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ORIGINAL ARTICLE

The IGCP 714 Project "3GEO – Geoclimbing & Geotrekking in Geoparks" – Selection of Geodiversity Sites Equipped for Climbing for Combining Outdoor and Multimedia Activities

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Abstract
The *IGCP 714 project "3GEO – Geoclimbing & Geotrekking in Geoparks*" is financed by the International Geoscience Programme (IGCP) and supported by the International Union of Geological Sciences (IUGS). In this paper, we report on the results of the first phase of the project focused on the criteria to be adopted to select geodiversity sites equipped for climbing or trekking. The selection of geoclimbing sites and geotrekking routes is aimed at combining multimedia tools and outdoor activities for Geosciences promotion and conservation in UNESCO Global Geoparks, aspiring geoparks or geoparks project, and also in protected areas featuring geoheritage sites. Indeed, both outdoor activities and multimedia tools favour the pursuing of many of the United Nations Sustainable Development Goals (e.g., 3, 4, 8, 11). An international consortium of geoscientists from 12 different countries selected, through the proposed procedure, 22 geoclimbing sites, and then they also detected 30 geotrekking routes mirroring Earth geodiversity. At some test sites (geoclimbing and geotrekking) multimedia tools and digital outcrop models have been developed through different methodological approaches (e.g., Structure from Motion and Multi-View Stereo photogrammetry), to open the way to the second part of the project still in progress. These sites and the relative virtual models are herein also shown. The final aim of the IGCP 714 project is indeed to create an open data repository (digital outcrop models, videos, virtual tours, photos, scientific information, and interpretations) to upload data of the selected sites to mirror Earth geodiversity for different users including tourists and school groups.

Keywords Geodiversity · Geoconservation · Geoclimbing · Geotrekking · 3D-modeling · IGCP-UNESCO

Introduction

The IGCP 714 project named "*3GEO – Geoclimbing & Geotrekking in Geoparks: methods and tools for enhancement, sustainable fruition and educational projects*" was launched in 2021 (and is still ongoing), under the framework of the UNESCO International Geoscience Programme (https://en.unesco.org/international-geoscience-programme/projects/714) and of the International Union of Geological Sciences (IUGS). It is aimed at enhancing the role of outdoor activities and multimedia tools for geoheritage promotion and geoconservation by creating a network of geoclimbing sites and geotrekking routes in the participating countries. In the Introduction, after an overview on the reasons why outdoor activities and multimedia tools for geoheritage analyses are relevant tools, the aims of and the participants to the IGCP 714 Project are described.

During the last decade, the scientific community has started to pay attention to outdoor recreational activities (e.g., climbing, trekking, rafting, biking) as potential tools for empowering Earth Sciences education and outreach. A recent review focused the attention on sport climbing practised at specifically equipped rock walls (Ruban and

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Ermolaev 2020). This interest grew to draw the attention of climbers towards Geosciences and, indirectly, towards the control of geology and geomorphology on climbing styles (i.e., types of holds) and difficulty grades (e.g., Garlick 2009; García-Rodríguez 2015a; Bollati et al. 2013, 2014, 2016, 2018a; García-Rodríguez and Fernández-Escalante 2017). The link of outdoor activities with geological and geomorphological contexts has been also analysed for other activities like rafting and canyoning (i.e., *georafting*; Zouros 2004; Gulas et al. 2019; Bollati et al. 2023), or orienteering and geocaching. For example, at the Steirische Eisenwurzen UNESCO Global Geopark (Austria), *georafting* is one opportunity available to visitors (https://fb.watch/hdHKDPaEDi/) (Zouros 2004; Gulas et al. 2019). Another example is mountain biking (or e-bikes), through which geosites can be explored along cycling trails. In this case, the dependence between the outdoor activity and the geological and geomorphological context is not so straightforward because it involves the natural terrain, engineered pathways and other infrastructures (Senese et al. 2023).

Rocky outcrops, equipped for climbing, may be isolated or located along trekking trails. They are usually sites where aspects of Earth's history and diversity of lithological elements are well shown, where landscape vistas can be impressive and where different users (by ages, backgrounds, interests) spend leisure time (Bollati et al. 2016). These features make them potential *geodiversity sites* (sensu Brilha 2018), where the diversity of lithological and structural elements may be particularly represented (Bollati et al. 2018b). They provide opportunities to foster geoeducation and geotourism, delivering alternatives for local communities' sustainable development, especially in agreement with the UNESCO´s 2030 Agenda and its Sustainable Development Goals (SDGs), as already described for other outdoor activities (Bollati et al. 2023).

In particular cases, if the scientific value is relevant, some climbing spots such as outcrop features (e.g., caves, fault scarps, columnar basalts, pinnacles and pillars; Bollati et al. 2016) or blocks (e.g., erratic boulders or rock-avalanche boulders; Motta and Motta 2007), may be classified as *geosites/geoheritage sites* (sensu Brilha 2018).

According to some authors (García-Rodríguez and Fernández-Escalante 2017; Bollati et al. 2018a), these sites and related activities may have high geoeducation potential (SDG 4, *Quality education*), and are potentially unexploited locations for communicating and explaining geodiversity and Earth's history (Bollati et al. 2018a; García-Rodríguez 2019; Williams and McHenry 2021), inspiring landscape users, especially in a multimedia and user-led context. Furthermore, they could be a potential tool to achieve social and health goals (e.g., Baláš et al. 2017; Siegel and Fryer 2017; Hrušová and Chaloupská 2019), in accordance with the SDG 3 (*Good health and well-being*). As geodiversity sites, they may provide geosystem services (Gray et al. 2013): rock climbing and hiking are listed among the cultural services offered by geodiversity to Society, and they are included as part of geotourism and associated leisure activities. Figure 1 illustrates some iconic geological landscapes around the world where climbing is practised. They show how the variety of magmatic (Fig. 1a-d), sedimentary (Fig. 1e-i), and metamorphic (Fig. 1j) rocks and their different morphogenetic and morphoclimatic environments, may offer and influence different styles of climbing progression. The frames shown in Fig. 1 are extracted from multimedia videos that are available on the web (links are provided in the caption) and that were proposed by previous authors as useful for educational activities (Bollati et al. 2018a).

By virtue of these potentialities, the chance of providing multidisciplinary activities in Geoscience education to be performed with schools (including Earth Sciences, Physical Education, Maths, Visual Arts; Bollati et al. 2018a) or within the climbing community (García-Rodríguez and Fernández-Escalante 2017) may be significant and innovative. However, despite it, geoclimbing sites have not been frequently investigated as a geoeducational tool, for instance in Geoparks or at other sites where outdoor climbing takes place not only in natural sites, but also in anthropic sites like abandoned quarries.

Considering the potential of outdoor sites used for sports climbing or trekking as geodiversity sites or geosites, and as geoeducational tools, in literature two main issues emerges: (i) the geoconservation of sites that are actively used for climbing or trekking at present; and (ii) potential natural hazards that may exist at these sites and that may limit the potential for Geoscience engagement.

The geoconservation issue is particularly relevant for sports climbing, that is an increasingly popular activity (Sheel 2004) (e.g., for England and United States; Siegel and Fryer 2017). In 2000 in Europe, the International Union for Conservation of Nature (IUCN) estimated there were 1.6 million climbers active over more than 16,000 climbing areas (Hanemann 2000). Such activities may produce significant income at both local and regional scales (Hanemann 2000), especially where other sources of economic support are decreasing (Maples et al. 2017). This can also contribute to SDG 8 (*Decent work and economic growth*) as a sustainable economic activity in remote rural areas. In some cases, climbing walls can be used where quarry surfaces have been abandoned, but not all quarries are suitable for this purpose (Hanemann 2000) and refurbishing natural rock faces may be a good strategy for developing sites that are otherwise degraded. Conversely, if sites are overdeveloped for tourism, negative environmental impacts may result (Clark et al. 2020, and references therein). Climbing sites may be characterized by a fragile equilibrium between their usage and impact on ecosystems (e.g., bird nesting or

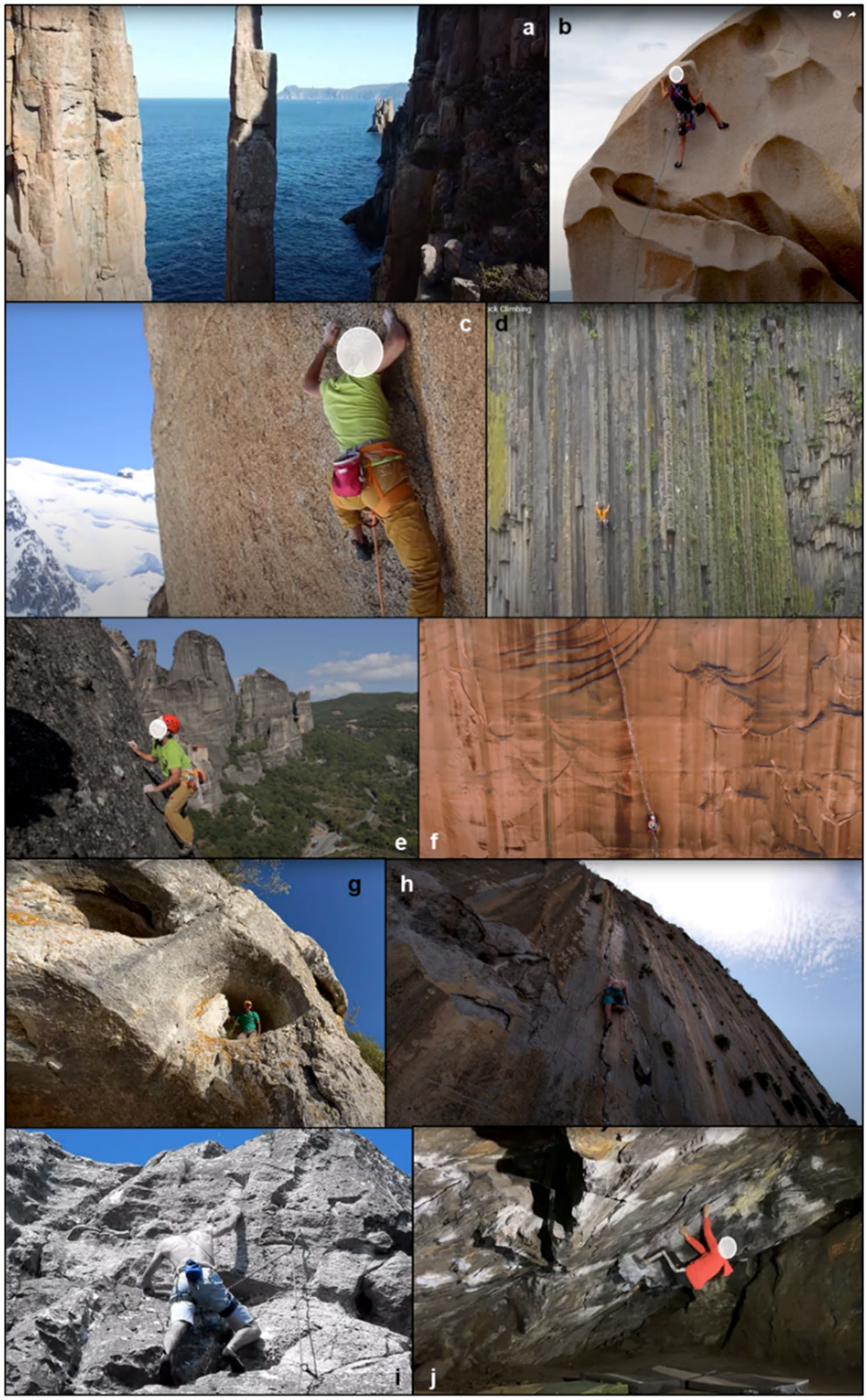

Fig. 1 Geodiversity portrayed in climbing sites around the world in frames from web-based videos. (**a**) One of the dolerite pillars of the Cape Hauy, Tasmania, Australia (https://www.youtube.com/watch?v=MSmR2kTeG4Y&ab_channel=RadekL%C3%A1nsk%C3%BD); (**b**) Granite and tafoni along the Sardinia coast, Italy (https://www.youtube.com/watch?v=1VLN03fscJM&ab_channel=MichalGajdos); (**c**) granite in the high mountain environment of the Monte Bianco (border between Italy and France) (https://www.youtube.com/watch?v=SWCZ55aY4C4&ab_channel=FedericoRavassard); (**d**) Columnar basalt in Armenia (https://www.youtube.com/watch?v=5UopbxZ8tnk&ab_channel=RockandIcemagazine); (**e**) Conglomerates at Meteora in Greece (https://www.youtube.com/watch?v=efRRnI_SfwM&ab_channel=PetzlSport); (**f**) Cracks in sandstone in Utah, USA (https://www.youtube.com/watch?v=xJvNu49kjbw&t=9s&ab_channel=BlackDiamondEquipment); (**g**) Caves in limestone in Portugal (https://www.youtube.com/watch?v=Eo23QtA29KI&ab_channel=BetaClimbers); (**h**) The impressive fault surface of limestone in Plakia, Crete, Greece (https://www.youtube.com/watch?v=BkNj_o-z8zs&ab_channel=micha%C5%82kot); (**i**) Travertine limestones in Dreveník (Slovakia) (https://www.youtube.com/watch?v=UxIB3AUXnRU); (**j**) Foliated structure of schists in Leavenworth (Kansas, USA) (https://www.youtube.com/watch?v=a3JnfuUBiRs&ab_channel=BetaDistribution)

