camera was used to capture data from the ground of the climbing wall. The survey was performed using an automated vertical dimension mission up to the legally permitted limit of 120 m above ground level, supplemented with manual data capture using a smartphone camera, fixed at 5-s intervals. The data was processed through Agisoft Metashape 1.8.5 using the UAV (photogrammetry) workflow, and the resulting DOM is available on Sketchfab of the IGCP 714 project (<https://skfb.ly/psJZt>, <https://skfb.ly/psJZA>). This DOM has been used to complement outdoor activities for school students, enhancing their understanding of the geosite, used both before and after the field visit. Bollati et al. (2018) tested the integration of

outdoor and geoclimbing activities, where school students were guided by professional alpine guides and geologists at the Balmalfredda climbing wall and trekked along the different fluvio-glacial gorges of the Urieggio Glacial Garden.

5. Discussion

This study presents a workflow for creating DOMs of geoheritage sites and geodiversity sites of varying scales that are popular with recreational climbers or located on trekking routes. The workflow aims to build capacity in Geoparks practitioners, researchers, and educators by improving the techniques for creating content on geoheritage features and enhancing geoscience communication. The workflow is designed to be accessible to Geopark practitioners, educators, and researchers, and repeatable by employing common and relatively low-cost GIT tools using established 3D surface reconstruction methodologies.

The 3D data capture technologies employed in the workflow are widely accessible, though certain specific equipment may be necessary for capturing geoheritage features under particular conditions. For instance, LiDAR technology is especially effective in low-light environments, and UAVs are required for capturing terrane-scale features. DSLR or other high-quality cameras are commonly used by geoscientists in field surveys. They are particularly well-suited for creating 3D models of low-relief objects or for complementing UAV surveys. The cost of acquiring a capable smartphone equipped with a high-quality camera or LiDAR sensor is generally affordable, and consumer-level UAVs fall within the budgetary constraints of most UGGPs. Additionally, the small size of these capture devices makes them highly portable and practical for use by Geopark practitioners, as well as educators and researchers. This portability allows for the easy transportation of equipment to



Fig. 9. (A) A DOM of the doleritic Columnar Jointed ‘Organ Pipes’ on kunanyi/Mount Wellington with geological annotations. (B) Johnstone’s Knob and (C) Albert’s Tomb DOMs are isolated tors made accessible via links with the main Organ Pipes DOM (<https://skfb.ly/psJXp>; <https://skfb.ly/6TvWX>).

various geoheritage sites and geodiversity sites, facilitating the capture of detailed data in diverse field conditions. Geopark practitioners, can easily capture field data for UGGp operations e.g. for a geosite inventory or for monitoring degradation, as well for geoscience communication. Educators can utilise these tools for hands-on teaching experiences, bringing real-world geoscience into the classroom and integrating manual laboratory activities with the digital equivalent (Bollati et al., 2024b). Researchers, on the other hand, benefit from the ability to collect high-resolution data efficiently, enhancing the quality and scope of their studies.

The primary purpose of these DOMs is to raise awareness of geoheritage and deepen understanding of geodiversity, thereby fostering improved geoconservation practices within UGGps. These DOMs offer detailed, multidimensional representations of geoheritage features, enabling the visualisation of outcrops and landforms. Although a DOM provides visualisation, it alone is not suitable for educational purposes and requires integration with other GIT tools to be effective in geoscience communication. For effective geoscience communication, DOMs need to be accessible and supplemented with educational materials. This can be facilitated through other accessible GIT tools, such as Web-GIS, and immersive technologies such as Virtual Reality (VR) or Augmented Reality (AR), which are particularly important for providing engaging experiences for general public as well as students, climbers, and trekkers.

The use of DOMs has been increasingly recognised for its role in producing interpretative illustrations for environmental education. Studies such as those by Quoos et al. (2021) and Lemmi and Quoos (2024) employed both smartphone and UAV photogrammetry to generate 3D representations of the landscape within the Baleia Franca Environmental Protection Area in Brazil. These representations enable

the visualisation of 3D models using AR directly on a smartphone without the need for specific applications. This educational resource was developed to enhance the understanding of the heritage and cultural aspects of these sites.

