Identification, cataloguing and preservation of outcrops of geological interest in monogenetic volcanic fields: the case of La Garrotxa Volcanic Zone Natural Park

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Abstract

Volcanic zones are important geoheritage sites. Active volcanic fields are of special interest because they allow to observe the complex and interesting stratigraphic relationships that often characterise their products and processes, as well as landscapes of unusual beauty. These geological sites enable visitors to appreciate the full complexity of volcanic activity and the importance of the geoheritage values that should be preserved. To ensure a correct preservation of these zones while opening them up to visitors, management plans should establish and consolidate a network of outcrops that allow visitors to get to know the area in question and preserve its geological heritage and the social and economic dynamism. In La Garrotxa Volcanic Field, most of which is protected by a natural park, a new methodology has been created to

identify the sites of greatest geological interest and, above all, those that exemplify the diversity of eruptive styles and volcanic products and landforms in the area. Taking into account the most relevant management requirements (conservation and dissemination), in 1994 a total of 60 outcrops were classified as points of geological interest of the area. In this study we further present a specific methodology to select the most suitable sites for the preservation of the main volcanological features of La Garrotxa Volcanic Field. A group of 12 sites were selected from the initially identified outcrops and included in an itinerary as the most representative geological and pedagogical sites while also bearing in mind their ease of access and preservation and the possible impact of visitors (e.g. erosion). The following five criteria were considered when restoring these outcrops: integration into the landscape, consolidation of their geology, regulation of visits, the mitigation of risk, and the participation of the people that live in the area.

Keywords

Catalan volcanic zone
Geological heritage
Monogenetic volcanism
Spain
Outcrops
Geosites

Introduction

Geoheritage and geoconservation are important global endeavours designed to preserve Earth Science features recognised by various international and international conservation bodies and enshrined in numerous agreements, conventions and inter-governmental initiatives (Brocx and Semeniuk 2007). Geodiversity embraces all of the geological aspects identified on Earth and as such is a measure of the geological diversity of a particular area; geoheritage, on the other hand, is defined as those parts of geodiversity that are important for reconstructing the history of our planet (Sharples 1993; Gray 2019) and thus is a measure of the value of the geological elements that are present therein (Gray 2013, 2019). Geodiversity and geoheritage benefit society, as they provide evidence of

our understanding of the history of the Earth and are a convincing reason for the conservation of geological values (Gray 2019).

Geoconservation includes the protection of geoheritage features and geosites and, more generally, the application of geoconservation principles in the sustainable management of protected areas and the wider landscape (Gordon et al. 2018). In this sense, geoconservation involves the protection of those elements of geodiversity that are of high geoheritage value, mainly for scientific reasons but also for their educational, cultural, aesthetic, spiritual and ecological content (Crofts and Gordon 2015; Gray 2013; Gordon et al. 2018). Therefore, the success of the conservation of the geodiversity of an area will depend on how well we protect its natural geological heritage (Németh et al. 2017); thus, geosite selection and conservation management and monitoring are critical aspects of geoconservation strategies at all levels (Carcavilla et al. 2008; Gordon et al. 2018).

The study and appreciation of the geodiversity of an area are essential elements in the identification and protection of the geological values that best represent its geological heritage. First, it is crucial to undertake a geodiversity assessment based on a selection of criteria dependent on factors such as the purpose of the assessment, the type of landscape in the study area and its spatial dimension, the significance of the different geological values to be preserved, and the availability of spatial data at an appropriate scale (Brocx and Semeniuk 2007; Zwolinski et al. 2018). Once this assessment has been conducted, the next step is to identify the elements that reflect the geological value of the area and contribute most to explaining its geological history. Finally, it is necessary to decide which management and preservation policies from various perspectives—i.e. based on geotouristic, geoconservation and geoeducation values—are of greatest importance (Németh et al. 2017).

Numerous examples exist of geodiversity preservation and of how it can be based on the specific characteristics of an area, the geological values to be protected and current political and administrative regulations (e.g. Burek and Colin 2008, and references therein; Brilha 2016, 2018). The result of all these efforts to preserve these geological values is reflected in the UNESCO geoparks, the national and natural parks that protect geological features and many other protected geosites that exist worldwide. The

protection and preservation of geological values should not mean that they are inaccessible to the general public. On the contrary, protected geological sites, whenever possible, should be visitable, provided that their conservation is guaranteed and visitors are furnished with correct information about their relevance and their local value. Therefore, geoheritage protection also means drawing up the best possible management and conservation protocols for the identification, access and dissemination of all points of observation that define a particular protected area (Planagumà and Martí 2018).