endemic flora; Brambilla et al. 2004; Holzschuh 2016; de Castro-Arrazola et al. 2021) and geological integrity (e.g., Kubalíková and Kirchner 2016; Rop 2020). An in-depth analysis on the sustainable management of climbing areas in Europe is provided by the IUCN (Hanemann 2000), but this report focuses only on biodiversity and not on other environmental impacts (e.g., geological features). For instance, as very recently analysed by Yeste-Lizán et al. (2023), rock cliffs equipped for climbing may be damaged by fires, that could be natural or triggered by humans and may affect both biotic and abiotic features. Moreover, climbing activity may cause damage to rock surfaces, for example, by the opening of new routes (e.g., Reighart 2007), or by rock abrasion or chalk use on the rock to increase hand grip (Kubalíková and Kirchner 2016). Moreover, different types of climbing (bouldering, sport climbing with permanent protection, traditional climbing with removable protection for different climbing grades; Clark et al. 2020) may impact differently. A range of management strategies may be required to address the needs of both climbers and ecosystem conservation (Hanemann 2000). Hanemann (2000) proposed zoning regulation, temporary closure (working well for bird nesting or blooming seasons), and restrictions for big groups, accompanied by adequate information on the motivation for which some solutions are selected. The balance between the positive consequences of geoclimbing sites promotion, and geoconservation (including conservation of living nature, where necessary), is a topic still debated and is also considered in the frame of the IGCP 714 project.

The second issue concerns potential geomorphological hazards affecting geodiversity hotspots where climbing and trekking are practiced. Natural hazards are mainly related to rockfalls (Panizza and Mennella 2007) which can be dangerous for climbers and trekkers. On the one hand, indices have been recently developed to assess the security of rock walls equipped for climbing (Beni et al. 2022). In some countries, a geological technical report is mandatory for opening new rock walls equipped for climbing. Technical guidelines are useful for minimizing the risk, albeit all outdoor activities have inherent risk, and this should be taken into account accordingly. Climbing activities in general should be supervised by licensed and qualified professionals, who has knowledge about Earth processes in order to minimize risk and to disseminate Geoscience topics. Direct observations of morphological-geomechanical elements affecting rock mass instability, could also promote Geoscience education in developing a better awareness of mountain risks and encourage virtuous self-protection behaviour by climbers. Increasing awareness on natural hazards in Society is clearly promoted for instance in Italy in the framework of the National Strategies for Sustainable Development (NSSD; https://www.fao.org/faolex/results/details/en/c/LEX-FAOC188722/), which explicitly includes: "Decrease the exposure of the population to environmental risk factors", "Spread healthy lifestyles and strengthen prevention systems"; and "Preventing natural and anthropogenic risks and strengthening resilience of communities and territories".

In light of geoconservation and risk mitigation, investigations on natural climbing walls as geodiversity or geoheritage sites and as tools for Geoscience popularization, are gradually becoming common. A new term, *geoclimbing*, has been introduced, derived from case studies in the Italian Alps (Bollati et al. 2014) and Spain (García-Rodríguez and Fernández-Escalante 2017). *Geoclimbing* links the climbing activity to education on geological and geomorphological features of the rock outcrops where climbing occurs. A methodology to detect and select, according to specific criteria, the best geoclimbing sites in a region, has been proposed and tested in the Italian Alps (Bollati et al. 2016), as well as a methodology to plan educational experiences with secondary school pupils. In Spain, activities for teaching geology in schools through climbing have been developed in mountain regions (i.e., Central Iberian Range granite; García-Rodríguez 2015a). This latter derives from a detailed analysis of the relationship between rock features and climbing routes (García-Rodríguez and Fernández-Escalante 2017). In the framework of schools' activities, *geoclimbing* was also proposed in combination with *geotrekking* (i.e., trekking or hiking aimed at discovering Earth Science information along specific trekking routes that are influenced by geofeatures; Bollati et al. 2018a). This multidisciplinary experience with schools was also enriched by the use of multimedia videos (YouTube and Vimeo; Fig. 1) where climbers on famous rock walls are shown. This helps pupils in determining the kind of rocks on which the climbers ascend, and to broaden the analysis of the typology of rocks and landforms (i.e., geodiversity; Bollati et al. 2018a, b). Ruban and Ermolaev (2020) suggested that geoclimbing and geotrekking routes from around the world could be useful to depict Earth geodiversity.

When sites of interest are remote, difficult to be reached or subject to hazard risk, or the topic is very tricky, a valuable alternative or complementary activity to on-site visiting is the use of immersive technologies. They include virtual, augmented and mixed reality and digital technologies can be of benefit (Hincapie et al. 2023; Pasquarè Mariotto et al. 2023). In recent decades, the development of digital technologies and its increasing use for geoheritage promotion and management is evident (Williams and McHenry 2020; Pasquarè Mariotto et al. 2023), mainly because they favour comprehensive geoheritage management. Hincapiè et al. (2023) argued that education and geoconservation are the main aims of digital technology applications to geoheritage. Different digital products in geologically-relevant areas like UNESCO Global Geoparks can be communicated directly by managers through website, apps and social networks, offering virtual visits even for disabled people and scheduling a trip in these areas in the future (Fassoulas et al. 2022).

The most recent methods for creating Digital Outcrop Models (DOMs) and multimedia apps at geodiversity and geoheritage sites can be used to highlight the diverse geological and geomorphological features of a locality at different spatial scales (from micro to macro). This allows Geoscience concepts to be successfully and more easily transferred to people of all ages, backgrounds and interests. There are several available examples in literature offering opportunities for user-led activities, improving interactive and independent skills, through social media, geotagging, downloading routes to smartphones with interactive real-time content, and use of QR codes. (e.g., Cayla et al. 2014; Giordano et al. 2015; Aldighieri et al. 2016; Martínez-Graña et al. 2018; Santos et al. 2018; Perotti et al. 2020; Goyanes et al. 2021; Papadopoulou et al. 2021; Pasquarè Mariotto and Boniali 2021; Williams and McHenry 2021; Fassoulas et al. 2022; Hincapiè et al. 2023). These connections allow the user to link to additional multimedia resources and further information (e.g., geology and geomorphology) about sites, as well as planning before the field visit and revising content after the experience (Giordano et al. 2015).

Despite presenting several advantages, it is worth, finally, to be considered which have been highlighted as the limitations of using technologies like Unmanned Aerial Vehicles (UAVs) in conservation and environmental management: e.g., costs, regulations, safety, wildlife impact, difficult and long processing of data (Walker et al. 2023). Moreover, as Hincapiè et al. (2023) underlined, one limitation of technologies based on internet connection, is related to possible internet connectivity in the field, especially in remote areas. However, this last issue can be overpassed by downloading apps before the visits that are based on GPS rather than on internet connection (e.g., *e-geodiscover* apps of Psiloritis UGGp; Fassoulas et al. 2022).

In this framework, we present the results related to the first years of the project. Hence, the aim of this paper is to focus on the results about (i) the selection of specific study sites equipped for climbing, or popular for trekking, in each country, and (ii) the creation of the first pilot 3D models of selected sites in the view of developing later on a robust and accessible 3D modelling workflow as a base to develop a digital platform for dissemination of geological and geomorphological information about geosites and geodiversity sites that are used by the geoclimbing and geotrekking communities.

The IGCP 714 Project "3GEO – Geoclimbing & Geotrekking in Geoparks": Aims and Participants

Based on the illustrated framework, an international team of interested individuals and research groups was assembled in order to: i) increase attention towards geoclimbing sites and geotrekkings as geoeducation resources; ii) build a data repository of web-based multimedia materials of iconic climbing cliffs and trekking routes all over the world. The selected areas of the project include UNESCO Global Geoparks (UGGps) as well as aspiring geopark areas or other types of protected areas within individual countries. Among them, UGGps are primary geotourist destinations for Geoscience popularization and communication, where sustainable geoconservation management strategies already exist. UGGps represent hotspots of geodiversity, and focus on geotourism, geoeducation and on developing users' experiences, as well as on the enhancement of local communities and developing socioeconomic opportunities consistent with the SDGs (e.g., Martini and Zouros 2008; Catana and Brilha 2020; Gordon et al. 2021; Fassoulas et al. 2022).

The premise behind this project is to focus on geoclimbing and geotrekking activities as a medium to popularize Geoscience through geoheritage and geodiversity and sustainable geotourism practices. Through studying a series of iconic sites in specific areas, globally through field surveys and traditional or innovative techniques (i.e., 3D reconstruction of sites), it will be possible to propose both field and virtual activities to understand the origin and evolution of landscapes and to show virtual or on-site information panels offering geological interpretation at geotrekking and geoclimbing sites. This combined "virtual and on-site approach" has several advantages: (i) the impulse to preserve natural sites (i.e., geoconservation) in the framework of a sustainable development; (ii) the possibility for people with disabilities or limited access or mobility to explore georesources; and (iii) the opportunity of overcoming of travel restrictions triggered by Covid-19-like situation, and of reducing CO_2 emissions (Scerri et al. 2020; Fassoulas et al. 2022).

A YouTube channel (https://www.youtube.com/@GEOIGCP/featured) was created, and a Sketchfab account was opened, in order to store the realized DOMs and to disseminate activities and scientific results through thematic videos. Method development and standardization are useful for the consistent collection and analysis of any digital data, to guarantee an equal quality of data acquisition among partners and to facilitate the comparison of different sites (Scerri et al. 2020). Moreover, digital data that can be accessed and shared consistently can allow a discussion on how to conduct systematic site analysis. In this context, non-specialists and novice researchers, through teaching initiatives, may learn new methods of site visualisation for different audiences using multimedia platforms (Scerri et al. 2020; Pasquarè Mariotto et al. 2023).

All these aspects of the IGCP 714 project are summarized in Fig. 2, a graphical abstract created for the UNESCO webpage dedicated to the IGCP 714 project (https://www.unesco.org/en/iggp/igcp-projects/714?hub=67817).