To increase the accessibility of DOMs produced with our workflow, a Web-GIS digital platform can provide access to the DOMs, along with location data and supplementary information such as geological data to provide context, through interactive, user-friendly interfaces that allow for manipulation of DOMs. To illustrate this, a Web-GIS application using ESRI’s ArcGIS Online has been developed for the 3GEO project (<https://arcg.is/8u15L>, see Fig. 11). This user-friendly application provides an intuitive platform for exploring virtual geoclimbing and geotrekking worldwide. With a user-friendly map interface like Google Maps, users can navigate various geoheritage and geodiversity sites enriched with geological attributes and links to DOMs. DOMs can be hosted on a number of platforms for visualisation such as YouTube or Sketchfab (as for the IGCP 714 case: <https://skfb.ly/psJYo>) for various levels of interactivity and immersion. For example, the Premia-Balmafregia geoclimbing site provides a video tour of the geoheritage feature (Fig. 11C), and Disappearing Tarn geotrekking site (Fig. 11D), provides an interactive DOM annotated with geological information about its formation.

Additionally, links can be provided to external websites providing information about trekking and climbing routes to further engage recreational users of these geoheritage features. The key benefits of using these GIT tools include being able to deploy them with limited technical background, build with a no-code application builder, seamless integration with the ESRI ecosystem, and comprehensive cloud-based capabilities.

To further enhance the visualisation and communication



Fig. 10. (A, D) The “Tango” climbing route at Premia Balmafregia climbing wall. (B) DOM created using the UAV (photogrammetry) workflow (<https://skfb.ly/psJZt>). (C) Micaschist, showing mica- and quartz-rich layering. (E) Student climbing the “Tango” route during the geoclimbing experience with secondary school students.

effectiveness of DOMs, a VR experience can also be developed using VR platforms for a fully immersive experience. Several DOMs can be linked into a virtual geotrail experience, allowing users, including those with accessibility issues, to visit several geoclimbing and geotrekking sites in an area. Annotations incorporate detailed information about the geological evolution of the region and the significance of each geoheritage site or geodiversity site, as well as embedding climbing route annotations directly onto geoclimbing DOMs.

To illustrate this, a virtual geotrail was created in the Wellington Park, Tasmania, Australia using 360 VR by ESRI, linking three DOMs, one terrane-scale geosite with embedded outcrop-scale features, one outcrop-scale geodiversity site, and one terrane-scale geodiversity site that has mixed recreational uses (<https://arcg.is/00umX9>, see Fig. 12). The main geosite on the virtual geotrail, the Organ Pipes DOM (<https://skfb.ly/psJXp>) is presented as several stops, visiting different sections of this terrane-scale geoheritage feature, including several outcrop-scale sub-features with separate DOMs. Each DOM has annotations, containing information about the geological history, and displays the key climbing areas with routes that can be selected for specific information about the climb including a description and the grade of the route (Fig. 12A and B). This example also includes a mixed-use geodiversity site, Devil’s Gulch (<https://skfb.ly/6DGG7H>), that is mainly used for trekking but contains a few climbing routes (Fig. 12C).

This VR experience has been used at various public and student outreach events to engage tertiary and high school students, as well as climbers, and trekkers. The VR interface is very easy to use, with all the stops presented in the interface at the bottom of the display, taking you to a new 360° panorama with clickable annotations. The experience is also cross platform compatible, accessible through mobile, desktop, and VR goggles (Fig. 12D), and is easily configurable, as an extension of an ArcGIS Online web-GIS application.

A secondary purpose for the DOMs that can be useful for Geoparks is in research. DOMs can assist in the analysis of geomorphological processes by allowing visualisation of processes such as fracturing, water seepage, and the presence of biological crusts. The ability to rotate the image represents a substantial improvement over conventional photography. The software used to create these DOMs also generates a folder containing all the individual images from the scanning process, which can be invaluable for observing DOM details. Additionally, the apps facilitate the immediate creation of moving videos of the DOMs, which can be easily uploaded to social media platforms to demonstrate impacts of research and provide further outreach. For both field and desktop study, DOMs are excellent tools for detailed analysis, allowing measurements, surface calculations, slope assessments, and the observation of rock details from various angles. These DOMs help identify rock flaking mechanisms, fracture morphology, rock texture, surface

