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ORIGINAL ARTICLE

Conservation of the Geological Heritage of Volcanic Fields: La Garrotxa Volcanic Zone Natural Park, Spain

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Abstract
This article evaluates the strategy approved in 2000 for managing the geological heritage of La Garrotxa Volcanic Zone Natural Park (PNZVG). The conservation of geodiversity and geological heritage provides a foundation for the conservation of other types of heritage, for example, in the fields of forestry, agriculture, industry, and urban development. The human imprint on this natural Park is significant, and most of the land it contains is privately owned and is commercially productive. Consequently, the management of its volcanic strata is a highly complex affair as preservation must be compatible with the types of land use that dominate in this protected area. The PNZVG's strategy for managing its geological heritage stems from the need to promote the efficient conservation of its values based on knowledge and greater awareness of this volcanic field. Quaternary volcanic fields such as this one—which may have experienced volcanic activity in the Holocene—are characterised by their excellent state of conservation, which ensures that their volcanic morphologies and the geological processes that have created them are fully visible. In 2000, the natural Park became one of the first protected areas in the world to put into practice a strategy for preserving the geological heritage of its volcanoes. Twenty years later, an accurate evaluation of this process will help other volcanic zones design their own strategies for preserving their geological heritage. To sum up, both challenges and objectives are necessary for ensuring good management of a protected area such as this.

Keywords Volcanic field · Geological heritage · Geodiversity · Protected natural area · Awareness-raising

Introduction

Currently, it is widely accepted that geoconservation benefits our human societies as it provides understanding that helps grasp the history of our planet (Gray 2019); in addition, geoconservation is also valuable as a tool guaranteeing many important ecosystemic services linked to our planet's geology that, for instance, afford support (soils, cliffs and caves), supply (minerals, energy and water), regulation (climate and flood control), and cultural advancement (scientific knowledge and geotourism) (Gray et al. 2013). The geoconservation of a site or area requires a thorough knowledge of its geodiversity, as well as awareness of how geological heritage can be conserved using the principles of sustainable management (Gordon 2019). Implicit in the protection of the most valuable elements of geodiversity is the task of safeguarding our geological heritage, the main motivation for which is scientific, although educational, cultural, aesthetical, spiritual, and ecological components are also highly relevant (Gray et al. 2013; Crofts and Gordon 2014; Gordon 2019). The success in conserving the geodiversity of an area will depend on how well its natural geological heritage can be preserved (Németh et al. 2017b); hence, the selection of geozones and geosites and how they are to be managed and monitored are pivotal aspects of geoconservation strategies at all levels (Carcavilla et al. 2008; Gordon 2018).

The study and the appreciation of the geodiversity of an area are crucial steps when attempting to identify and protect the geological values that best represent its geological heritage. First, it is essential to evaluate the geodiversity by selecting a series of criteria that will depend on factors such as the types of landscape present in the study area, their extent, the importance of the various different geological

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features to be preserved, and the availability of spatial data at an appropriate scale (Brocx and Semeniuk 2007). Once this evaluation has been performed, the next task is to identify the elements that better reflect the geological value of an area and which most contribute to the understanding of its geological history. Finally, it is also necessary to decide what type of management and conservation policies—i.e. based on geotourism, geoconservation, and/or geoeducation—are of greatest importance (Németh et al. 2017a).

Habitually, both the management plans in protected areas and the people in charge of management on the ground take into account the importance of conserving a region's biodiversity. This aspect of conservation has for many years been regulated by international agreements such as the Convention on Biological Diversity (1992) and is generally accepted to be the *raison d'être* behind many protected natural areas. However, this focus on biodiversity tends to underestimate the significance of our geological heritage and geodiversity. It is important to remember that the rocks, sediments, soils, and geological processes and their evolution are all vital components of the future of our planet and our societies. Gray (2014) has synthesized the key concepts in conservation, which include intrinsic, cultural, aesthetical, economic, and functional values, as well as its importance for research and education. Today, the awareness of geoconservation has grown and now goes beyond purely educational and aesthetic considerations to embrace the role of geodiversity and geological heritage as providers of ecosystemic services (Gray 2019). An is mostly geological; good examples include Yellowstone National Park in the USA, already established in 1872 to conserve its geothermal features, and National Park of El Teide, one of the first protected areas declared in Spain (Fig. 1).

Today, there are many good examples of where the planet's geodiversity has been well preserved and of how this protection is based on the specific characteristics of an area, the geological values that require protection, and existing political and administrative requirements (Prosser 2013; Brilha 2016; Brilha et al. 2018). The efforts aimed at preserving these geological values led to the declaration of the UNESCO Global Geoparks, the natural and national Parks that protect geological landscapes, and the many other geosites and protected natural monuments throughout the world. The protection and preservation of geological sites of interest do not imply that they should be closed off to the general public. Provided that their conservation is safeguarded, protected geological sites must be made visitable, and good-quality information regarding their significance in both general and local contexts must be made available. Thus, the protection of our geological heritage implies the search for the best possible management and conservation protocols, which will permit access to and the identification and study of all the key observation sites that reflect the history of a particular protected area (Planagumà and Martí 2018).

Fig. 1 Path at Roques de Garcia in El Teide National Park, one of the most walked paths anywhere in the world. In 2019, 4,330,994 tourists visited this Park

The UNESCO Global Geoparks programme was actually set up in 2015. Prior to 2015, the programme was called the Global Geoparks Network (GGN), and it was established in 1998. Since 2015, all of the original GGN members are officially designated as UNESCO Global Geoparks, which contemplate geoconservation at different territorial levels: regional (< 10,000 km^2), large scale (< 100 km^2), and local (< 1 km^2) (Brocx and Semeniuk 2007). A central tenet of this programme is that each territorial scale should define the objectives, actions, indicators, and types of assessment that will form part of its particular geoconservation strategies (Gordon 2019). The past 20 years is time enough to analyse and evaluate the conservation of the geological heritage at territorial scale; this period is also long enough for natural processes such as erosion to have visibly affected parts of our geological heritage (Palacio-Prieto et al. 2016) or for the impact of human-provoked changes such as building and infrastructure projects (Tamayo-Salamanca et al. 2014), the overvisitation of tourist areas (Dowling and Newsome 2018), mining and wars (Kiernan 2012) to become apparent. Hence, it is important to evaluate and analyse the indicators and the state of our geological heritage in relation to the first conservation initiatives taken in this field; this is the case of the PNVZG, declared in 1982, and its geoconservation strategy implemented from 2000 onwards.