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Volcanic zones are home to complex and interesting stratigraphic relationships (Cas and Wright 1988) and are often endowed with immensely important geoheritages. Active volcanic fields are of special interest since they tend to boast rich soils and accessible sites of exceptional geological interest and beautiful landscapes, along with active volcanic features (Németh et al. 2017; Casadevall et al. 2019). In fact, active volcanic zones have become increasingly attractive to geotourists, who seek both live and extinct volcanic landscapes, as well as adventure and enjoyment. Therefore, as occurs in other protected geozones, the creation of a network of outcrops is a key step in the preservation of local geological heritage and the protection of related social and economic dynamics in these protected volcanic zones.

In this study we discuss how the protection of a volcanic heritage zone has been carried out in La Garrotxa Volcanic Field (Martí et al. 2011), a large part of which lies within the boundaries of a natural park (La Garrotxa Volcanic Zone Natural Park, PNZVG) that annually receives around 350,000 visitors. In order to identify and define a network of visitable outcrops that could best represent the main geological and volcanological values of the area (Table 1, Fig. 1), a specific methodology was developed with objective to incorporate the whole diversity of eruptive styles, products and landforms present in the area. Thus, in order to identify the most representative features, within this area of 200 km², in terms of their relevance and potential dissemination, a hierarchical selection of outcrops of geological interest was carried out; it also took into account access, future management and preservation criteria and the need to minimize risks for visitors. Here we describe how this methodology was developed and

applied and analyse the results of its implementation in this area over the past 30 years.

Table 1
Different types of volcanic deposits in La Garrotxa Volcanic Zone Natural Park.

		Volcanic deposit		Examples of outcrops
Effusive		1	Lava flow with basalt columns	Castellfollit de la Roca, El Boscarró (Sant Joan les Fonts)
		2	Lava flow with rootless volcanic cones	Bosc de Tosca, Pla de Dalt
		3	Lava flow with lenticular formations and blisters	Molí Fondo (Sant Joan les Fonts)
Explosive	Strombolian	4	Welded pyroclasts in rootless volcanic cones	Parc de Pedra Tosca, Pla de Dalt.
		5	Pyroclasts in spatter cones	La Pomareda
		6	Pyroclasts (blocks, lapilli and bombs) in Strombolian fall deposits	Former quarries on volcanoes of Rocanegra and Puig Jordà
	Violent Strombolian	7	Pyroclasts (blocks, lapilli and bombs) in violent Strombolian fall deposits	Former quarries on El Croscat.
		8	Pyroclast layers in violent Strombolian fall deposits	Outcrop along Torrent de Can Bosquet
	Phreatomagmatic	9	Pyroclastic flows with Eocene lithics	Former quarry on Can Tià, along track to Mas El Cros in Santa Margarida.
		10	Explosive breccia	Former quarry of Can Barranc del Cairat

		Volcanic deposit	Examples of outcrops
		11 Pyroclastic flows with volcanic lithics	Former quarry on south flank of El Montsacopa; former quarry on El Croscat.
		12 Basaltic ignimbrites	El Carrer, Can Bufador de la Garrinada

Fig. 1
Aerial photograph of the northern side of La Garrotxa Volcanic field

Geological setting

La Garrotxa Volcanic Field (LGVF) (Fig. 1) lies in the north-east Iberian

Peninsula (Fig. 2) and forms part of the Neogene-Quaternary Catalan Volcanic Field, which is associated with the European Rift that extends from the Alboran Sea to the centre of the continent (Lewis et al. 2000; Martí et al. 1992). This rift began to form as a result of the distension initiated 20 Ma during the Neogene when the Alpine orogeny affecting southern Europe came to a halt. The volcanism associated with this rift is alkaline in type and has given rise to a number of volcanic zones, of which LGVF (200 km²), lying between the cities of Girona and Olot, is the most recent. This volcanic field (Fig. 3) contains around 50 cinder cones (Bolós et al. 2014), as well as numerous lava flows, tuff rings and maars dating from the Middle Pleistocene (0.12–0.78 Ma) to the beginning of the Holocene (0.01 Ma) (Bolós et al. 2014). These volcanic features lie atop Eocene sedimentary rocks and Quaternary alluvial deposits, as well as a series of Paleozoic granites and schists (Losantos et al. 2000). The magma generated in this volcanic field is basaltic, basanite, nepheline basanite and olivine basalt; in many cases the magma is the primary source and is not differentiated or contaminated by materials from the Earth's crust (Cebría et al. 2000).