The number of countries involved in the IGCP 714 has increased from five in 2021 (Italy, Greece, Oman, Portugal, South Africa), to twelve in 2022 (seven more: Australia, Brazil, Chile, India, Poland, Spain, United Kingdom) (Fig. 3 and details in the Supplementary Information 1). Some of the partners are UNESCO Global Geoparks (Estrela,

Fig. 2 The conceptual sketch of the IGCP 714 Project (modified from https://www.unesco.org/en/iggp/igcp-projects/714?hub=67817)

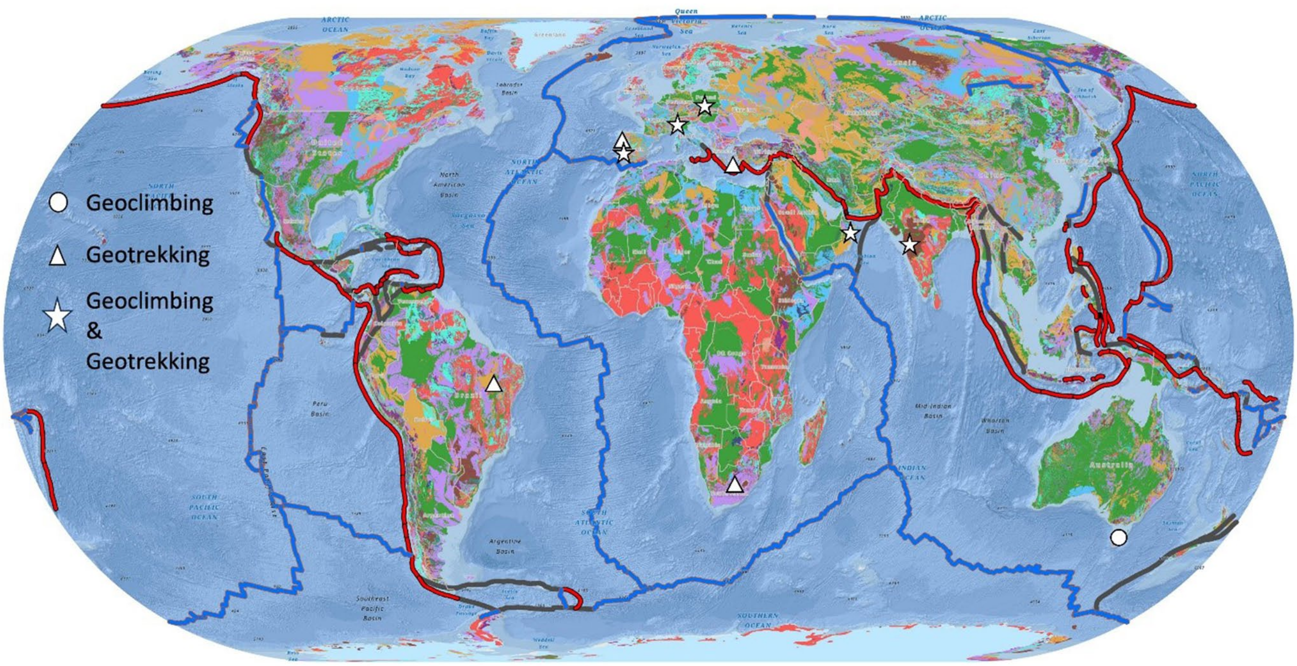

Fig. 3 Map showing the distribution of the countries where sites selected for the project are located. A detailed version is presented in Supplementary Information 1. The lithological map of the world (GLiM, by Hartmann and Moosdorf 2012) reports the main lithological types, as grouped in the GLiM database. The main tectonic boundaries are ridges, trenches and transforms. The original GLiM vector file was re-sampled and converted to raster with a 500 m resolution

Portugal; Psiloritis, Greece; Sesia Val Grande, and Rocca di Cerere, Italy), others are aspiring geoparks or geopark projects (Charnwood Forest Geopark, United Kingdom; Serra do Sincorà Geopark, Brasil) or natural protected areas (Golden Gate Highlands National Park, South Africa; La Pedriza and Peñalara included in the Sierra de Guadarrama National Park, Spain; Tatra National Park, and its surrounding, Poland-Slovakia; Wellington Park, Australia). All the participants to IGCP 714 bring their own expertise to achieve the goals of the project. Strengthening the networking capabilities of geoparks in different locations, for instance, historical UGGps may provide support to those areas aspiring to become a UGGp.

The selected areas in Italy are characterized by iconic geodiversity and geoheritage sites: the Sesia Val Grande UGGp in the Central-Western Italian Alps, and the Rocca di Cerere UGGp within the Sicilian-Maghrebian Chain. The contexts are diverse from a geological and geomorphological point of view, allowing for comparison of different geoclimbing sites and geotrekking routes: the Alpine high mountain environment and climate, featured mainly by metamorphic rocks and glacial modeling (Sesia Val Grande UGGp; Perotti et al. 2020; Bollati et al. 2016), and the Mediterranean ones, mainly sedimentary rocks with the presence of the largest concentration of Messinian evaporite deposits and a long-lasting history of caves and mines (Rocca di Cerere UGGp; Cirrincione et al. 2022). In this areas DOMs have been already produced and the potential of geoclimbing and geotrekking for activities with schools in collaboration with local mountain guides have been already tested (Bollati et al. 2018a).

In the Poland area the aim is to reduce the phenomenon of overtourism in the most overloaded parts of the Tatra National Park, which are e.g. Morskie Oko lake, Kasprowy Wierch peak and Giewont peak (e.g. Delekta et al. 2020). The emphasis at this site is to develop geotrekking routes and geoclimbing sites in neighboring mountain ranges, which are less popular for tourists. Many geosites have been already described in the area around the Tatras, and also geodiversity has been analysed in this area (e.g. Chrobak, et al. 2021, Chrobak-Žuffová 2023). The focus is put on promoting the area around the Tatras as geotouristic attractions among residents and tourists visiting the Tatra National Park.

Charnwood Forest aspiring UGGp (United Kingdom) is being developed as part of the Charnwood Forest Landscape Partnership Scheme and is funded by the National Lottery Heritage Fund. With many geosites being former quarries, the Geopark is a region of major interest for the British climbing community. The Geopark works closely with the British Mountaineering Council to improve the conservation of sites and expand access for climbing which in turn supports local business.

The two Spanish areas (La Pedriza and Peñalara) are located within the Sierra de Guadarrama National Park. La Pedriza is a granite massif suitable for the representativeness of landforms (García-Rodríguez 2015a, b, 2019; García-Rodríguez and Fernández-Escalante 2017). La Pedriza is also the most important school for grip-climbing in Spain, where climbers come from all over Europe. The Peñalara massif is formed by metamorphic rocks (gneiss) and represents the best example of glacial morphology in the Sierra de Guadarrama. Peñalara is also one of the main climbing schools in the Central Range where rock and ice climbing is practiced. DOMs have been elaborated for educational purposes of micro- and meso-landforms, and of rock textures that influence climbing.

The Estrela UGGp (Portugal) comprises the Serra da Estrela Mountain and surrounding areas, throughout 2216 km^2 and nine municipalities (de Castro et al. 2022). Its rich geological history extends over 650 million years but today's landscapes have been shaped mainly by late Pleistocene glaciations that modelled stunning landscapes (Vieira et al. 2020). Estrela's potential for outdoor activities, from education to leisure, is outstanding, bearing the only ski station in Portugal as well as more than 1000 km of trekking routes. Tourism in this area is an important economic activity. Geoclimbing could presents great development potential due to the availability of granitic outcrops, although the sensitivity of high-elevation ecosystems imposes some restrictions of use applied by the Natural Park management. Seven geotrekking routes are currently under investigation, while IGCP 714 may provide an additional contribution to the ongoing creation of a mountain sports charter for Serra da Estrela, which would regulate and foster geoclimbing and other activities in the area.

In the Psiloritis UGGp (Crete Island, Greece) digital tools to promote geoheritage have been already developed (Fassoulas et al. 2022), and two geoclimbing sites are proposed for the IGCP 714 project: (the Voulismeno Aloni doline and Patsos gorge), as well as some of its geotrekking routes (Migias, Patsos, and Gafaris-Rouvas). A 3D model for the Migias geotrail has been developed, along which geointerpretation is also provided through a combined virtual tour. The Psiloritis UGGp, being one of the oldest in Europe, may serve to suggest geoeducational and geotouristic activities to other participants, especially aspiring geoparks.

The selected area in India is located in the Deccan Volcanic Province. The proposed geotrekking (Sandan slot canyon) and geoclimbing (Tail Baila) represent the Deccan volcanic landforms (i.e., the typical basaltic geomorphology), along with features of mafic volcanic rocks and related rock types. The Deccan Volcanic Province, because of its landscapes and their geological significance, has the potential to develop as an important geotourism destination, which is attracting many visitors from all over the world, also in virtue of outdoor activities. Hence, geotrekking and geoclimbing activities are aimed to develop places of geotourism in the Deccan.

The Chapada Diamantina National Park, a protected area in the Serra do Sincorá Geopark, represents one of the highlights of Brazil´s trekking destination (da Glória Garcia et al. 2022; de Araújo and Pereira 2022). The geoheritage inventory is focused on the Pati´s Valley, a complex geosite of geomorphological relevance, which is accessible only by trekking routes and attracts visitors from all over the world.

In South Africa, the major site examined is in Golden Gate Highlands National Park, a mountain front landscape developed in Karoo Basin sandstones and characterised by bare sandstone bedrock summits and cliffs, different slope and fluvial landforms, and different sandstone weathering forms with caves and rock shelter sites with archaeological evidence (Holmes et al. 2016). The National Park includes paths and trails for walking, trekking, horse riding and other outdoor mountain activities with well-developed tourist facilities. Potential exists for development of geotourism and driving as well as walking trails in some areas, however much of the land is privately owned and access is sometimes difficult.

In Australia, the development and promotion of new technologies to disseminate geoscience information and increase popularisation of natural and cultural heritage is focused in the Wellington Park, Tasmania (Williams and McHenry 2021). The major area examined is part of the most extensive exposure of Jurassic dolerite in the world.

In order to disseminate information and results of the project, social network profiles have been also opened on Facebook (https://www.facebook.com/profile.php?id=100075680001976) and Instagram (https://www.instagram.com/IGCP714_3geo/).

A thematic workshop with fieldtrip (Fig. 4) was organized in the framework of the 16th European Geoparks Conference, held in Verbania (Italian Alps), in September 2022, and many online meeting were also occasion of discussion about the topics.

Methods

In this section the methodology used to select and evaluate the geodiversity sites equipped for climbing is described. The methodology applied to create the 3D models at test sites is also illustrated.

Selection and Evaluation of Geodiversity Sites Equipped for Climbing

The geoclimbing sites are new entities in the framework of Geoscience conservation and promotion, and very recent are the proposals for methodology to select such sites (Ruban and Ermoalev 2020). In 2016, Bollati et al. proposed a methodology, previously applied generically to geoheritage sites, but focused specifically on climbing activities in an Italian alpine sector. The methodology consists in a preliminary selection of geodiversity sites (sensu Brilha 2018) equipped for climbing, not presenting evident hazards, accessible through simple paths, with adequate space to host also groups of people, and where rocky surfaces are clean, to have the possibility of appreciating the geological and geomorphological features in relation to climbing progression.

The first step was to structure a spreadsheet to collate systematically case studies from the different project partners (Supplementary Information 2). It includes information on both geoclimbing and geotrekking routes, and their reciprocal connections. The inventoried descriptive information includes: the geographical locations of individual sites, their geological and geomorphological settings, the scientific value of the sites and the ecological and/or cultural (e.g., archaeological) relevance, any other additional values of the sites (socioeconomic, aesthetic), and whether sites fall within a UGGp or aspiring geopark, or in any other type of protected area (e.g., National Park). Moreover, information on site accessibility (spatial and temporal), potential hazards and vulnerability of users was also inventoried, including potential threats to site conservation.

According to this qualitative information, a more quantitative assessment has been performed. Bollati et al. (2016) used numerous criteria and sub-criteria (i.e., scientific value, additional value, global value, potential for use, index of use, scientific index, educational index) to discriminate among the sites the best ones where performing promotion as well as geoconservation strategies if necessary. Within the IGCP 714 project the authors applied a simplified version of the methodology (see Supplementary Information 3), based on the fundamental values previously proposed (i.e., scientific value, additional value and potential for use). The methodology has been simplified in order to adapt to different contexts and to different operators: in particular, the potential for use was calculated not considering the spatial accessibility as assessed including trail parameters. The participants assess their own sites to then discuss how the obtained results are comparable to the average values in literature (i.e., Bollati et al. 2016). The values by Bollati et al. (2016) have been indeed recalculated using the simplified procedure herein applied in order to have comparable results.