Volcanic zones exhibit complex but fascinating stratigraphic relationships (Cas and Wright 1987) and often possess geological heritages of untold value. Proof of this is the large number of protected volcanic zones that exist (Németh et al. 2017a), whose conservation is essential given their soils that favour biodiversity, the beauty of their landscapes, and their intangible cultural and spiritual values. For instance, 80 of the sites that have been declared world heritage sites are of volcanic origin (Casadevall et al. 2019). One type of volcanic zone that has been protected in many different ways is the monogentic volcanic fields, formed by a variable number of small volcanic cones and lavas and other associated pyroclastic deposits originated by multiple different eruptions, since they generally boast rich soils, easily accessible sites of geological interest, and aesthetically pleasing landscapes (Németh et al. 2017b; Casadevall et al. 2019). A good example is the European Rift, which contains nine volcanic fields with some type of protection (Fig. 2) (Planagumà and Martí 2020). In recent years, volcanic zones have begun to attract ever more geotourists in search of active and dormant volcanic landscapes, good food, adventure, and pleasurable experiences. Consequently, just as occurs in the fields of biodiversity and threatened species conservation, the preservation of local geological heritage can generate positive social and economic values in the site in question (Planagumà and Martí 2018).

In a previous paper, we analysed the economic impact of the PNZVG designation (Planagumà and Martí, 2018). In this new article, we examine the results of the indicators that assess the strategy that was designed 20 years ago by the PNZVG to manage its geological heritage. Currently, after 20 years of implementation, no framework exists for analysing whether or not its geoconservation aims and policies have worked as planned, or how they could be improved. Two decades later, the impact of erosive processes, vegetation growth, and educational programmes, for example, can be analysed, and the results used to improve geoconservation, above all, provide tools for conserving geological values in other volcanic areas. We also identify some actions pending that could contribute to improve geoheritage management and conservation in the PNZVG.

Situation

La Garrotxa Volcanic Zone lies in the northeast of the Iberian Peninsula and is part of the Neogene-Quaternary Catalan volcanic province of the European Rift (Fig. 2) that extends from the Alborán Sea into central Europe (Martí et al. 1992). This rift originated during the Neogene distension that began 20 Ma as the alpine orogeny affecting southern Europe slowed. The associated volcanic activity is

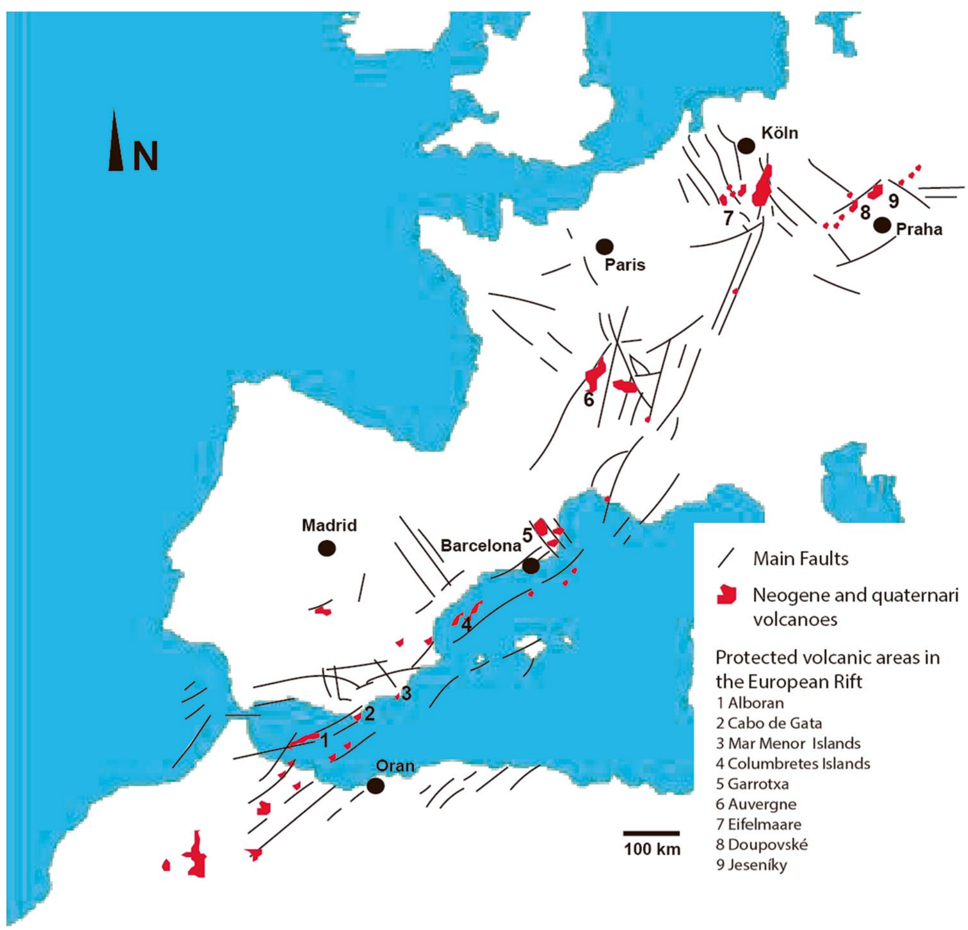

Fig. 2 The European Rift with its associated volcanic areas, and the nine zones that enjoy some degree of protection according to the International Union for Nature Conservation

alkaline in nature and has given rise to a number of different volcanic zones (Fig. 2). La Garrotxa Volcanic Zone, covering around 600 km^2 and lying between the cities of Olot and Girona, is one of the youngest. It harbours around 50 volcanic cones, lava flows, tuff rings, and maars dating from the Middle Pleistocene (0.12–0.78 Ma) and beginning of the Holocene (0.01 Ma) (Fig. 3). Its volcanic features lie atop Eocene sedimentary formations folded during the alpine orogeny and Quaternary alluvial deposits. The magma that originated this field is both basaltic and basanitic (a mixture of basanites with nepheline crystals and basalts with olivine crystals) (Cebría et al. 2000). In many cases, the magma ascended directly from the mantle and was not differentiated or contaminated by materials from the crust.

Most of the volcanic activity in this field was strombolian and gave rise to cinder cones formed by fall deposits (lapilli and blocks). Many of these monogentic cones (e.g. Rocanegra, Montolivet, Sant Marc, and L'Estany volcanoes) are characterised by horseshoe-shaped craters. Nevertheless, if the magma came into contact with the aquifer, the resulting eruptions were more complex and phreatomagmatic phases occurred that produced gas explosions and emitted fragments of the substrate (lithics) as pyroclastic flows and breccia (Martí et al. 2011). Combined with the strombolian fall deposits, these other types of deposits created a complex variety of eruptive sequences that in some cases include maars and tuff rings (e.g. Santa Margarida, La Garrinada, El Racó, and Can Tià volcanoes) (Martí et al. 2017).

The excellent state of conservation of these volcanic cones, the rich soils of their associated fields, and the biodiversity they generate were the main factors prompting the declaration of the PNZVG in 1982, the first natural Park (IUCN category V) to be established in Catalonia since Spain's return to democracy. The management of protected areas in the Spanish state was handed over to the autonomous communities, the only exception being the national Parks that are run jointly by regional and state authorities. In Catalonia, the planning mechanism that oversees its network of protected areas is the 1992 Areas of Natural Interest Plan (PEIN). Most of these areas were incorporated in 1997 into the European Natura 2000 network, the legal framework that guarantees the conservation of much of Europe's natural heritage.