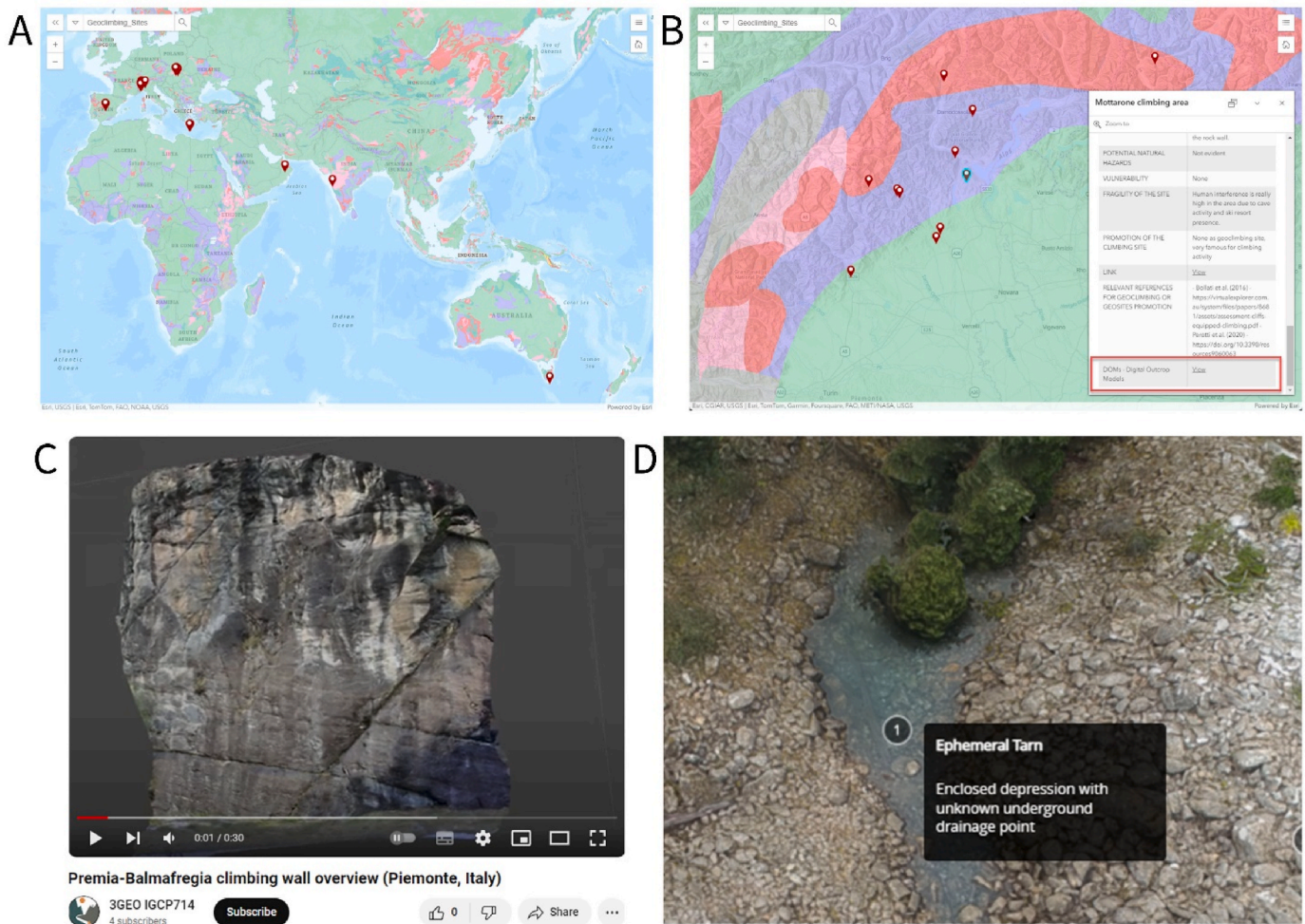


Fig. 11. (A) Web-GIS application of geoclimbing and geotrekking sites, (B) providing detailed geological information and links to DOMs, (C) using a range of visualisation platforms including YouTube (https://www.youtube.com/watch?v=U_8NYBlBZ5A) (D) and Sketchfab (<https://skfb.ly/6XxyC>).

calcifications. High resolution DOMs, capable of identifying details as small as 1–2 cm, can be captured over time, allowing monitoring to occur, providing valuable insights into its geomorphological evolution.

Ultimately, the outcome of using DOMs for education or research is to ensure that the geoheritage and geodiversity in UGGPs is protected for perpetuity. DOMs offer a detailed and interactive way to study and present geoheritage features, making them invaluable tools for both researchers and educators. By investing in the development of these DOMs, UGGPs can provide more engaging and informative experiences for visitors, thereby increasing public appreciation and understanding of geoheritage. This will require some investment from UGGPs themselves, through their own budgets, and the sharing of best practice training, which could be facilitated through regional Geopark networks. Additionally, collaborating with universities and industry partners can make these initiatives more economical by sharing costs and resources. Such partnerships can also bring in advanced GIT tools and expertise, further boosting the effectiveness of creating DOMs, leading to improved geoconservation outcomes.