Fig. 2

Map of the European rift, the main volcanic zones and protected volcanic areas

Fig. 3
Map of the geodiversity of the volcanic deposits in La Garrotxa Volcanic Zone

Most of the volcanoes in LGVF lie around the city of Olot and the village of Santa Pau, or, as in the case of the volcanoes of La Crosa de Sant Dalmai, Canet d'Adri and Puig de Granollers, a few kilometres south of the latter locality (Bolós et al. 2014). These small monogenetic cones arose as a result of a succession of different pulsations of magma that rose to the surface through a series of secondary NW-SE running faults associated with the major Llorà and Amer faults, active since the Miocene (20 Ma) (Martí et al. 1992), that generated fissural activity. The volume of these magmatic pulsations was moderate ($0.01\text{--}0.2\text{ km}^3$) (Bolós et al. 2014), and the resulting lava was emplaced in spatter and scoria cones, lava flows, maars and tuff rings. Due to the varied lithology of the substrata and the variety of hydrogeological features it has generated, the volcanic cones display a great variety of sequences and types of volcanic deposits (Martí et al. 2011). For instance, in the volcano of Crosa de Sant Dalmai, the magma interacted with the Quaternary alluvial aquifer, while in the volcano of Can Tià interaction occurred with the Eocene sedimentary aquifer.

The main type of volcanic activity in this area was Strombolian and gave rise to scoria cones composed of a series of fall deposits (lapilli and blocks). Many of these monogenetic cones (e.g. the volcanoes of Rocanegra, Montolivet, Sant Marc and L'Estany) are characterised by the presence of horseshoe-shaped cones. In some cases, however, where magma and groundwater from shallow aquifers interacted the eruptions were more complex and were characterised by phreatomagmatic phases involving phreatic explosions with ejection of lithic fragments from the substrate, as well as different types of pyroclastic density currents and phreatomagmatic fallout (Martí et al. 2011). Examples of this type of volcanic activity include the volcanoes of Santa Margarida, Croscat, Garrinada, Crosa de Sant Dalmai, Canet d'Adri and Can Tià (Martí et al. 2011). As a whole, Strombolian and phreatomagmatic activity have created a complex variety of eruptive sequences and volcanic morphologies that include cinder cones, maars, lava flows, rootless cones and lava tubes.

The inspection of the lithic fragments found in the phreatomagmatic deposits has permitted to identify the existence of three main aquifers that interacted with basaltic magma during the construction of LGVF (Martí et al. 2011). One aquifer lies at around 300–100 m and another much nearer the surface, just a few dozen metres below ground level. The deeper of the two lies in Eocene detritic sedimentary rocks (Bellmunt Formation), which consist of continental sediments composed of conglomerates, mudstones rich in feldspars and red lutites; the more superficial aquifer lies within alternating beds of volcanic and Quaternary alluvial deposits composed largely of unconsolidated sands, clays and volcanic rocks (lavas and pyroclasts) dating from previous eruptions. Finally, there is a third aquifer that also played an important part in some of the most explosive eruptions in LGVF (Puig de Banya del Boc and Crosa de Sant Dalmai), which lies within highly fractured Paleozoic rocks at depths varying from a few hundred metres to just a few metres, depending on the tectonics of each particular area (Bolós et al. 2012; Pedrazzi et al. 2014).

Therefore, the volcanoes of the La Garrotxa reveal how complex a small volcanic field can be when magma interacts with groundwater, thus producing a great diversity of eruptive sequences which contrast with the relative monotony of the co-existing Strombolian volcanism. This complexity is heightened if the aquifers possess differing hydrogeological

characteristics and the structure of the terrain is heterogeneous due to tectonic movements and/or differences in local stratigraphy (Martí et al. 2011).

La Garrotxa Volcanic Zone Natural Park

La Garrotxa Volcanic Zone Natural Park (PNZVG, in its Catalan spelling) covers an area of 15,000 ha and includes most of the northern part of La Garrotxa Volcanic Field (Fig. 3). The Park contains both public and private land, including built-up areas with 33,000 inhabitants and forty well-preserved volcanic cones, twenty-six of which are natural reserves (Planagumà 2017). The PNZVG was declared by the Parliament of Catalonia in 1982 (Law 2/1982, March 3) to guarantee the protection of the volcanic area of La Garrotxa. It was declared as a Natural Site of National Interest to ensure that its flora, volcanic geomorphology and exceptional scenic beauty would be preserved.