Besides selecting and assessing geoclimbing sites, participants have also chosen geotrekking routes located in the investigated areas. No quantitative assessment was performed at these locations but only a qualitative description is provided (see Supplementary Information 2).

Development of Digital Outcrop Models (DOMs) at Test Sites

Since not all the project participants have expertise in 3D model realization, and one of the aims of the project is to create a shared methodology for DOM development, some test sites have been object of a preliminary test for 3D modelling.

Thus far, 3D models of both geoclimbing and geotrekking routes, of entire rock walls or trails, and of other landscape features using different techniques, have been produced at these test sites.

Image acquisition has been carried out independently through digital reflex cameras, and UAVs, to obtain high-resolution photogrammetric and point cloud data. In specific cases, especially concerning geotrekking routes, UAVs have also been used to shoot 360° panoramas from several ground points along trails so that a virtual tour can be produced (e.g., Fassoulas et al. 2022).

Fig. 4 Shots from the fieldtrip during the IGCP 714 meeting in September 2022. There is also a video of the meeting available at https://youtu.be/KkXFa9_1-Y4

Software used from acquisition to analysis phases might be different in the different case studies (see details in the Results section). These may include Pix4D mapper and Pix4D capture (Pix4D 2017), Agisoft Metashape (Agisoft LLC 2010), 3DF Zephyr Free® software (3D Flow®, Italy) and LIME-VOG (Buckley et al. 2019). When the field survey is performed using UAVs, a Pix4D capture app (Pix4D 2017) was essential to automatically acquire nadir and different angle images of a specific designated area up to hundreds of m^2, taking care of height of flight which regulates the ground resolution (cm/pixel): the higher the flight elevation, the lower the output resolution. The technique to generate DOMs has been *Structure from Motion*. The adopted workflow could be schematic and intuitive, where images are aligned through common points (Westoby et al. 2012; Carrivick et al. 2016), then a sparse point cloud is generated, the cloud can be intensified in the number of points (dense cloud), a 3D model (as a texturized mesh) is generated, and, at the end, a DOM and an orthomosaic can be exported in different formats. In some of the developed models, information on geology and geomorphology has already been depicted using annotations with links to sub-models, while in others this is still in progress. In the case of geoclimbing sites, geological and geomorphological information can be integrated as annotations with the climbing routes (Williams and McHenry 2021), showing their influence on climbers' progression.

Some of the DOMs are being uploaded on the web through different platforms, that allow for user interactions with these models, for autonomous exploration (e.g., Sketchfab), or through pre-set videos for guiding the experience of the viewer and indicating and explaining the key geological elements (e.g., YouTube).

Physical models of geosites were also accomplished in recycled plastic. In order to create the final 3D model to be executed in a 3D printer, the mesh file from Pix4D Mapper software is simplified using Blender software (v3.4). A base is added to the mesh where relevant text (geosite name, for instance) is added to the physical model. Printing settings (print speed, layer height, scale) and GCODE were defined in PrusaSlicer (v.2.5.2). Finally, printing is accomplished in a Prusa MK3S + 3D printer (Goyanes, pers. comm.).

The final goal is to develop a dedicated repository on the web (e.g., Web-GIS) that could be browsed and queried by users for different purposes (Williams and McHenry 2021). 3D printing products, moreover, may be useful for impaired-vision people, favouring inclusion. All these products can also be used side-by-side with outdoor activities, such as for school groups (Bollati et al. 2018a). For these reasons, it is important to develop a common methodology to standardise a range of products.

Results

Selection and Evaluation of Geodiversity Sites Equipped for Climbing

The results of the first step of qualitative selection are collected in Supplementary Information 1 and 2. In Supplementary Information 1, the location of the 22 geoclimbing (GC- in the Supplementary Information 2) and 30 geotrekking routes (GT in the Supplementary Information 2) on the lithological map of the world (GLiM, by Hartmann and Moosdorf 2012) is reported. It is important to underline that the chosen geological setting, involved in the project, depend strictly from the participants to the IGCP 714 project.

The spreadsheet available as Supplementary Information 2 includes all the records selected for the project. The codes made up by 2 letters (GC- or GT) and a number, used in the following descriptions, correspond to the ID of each site in the Supplementary Information 2.

In Fig. 5 (a, b) the distribution of sites among the partners is shown and their status as recognized geosite (sensu Brilha 2018) is indicated (Fig. 5c). Their geo-tectonic distribution is reported in Fig. 5d. In general, the included sites belong to accretionary complex provinces for the great majority (72%); the rest is distributed among orogenic belt, ophiolite complex, volcanic arc and craton settings (Hasterok et al. 2022). In Fig. 5e, the most common rock types encountered are graphed. The detailed data will be discussed in the following sections.

Geoclimbing Sites

Most of the geoclimbing sites are not recognized as geosites (14 of 22 sites, 64%) (Fig. 5a).

Analysing the general features of the geoclimbing sites, in the specific about lithological geodiversity, the selected sites encompass a varied range of rocks, with 41% metamorphic, 32% sedimentary and 27% magmatic (Fig. 5e). Pictures depicting this geodiversity are collected in Figs. 6, 7 and 8.

Considering their distributions, 10 sites of 22 (45%) are located in UGGps (Sesia Val Grande, Italy, GC-2–9, Fig. 8d, f; Psiloritis, Greece, GC-12, 13; Fig. 7f), and 12 sites (54%) are well-known tourist destinations located in National Parks or in nature conservation areas within a Nature 2000 site, or Wildlife Reserve (GC-5, 8; GC-12-20, Fig. 7f; GC-22, Fig. 6d).

According to the features described in details later on, the results of the quantitative evaluation of geoclimbing sites are summarized in Fig. 9 and the details in Supplementary Information 3. Moreover, in Table 1 a summary of the main values is reported.

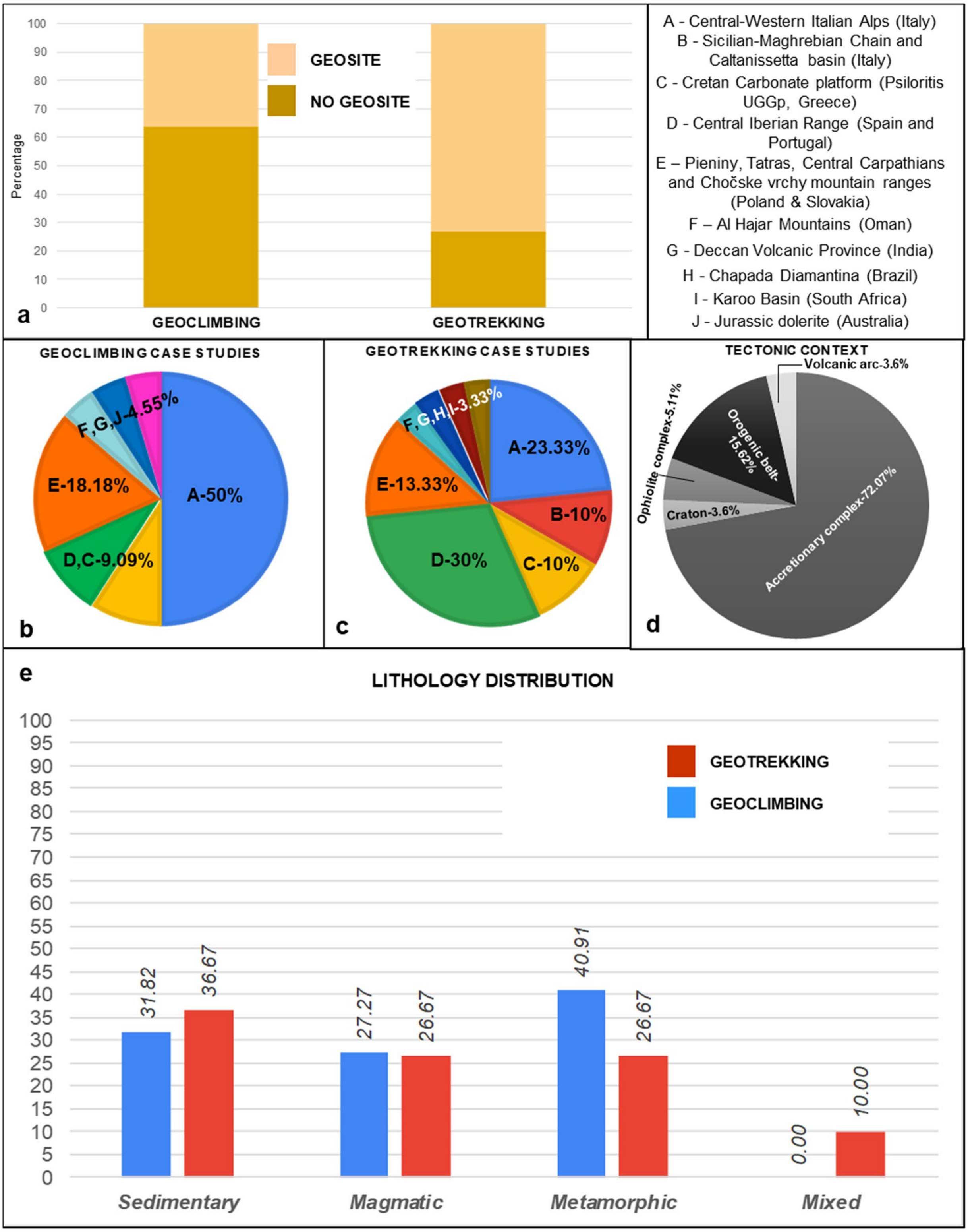

Fig. 5 Data analysis of the studied site. (**a**) Graphs of the studied sites as geosites; (**b**) Distribution of geoclimbing; (**c**) Distribution of geotrekking; d) Geo-tectonic distribution in the global geologic provinces as reviewed by Hasterok et al. (2022); (**e**) Lithology distribution among the different typologies of studied sites. Legend in the right upper part refers to different geological contexts of sites in graphs b and c: A- Central-Western Italian Alps (Italy), B- Sicilian-Maghrebian Chain (Italy), C- Cretan Carbonate platform (Psiloritis, UGGp, Greece), D- Central Iberian Range (Spain and Portugal), E- Tatra Mountains and its surrounding (Poland & Slovakia), F- Hajar Mountains (Oman), G- Deccan Plateaux (India); H- Chapada Diamantina (Brazil); I- Karoo Basin (South Africa); J- Australian Gondwana rifting

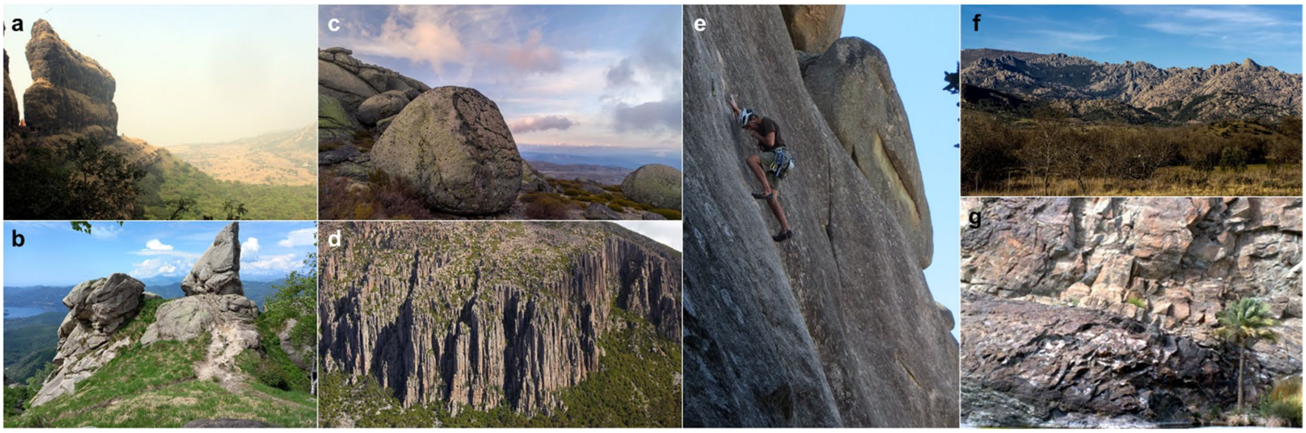

Fig. 6 Examples of the landscapes sculpted in magmatic rocks and selected for the 3GEO Project. (**a**) Tail Baila (Deccan Plauteaux, India) geoclimbing on basaltic lava flows (GC-21); (**b**) Mottarone (Sesia Val Grande UGGp, Italy) geoclimbing on Permian granites (GC-4); (**c**) Poios Brancos (Estrela UGGp, Portugal) geotrekking through granite blocks suffering diverse weathering processes (GT-16); (**d**) Organ pipes (Australia), geoclimbing on dolerite pillars (GC-22); (**e**) La Pedriza (Sierra de Guadarrama, Spain), geoclimbing on granitic slabs (GC & GT-14) (photo courtesy of J.L. Salcedo); (**f**) La Pedriza geotrekking on granitotids (GT-14) (photo courtesy of Haday Lopez); (**g**) the limit between the oceanic crust and the mantle in the Oman geotrekking route (GT-27)