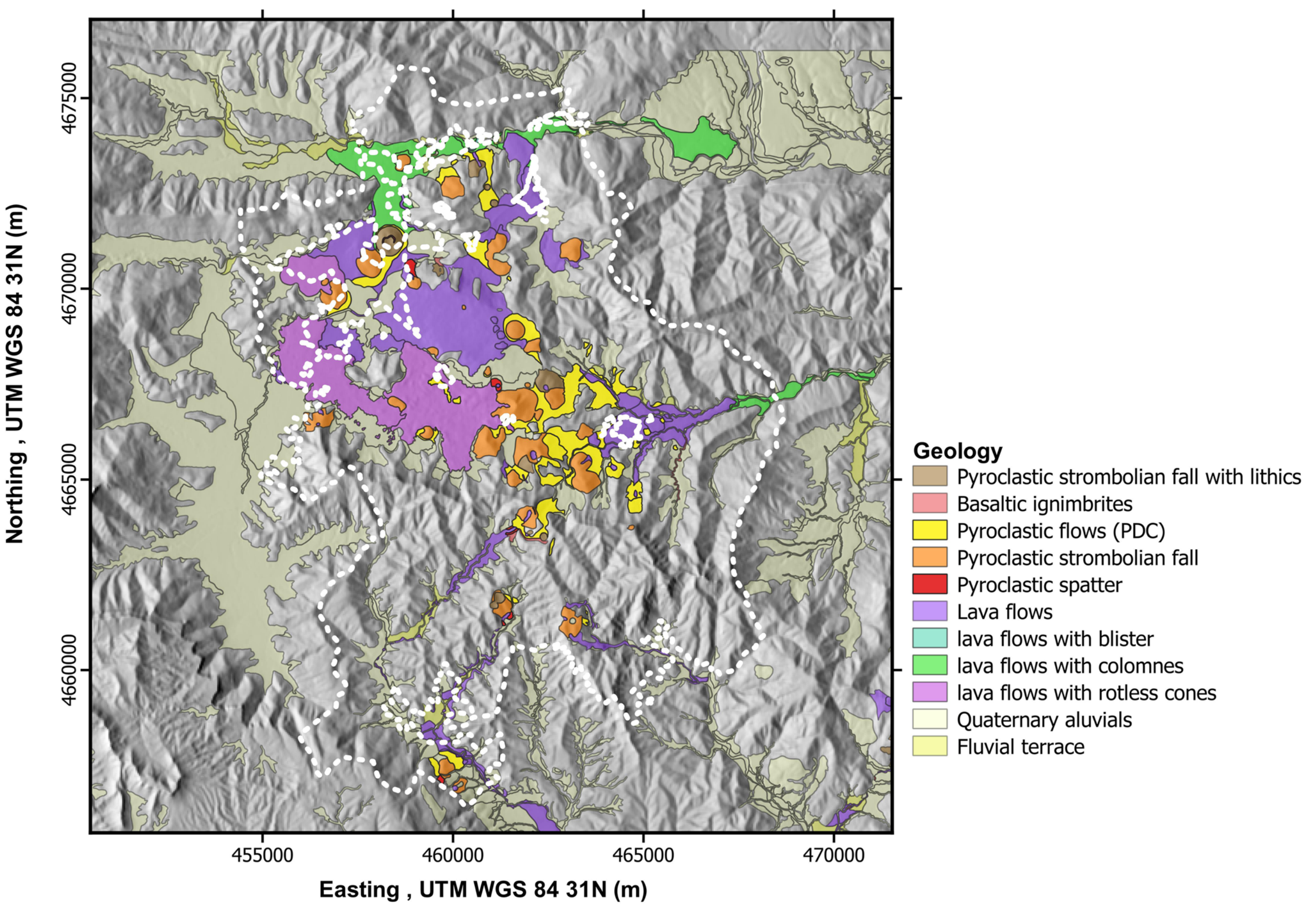

Fig. 3 Map of the geodiversity in and around La Garrotxa Volcanic Zone Natural Park

The PNZVG covers 15,000 ha and lies in the centre of the county of La Garrotxa in northern Catalonia. It contains 40 monogenetic volcanic cones, of which 28 are protected as natural reserves (IUCN category IV), and it is regarded as the best preserved volcanic field in the Iberian Peninsula. The human influence is notable in this natural Park since within its boundaries live 33,000 people. In all, 98% of its land area is private property owned by many different landowners, a fact that complicates enormously the running of this Park (Fig. 4).

The urban and industrial growth in Spain and in Catalonia that took place in the 1960s and 1970s provoked a series of impacts that seriously threatened the country's natural—and, by extension, geomorphological—values (Abarquero-Zorrilla and Vila-Subirós 2010). The most obvious case was the quarrying of lapilli from Croscat volcano, to which we can add the threat of mining for radioactive minerals, the continued pollution of the river Fluvià and its tributaries by sewage, the proliferation of fly-tipping including the tip at Fontfreda (Sant Joan les Fonts) underneath a basaltic cliff of exceptional patrimonial value, the building of residential areas and associated service infrastructure on the very volcanoes, and the growing urban and industrial sprawl of the area as a whole (Abarquero-Zorrilla and Vila-Subirós 2010). These abuses led to the organisation of a series of protest campaigns, which culminated in 1976 with the creation of the highly active Commission for the Protection of the Volcanic Zone and, subsequently, a year later, the setting up of Campaign for the Protection the Natural Heritage of the Catalan Countries organised by the Congress of Catalan Culture. Finally, on 3 March 1982, the Catalan Parliament approved Law 2/1982 on the Protection of La Garrotxa Volcanic Zone, which declared this volcanic zone a natural site of national interest with the avowed aim of conserving its highly singular flora, geomorphological character, and outstanding beauty (Bassols Isamat 2008). This law also established a series of integral reserves of geobotanical interest that would counteract any future action liable to destroy, deteriorate, transform, or disfigure the area's geomorphology and flora.

Initially, the management of the PNZVG's geological heritage focused on the conservation of the geomorphology of its volcanic cones, the restoration of the quarry in Croscat, and the mitigation of the degradation of certain highly visited cones and craters (e.g. Santa Margarida and Montsacopa). In 2000, a management strategy for the Park's geological heritage was mapped out to analyse the state of knowledge, conservation and awareness of the volcanoes, and to institute future strategic objectives and lines of work. This new strategy was incorporated into the Parks' special plan, approved in 2010, that is today the mainstay of its territorial and resource-use planning.