6. Conclusions and future work

The use of innovative GIT tools for geoscience communication, such as DOMs, is highly appreciated by the general public and school students, as demonstrated by [Bonali et al. \(2021\)](#). To facilitate the use of these technologies, there has been a proliferation of the methods for creating DOMs of geoheritage sites and geodiversity sites ([Hincapié](#)

et al., 2023; Pasquaré Mariotto et al., 2023).

With the rapid evolution of GIT tools, there was a need to produce a consistent workflow for creating DOMs that is repeatable, accessible, low-cost, and effective in raising awareness of geodiversity. Therefore, the development of a standardised and common workflow for DOMs for IGCP 714 was essential. Integrating additional GIT tools such as Web-GIS and VR adds educational content to DOMs, providing effective educational experiences for climbers, trekkers, students, and the general public. Moreover, there are opportunities to use DOMs in research to study geosites. Both educational and research applications contribute to a better understanding of geodiversity and improved geoconservation outcomes.

This workflow has shown how GIT tools can be used to promote geodiversity through geoscience popularisation, making geoscience education and geoheritage accessible to a broader audience, including those with accessibility issues. However, the workflow alone is not enough to realise the full potential of this DOM workflow. To equip Geopark practitioners with the requisite skills to capture and process data to produce DOMs and integrate them into engaging and immersive GIT tools, further investment in capability, software, and hardware is required. This will address the disparity in economic resources among different UGGPs, as the availability of equipment for constructing DOMs (e.g., UAVs, smartphones) varies. Further work will involve training Geopark practitioners to create similar DOMs, not only at geoclimbing sites but also along geotrekking routes ([Fassoulas et al., 2022](#)) and for other geosites and geodiversity sites that are used for recreation. This