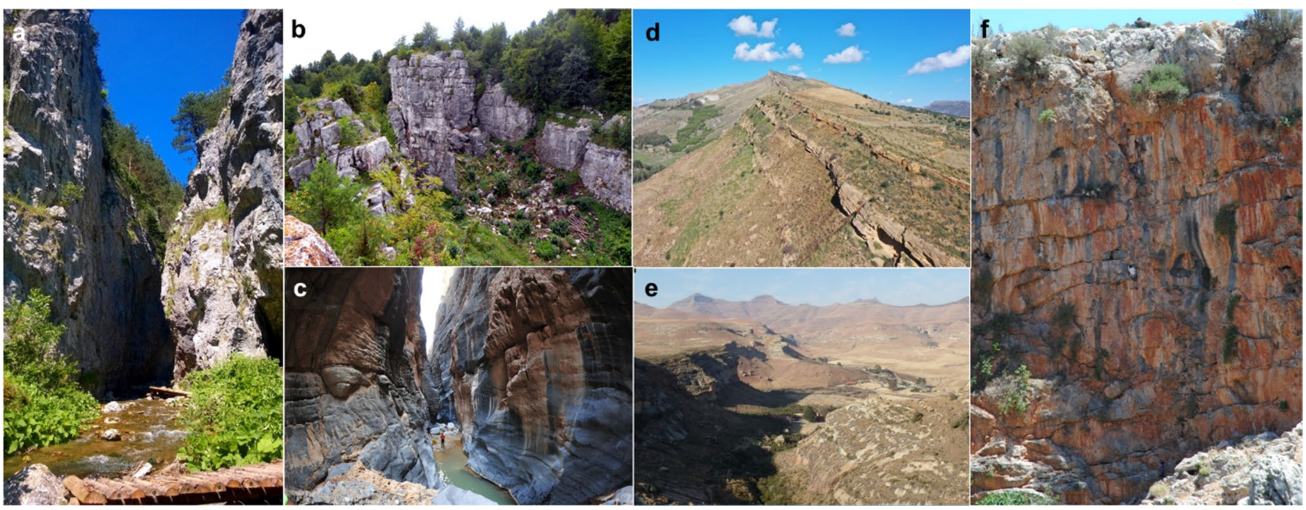

Fig. 7 Examples of the landscapes sculpted in sedimentary rocks and selected for the IGCP 714 project. (**a**) Prosiek stream (Choč Mountains, Slovakia), geotrekking along a gorge carved in Triassic limestones of the Choč Nappe (GT-24); (**b**) the Drevenik Quaternary travertine hill, Hornádska vrchovina, Slovakia; (**c**) Snake Gorges (Al Hajar Mountains, Oman), geotrekking and canyoning along a gorge excavated in Proterozoic tectonized and karstified limestone (GT-27); (**d**) Capodarso cuesta (Rocca di Cerere UGGp), geotrekking along a sandstone ridge in the Sicilian-Maghrebide chain (GT-10); (**e**) Golden Gate Highlands National Park (South Africa), geotrekking to discover the sandstone landscape of the Karoo Basin (GT-30); (**f**) Voulismeno Aloni (Psiloritis UGGp, Greece), geoclimbing in a sinkholes carved in Triassic limestone (GC-12)

In general, the geoclimbing sites obtained high values if compared with the average of the 14 sites assessed by Bollati et al. (2016) at regional scale in an Italian alpine sector. About 68% has a scientific value above this average, 91% for what concerns additional values, 77% the potential for use and the total score as well. The pool of sites evaluated by Bollati et al. (2016), present the limit of belonging to a regional cluster of sites. Even if the geodiversity of the region was considered high, they may be featured by some common traits, which, if negative, could penalize all the sites. In the IGCP 714 case, the best sites in the different areas had been preliminary detected before undergoing evaluation.

In some cases, GCs have obtained a quite low score in term of scientific and total value, well below the average. For instance, GC-5 and GC-6, located in the Sesia Val

Fig. 8 Examples of the landscapes sculpted in metamorphic rocks and selected for the IGCP 714 project. (**a**) Vale do Patì (Serra do Sincorá Geopark Project, Brazil) geotrekking along a valley carved in Proterozoic metasediments (GT-29); (**b**) Pai Inácio, a legend hill in the Serra do Sincorá Geopark Project featured by steep walls carved in low metamorphosed sandstones of Mesoproterozoic age (GT-29); (**c**) Southern gorge of the Uriezzo Glacial Garden (Western Italian Alps), geotrekking along a glacial carved gorge (GT-1); (**d**) Torre delle Giavine (Sesia Val Grande UGGp, Italy), geoclimbing on gneiss of the Sesia Lanzo zone (GC-7); (**e**) Peñalara (Sierra de Guadarrama, Spain), geotrekking in a region intensely modelled by glaciers (GC-15; GT-15); (**f**) Ornavasso (Im Schlasti in Walser language; Sesia Val Grande UGGp, Italy), geoclimbing on mafic granulites of the lower crust of Southern Italian Alps (GC-3)

Grande UNESCO Global Geopark, have been scored below both the averages (scientific and total; Table 1; Fig. 9; Supplementary Information 3), but they represent reference places in the area for practising of climbing also with school students, and they are traditional places where lithological and geomorphological features are pretty good for dissemination. Moreover, they are penalized by the low developed touristic context and the scarce connection with surrounding sites.

Most of the sites are located in aesthetic landscapes or are themselves aesthetic rock outcrops (1 over 1, Supplementary Information 3) (GC-1, 4, Fig. 6b; GC-17; GC-20–22, Fig. 6a, d). Some morphological and lithological conditions favour rock cliffs to host endemic plant species (GC-13, Fig. 8e, GC-15; GC- 16, 17, 19) or bird habitats (Fig. 7f, GC-12; Fig. 6e, GC-14), in some case conferring the value of ecological support role to the site (0.67–1 over 1). However, as underlined in literature (see Introduction), these ecological attributes might be incompatible with geoclimbing or trekking activities.

Of the proposed geoclimbing sites (Fig. 5b), half of the sites (11 sites of 22; 50%) are located in the Central-Western Italian Alps (Figs. 6b, c; 8c, f), followed by those in the mountain chains between Poland and Slovakia (Pieniny, Tatras, Central Carpathians and Chočske vrchy mountain ranges; 4 sites; 18%). In the Central Iberian Range (Spain; Figs. 6e, and 8e) as well as in the Cretan carbonate platforms of the Psiloritis UGGp (Greece), respectively two sites have been selected (9%; Fig. 7f). One site (4.5%) has been then chosen for the Deccan Volcanic Province (Fig. 6a), one (4.5%) for the carbonate platform of Oman, and one (4.5%) for the Jurassic dolerite domain of Australia (Fig. 6d).

Geoclimbing sites located in the Central Western Italian portion of the European Alps, testify to different stages of the evolution of this mountain chain (GC-1-GC-11; Figs. 6b; 8c, d, f). They are featured by different kinds of rocks, mainly metamorphic (micaschists, orthogneiss, mafic granulites, amphibolites; GC-1-3, Fig. 8c, f; GC-5-8, Fig. 8d; GC-10-11), but also magmatic (granite, GC-4, Fig. 6b; GC-9) related to both Hercynian and Alpine orogenic episodes. Most of these (7) are located in the Sesia Val Grande UGGp (GC-2-3, Fig. 8f; GC-5-9, Fig. 8d), whilst others (GC-10-11), even if of relevant geological value, are not included in any geopark area.

Rock cliffs belonging to carbonate platforms are in Crete Island (Greece), where the carbonate rocks of mainly Jurassic-Cretaceous age crop out in the Psiloritis UGGp (GC-12-13; Fig. 7f), and in Oman in the Al Hajar Mountains (GC-20).

Between Poland and Slovakia, limestone rock walls have been selected in the western Tatras (GC-19) and Pieniny Mountains (GC-16), as well as the travertine of Hornad basin in the Central Carpathians (GC-17).

Granitic and porphyroides crop out at sites in the Western Italian Alps (GC-4; Fig. 6b; GC-9), and in the High Tatras Mountains (GC-18). In the Central Iberian Range sites in Spain, Variscan geoclimbing sites are found in granitoides (GC-14; Fig. 6e) and gneiss (GC-15; Fig. 8e) in the Sierra de Guadarrama National Park.

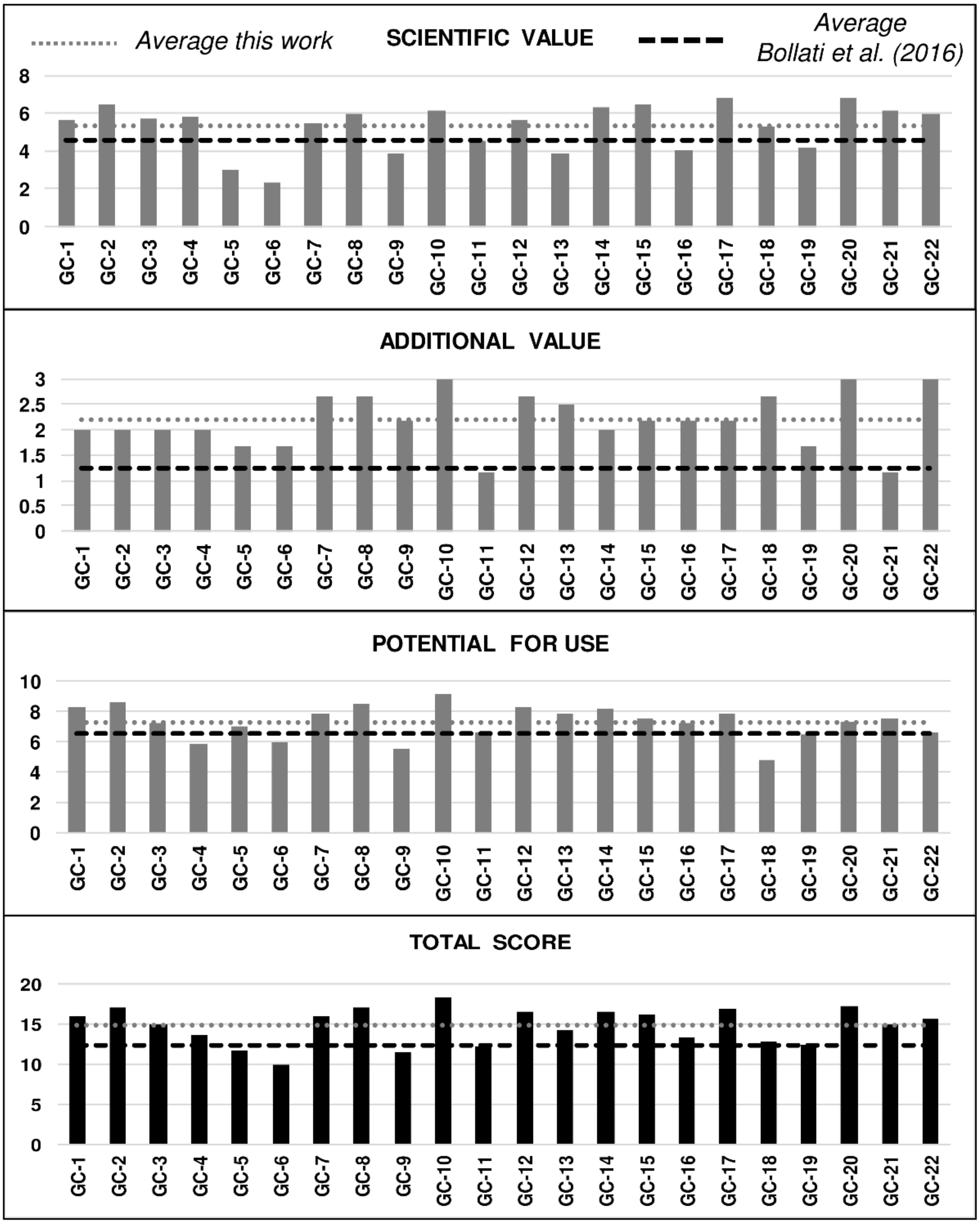

Fig. 9 Graphs of the results of the studied sites assessment in relation to the average values obtained by previous authors (Bollati et al. 2016)