Two main elements can be distinguished in the geological heritage of the PNZVG: volcanic morphologies and outcrops (Fig. 4). Their importance lies in the uniqueness of their constituent materials and the representativeness of the geological processes that allow them to be interpreted as the result of hundreds of thousands of years of geological and volcanological activity. The best-preserved volcanic cones are protected as natural reserves, while other geological outcrops are catalogued as outcrops of geological interest. The regulations governing the protection of this geological heritage are enshrined in the PNZVG's management plan (Planagumà 2017).

Fig. 4

Map of the selected outcrops

All the natural reserves (i.e. all the best-preserved volcanic cones) (Fig. 4) are natural areas that receive special protection, conservation and management to prevent any deterioration, transformation or disfiguring of their geomorphology or flora. The protection of the geological heritage of the PNZVG ensures that no activities that might provoke or accelerate erosive processes or increase the instability of the substrata may be performed and that the singular volcanic soils present in most of the area are strictly preserved. In addition, the outcrops considered of geological interest are identified and catalogued, and strict regulations govern their protection. For instance, no activity that might degrade or deteriorate the protected area or hamper its observation or study is permitted. Moreover, excavations and other types of earth movements are forbidden unless they are designed to improve or restore the volcanic outcrops for scientific or educational purposes and have been approved by the protected area's management team. The areas adjacent to these outcrops should also be kept free of any disturbance that might obstruct their observation. The PNZVG gives priority to the active management of outcrops of exceptional interest and seeks agreements and collaboration with landowners as a way of guaranteeing the maximum protection for these sites, if necessary in combination with external support.

Criteria Used to Select the Outcrops that Best Represent the Volcanic Geological Heritage of the Zone

In addition to the rich soils and benign climate that favour the development of dense vegetation cover (Oliver 2016) and despite the burgeoning economic development of this relatively well-populated zone, the PNZVG harbours a large number of visible volcanic outcrops. The first special protection plan designed to regulate the conservation of this protected area catalogued 50 sites of geological interest (Planagumà 2017). Given that the conservation of so many sites is costly in terms of both human and economic resources, a methodology was established to select the most interesting outcrops and illustrate the great variety of types of volcanic deposits existing in the area.

Therefore, as part of the protection of this volcanological geoheritage and to facilitate public access in a sustainable manner, a selection of the most representative outcrops of the greatest geological and volcanological interest was established based on their relevance in terms of three main aspects: research, conservation and dissemination. After testing 50 selected outcrops and 10 further outcrops discovered in recent years during a study of ephemeral sites (Bolós et al. 2014) (Table 3 and Fig. 4), 12 outcrops of great geological interest were identified (Table 3 and Figs. 4, 5, and 6). The remaining outcrops were discarded as being poorly representative, poorly accessible, or irreversibly damaged or due to a combination of two or more of these reasons (Figs. 5 and 7).

Fig. 5

Graph showing the relationship between dissemination and conservation prioritizing outcrops. Red dots correspond to the outcrops; recommendations for active management are in the grey square (top and left)

Fig. 6.

Photographs of the outcrops of greatest interest. **(a)** cliffs at Castellfollit de la Roca (columnar jointing in lava flows), **(b)** quarry at El Boscarró (columnar and platy jointing in lava flows), **(c)** Molí Fondo (columnar and platy jointing in lava flows), **(d)** quarry at Can Barranc (lithic breccias and scoria deposits), **(e)** quarry at Montsacopa volcano (succession of Strombolian and phreatomagmatic deposits), **(f)** La Pomareda (succession of Strombolian agglomerate, scoria (lapilli) fallout deposit, and lava flow), **(g)** quarry NE of El Croscat (full succession of the Croscat Strombolina deposits), **(h)** track to El Cros (dilute PDC deposits and scoria fallout deposits), **(i)** quarry at Can Tià (transition between Strombolian -scoria fallout deposit- and phreatomagmatic-lithic rich fallout and basaltic ignimbrite-phases in the same eruption), **(j)** Torrent de Cal Bosquet (succession of dilute PDC (surges) deposits), **(k)** Quarry at El Rocanegra (Strombolian (scoria) fallout succession), **(l)** El Carrer (basaltic ignimbrite)

Fig. 7

Photographs of the outcrops of less interest. (1 and 2) Little use for illustrating geological processes (scoria fallout deposits) due to extensive vegetation coverage, (3) problems with landowner, (4) poor observation (lava flows) possibilities, (5) poor state of conservation (former quarry used now as illegal dump) and (6) inaccessible or only observable from long distance (columnar jointing in a lava flow)

These selected outcrops (Fig. 6) represent the main aspects of the volcanic activity that has characterised the evolution of La Garrotxa Volcanic Field. However, other outcrops that were potentially the most informative for visitors and other aspects such as state of preservation, facility of access, future management and their landownership were also taken into account.