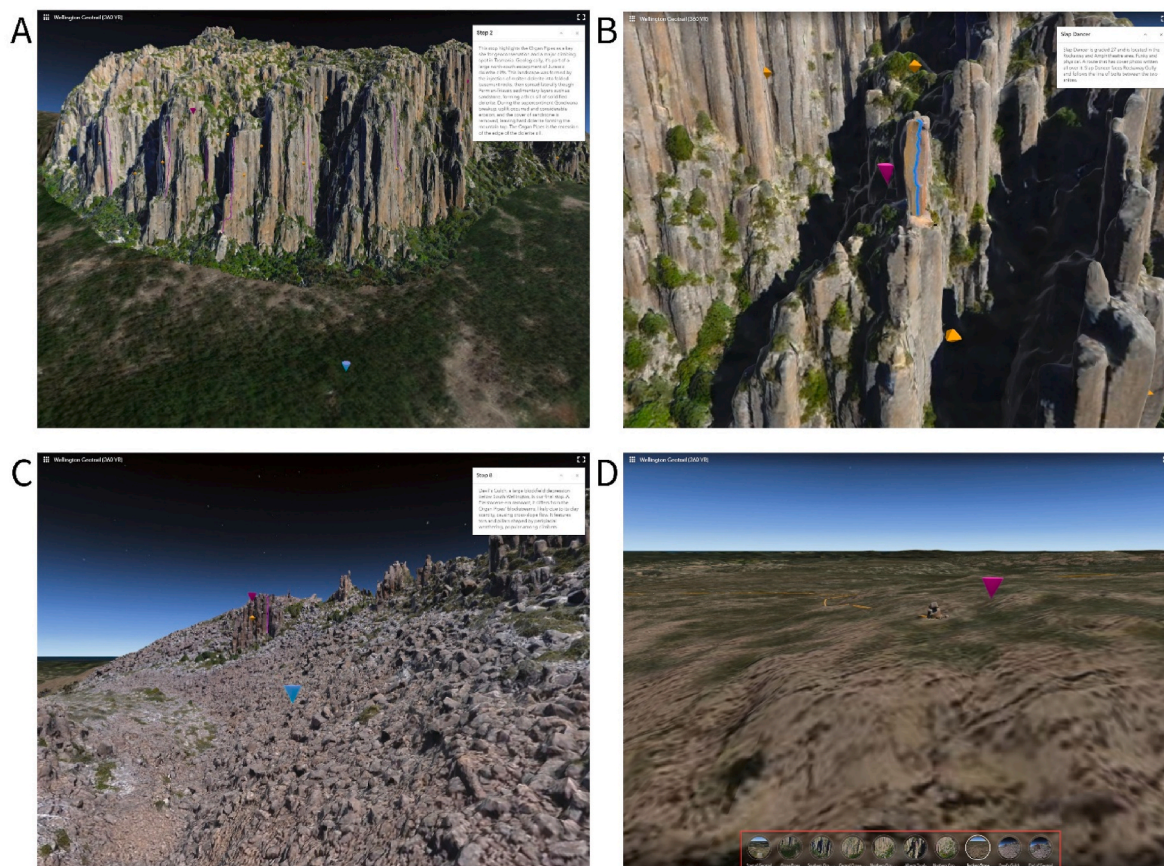


Fig. 12. (A, C) VR experience highlighting annotated geoscience information, and (B) climbing routes along a thematic virtual geotrail. (D) The VR experience consists of a number of 360° panoramas navigable using a user-friendly interface.

will ensure that Geopark practitioners can implement this workflow and provide effective geoscience communication.

Building on our workflow, recent advancements in artificial intelligence are opening new possibilities in the analysis of DOMs, enhancing the identification of key geological structures such as fractures, stratigraphic discontinuities, and significant morphological patterns. Machine learning and deep learning algorithms have already been successfully applied for seismic data interpretation (Wang et al., 2018) and geohazard detection (Ma and Mei, 2021). In the future, such technologies could potentially be integrated into this workflow to enable automated and more detailed mapping of geological features. However, significant challenges remain, particularly in handling geological features at different spatial scales—ranging from crystal to terrane scales—as current technologies and software lack the compatibility to seamlessly link features across these scales. Nonetheless, ongoing technological advancements could eventually enhance DOM surveying and analysis for geoheritage sites in UGGPs, making AI-driven workflows a promising area for future research.

CRediT authorship contribution statement

Mark A. Williams: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Gianluca Tronti:** Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Data curation. **Raiza Sartori Peruzzo:** Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Data curation. **Manuel García-Rodríguez:** Writing – original draft, Software, Data curation. **Eugenio Fazio:** Writing – original draft, Software, Data curation.

Michele Zucali: Writing – review & editing, Software. **Irene Maria Bollati:** Writing – original draft, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

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Data availability

Data will be made available on request.