Table 1 Summary of the values calculated for the geoclimbing sites compared to the value obtained at Bollati et al. (2016) sites

	Scientific Value	Additional Value	Potential For Use	Total Score
Min	2.33	1.17	4.86	10.00
Max	6.84	3.00	9.10	18.27
Average	5.31	2.19	7.31	14.80
Potential maximum	8.00	3.00	10.00	21.00
Sites above IGCP 714 sites average	63.64%	36.36%	54.55%	59.09%
Sites above average of sites in Bollati et al. (2016)	68.18%	90.91%	77.27%	77.27%

Volcanic and sub-volcanic rocks are listed such as the spectacular pillars sculpted in dolerite related to Gondwana rifting, the Organ Pipes in Australia (GC-22; Fig. 6d), and a geoclimbing site in the basaltic lava flows of the Deccan Trap Volcanic Province in India (GC-21; Fig. 6a).

Concerning the diversity of geomorphological elements at geoclimbing sites, a rich variety of landforms is represented, also at site scale. In the main mountain ranges in Europe (Italian Alps, Central Iberian Range, High and Western Tatras, Pieniny Mountains and the Central Carpathian Paleogene Basin), glacial landscapes dominate, in some cases with more recent traces of mass movement or fluvial processes. According to the quantitative assessment, 82% of the geoclimbing sites are featured by more than 1 rock types and/or more than 1 landform (Supplementary Information 3).

Lithology-related landforms are present in the case of limestone (sinkholes, karren field, gorges and caves; GC-8; GC-12–13, Fig. 7f; GC-16-17) and granites (GC-4. Figure 6b; GC-14; Fig. 6e). Structural conditioning of rock morphology is also evident from micro-, meso- (GC-2) to macro scales (in particular GC-7, Fig. 8d; GC-18-19; GC-22; Fig. 6d).

Concerning cultural evidence related to the inventoried geoclimbing sites, 77% of them are featured by cultural assets, in some case strictly related to the geoclimbing site (36%) (Supplementary Information 3). Some places in the Alps are located along important historical roads like the Cadorna Route, a military road of the First World War (GC-3; Fig. 8f), or the Francigena Route (GC-10), a religious route connecting since the Middle Ages, Rome to Central Europe. Moreover, castles (GC-9, GC-17), ancient settlements, historical forts and shelters, as well as art depictions (GC-20-21; Fig. 6a), are related to the sites, but also specific cultures (e.g., Walser culture at GC-3, Fig. 8f; GC-5), that characterized the European Alps where travellers passed during the 17th-19th Centuries. In Greece, geoclimbing sites are associated with myths and legends (GC-12; Fig. 7f), or with a religious temple (GC-13). Finally, mountaineering history can be considered a cultural value too and featured Polish site of Mnich (GC-18). A great part is in regions which are famous tourist destinations, but a part (5%; Supplementary Information 3) is also located in minor mountain valleys (e.g., Sesia Valley, GC-5-9, Fig. 8d; Pieniny Klippen Belt and Central Carpathians; GC-16-17).

Depending on altitude, the proposed geoclimbing sites are accessible throughout the year (50%; Supplementary Information 3) or except with snow and rain (50%; Supplementary Information 3). Moreover, sites are generally accessible by car or through a short walk that makes them suitable for educational purposes (95%; Supplementary Information 3).

In six cases cliffs are located on private property (GC-1-2) (27%, Supplementary Information 3). Other legal constraints may derive from the sites being located within protected areas. For such problems some partners (e.g., in the Charnwood Forest and Estrela UGGp), despite including geotrekking routes, are still working to detect suitable geoclimbing sites. The difficulties are mainly related to the agreement for their management between geoscientists, climbers and local entities, as well as private owners. Other issues include legal liability, insurance, car access/parking, information/publicity, actions such as scrub clearance, and risk management, a problem also noted in the IUCN report (Hanemann 2000).

Many of the study sites are connected to other sites of geological and geomorphological interest in the surrounding area (64% in particular with sites genetically related; Supplementary Information 3), or to specific geotrekking routes also identified within this project (see next paragraph). This occurrence enriches the potential educational and touristic benefits on offer at these sites, helping the visitor to contextualize specific features into a wider geological and geomorphological setting. At some sites, experience of geoclimbing with schools has been already occurred (e.g., GC-1; Bollati et al. 2018a), and in some cases the relation between climbing routes and Geoscience features has already been explored (GC-1; GC-10-11, GC-14-15, Fig. 6e; GC-22, Fig. 6d).

Finally, the geohazards characterizing climbing walls are potentially relevant, depending on the natural features present, but also on how the sites are maintained. For this reason, a proper evaluation by certified professionals is always required before starting or developing any geoclimbing activity.

Geotrekking Routes

In order to enrich access to and to promote public understanding of geodiversity, 30 geotrekking routes are proposed, in some cases coupled with geoclimbing sites. Many geotrekking routes, located in the same regions as geoclimbing sites, allow for a broader overview of the geological and geomorphological settings of the region, from the outcrop scale to the landscape scale. Geotrekking could be considered a more diffuse activity, and potentially more diverse than geoclimbing and so can appeal to a wider and more diverse audience in terms of age and interest. Moreover, geotrekking may be considered less impactful than climbing and so it may be easier to be proposed and to manage the development of these activities. In many cases geotrekking routes (73%, 22 trails) already allow for accessing to geosites (Fig. 5a). This high percentage compared to geoclimbing sites may be also because geotrekking routes are sometimes very long (e.g., the longest is 22 km, see Supplementary Information 2), a feature which increases the possibility of including different sites of geological interest in the same context.

For the same reason, in the case of geotrekking, an additional category is represented in Fig. 5e: the mixed type of rocks visible along the trail, representing the 10% of the study cases. This is due to the fact that along a trail it is normal to find more than one category of rock. However, geotrekking routes identified have a prevalence of sedimentary (37%) in respect to magmatic and metamorphic rocks (27% for both).

According to Fig. 5c, the greatest number of geotrekking routes (30%) is located in Central Iberian Range, where there is a significant contribution from the Estrela UGGp, in Portugal (GT-16-22, Fig. 6c), and from Sierra de Guadarrama, in Spain (GT-14-15, Figs. 6f, and 8e). There, granite weathering and glacial erosion landforms are the dominant traits. Also in this case, endemic species enrich the tourist experience, but at the same time increase the fragility of the environment.

Sites of the Central Iberian Range are followed in percentage by geotrekking routes in the Central-Western Italian Alps (23.33%; GT1-7; Fig. 8c). Most of these show glaciological evidences from Pleistocene glaciations, leaving iconic glacial landmarks (GT-1, 7, Fig. 8c; GT-4-7). Among them, worth of note is the Ivrea Morainic Amphitheatre (GT-6), the best preserved end-moraine system in the Alpine region, which hosts one of the most relevant example of lateral moraine internationally recognised (Canavese et al. 2018). In the Central-Western Italian Alps, the use of geotrekking sites by Italian schools has been already tested as successful (Bollati et al. 2018a) at GT-1 and GT-7. This approach allows for a widening of the view on geological features in the areas surrounding the rock cliffs, including cultural aspects.

In the Central-Eastern Europe chains of Poland and Slovakia, four geotrekking routes have been selected (GT-23–26, Fig. 7a, b), while in the Mediterranean islands of Sicily (Italy, Sicilian-Maghrebide chain and Caltanissetta Basin; GT8-10, Fig. 7d) and Crete (Greece, Carbonate platform), three trails have been selected (GT-11–13). In Sicily, siliciclastic and evaporite rocks dominate, and the long-lasting history of mines and caves is a distinctive trait. Along geotrekking routes (GT-8–10, Fig. 7d) interesting evaporite outcrops mark the most drastic geological event of the Mediterranean area, the Messinian Salinity Crisis. Culturally relevant is the history of sulphur exploitation of the nineteenth century, as landmarks of the economic boom in Sicily (Cirrincione et al. 2022). Human settlements (e.g., ruins of Morgantina archeological area with well-preserved Greek theatre—Final Bronze—Early Iron Age settlement, 11th-18th centuries BC; GT-9; Bell and Halloway 1988) are strictly related to geological and geomorphological features: castles are located on rocky spurs (e.g., Li Gresti and Pietratagliata Castle) and on vertical arenaceous beds, while ancient caves were used as prehistoric shelters.

Outside of Europe, the following geotrekking routes have been selected.

In Oman, the Al Hajar Mountains (GT-27; Figs. 6g, and 7c), and in India, the Deccan Volcanic Province (GT-28), are featured by similar rocks and landforms of the corresponding geoclimbing sites (respectively GC-20 and GC-21): prevailing volcanic rocks in India, and Proterozoic tectonized and karstified limestone in Oman (Fig. 7c; Al Kindi et al. 2022).

In Brazil, site GT-29 (Fig. 8a, b), in the territory of the Serra do Sincorà Geopark Project (Pereira 2022), is located in the protected area of the Chapada Diamantina National Park. Valleys, canyons, caves and residual hills are carved in low grade metamorphosed siliciclastic rocks, dated to the Mesoproterozoic. Endemic species of flora are present. To reach this site, many geotrekking routes cross canyons but official guides have to guide visitors.

In South Africa, the sandstone of the Karoo basin (GT-30; Fig. 7e) shows slope and fluvial processes, as well as evidence for diverse sandstone weathering landforms. Herein caves and rock-shelters are important because they characterize the relationship between the abiotic environment and human settlement, conferring to the trail a high cultural value. There, the ecological value is increased by the presence of endemic species of both flora and fauna.

The exploitation of georesources in a mine or quarry, is a specific form of heritage (GT-2, GT-4, GT8-10) and culturally very relevant. In southern Italy, the sulphur and, more generally, the salt extractive history in Sicily is recorded by numerous mines located within the Rocca di Cerere UGGp, among which is Floristella park trekking route (GT-8), Giumentaro and Trabonella mines (GT-10). The latter was the bigger and most advanced of Central Sicily (Italy). Today they are part of the industrial archaeological heritage and mark the prosperity of Sicily Island during the 19th century. Since 2019, the Floristella mining park (GT-8) is included in the European Route of Industrial Heritage (ERIH) under the auspices of the Council of Europe,

As for geoclimbing sites, the potential hazards along geotrekking routes require adequate preparation and risk management. Hazards may depend on meteorological conditions where, for instance, the path goes along a gorge (e.g.; GT-1; Fig. 8c; GT-11-12, Fig. 7a; GT-27, Fig. 7c), and heavy rainfalls or flash floods may present dangerous situations to users, due, for instance, to difficulties in escaping. Rock falls may also affect the routes as with climbing sites, and should be monitored. For such purposes, DOMs and remote sensing analyses are advanced tools suitable to address these issues.