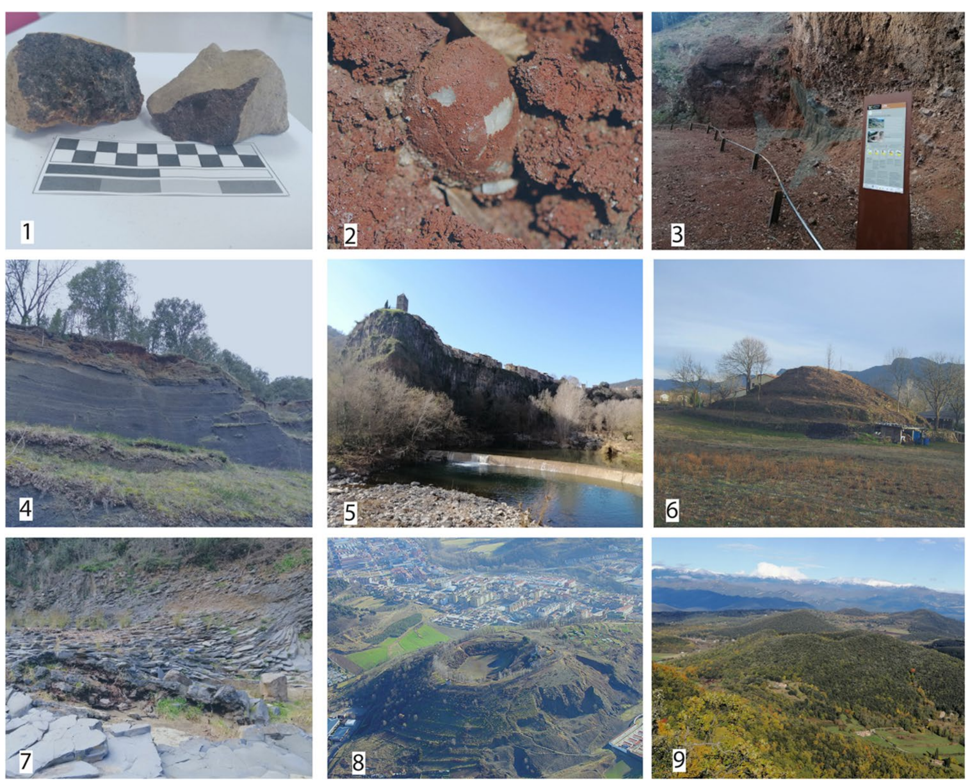

Fig. 4 Elements of the geological heritage of La Garrotxa volcanic field. 1 Example of pyroxenite from the earth's mantle; 2 Sanidine; 3 former quarry in the Sant Marc volcano; 4 Strombolian and phreatomagmatic fall deposits in the former quarry in the Croscat volcano; 5 cliff at Castellfollit de la Roca composed of two lava flows; 6 rootless volcanic cone (*tossol*) on the Bosc de Tosca lava flow; 7 blister at El Molí Fondo; 8 cinder cone and circular crater of the Montsacopa volcano; 9 craters of the Santa Margarida and Croscat volcanoes

The Strategy for Managing the Geological Heritage

The geological heritage of the PNZVG contains many points of interest, ranging from volcanic elements just a few centimetres in size (the enclaves of rocks from the Rocanegra volcano and the sanidine crystals of the Pomareda volcano), through outcrops that illustrate unique geological sequences and processes, to geomorphological features such as rootless volcanic cones, lava flows, craters, cinder cones, and large extensions of terrain that help us interpret complex eruption clusters such as those of Santa Margarida-Croscat. All these elements are of geological importance at scales that vary from the local and regional to the international (Fig. 5).

In 2000, 18 years after the declaration of the natural Park, the overriding idea was that the geomorphology of the volcanic cones was no longer under threat given that the quarrying had ceased, and a number of restoration projects fostering the conservation of the area's geological heritage were underway. Nonetheless, it was also clear that in many cases, the management of land use in the Park had not been completely successful in highlighting the morphology of the cones and craters, and as a consequence of the fly-tipping, landslips, and vegetation encroachment, the visiting conditions of many of the Park's most significant outcrops and their overall visibility had been negatively affected. Fortunately, these processes are generally reversible and can be remedied if appropriate measures are taken.