References

- Albers, B., De Lange, N., Xu, S., 2017. Augmented citizen science for environmental monitoring and education. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* 42, 1–4. <https://doi.org/10.5194/isprs-archives-XLII-2-W7-1-2017>.
- Aldighieri, B., Testa, B., Bertini, A., 2016. 3D exploration of the san lucano valley: virtual geo-routes for everyone who would like to understand the landscape of the dolomites. *Geoheritage* 8 (1), 77–90. <https://doi.org/10.1007/s12371-015-0164-x>.
- Bollati, I., Masseroli, A., Dongre, A., Knight, J., Williams, M., Fernández-Escalante, E., Forzese, M., Goyanes, G., Kandekar, A., Maniscalco, R., Nikolakakis, E., Palomba, M., Pelfini, M., Tronti, G., Zanoletti, Enrico, Zerboni, A., Zucali, M., 2024a. The IGCP 714 project “3GEO – geoclimbing & geotrekking in geoparks” – selection of geodiversity sites equipped for climbing for combining outdoor and multimedia activities. *Geoheritage* 16, 79. <https://doi.org/10.1007/s12371-024-00976-4>, 2024.
- Bollati, I., Masseroli, A., Scanduzzi, C., Tronti, G., Zucali, M., Pelfini, M., 2024b. Tips for new educational experiences in the secondary school based on outdoor activities and 3D modelling of rock outcrops equipped for climbing. *Rendiconti Online Della Società Geologica Italiana* 62, 35–44. <https://doi.org/10.3301/ROL.2024.06>.
- Bollati, I., Gatti, C., Pelfini, M., Speciale, L., Maffeo, L., Pelfini, M., 2018. Climbing walls in Earth Sciences education: an interdisciplinary approach for the secondary school (1st level). *Rendiconti Online Società Geologica Italiana* 44. <https://doi.org/10.3301/ROL.2018.19>.
- Bollati, I., Fossati, M., Zanoletti, E., Zucali, M., Magagna, A., Pelfini, M., 2016. A methodological proposal for the assessment of cliffs equipped for climbing as a component of geoheritage and tools for Earth Science education: the case of the Verbanio-Cusio-Ossola (Western Italian Alps). *J. Virtual Explor.* 49.
- Bollati, I., Zucali, M., Giovenco, C., Pelfini, M., 2014. Geoheritage and sport climbing activities: using the Montestrutto cliff (Austroalpine domain, Western Alps) as an example of scientific and educational representativeness. *Italian Journal of Geosciences* 133 (2), 187–199. <https://doi.org/10.3301/IJG.2013.24>.
- Bonali, F.L., Russo, E., Vitello, F., Antoniou, V., Marchese, F., Fallati, L., Bracchi, V., Corti, N., Savini, A., Whitworth, M., Drymon, K., Mariotto, F.P., Nomikou, P., Sciacca, E., Bressan, S., Falsaperla, S., Reitano, D., Van Wyk De Vries, B., Krokos, M., et al., 2021. How academics and the public experienced immersive virtual reality for geo-education. *Geosciences* 12 (1), 9. <https://doi.org/10.3390/geosciences12010009>, 2022.
- Boothroyd, A., Henry, M.M., 2019. Old processes, new movements: the inclusion of geodiversity in biological and ecological discourse. *Diversity* 11. <https://doi.org/10.3390/d11110216>.
- Brilha, J., Gray, M., Pereira, D.I., Pereira, P., 2018. Geodiversity: an integrative review as a contribution to the sustainable management of the whole of nature. *Environ. Sci. Pol.* 86, 19–28. <https://doi.org/10.1016/j.envsci.2018.05.001>.
- Brilha, J., Reynard, E., 2018. Geoheritage and geoconservation: the challenges. *Geoheritage: Assessment, Protection, and Management* 2018, 433–438. <https://doi.org/10.1016/B978-0-12-809531-7.00025-3>.
- Brocx, M., Semeniuk, V., 2011. The global geoheritage significance of the Kimberley Coast, Western Australia. *J. Roy. Soc. West Aust.* 94 (2), 57–88.
- Campos, N., Quesada-Román, A., Granados-Bolaños, S., 2022. Mapping Mountain landforms and its dynamics: study cases in tropical environments. *Appl. Sci.* 12 (21), 10843. <https://doi.org/10.3390/app122110843>.
- Catana, M.M., Brilha, J.B., 2020. The role of UNESCO global geoparks in promoting geosciences education for sustainability. *Geoheritage* 12 (1). <https://doi.org/10.1007/s12371-020-00440-z>.
- Cayla, N., Hoblé, F., Reynard, E., 2014. New digital technologies applied to the management of geoheritage. *Geoheritage* 6, 89–90. <https://doi.org/10.1007/s12371-014-0118-8>.
- Corradetti, A., Seers, T., Mercuri, M., Calligaris, C., Buseti, A., Zini, L., 2022. Benchmarking Different SfM-MVS Photogrammetric and iOS LiDAR Acquisition Methods for the Digital Preservation of a Short-Lived Excavation: A Case Study from an Area of Sinkhole Related Subsidence. *Remote Sensing* 14 (20), 5187. <https://doi.org/10.3390/rs14205187>.
- Corsaro, R.A., Cristofolini, R., 2000. Subaqueous volcanism in the Etnean area: evidence for hydromagmatic activity and regional uplift inferred from the Castle Rock of Acicastello. *J. Volcanol. Geoth. Res.* 95, 209–225. [https://doi.org/10.1016/S0377-0273\(99\)00130-4](https://doi.org/10.1016/S0377-0273(99)00130-4).
- Crofts, R., Gordon, J.E., Gray, J., Gunn, M., Santucci, J., 2020. Guidelines for geoconservation in protected and conserved areas. *Best Practice Protected Area Guideline Series* 31. <https://doi.org/10.2305/IUCN.CH.2020.PAG.31.en>.
- de Pedraza, J., Carrasco, R.M., Domínguez-Villar, D., 2014. Geomorphology of La Pedraza granitic massif, Guadarrama. *Landscapes and Landforms of Spain*, pp. 71–80. https://doi.org/10.1007/978-94-017-8628-7_5.
- Deliry, S.I., Avdan, U., 2021. Accuracy of unmanned aerial systems photogrammetry and structure from motion in surveying and mapping: a review. *Journal of the Indian Society of Remote Sensing* 49, 1997–2017. <https://doi.org/10.1007/s12524-021-01366-x>.