Development of Digital Outcrop Models (DOMs) at Test Sites

In the first two years of the project, some 3D models have been developed using different methodologies at different geoclimbing (GC-1, 2, 3, 4, 7, 14, 15, 22) and geotrekking routes (GT-10, 13, 14, 16, 17, 18, 19, 20, 21, 22). For this reason, in this section the results are described in relation to the methods applied and the aims for which the models have been prepared. Some of the models are going to be accessible also through QR codes linking to the YouTube channel of the IGCP 714 Project (https://www.youtube.com/@GEOIGCP/featured) where some preliminary versions are stored. Some of them are also stored on Sketchfab, a web-based 3D content viewer, for visualisation and public communication, or on specific UGGP websites. Finally, some of this models are still only available only on the geopark webpages. All the available links are included in the Supplementary Information 2.

In Southern Italy, in the context of the Sicilian-Maghrebide chain and of the Caltanissetta basin, a great variety of trekking routes for different levels of expertise can show visitors how geology and nature connect with the archaeological and cultural heritage. In this regard, two digital models of gorges in the Rocca di Cerere UGGP have been processed. The first covers an area of more than 3 km^2 representing the two peaks of Capodarso and Sabucina in central Sicily (GT-10) (Fig. 10a). The second represents a small valley (<0.5 km^2), with similar geological features to the first (Fig. 10b). Both models have been acquired with a quadcopter DJI drone and the Pix4D capture app (v. 1.0.0; Pix4D 2017), while data analysis and presentation was made through Agisoft Photoscan Professional (v. 1.8.4; Agisoft LLC 2010). Two tiled models have been then exported for three main purposes: (i) interpreting the main geological features through the software LIME-VOG (Buckley et al. 2019), (ii) tracing with cm-scale accuracy safer trekking routes (Forzese et al. 2021) and marking partly-covered archaeological sites, otherwise not even visible on site or by satellite survey; and (iii) developing an interactive geotourism tool, which experienced in the area a severe decrease after the Covid-19 pandemic started.

In the Sesia Val Grande UGGp, located in the Central-Western Italian Alps and surrounding areas, five rock cliffs equipped for climbing were identified for DOMs visualization (GC-1-4, 7). The methods applied herein include digital reflex cameras and a UAV (ANAFI Parrot and DJI Mavic 2 Pro). Images were acquired using the Pix4D capture app (v. 4.11.0; Pix4D 2017). DOMs were finalized using the software Agisoft Metashape (v.1.8.5; Agisoft LLC 2010) and 3D Zephyr Free (v. 6.513; 3D Flow®, Italy). 3D models of single iconic landmarks (e.g., weathering pits; Fig. 10c) or whole rock cliffs have been undertaken. The next steps will include depicting rock wall features and climber routes on the models, to propose interactive reading of rock and landforms influencing climbing, and bespoke 3D models and virtual tours along geotrekking and climbing routes.

3D models have been realized along geotrekking routes in the Serra de Estrela UGGp (Portugal, GT-16-22). Along the proposed geotrekking routes, single sites of geological interest have been surveyed to create 2D and 3D digital models useful for detailed mapping and interpretation of the geosites (Fig. 10d), monitoring the impact of visitors (Soncco et al. 2022), and producing innovative experiences for people with visual impairment or low mobility (Goyanes et al. 2021). These models were realized using a DJI Phantom 4 Pro UAV, planning the flight missions with the app Map Pilot in order to use the terrain following tool. The images were processed in the software Pix4D Mapper (v. 4.8.4; Pix4D 2017) in order to create the orthomosaics and DSM (2D) and the mesh (3D) files. Finally, physical 3D models have been made to reproduce iconic geosites along the trail, such as the granitic columns exemplified in Fig. 10e.

Still in the Central Iberian Range, in Spain, two geoclimbing (GC-14-15) and geotrekking areas (GT-14-15) are included in a National Park with significant restrictions on flying UAVs. This represents a limitation to obtain 3D images of the whole walls and climbing routes. There, the activity is focused on producing 3D models of the geomorphology of the walls at micro- and meso- scales (Fig. 9f) without the need for UAV survey. Several 3D models of granitic landforms (e.g. piles, tafoni, polygonal cracks, fractures, dykes, xenoliths) have been carried out in La Pedriza (GC-14; GT-14). The textural characteristics of the climbing routes are also being studied using 3D modelling by using LiDAR technology mounted on Apple products (iPad pro and IPhone 14 pro). These models allow an accuracy of a few millimetres, suitable for studying textural changes of rocks such as granite. These models are useful for evaluating the process of rock weathering and its influence on climbing.

In the Psiloritis UGGp (Greece), and under an INTERREG project titled "GEO-IN" a 3D model has been produced along the Migias Geotrail (GT-13; Fig. 10g) which runs across a gorge and then a plateau in the Psiloritis Mountains. The model was used to develop a virtual tour along the trail using 360° panoramas that guide visitors along the important geological, natural and cultural features of the trail. The 3D model was mainly compiled from UAV images captured through a DJI Mavic Pro 2 drone and the Pix4d Mapper app (Pix4D 2017). Images were taken from 8 different places over the geotrail, as well as from ground-based images with static cameras. In order to develop the virtual tour, 360° panoramas were shot from 180 different points along the trail, using a man-carried camera. This virtual tool and the models are connected with UGGp webpage (www.psiloritisgeopark.gr) and can be viewed, only in Greek at

Fig. 10 Some examples of the 3D models developed for different geoclimbing sites and geotrekkings by project participants. (**a**, **b**) Mt. Capodarso and Mt. Sabucina in central Sicily (GT-10; Fig. 7b); (**c**) Weathering pit in the Mottarone granite climbing area (GC-4; GT-4; Fig. 6b); (**d**, **e**) Virtual and printed 3D models in the Estrela UGGp (GT-18); (**f**) Climbing boulder in La Pedriza. (**g**) Migias geotrails with the virtual app linked (GT-13); (**h**) Organ pipes 3D model (Australia) (GC-22, Fig. 6d)

present. The tour marks and interprets 16 points of interest along the trail, 7 of them being of geological interest (like a gorge, folds, karstic structures and rock types), 6 of them cultural and others of natural value. From the 3D model, the user can choose embedded panoramas to experience the virtual tool or can click on the points of interest and get the necessary information through popup windows.

In Australia, the Organ Pipes geoclimbing site (GC-22) is considered the major focus of climbing activity in Tasmania, and is unique in Australia in the sense the site has a remote adventure feel, and is only 20 min from the urban sprawl of Hobart, the state capital of Tasmania. The 3D model of the Organ Pipes (Fig. 10h) was realized using a UAV to perform an aerial survey, collecting images from a series of flights from different perspectives. The high-resolution data captured from UAV flights was used to create multiple 3D models of large- and small-scale features. Agisoft Metashape software version 1.5.3 (Agisoft LLC 2010) was used to process the data from UAV flights to create 3D models using Structure from Motion (SfM) photogrammetry techniques. Annotations were created on the 3D model, highlighting geological features and to provide links to smaller scale features (e.g., Albert's Tomb https://skfb.ly/6LXzC). Additionally, 3D models and UAV fly-by videos were attached to this site and other within the Wellington Park Geosite Inventory Web App (i.e., https://arcg.is/WLuan) that was designed for public outreach and management visualisation.

Discussion and Future Perspectives

The results of the qualitative and quantitative assessment of geodiversity sites equipped for climbing, and of geotrekking routes, as first step in the framework of the *IGCP 714 project "3GEO – Geoclimbing & Geotrekking in Geoparks",* demonstrate how sites, where outdoor activities are practised, may have high values as geodiversity sites. In specific case they may be valued also as geoheritage elements even if they are not yet recognized as geosites. Indeed, most of them were equipped for climbing before geosites inventories became popular practices in the different countries. Important to underline in this context is that in many geosite inventories, the integrity of a site is one of the evaluation parameters for determining the status of geosite. In this context, even if these rock outcrops may have a high scientific value and representativeness (as emerged from the results), they had previously become reference sites for this outdoor activity and hence now they are potentially undergoing human pressure. Since the site may be compromised by belays and anchors and climbing activity in general (Gray 2005; Kubalíková and Kirchner 2016; Rop 2020), they were probably disregarded. However, these non-geosites could be potentially considered as important geodiversity sites (sensu Brilha 2018).

Usually the methodologies applied for geoheritage sites assessment are subjective and results depend upon the evaluators perspective. Anyway, in this case it could be considered a practice way to compare sites from different regions, and also with previous works (e.g., Bollati et al. 2016). The methodology also helped to highlight which are the weakness of each geoclimbing site.

For instance, if sites are penalized by the low developed touristic context and the scarce connection with surrounding sites (GC-6; Supplementary Information 3), the geopark institution could help local communities to increase visibility and to push activities of Earth Science dissemination, as well as the creation of network of sites, through innovative approaches like the one proposed by IGCP 714 project.

Another problem is related to location of sites in protected areas. For instance, in the Estrela UGGp, the most suitable geoclimbing sites are located in the higher plateau of Serra da Estrela, an area with natural heritage of international relevance and, as such, bears several designations to assure its protection (Natura 2000, Biogenetic Reserve, Ramsar site, Portuguese Natural Park and UNESCO Global Geopark). Thus, the Serra da Estrela Natural Park's management plan takes the Higher Plateau as the highest priority section, and consequently has the highest restrictions of use, including sports climbing. Considering the potential of climbing for educational and scientific purposes, a working group has been set to regulate these activities through a Mountain Sports Charter for Serra da Estrela. Results from the IGCP 714 project may add further details and rationale, supporting this process.

Indeed, the obtained results indicate the necessity of fixing some weak points at the different sites, finding adequate strategies, according to local features, and a balance for promoting and conserving these important georesources already impacted by humans since equipped for climbing.

The *IGCP 714 project "3GEO – Geoclimbing & Geotrekking in Geoparks"* represents hence an important step towards the development of:

(1) new approaches for geoheritage education, and communication of Geoscience and know-how transfer through international collaborations in the field of geoclimbing and geotrekking;
(2) new multimedia and interactive tools based on DOMs (Digital Outcrop Models) of individual sites in order to increase awareness in different user communities about the value of geodiversity and geoheritage sites;
(3) a global community of practice of geoheritage researchers focused specifically on supporting the ambitions of aspiring geoparks and other protected areas in the field of geoheritage communication and outreach to different communities.

In general, outdoor activities like geoclimbing and geotrekking may favour the achievement of some of the Sustainable Development Goals (SDGs 3, 4, 8, 11; Bollati et al. 2023), that will be herein discussed.

An immediate link is with SDG 3 (*Good health and well-being*), since outdoor activities and engagement with nature allow for improved sociality and wellness (e.g., Baláš et al. 2017; Siegel and Fryer 2017; Hrušová and Chaloupská 2019).

SDG 8 (*Decent work and economic growth*) is pertinent because of the role of geotourism in sustainable economic development of often remote rural areas. An exemplary case is described in the results section, for the GC-5 (Ronco), located in the Sesia Val Grande UNESCO Global Geopark but in a less known sector. More in the specific, since for geoclimbing, geotrekking and other analogous, the support from practitioners working in the territory (e.g., mountain guides, environmental guides) is always recommended, new economic opportunities can be born for remote areas as well. All this, anyway, requires quantitative indicators of the benefits that could be obtained by local communities.

Concerning SDG 4 (*Quality education*) and SDG 11 (*Sustainable cities and Communities*), they are strictly linked since awareness about natural resources value could be reached through innovative educational tools. Promoting knowledge about the importance of georesources has a central position among the aims of the IGCP 714 project. Through innovative tools like 3D visualization, in combination with sport and recreation activities, the quality of education and awareness of wider environmental and Geoscience issues may also benefit.

Considering again SDG 11 in the specific, and geoconservation issues at geoclimbing sites, it is relevant that some of the selected rock cliffs, equipped for climbing for an extended period of time, are also *geosites* or *geodiversity sites* (sensu Brilha 2018). Considering the IUCN report on how to manage the climbing areas sustainably in Europe (Hanemann 2000), attention has been up to now paid only to impacts on fauna and flora. The potential damage to geofeatures, and the recognition of their value, is still lacking and has only recently been mentioned in the literature (e.g., Gray 2005; Kubalíková and Kirchner 2016; Rop 2020). Indeed, among the reasons given in the IUCN report for climbing restrictions in certain areas, none refers to the Earth Science scientific value of the site.