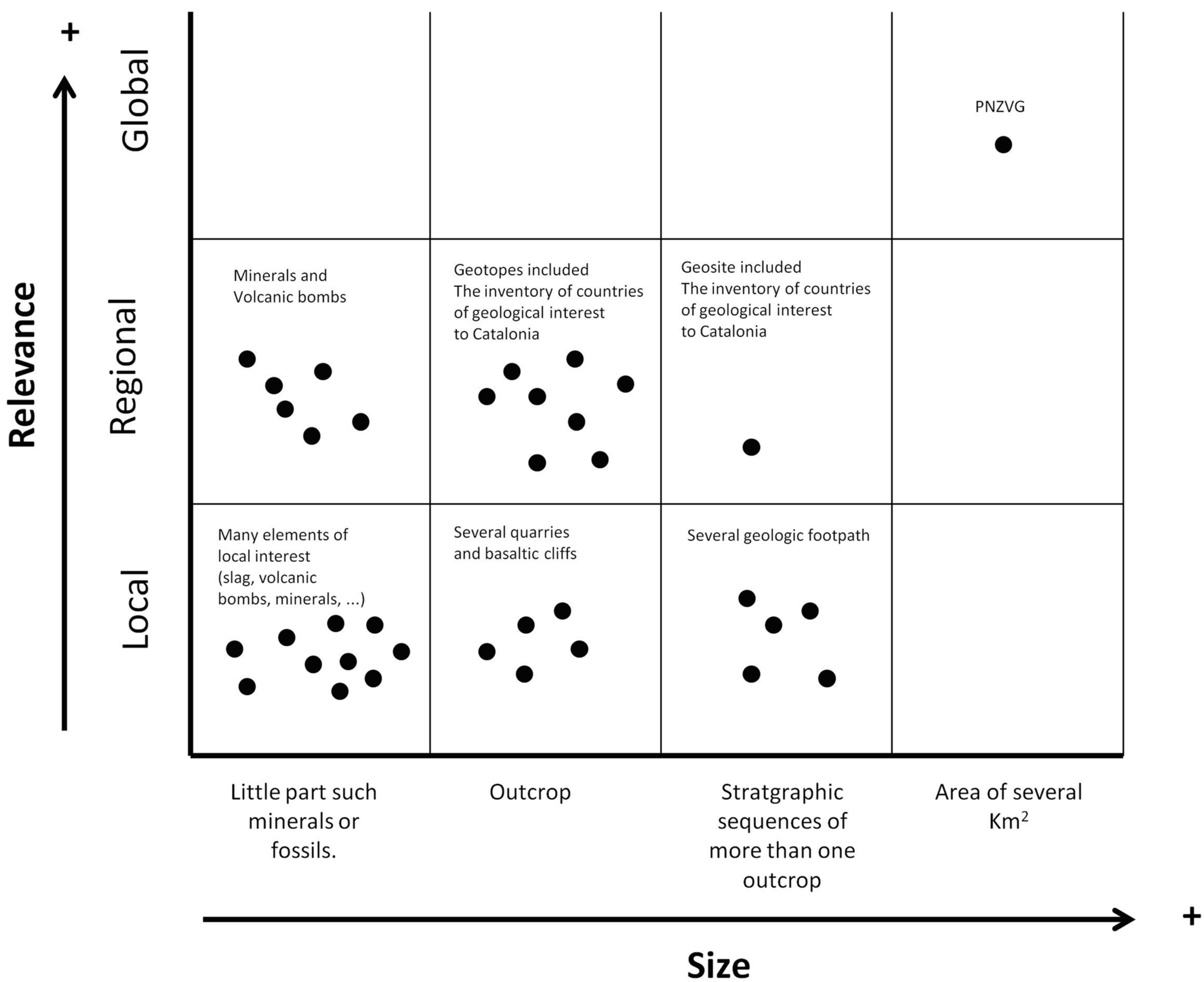

Fig. 5 Relationship between the local, regional and international relevance and the size of the site of geological heritage. In the study zone, no single outcrop, either volcanic or mineral, is of international importance. The international relevance of the area is due to the diversity of eruptive sequences and their relationship with the region's natural, cultural, and intangible heritage (Marti and Planagumà 2017). Adapted with permission from an original idea by Enrique Díaz-Martínez and Luis Carcavilla

The Park's conservation strategy comprises three general objectives: (i) improve knowledge of vulcanism in the PNZVG; (ii) conserve the geological and scenic values of the vulcanism in the PNZVG; and (iii) educate the local population to appreciate the importance of conserving their geological heritage. In addition, there are a series of more specific objectives that depend on these three general aims (Table 1). This strategy also proposes ways of evaluating the Park's work via a series of quantitative indicators that include the number of scientific articles in which the monitoring of ephemeral outcrops is mentioned and the number of places of geological interest that have been conserved and restored; likewise, it is important to evaluate certain qualitative indicators that analyse participation by local groups and citizens and the Park's educational programmes and the impact they have had.

Evaluation

A series of indicators aimed at measuring how the strategy's objectives have been implemented were designed. These indicators determine whether or not the objectives have been fulfilled and, additionally, provide quantitative data that can be analysed and used in future work aimed at improving geoconservation in the PNZVG.

In this article, we highlight eight indicators that illustrate the state of the geoconservation in this volcanic zone and directly quantify certain relevant aspects; moreover, these indicators also shed light on improvements in the environmental services that geology provides our societies.

i) **Information of interest derived from the monitoring of ephemeral outcrops (ecosystemic cultural services)**. Dynamic economic activity implies the need to dig into the subsoil to carry out work on buildings and infrastructures (Fig. 6). In volcanic fields, these ephemeral sites, which are otherwise often completely covered by vegetation, are of great interest given the opportunities they provide for improving knowledge of local vulcanism. These outcrops vary greatly in terms of the type of deposits they reveal (Martí et al. 2011), some of which are fairly limited in size.

Thus, since 2004, the PNZVG has promoted the inventory and description of these ephemeral outcrops, and from the onset of this programme up to 2019, a total of 154 points—including sites exposed by geological survey work, the digging of wells and construction projects—have been studied (PNZVG report). The infor-

Table 1 List of objectives stated in the Park's geoconservation strategy and their degree of fulfilment

	Objectives	Fulfilment (yes/no/partially)
	Improve knowledge of the geological heritage of La Garrotxa Volcanic Zone Natural Park	
1	Create a database of geological heritage sites that can be integrated into the Park's GIS	Partially
2	Characterise the eruptive behaviour of the 12 most singular volcanoes in the area	Partially
3	Promote collaboration with universities and other research centres	Partially
4	Propose ways of integrating studies of volcanic and seismic risk into territorial planning	No
5	Define research priorities in the fields of petrology, geochemistry, palaeoclimatology, and tectonic-structural studies	Yes
6	Create 1:25,000 geological maps	Yes
7	Plan and monitor the incorporation of new data obtained from the study of ephemeral sites and boreholes	Yes
	Conserve the geological and scenic values of volcanic landscapes	
8	Restore and conserve the meadows and crops sown in craters and around the base of cones to facilitate the observation and geomorphological study of the volcanoes	Partially
9	Restore and conserve well-preserved outcrops, create a network of points of geological interest, and aim for quality viewing experiences	Yes
10	Integrate the areas and outcrops of interest into municipal planning	Yes
11	Programme on an annual basis the activities and measures required to conserve the volcanic heritage	Yes
12	Draw up catalogues and 1:5000 maps of the most interesting volcanic features	Partially
13	Review every 5 years the Park's volcanic heritage and protect those elements of greatest interest	No
	Educate the local population in the importance of the conservation and protection of the Park's geological heritage	
14	Review and update if necessary existing educational recourses	Yes
15	Design activities and create resources (publications and infrastructure) that can be used to promote the importance of the volcanoes	Yes
16	Design and place informative signage for the network of points of geological interest	Yes

Fig. 6 Photographs of ephemeral geological elements and outcrops exposed by building work, boreholes or the construction of large infrastructures. 1 Pyroclastic flow deposits in a building site in Olot; 2 cinder cone deposits in the centre of Olot that enabled us to map a new volcano; 3 work on a new car Park that enabled us to characterise new lava flows; 4 lava flow and deposits that filled a lava tunnel exposed during work on a new water deposit; 5 dyke revealed during the construction of a new football pitch; 6 new lava flows exposed during the building of a dual-carriageway; 7 and 8 aragonite and spherical calcite found during the drilling of a borehole, both caused by hydrothermal activity occurring after an eruption. Both are now deposited in the Geological Museum of Barcelona; 9 lava flows and palaeosol exposed during the construction of a warehouse in an industrial estate

mation that has been gathered has broadened our knowledge of the volcanic features of the area and provided invaluable data for scientific articles and maps (Table 2), as well improving our understanding of the overall geodiversity of the area and its volcanic deposits.

ii) **Production and updating of geological maps**. The strategy has also promoted the taking of geological inventories and geological mapping. Volcanic and other types of cartographic work reveal how a volcanic zone or a volcano has evolved and so further understanding of local vulcanology (Branca et al. 2011). Over the past 20 years, some of the most important maps of this volcanic area that have been drawn are those that illustrate its volcanism (Losantos et al. 2000; Bolós et al. 2014), tectonics (Bolós et al. 2015), eruption risk (Bartolini et al. 2015), and its rootless volcanic cones (Fig. 7). Nevertheless, few have been published anywhere other than in scientific journals, and so the information they contain has largely remained within the realm of scientific study.