- Dong, Z., Tang, P., Chen, G., Yin, S., 2024. Synergistic application of digital outcrop characterisation techniques and deep learning algorithms in geological exploration. *Sci. Rep.* 14, 74903. <https://doi.org/10.1038/s41598-024-74903-6>.
- Fassoulas, C., Nikolakakis, E., Staridas, S., 2022. Digital tools to serve geotourism and sustainable development at psiloritis UNESCO global geopark in COVID times and beyond. *Geosciences* 12 (2). <https://doi.org/10.3390/geosciences12020078>.
- Fazio, E., Ortolano, G., Alsop, G.I., D’Agostino, A., Visalli, R., Luzzi, V., Salvemini, F., Cirrione, R., 2024. Enhanced structural analysis through a hybrid analogue-digital mapping approach: integrating field and UAV survey with microtomography to characterise metamorphic rocks. *J. Struct. Geol.* 187, Scopus. <https://doi.org/10.1016/j.jsg.2024.105213>.
- García-Rodríguez, M., 2015. Environmental education and sports. How geomorphology conditions climbing. The example of the Pedraza del Manzanares (Madrid). *Enseñanza de Las Ciencias de La Tierra* 320–329.
- García-Rodríguez, M., Fernández-Escalante, E., 2017. Geo-Climbing and Environmental Education: the Value of La Pedraza Granite Massif in the Sierra de Guadarrama National Park, Spain. *Geoheritage* 9 (2), 141–151. <https://doi.org/10.1007/s12371-016-0187-y>.
- Garlick, S., 2009. *Flakes, Jugs, and Splitters A Rock Climber’s Guide to Geology*. Rowman & Littlefield.
- Granados-Bolaños, S., Quesada-Román, A., Alvarado, G.E., 2021. Low-cost UAV applications in dynamic tropical volcanic landforms. *J. Volcanol. Geoth. Res.* 410, 107143. <https://doi.org/10.1016/j.jvolgeores.2020.107143>.
- Goyanes, G., Vieira, G., Soncco, C., Castro, E., 2021. 3D modelling of geosites—from surveying to outreach. In: *9th International Conference on UNESCO Global Geoparks*, vol. 270.
- Gray, M., 2021. Geodiversity: a significant, multi-faceted and evolving, geoscientific paradigm rather than a redundant term. *Proc. Geologists’ Assoc.* 132, 605–619. <https://doi.org/10.1016/j.pgeola.2021.09.001>.
- Gray, M., Gordon, J.E., Brown, E.J., 2013. Geodiversity and the ecosystem approach: the contribution of geoscience in delivering integrated environmental management. *Proc. Geologists’ Assoc.* 124 (4), 659–673. <https://doi.org/10.1016/j.pgeola.2013.01.003>.
- Hincapié, M., Cifuentes, L.M., Valencia-Arias, A., Quiroz-Fabra, J., 2023. Geoheritage and immersive technologies: bibliometric analysis and literature review. *Episodes* 46, 101–115. <https://doi.org/10.18814/epiugs/2022/022016>.
- Jha, S.N., 2022. Smartphone LiDAR market. <https://www.factmr.com/report/smartph-one-lidar-market>.
- Jordan, B.R., 2019. Collecting field data in volcanic landscapes using small UAS (sUAS)/drones. *J. Volcanol. Geoth. Res.* 385, 231–241. <https://doi.org/10.1016/j.jvolgeores.2019.07.006>. https://ui.adsabs.harvard.edu/link_gateway/2019JVGR.385.231J/.
- Lemmi, J.A., Quoos, J.H., 2024. Ilustração para educação ambiental de locais de interesse patrimonial na APA da Baleia Franca. *Physis Terrae - Revista Ibero-Afro-Americana de Geografia Física e Ambiente* 6 (1), 25–44. Retrieved from: <https://revistas.uminho.pt/index.php/physisterrae/article/view/5508>.
- Luetzenburg, G., Kroon, A., Bjørk, A.A., 2021. Evaluation of the Apple iPhone 12 Pro LiDAR for an application in geosciences. *Scientific Reports* 11, 22221. <https://doi.org/10.1038/s41598-021-01763-9>.
- Ma, Z., Mei, G., 2021. Deep learning for geological hazards analysis: data, models, applications, and opportunities. *Earth Sci. Rev.* 223, 103858. <https://doi.org/10.1016/j.earscirev.2021.103858>.
- Martínez-Grana, A.M., Goy, J.L., González-Delgado, J.A., Cruz, R., Sanz, J., Cimarra, C., de Bustamante, I., 2019. 3D virtual itinerary in the geological heritage from natural areas in Salamanca-Ávila-Cáceres, Spain. *Sustainability* 11 (1). <https://doi.org/10.3390/su11010144>.
- Monge-Ganuzas, M., Guillén-Mondéjar, F., Díaz-Martínez, E., Herrero, N., Brilha, J., 2024. Geoconservation at the international union for conservation of nature (IUCN). *Phil. Trans. Math. Phys. Eng. Sci.* 382 (2269). <https://doi.org/10.1098/rsta.2023.0053>.
- Papadopolou, E.E., Papakonstantinou, A., Vasilakos, C., Zouros, N., Tataris, G., Proestakis, S., Soukellis, N., 2022. Scale issues for geoheritage 3D mapping: the case of Lesvos Geopark, Greece. *International Journal of Geoheritage and Parks* 10 (3), 435–446. <https://doi.org/10.1016/j.ijgeop.2022.08.006>.
- Papadopolou, E.E., Vasilakos, C., Zouros, N., Soukellis, N., 2021. DEM-based UAV flight planning for 3D mapping of geosites: the case of olympus tectonic window, Lesvos, Greece. *International Journal of Geo-Information* 10 (8). <https://doi.org/10.3390/ijgi10080535>.
- Pasquaré Mariotto, F., Bonali, F.L., 2021. Virtual geosites as innovative tools for geoheritage popularisation: a case study from Eastern Iceland. *Geosciences* 11 (4). <https://doi.org/10.3390/geosciences11040149>.
- Pasquaré Mariotto, F., Corti, N., Drymon, K., 2023. Advanced technologies for geosite visualisation and valorisation: a review. *Appl. Sci.* 13. <https://doi.org/10.3390/app13095598>.
- Perotti, L., Bollati, I.M., Viani, C., Zanoletti, E., Caironi, V., Pelfini, M., Giardino, M., 2020. Fieldtrips and virtual tours as geotourism resources: examples from the Sesia val Grande UNESCO global geopark (NW Italy). *Resources* 9 (6). <https://doi.org/10.3390/RESOURCES9060063>.