These 12 outcrops were then subdivided into two groups according to their interest in terms of (i) conservation and (ii) dissemination and public use. In the former group aspects such as the state of conservation; potential for restoration; the rarity and exceptionality of its scientific features, whether

or not it was a typical locality for geological description; its potential from a pedagogical point of view and its spectacularity and beauty were evaluated. In the latter group, the aspects to be considered were the potential for dissemination and use for tourism, their pedagogical value and potential for developing scientific activities, as well as how ease was access and observation, the type of landownership of the outcrop, and the fragility of both the natural and social environment (Table 2).

Table 2

Criteria for selecting the main outcrops

Conservation	Public use and awareness-raising
A) Conservation state 3 Well conserved or easily restorable 2 Poorly conserved and difficult to restore 1 Poorly conserved and impossible to restore	A) Possibility of use for activities (scientific, educational, tourism, recreation) 3 Possible use for three type of activities 2 Two types 1 One type
B) Abundance/uniqueness 3 The only outcrop of this type in the natural park 2 Two other outcrops of this type exist in the natural park 1 More than five other outcrops of this type exist	B) Observation conditions 3 Good 2 Average 1 Poor
C) Useful for illustrating volcanic processes 3 Very useful 2 Moderately useful 1 Of little use	C) Accessibility 3 Quick access from main roads for all types of vehicles 2 Access along unsurfaced roads not suitable for all vehicles 1 Far from roads (over 30 min on foot)
D) Type locality 3 Used to describe a volcanic-related process 2 Used to illustrate a description of a volcanic-related process 3 Not used to illustrate a description of a volcanic-related process	D) Private property 3 Outcrop on public property or where landowner is amenable 2 Permission required from landowner 3 Problems with landowner
E) Associated with other features of interest 3 Associated with other natural or cultural features of interest 2 Few associations 1 Not associated	E) Surroundings 3 Visits do not affect the natural, social o architectural surroundings 2 Visits may slightly affect surroundings 1 Visits will seriously affect surroundings

Conservation	Public use and awareness-raising
F) Diversity of elements (mineralogical, geomorphological, dynamism, etc.) 3 More than three other visible elements 2 Two or three other visible elements 1 One visible element	F) Space 3 More than 30 people can access the site at once 2 15–29 people can access the site at once 1 Fewer than 15 people can access the site at once
	G) Fragility 3 Visits do not cause any degradation of the site 2 Visits could cause deterioration of the site 1 Visits could seriously damage the site
6–10 Category 3 Low conservation interest 10–14 Category 2 Moderate conservation interest 15–18 Category 1 High conservation interest	7–12 Not apt for visits or raising awareness 12–17 Potentially apt for visits or raising awareness 18–21 Excellent possibilities for visits or raising awareness

Table 3

Catalogue of outcrop interest and value

		Conservation state	Abundance/uniqueness	Useful for illustrating volcanic processes	
1	CINGLERA TURONELL	1	1	2	1
2	CINGLERA FLUVIÀ N	2	3	3	2
3	CINGLERA TURONELL, S	1	1	1	3
4	CINGLERA CAN GRIDO-CAL SORDET	2	1	2	4
5	CINGLES DE LA CANOVA	2	1	1	5
6	MOLI FONDO	3	3	3	6
7	BOSCARRO	3	3	3	7

		Conservation state	Abundance/uniqueness	Useful for illustrating volcanic processes	
9	CINGLE DE FONTFREDÀ	3	2	2	2
10	TORRENT DEL SOLER	1	1	1	1
11	NOC D'EN COLS	2	1	1	2
12	CINGLE DE LES COLS	3	2	3	1
13	LES TRIES	1	1	1	1
14	MOLI DE LA TORRE	1	1	1	1
15	MOLI DE TIRABURRES	1	1	1	1
16	VOLCÀ GARRINADA	3	2	3	1
17	VOLCÀ MONTSACOPA (Gredera E)	2	1	2	2
18	VOLCÀ MONTSACOPA (Gredera S-W)	3	3	3	1
19	VOLCÀ RACÓ (Gredera N)	1	2	2	2
20	BARRANC DE GARROFÀS	3	3	3	2
21	LA POMAREDA	3	3	3	1
22	GREDERA S (Costat Carretera)	2	1	2	2
23	VOLCÀ CROSCAT (Gred N-W, abocador)	2	1	2	2