iii) **Characterisation of the volcanoes in the PNZVG**. Knowledge of the volcanoes is essential if they are to be conserved and promoted as a resource for sustainable tourism (Planagumà and Martí 2018). The Park's strategy centres on the study of the most visited volcanoes and the most significant cones in the volcanic field as a

Table 2 Published scientific articles and the contribution made by the Park's database of ephemeral outcrops to each one

Year	Article/publication	New geological contribution
2007	The geological chart of the Volcanic Zone of La Garrotxa Natural Park. (Losantos et al. 2000)	New lava flows and volcanoes
2009	Changing eruptive styles in basaltic explosive volcanism: Examples from Croscat complex scoria cone, Garrotxa Volcanic Field (NE Iberian Peninsula) (Di Traglia et al. 2009)	New phases of Croscat volcano
2010	Complex interaction between Strombolian and phreatomagmatic eruptions in the Quaternary monogenetic volcanism of the Catalan Volcanic Zone (NE of Spain). (Martí et al. 2011)	More stratigraphic sequences
2014	Volcanic stratigraphy of the Quaternary La Garrotxa Volcanic Field (north-east Iberian Peninsula). (Bolós et al. 2014)	The relative age of the stratigraphy
2015	Volcano-structural analysis of La Garrotxa Volcanic Field (NE Iberia): Implications for the plumbing system. (Bolós et al. 2015)	New fissure eruptions
2017	Basaltic ignimbrites in monogenetic volcanism: the example of La Garrotxa volcanic field. (Martí et al. 2017)	New pyroclastic flows

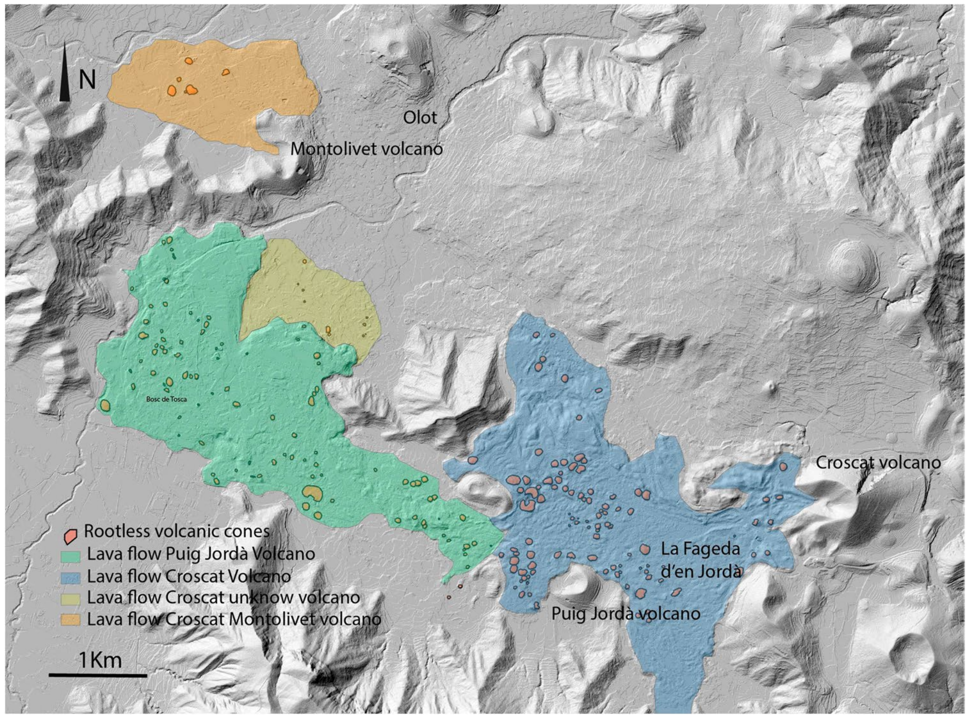

Fig. 7 Map of the distribution of the rootless volcanic cones on the lava flows in the La Garrotxa Volcanic Zone Natural Park. This map was made possible by the participation of local people

whole. In all, six articles have been published focussing on the characterisation of the volcanoes in general and improving our understanding in particular of Croscat, Santa Margarida, Rocanegra, La Pomareda, La Garrinada, and El Montsacopa volcanoes. The sites studied are the natural reserves in this volcanic field that receive most visits (355,000 visitors annually, Institut Cerdà, 2015). According to oral visitor surveys conducted by the Park, at least 315,000 people (local people and visitors) visit one or other of the Park's volcanoes every year, of which 125,000 head for the Croscat lava flow (Fageda d'en Jordà), 50,000 the former quarry in Croscat, 65,000 the crater of Santa Margarida, and 75,000 El Montsacopa.

iv) **Conservation of outcrops of geological interest**. The main factors that influence the vulnerability of the outcrops of geological interest in the PNZVG are the erosion caused by visitors walking along paths and on poorly consolidated pyroclastic deposits (Fig. 8) and natural erosion provoked by rain. These types of impacts in the highly visited former quarry in Croscat can damage up to 50 cm of an outcrop annually and affect 450 m^3 of deposits in a year of high rainfall (Geyer et al. 2015). Of the sites included in the PNZVG's inventory of outcrops of geological interest, the number that are actively managed has risen from two to seven over the past 20 years, of which six are now managed in conjunction with other local entities.

v) **Interpretation material.** Over the past 20 years, a series of resources aimed at interpreting the volcanoes have

Fig. 8 Example of the erosion caused by visitors to the outcrops in the former quarry in Croscat volcano. 1 and 2 are holes that have been dug by hands; the arrows indicate where the wall has collapsed after the continual scratching at the surface of the lapilli by visitors

been produced for a variety of different audiences. One of the indicators used is how these resources evolve in the wake of fresh scientific knowledge. They are constantly being updated, and this indicator measures how they are maintained and revised, since one of the biggest problems that the visitor centres and the Park's publications have is ensuring that the material it offers visitors is kept fully up-to-date (Table 3).

vi) **Observation of the volcanic features (loss of the agroforestry mosaic)**. One of the most pressing problems in

Table 3 Educational material relating to the Park's geological heritage, how often it is revised, and whether or not it has incorporated new data on the Park's geological heritage

	Maintenance and revision	Has it incorporated new scientific material?
Exhibition in the Croscat Natural Reserve	First – 1995/second – 2009/third – 2020	Yes
Guide to the Park's Vulcanism	First edition – 2000	No, second edition
Vulcanological map	First edition 1986/second edition 2007	Yes
Park brochures	Renewed every 3–4 years	Yes
Itineraries	Temporary modifications	Yes
Interpretation panels	Modified every 8–10 years to incorporate new data	Yes
Educational programmes	Reviewed every 5–6 years	Yes

volcanic fields is the way cones and craters are lost to view due to forest encroachment provoked by the abandoning of traditional agricultural methods. This process can easily be monitored using aerial photographs (Woo and Worboys 2019), and appropriate management work can be taken as a result. In the natural reserve of Santa Margarida volcano (Fig. 9), the crater has become less visible, thereby hindering the correct interpretation of the circular geomorphology of this maar. Since 2000, the surrounding forests have encroached into the agroforestry mosaic on account of the decline in cultivated land in upland areas.