Potential proposals for reducing climbers' impacts on geoheritage and geodiversity (Fig. 11) at sites already equipped for climbing may include:

i) restricting climbing activities, especially at fragile geoheritage sites (i.e., *restrictive geoconservation*), moving the climbers to other rock walls that are not so scientifically valued (maybe geodiversity sites). In this specific case, in order to visit particularly fragile sites, the approach from remote, through 3D models, could be an interesting solution not impacting the site (Fig. 11). Hanemann (2000), indeed, suggests that climbing might be allowed in existing climbing areas only after providing evidence of no environmental deterioration. This solution, anyway, besides moving the problem to other sites and favouring overcrowding at the alternative climbing sites (Hanemann 2000), may lead to the risk of upsetting local climbing communities used to climb in some traditional places for which they feel a 'sense of place'. This may also induce bad or unsafe climbing practices.
ii) Educating, by clear communication strategies, the climber community, clubs and schools involved in activities at cliff sites, about the value of rocks they are climbing on (and connected biotopes; Hanemann 2000) (i.e., *involving geoconservation*). Witty (1998) reported that the experience of nature is necessary for the involvement in nature conservation practices, since you can only protect what you know. As underlined by Gordon et al. (2021), young visitors may gain a deeper understanding and appreciation of the values of geodiversity and geoheritage through place-based learning and engaging activities like climbing (Siegel and Fryer 2017): it stimulates interest in Earth Sciences favouring geoconservation and environmental practices (e.g., keeping paths clear and maintained as well as rock faces free of vegetation or loose material, or by acting as local wardens or rangers). According to the authors, if people understand the value of geoheritage and geodiversity elements, they are more inclined to show sustainable behaviour. Awareness and consciousness have already grown in climber communities (Kooner 2018), and this could be hence a mechanism to encourage minimum impact practices (Hanemann 2000; Gordon et al. 2021). This is appropriate where there is already, for instance, a long tradition of climbing, and where rock walls have been equipped with appropriate safety equipment for a long time (e.g., Kooner 2018; Clark et al. 2020 and references therein). Three different examples of involving geoconservation at climbing sites are now described, among them, the first, is an evaluated geoclimbing sites of the project.

In the Sesia Val Grande UNESCO Global Geopark, the GC-8 (Ara) is a climbing wall carved in limestones where beautiful caves are used to climb. Limestone in the region are quite rare and nearby the climbing wall, few calcareous outcrops present an analogue beautiful cave cluster named "Giardino delle Grotte di Ara" (The Garden of Ara caves, a geosite of the Geopark). In this case the balance between geoconservation and sport activities is working: a part of the karst landforms are protected, while the other one is opened to be used for sport activities. The suggested improvement, as emerged from the herein presented quantitative assessment, could be related to the amelioration of the physical connection between these two localities through a thematic path, explaining all these aspects related to these differently-treated resources.

The second case is located at Plakias, in Crete Island (Greece), where a geosite shows an impressive fault plane (Fassoulas 2000). It is also a well-known climbers' destination. The site is threatened by the building of new infrastructure rather than by climbing itself. The climbing community was promoting a petition and consultation to stop this development. Finally, a court decision cancelled the construction permission and the Ministry of Environment initiated the procedure to nominate the area, after a study

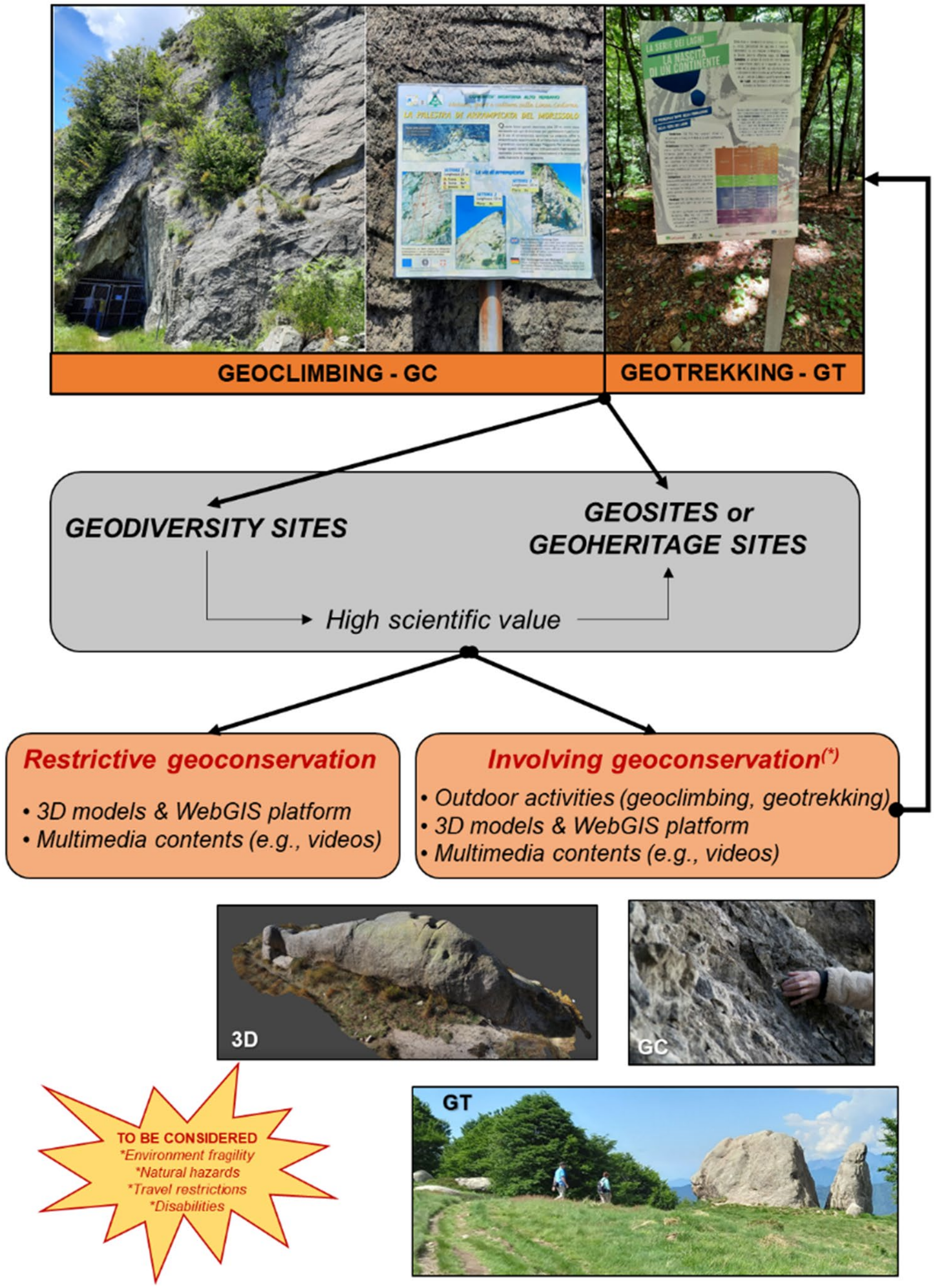

Fig. 11 Summary sketch of geoclimbing and geotrekking in the view of promotion and geoconservation

conducted by the Natural History Museum of Crete, as a Protected Natural Monument.

Another interesting case is represented by the Bohemian Paradise UGGp, where the *LNT-Leave No Trace* (Clark et al. 2020), a potential strategy that can reduce impacts on such kind of ecosystems, is applied. There, the towers of soft sandstone are weak landforms, and climbers have always used for safety rope rings with knots instead of metallic nuts and friends (i.e., removal metal equipment) (i.e., passive protection; https://www.summitpost.org/bohemian-paradise/810089). Therein, the use of chalk is also forbidden to prevent the surface of the rocks from being stained.

In all these examples, the nexus between climbers and their favourite destinations makes a ‘sense of place’, and the cooperation with climbers’ communities is fundamental for promoting sustainable usage and assisting local managers to design appropriately climbing areas (Clark et al. 2020). In this specific case, both the field approach through regulated outdoor activities and the approach from remote, through 3D models, could be an interesting solution, and may be recommended (Fig. 11).

More sensitive is the issue of equipping new climbing areas (see Charnwood Forest Geopark and Estrela UGGp cases) requiring specific precautions and measures that should consider, as well as biotic nature (Hanemann 2000), also the geoheritage to be preserved, especially if fragile.

In general, the best choice between restrictive practices uses or involving geoconservation should be based on local conditions and site features, both natural and socioeconomic (Hanemann 2000). Considering that only knowledge about what has value to be protected will be favoured for conservation strategies and priorities (Witty 1998; Hanemann 2000; Gordon et al. 2021), the IGCP 714 project is addressed towards an *involving geoconservation* approach in existing geoclimbing sites (Fig. 11), where Earth Science outreach may increase awareness of geoheritage and geodiversity sites (sensu Brilha 2018). In this process of *involving geoconservation*, i.e., a place-based learning approach (Gordon et al. 2021), climbing associations should be actively involved and trained about Earth Science.

The specific issues related to geoclimbing are quite different to those related to geotrekking (Fig. 11). Along the proposed geotrekking routes, indeed several geosites could be visited too, even if not potentially compromising their integrity. Although, having less impact on geofeatures, the main issues along the trails are related to crossing private property, so most proposed geotrekking routes are short and located in single areas.

The last SDG, connected to the project, is the SDG 17 – *Partnership*. It is related to the strong international network developed within the project to share information on methodology and geodiversity sites, and to favour partnerships with local stakeholders. Each partner, then, may bring original and diverse contributions to the project, and historical UGGps have an important role in mentoring aspiring UGGps. More in detail, through the experiences gained by the partners, indeed, it will be possible to create a shared methodology that can improve the easiness of the approach and that can find solutions that lower the potential high costs, one of the main issues connected with the use of innovative technologies (Hincapiè et al. 2023; Walker et al. 2023). Project inputs are also diverse and varying according to site-specific geodiversity (e.g., different kind of rocks, tectonic conditions, morphoclimatic environments), and socioeconomic and touristic conditions of the different sites (e.g., access to specific areas, size or remoteness of the site, whether the site is in a protected or private area or not). Furthermore, issues experienced by some of the partners (e.g., difficult relationships with local owners and stakeholders) may be dealt with by adopting common strategies across partner sites, by bringing expertise from other regions, especially partners with long term experience (e.g., by long-lasting UGGps).

Concluding, the combination of activities in the field and based on remote visualisation on rock cliffs or along trekking routes, several advantages can be identified. This approach can increase access to the site and to Geoscience information also for people with disabilities or limited access or mobility (Fig. 11), as well as the access to fragile or remote sites due to elevated costs or for conditions such as the Covid-19-like type (Scerri et al. 2020; Fassoulas et al. 2022; Hincapiè et al. 2023; Pasquarè Mariotto et al. 2023). The acquisition of data through new technologies (UAV, digital reflex cameras, smartphone LiDAR scanners) will allow for sharing material among project partners, stakeholders and the general public through multimedia tools and through social media platforms, and for monitoring of sites with periodic reassessment of site features. After creation of 3D models at pilot sites, a goal of the IGCP 714 project will be the development of a common methodology for acquisition of data and 3D visualization, deriving from the experiences of the different partners under different natural (geological and geomorphological), cultural, legal and socioeconomic conditions. The next steps are also to annotate all the 3D models with the climbing route information and provide geological and geomorphological layers that can be toggled on to disseminate Geoscience information to the geoclimbing communities. Through the organization of teaching opportunities for young people involved in management of aspiring or existing UGGps, but also in other research environments, each area could develop its own multimedia material to be upload in a common repository, as well as available to the public on the internet. Indeed, all the data acquired will be shared through a Web-GIS platform that could be useful for teaching and research purposes by a variety of users. These practices should raise awareness amongst climbers, trekkers and other stakeholders about the value of climbing sites or trekking routes as geodiversity or geoheritage sites, and about the sustainable use of the physical landscape considering geoconservation and natural hazard mitigation.

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Declarations

Competing Interest The authors have no competing interests to declare that are relevant to the content of this article.

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