		Conservation state	Abundance/uniqueness	Useful for illustrating volcanic processes	
24	VOLCÀ CROSCAT (Gredera N-E, Tall)	3	3	3	
25	V.PUIG DE MARTINYÀ (Gredera N-W)	2	1	1	
26	V.PUIG SAFONT (Gredera N-W)	2	2	1	
27	V.PUIG MARTINYÀ (Gredera N-E)	2	1	1	
28	V.PUIG DE MARTINYÀ (Gredera W)	2	1	1	
29	V.PUIG DE MARTINYÀ (Gredera W)	2	1	1	
30	PLA DE LES FORQUES	2	1	1	
31	TALÚS DE LES FORQUES	2	1	1	
32	V.SANTA MARG- Talús pista vessant N-E	3	3	3	
33	V.SANTA MARG- Flanc cràter N-E	2	1	2	
34	V.SANTA MARG- Flanc cràter NW	2	1	2	
35	V.ROCA NEGRA- Vessant N-W	3	3	3	
36	RIERA DE SANT ISCLE I	2	3	2	
37	RIERA DE SANT ISCLE II	2	3	2	

		Conservation state	Abundance/uniqueness	Useful for illustrating volcanic processes	
38	V. TRAITER (Gredera N-E)	2	2	2	
39	BARRANC DE MATABOUS	3	2	1	
40	V.CAN TIA	3	3	3	
41	CAN BARRANC del Corb	2	3	3	
42	V. CAN SIMÒ	3	2	2	
43	SALT DEL CLOT	2	1	2	
44	VALL DELS ARCS	2	1	2	
45	CINGLE DE CAN FORMIGA	2	1	1	
46	RIU SER	2	1	2	
47	TORRENT DE SANT MARTI	3	2	1	
48	TORRENTMAL	3	3	2	
49	EL CARRER (Riera dels Arcs)	3	3	3	
50	CAN BARRANC	2	3	3	
51	PEDRERA TURONELL	3	2	1	
52	CINGLERA TURONELL III	2	3	3	
53	CAN BARRANC DE BATET	3	2	2	
54	GREDERA DEL PUIG JORDÀ	2	1	2	

		Conservation state	Abundance/uniqueness	Useful for illustrating volcanic processes	
55	CINGLERA DE CAN XERBANDA	2	1	2	
56	CARRETERA DE COLLTORT	2	1	1	
57	GREDERA SANT MARC	2	1	2	
58	PEDRERA PUIG ROIG	3	2	2	
59	TRAVERTINS LA TORRE I	3	2	1	
60	TRAVERTINS LA TORRE II	3	2	1	

Table 4.

The 12 outcrops (Fig. 7) that encompass a full spectrum of the eruptive activities occurring in the Catalan Volcanic Field and illustrate a very complete range of the deposits found in typical basaltic volcanic fields.

Name	Location UTM31N - ETRS89	Exposed deposits	Number of visitors
Cliffs at Castellfolit de la Roca	X 461812 Y 4667201	Lava flow and columns	More than 10,000
El Boscarró former quarry	X4 59608 Y 4673798	Lava flow and columns, and lenticulars forms	More than 10,000
Molí Fondo	X 459551 Y 4673674	Three lava flows, blisters, columns and lenticular forms	More than 10,000
Former quarry at Can Barranc on El Cairat	X 460809 Y 4673538	Phreatomagmatic fall	Less than 100
Former quarry on El Montsacopa	X 457706 Y 4670571	Phreatomagmatic PDC with volcanic lithics	More than 10,000

Name	Location UTM31N - ETRS89	Exposed deposits	Number of visitors
La Pomareda	X 461203 Y 4667462	Spatter	Between 1000 and 10,000
Former quarry NE of El Croscat	X 461824 Y 4667203	Strombolian fall deposits	50,000
Track to El Cros	X 462725 Y 4665701	PDC with sedimentary lithics	Between 1,000 and 10,000
Former quarry on Can Tià	X 462476 Y 4663391	Basaltic ignimbrites	Less than 100
El Carrer	X 465875 Y 4664562	Basaltic ignimbrites	Less than 100
Torrent de Cal Bosquet	X 464132 Y 4667400	PDC with volcanic lithics	Less than 100
Former quarry on El Rocanegra	X 463181 Y 4665613	Strombolian fall deposits	Between 1000 and 10,000

What follows are short descriptions summarising the main aspects of each of the 12 selected outcrops that constitute the most important volcanic sites in the PNZVG.