vii) **vii) Training of local guides and environmental educators.** The main resource in any interpretation or education strategy is the guide or educator empowered with the task of inculcating a sentiment for a region's geological heritage in the people who live there or just visit. Thus, it is important to analyse the Park's training programme, which imparts scientifically rigorous knowledge and regularly offers refresher courses to the guides and educators working in the protected area. The PNZVG has to date run 20 annual training courses for guides and educators, as well as over 30 refresher sessions aimed at encouraging awareness of new scientific findings. In all, around 200 guides and educators have been trained, of whom around 100 have found work guiding local people and visitors. Today, on average, these guides have a 5-year work experience in the Park.

viii) **Geodiversity in 2021 compared to 1982**. The most singular geological sites in this volcanic field (Planagumà and Martí 2018) can be seen by contrasting archive images and modern aerial photographs. This exercise reveals how the visibility of the geological processes present in these sites has improved, remained the same, or worsened due to erosion or vegetation encroachment (Table 4). In the nine sites of greatest interest, at least one element has worsened in five, at least one has improved in three, and the overall conditions of conservation have remained stable in one. The visibility of other sites classified as outcrops of interest such as the former quarries in Rocanegra and Sant Marc volcanoes has improved over the past 20 years.

Discussion

When analysing the indicators proposed as tools for evaluating the Park's geoconservation strategy, it becomes clear that both intrinsic and extrinsic factors have to be taken into account. Examples of the former linked to current conservation efforts include the correct visualisation and better knowledge of points of geological interest, the incorporation of new sites as a result of fresh geological research, the development and management of new itineraries for visitors, and the promotion of local groups involved in geoconservation. The extrinsic issues affecting the Park include large-scale territorial dynamics produced by socio-economic change, public policy leading to important changes in land use, urbanisation of rural areas, and the evolution of urban areas.

Intrinsic Factors in Management

One of the key findings of the analysis of the indicators is that the Park has been successful in linking scientific advances to the creation and revision of its educational material. Almost all of its educational material incorporates new data, and the Park has shown its willingness to update this material periodically; this has established the PNZVG as a benchmark in the popularisation of geoscience for both the local population and visitors. This is due to the fact that, to disseminate information correctly, the most important assets are not large, expensive-to-run interpretation centres but, rather, policies committed to educating people and producing resources that can be easily brought up-to-date. On the other hand, it is important to

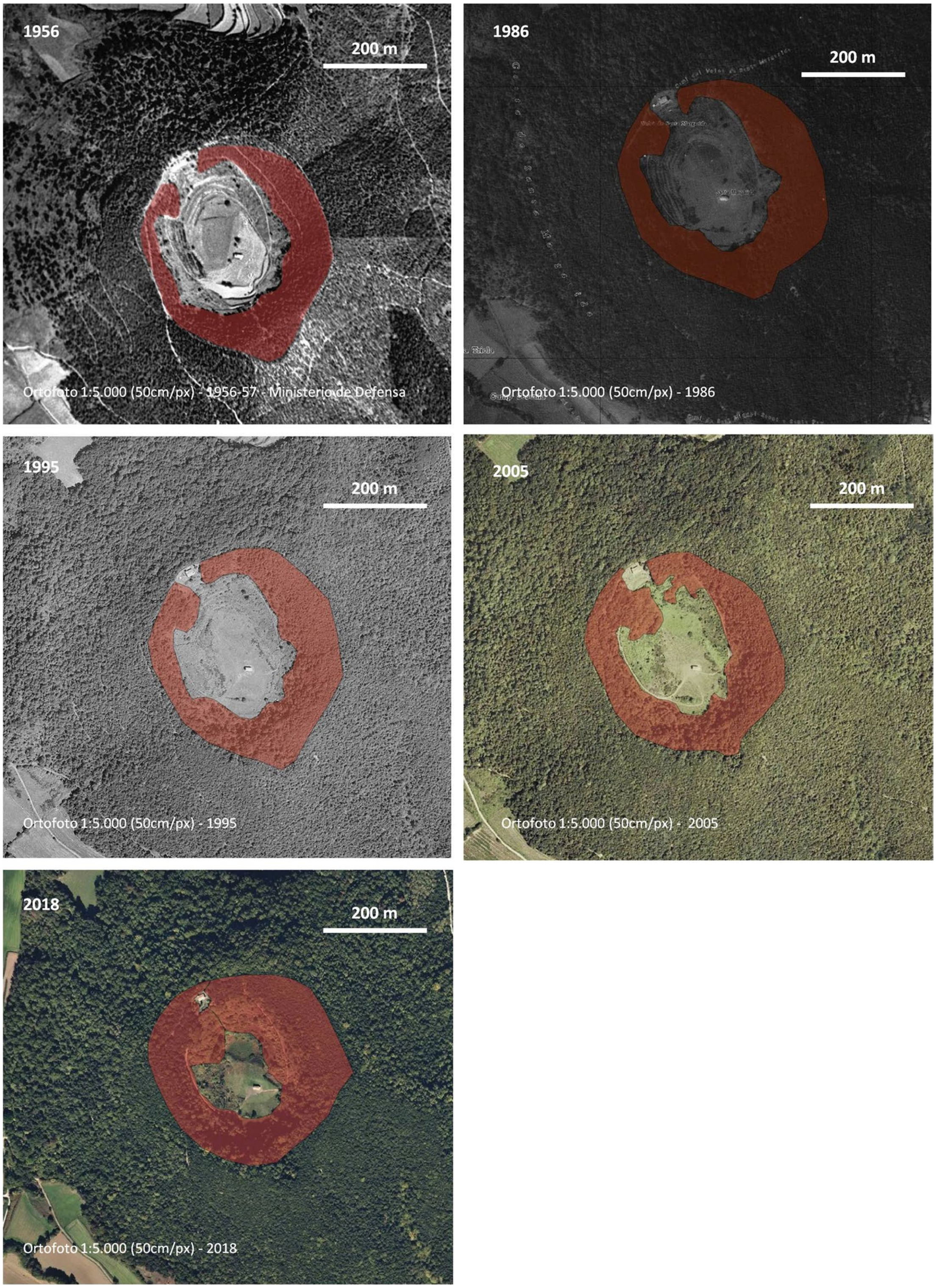

Fig. 9 Images showing the evolution of the forest in the crater of Santa Margarida volcano

recognise that the average number of years of work experience of the guides in the zone—5 years—is improvable as the stability of the workforce in the mid- and long terms is an important component of any set of human and material resources. If this average stands at only 5 years rather than the 10 years of an experienced guide, efforts still need to be made to establish a more stable workforce with, for instance, an average of 10 years of experience in the Park,

Table 4 Comparison between 1982, the year in which La Garrotxa Volcanic Zone Natural Park was declared, and 2021 of the state of the sites of greatest geological interest

Place		State
Croscat volcano	Quarry	Similar interpretation conditions
Santa Margarida volcano	Crater	Vegetation growth has worsened viewing possibilities
	Quarry	Improved
Castellfollit de la Roca	Cliff	Vegetation growth has worsened viewing possibilities
Boscarró y Molí Fondo	Outcrops	Improved
Montsacopa volcano	Crater	Vegetation growth has worsened viewing possibilities
	Quarry	Improved
Can Tià volcano	Outcrop	Similar interpretation conditions
La Pomareda volcano	Outcrop	Vegetation growth and erosion have worsened viewing observation possibilities
La Fageda	Lava flow	Similar interpretation conditions
Bosc de Tosca	Lava flow	Vegetation growth has worsened viewing possibilities

to guarantee the quality needed to achieve optimal results (Bonet 2017).