- Quesada-Valverde, M.E., Quesada-Román, A., 2023. Worldwide trends in methods and resources promoting geoconservation, geotourism, and geoheritage. *Geosciences* 13 (2), 39. <https://doi.org/10.3390/geosciences13020039>.
- Quoos, J.H., et al., 2021. Aplicação web de realidade aumentada (web AR) para a promoção do geopatrimônio e o geoturismo. *Anais do XIV ENANPEGE*. Realize Editora. <https://editorarealize.com.br/artigo/visualizar/78875>.
- Tavani, S., Billi, A., Corradetti, A., Mercuri, M., Bosman, A., Cuffaro, M., Seers, T., Carminati, E., 2022. Smartphone-assisted fieldwork: Towards the digital transition of geoscience fieldwork using LiDAR-equipped iPhones. *Earth-Science Reviews* 227, 103969. <https://doi.org/10.1016/j.earscirev.2022.103969>.
- Vandelli, V., Migoñ, P., Palmgren, Y., Spyrou, E., Saitis, G., Andrikopoulou, M.E., Coratza, P., Medjkane, M., Prieto, C., Kalovrektis, K., Lissak, C., Papadopoulos, A., Papastamatiou, N., Evelpidou, N., Maquaire, O., Psycharis, S., Stroeven, A.P., Soldati, M., 2024. Towards enhanced understanding and experience of landforms, geohazards, and geoheritage through virtual reality technologies in education: lessons from the GeoVT project. *Geosciences* 14 (5), 127. <https://doi.org/10.3390/geosciences14050127>.
- Wang, Z., Di, H., Shafiq, M.A., Alaudah, Y., AlRegib, G., 2018. Successful leveraging of image processing and machine learning in seismic structural interpretation: a review. *Lead. Edge* 37 (6), 451–461. <https://doi.org/10.1190/tle37060451.1>.
- Williams, M.A., McHenry, M.T., 2020. The increasing need for geographical information technology (GIT) tools in geoconservation and geotourism. *Geoconservation Research* 3 (1), 17–32. <https://doi.org/10.30486/gcr.2020.1901102.1019>.
- Williams, M.A., McHenry, M.T., Boothroyd, A., 2020. Geoconservation and geotourism: challenges and unifying themes. *Geoheritage* 12 (3). <https://doi.org/10.1007/s12371-020-00492-1>.
- Williams, M.A., McHenry, M.T., 2021. Tasmanian reserve geoconservation inventory assessment using Geographic Information Technology (GIT). *International Journal of Geoheritage and Parks* 9 (3), 294–312. <https://doi.org/10.1016/j.ijgeop.2021.05.001>.