Castellfollit de la Roca Basaltic Cliffs

Located about 7 km east of the city of Olot, these basaltic cliffs lie in the extreme north-east of PNZVG, between the rivers Turonell to the south and Fluvià to the north (Fig. 4). These cliffs are an excellent example of effusive activity and consist of two superimposed lava flows, 210,000 and 192,000 years old (Lewis et al. 2000), which have been partially eroded away by the two abovementioned rivers. The cliffs, which rise 50 m above these rivers and run for 1 kilometre, provide excellent views of the internal structure of a lava flow (Fig. 6a). The main feature of this outcrop is the well-developed columnar jointing that affects the succession of lava flows. Due to the existence of this pervasive network of joints, frost weathering (freezing-thawing) is concentrated along these cracks and eventually leads to the crumbling and fall of the blocks. They are then carried off periodically by the river when in floods, thereby preventing the fallen

blocks from building up and stabilising at the bottom of the cliff.

The lava flows rest on Eocene sandstones and marls, and Quaternary gravels, and consist of a 40-m thick layer of black and grey basalt. About 9 m from the top of the volcanic materials, a layer (0.2–1.5-m thick) of clay and pyroclasts, easily recognisable by the abundant herbaceous vegetation that grows there, divides the escarpment into two discrete parts, each one corresponding to a different lava flow. The lower zone of the lower lava flow has (i) a 5.5-m-thick, well-developed columnar jointing with prisms around 50 cm in diameter; (ii) an intermediate zone, 3.5-m thick, with lenticular jointing; and (iii) an upper zone, less than 1-m thick, with columnar jointing again but with columns that are only 30 cm in diameter. The upper lava flow has four different zones; the first three, starting from the base, are each 5–9-m thick and have obvious columnar jointing, while the uppermost zone is about 9-m thick and has well-developed spheroidal weathering.

The medieval village of Castellfolit de la Roca was built on top of these lava flows using, above all, rocks and stones from the flows themselves as building materials.

Sant Joan Les Fonts Lava Flows

In the town of Sant Joan les Fonts, there are two outcrops of interest (Fig. 4). Firstly, El Boscarró provides a vision of the relationship between well-developed columnar and lenticular jointing within a lava flow (Fig. 6b). Five layers can be distinguished here: the lowest has columnar jointing with 5- and 6-sided columns, 20–40 cm in diameter, and 2–3-metres high. The second and fourth layers have slab jointing, while between them in the third layer there is massive material with a few cooling cracks. The fifth and final layer, just below the soil level, is far more altered due to its proximity to the surface and has a marked spheroidal structure. North-west from the quarry face, a stream, La Riera de Bianya, flows along the contact zone between the volcanic materials and the reddish Eocene sedimentary materials.

At El Molí Fondo three lava flows are superimposed along the river Fluvià and are all visible and visitable: the oldest dates from 600,000 years ago (Araña et al. 1983), the second (150,000 years ago) exhibits lenticular

formations and blisters, while the youngest (133,000 years ago) is characterised by a well-formed series of basaltic columns (Fig. 6c).

Quarry at El Cairat

A good example of a breccia generated by a phreatomagmatic explosion can be found close to the eruptive centre of the volcano El Cairat on the ridge of Serra Molera in the north of the natural park (Fig. 4). El Cairat is a maar-type volcano with a 120-m-diameter crater excavated in the Eocene substrate (Martí and Mallarach 1987; Martí et al. 2011). It is one of the few examples in the studied area that is almost exclusively composed of phreatomagmatic deposits. The pyroclastic deposits that form this volcanic edifice were emplaced preferentially to the north and south of the crater. The observation point is an old quarry located at the base of the northern flank of the volcano. This outcrop has a 20-m-thick succession of pyroclastic deposits corresponding to lithic-rich explosion breccias and lapilli-sized fallout and pyroclastic surge deposits (Fig. 6d). The main characteristic of this succession of deposits is the presence of abundant lithic clasts from the red sandstone Eocene basement, which range in size from a few centimetres to up to 5 m.