Improvements in the sites of geological interest are a key part of the work to conserve the geological heritage. In this facet of the Park's work, the results are uneven. Thanks to its geoconservation strategy, although the active management of elements of geological interest has increased, the conservation of the whole of the Park's geodiversity is not as yet assured. One of the most critical actions undertaken is the move towards the co-management of the Park's geological heritage, understanding by co-management involving the local population in the direct management of the geological heritage through participation spaces, and management by municipalities and/or non-profit organisations of outcrops or areas of geological interest with the support of aid public. This ensures that conservation work is less likely to suffer the effects of changes in political policies (Planagumà and Martí 2018).

Extrinsic Factors: the Territorial Model

During the 20 years that the Park's geoconservation strategy has been operating, certain extrinsic factors have inevitably played their part. Despite the active management that has taken place during this period, the geological heritage of this volcanic field has suffered from the changes triggered by the loss of an agricultural mosaic due to the decline in traditional agricultural methods in upland areas. The overarching causes are both the abandoning of the land and the growth in the service industry centred increasingly on satisfying the needs of the tourist sector (Sigma 2016). Consequently, the vegetation has begun to encroach in some of the craters and on lava flows, and as Table 4 shows, over half of the sites of geological interest in the Park are now suffering from problems of this kind.

Construction work in the area has meant that many exposures of deposits of volcanic materials have appeared temporarily. The protocol for gathering information from these ephemeral sites has generated good on-the-ground knowledge of this volcanic field that a number of researchers have been quick to take advantage of.

A final extrinsic factor to take into account is climate change, which could lead to an increase in the rate of erosion of the volcanic deposits due to the increasingly frequent episodes of heavy rain (Sánchez et al. 2004). This is why the potential effects of climate change on the PNZVG is an aspect that is also considered in the explanations provided to visitors, as a way to illustrate them how sensitive the protected areas of volcanic origin may be to the action of climate change.

Additional Factors to be Considered

Apart from the intrinsic and extrinsic factors previously considered, there are other aspects relevant to improve management of geological heritage, and that we want to briefly consider here. One is the number and origin of visitors, as this gives the Park managers a good basis for assessing future visitor guidance and help with practical issues such as which language(s) should be used in the available literature such as brochures and maps, signs, and social media. Unfortunately, the evolution of the total number of visitors to the PNZVG is not available, but there is a record of the people informed and their origin in the information centres of the Park. In 2002, 41,228 visitors were reported, 80% of whom came from Barcelona and around the ZVG, 10% from the rest of Spain, 5% from France, 4% from the rest of Europe, and 1% of the rest of the world. These figures in 2019 (pre-pandemic year) remain almost the same with 41,316 reported visitors, 78% from Barcelona and surroundings close to the ZVG, 11% from Spain, 5% from France, 5% from Europe, and 1% from the rest of the world. These numbers are clearly much lower than the total number of visitors that the Park receive, but at least offers a representative sample that may be considered for such purpose. Additionally, there is currently no study of the overall load capacity of the PNZVG, or of any specific geological site of interest, although some car Parks have been reduced in size just as a measure to ensure that on specific days there is no overload of visitors.

Another important factor to be considered is the networking and sharing of best practices: Networking between protected areas can be a valuable means to improve management practices in natural Parks. This helps to collectively improve the quality of these protected areas. In the case of the PNZVG, no formal link has been established with other volcanic areas in the last 20 years, and only the first international VOLCANDPARK congress on protected volcanic areas was organised together with the International Association of Volcanology and Chemistry of the Earth Interior (IAVCEI) in 2012.

Finally, it should also be considered the monitoring of conditions that should be applied in order to ensure optimal conservation of Park features and to maximise visitor experiences. Such features include geosites (and “geozones”), trails, and roads and other visitor infrastructure. While such type of monitoring is already applied in some sites, as we have explained before (see Figs. 8 and 9), there is still not an extensive monitoring of the state of conservation of the geological values within the PNZVG. However, a photogrammetry monitoring system at geological points of interest is planned to detect natural and visitor erosion. Photographs would be taken from the field twice a year during each year, winter and fall to provide data on the evolution of these selected sites. This systematic monitoring will be incorporated as a formal part of the management plan for the PNZVG.

Conclusions and Future Challenges

The management of the geological heritage of volcanic fields is complex and challenging as their cones and fragile deposits, prone to erosion and degradation, are often found in densely populated areas. Yet, they also represent an excellent opportunity for popularising geoscience and increasing awareness of the need for territorial planning. If we incorporate the conservation of our geodiversity and geological heritage into our land management, we will strengthen our territory by adapting it to potential geological risks and local types of production; likewise, we will be able to build our infrastructures to suit the geological context and create greater awareness in the local population about the need to conserve their surroundings (Crofts and Gordon 2014).

For all these reasons, it is important that in these volcanic fields, the geological heritage should be conserved, not only through active management but also via territorial planning that incorporates geodiversity and geological heritage; specifically, we should work to prevent the loss of the traditional agricultural methods that help maintain the landscape mosaic that so favours the aesthetic appreciation of the volcanoes. Finally, a positive step would be to legally oblige all building and infrastructure work to carry out inventories of the geological heritage they uncover, just as occurs regionally in the case of archaeological remains.

The conservation of the geodiversity of La Garrotxa volcanic field also requires the active management of elements of its geological heritage that lie outside the Park, which include the Crosa de Sant Dalmai, Puig d’Adri, and Puig de la Banya del Boch volcanoes.

Another pertinent concept is the co-management of the geological heritage, a type of governability that will guarantee its long-term conservation. This idea can be extended to local geoconservation groups beyond the actual municipalities the volcanoes belong to, and will help stabilise the work of guides and educators who play such a significant part in the conservation of this heritage. As part of this co-management, the relationship between scientists, Park staff, and local population, as well as their decision-making abilities, must be taken into account and formalised.

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