Montsacopa

This is one of the most representative and best-preserved volcanic cones in the area. Located inside the city of Olot, Montsacopa, is a steep-sided cinder cone, 94 m in height and topped off with a circular, 120-m-diameter and 12-m-deep crater. On the south-eastern side of this volcano lie a series of Strombolian deposits resulting from the formation of a scoria cone, conformably above which there is a succession of pyroclastic density current (PDC) deposits caused by the interaction of the magma with a shallow aquifer (Fig. 6e). This outcrop reveals one of the most characteristic features of the La Garrotxa volcanism, namely, the co-occurrence of Strombolian and phreatomagmatic phases during a single eruption (Martí et al. 2011).

La Pomareda

The quarry at La Pomareda (Fig. 4), together with the two following outcrops (quarry at Croscat and the eastern flank of Santa Margarida), forms part of one of the most recent eruptions in the area, which took place

about 11–13 ka. In fact, La Pomareda, Croscat and Santa Margarida all lie on a 3-km-long eruption fissure oriented NW-SW, from where the eruption started at the southern end with a vent-opening phreatomagmatic phase, visible on the southern flank of the Santa Margarida outcrop. Subsequently, the eruption progressed to the central and northern sectors of the fissure extruding basaltic magma and generating massive spatter and occasionally rheomorphic, welded scoria agglomerates, visible at La Pomareda, and terminated in the centre of the fissure with an important cone-building event that formed the volcano of Croscat (Martí et al. 2011).

The outcrop at La Pomareda, located to the north of Croscat, is visible thanks to quarrying and corresponds to local black-to-reddish spatter deposits with welded blocks and bombs, covered subsequently by a layer of lapilli and a lava flow originating from the eruptive vent at Croscat (Fig. 6f). The scoria fragments are mostly flattened and are up to 1 m in width and, together with the welding, suggest a very proximal outcrop corresponding to the first stages of the purely magmatic eruptive activity along this eruptive fissure (Martí et al. 2011).

Quarry at Croscat

This quarry is located on the northern side of the volcano (Fig. 4) and was worked from the 1960s until the beginning of the 1990s. The excavations exposed an outcrop of pyroclastic materials, 150 m in height and 500 m in width, that today illustrate perfectly the different phases of the formation of a cinder cone generated by a violent Strombolian eruption phase (Di Traglia et al. 2009).

On the right-hand side, the quarrying was executed in great terraced steps to help stabilise the volcanic material. However, the middle and the left-hand side are less stable and landslips are more frequent. The different layers of fallout scoria consist of irregular, highly vesicular juvenile fragments, for the most part lapilli-sized, and are very well exposed in this outcrop (Fig. 6g). At the base of the sequence, several bombs are visible. The materials are mostly dark grey or black, although in the area closest to the centre of the edifice they are reddish and ochre. In the lowest part of the quarry there is a reddish layer of welded scoria, which corresponds to the first episode in the cone-building phase of the volcano and is very similar to that observed at La Pomareda. On top of the Strombolian fallout

succession, there is a 2-m-thick laminated layer of finer pale-brownish material that corresponds to phreatomagmatic material deposited at the end of the volcano's explosive activity (Martí et al. 2011).

Eastern flank of Santa Margarida

On the eastern flank of the volcano of Santa Margarida (Fig. 4), crowned by a maar-type crater, there is a visible outcrop of PDC. On top of a silty soil, which corresponds to the pre-volcanic substrate, lies a layer of compacted phreatomagmatic ash followed by massive lithic-rich pyroclastic flow deposits and several well-stratified beds of medium-to-coarse-grained, dilute pyroclastic surge deposits and associated fine-ash deposits forming, in total, a 3-m-thick succession (Fig. 6h). On top of this there is a layer of black juvenile lapilli scoria fragments and fairly rounded reddish-brown lithics (Eocene red sandstones). This fallout scoria and the previous phreatomagmatic deposits correspond to the initial eruption phases from the Santa Margarida vent (Martí et al. 2011). Finally, at the top of the sequence there is a deposit—a fine-grained scoria deposit with no stratification—that closely resembles the previous layer but without any lithics, which corresponds to the airfall deposits originating from Croscat.

Quarry at Can Tia

Located on the western side of the volcano of Can Tia, this quarry is one of the few examples of basaltic ignimbrites (massive, scoria-rich, dense PDCs deposits) that are visible in this volcanic field (Martí et al. 2017). Can Tia is a maar-type volcano, with a 270-m-wide and 20-m-deep flat-bottomed crater. It is asymmetrical—its lip is higher to the south—and the sequence of materials that built this volcano, observable in the quarry next to Can Tia, consist only of pyroclastic deposits (Fig. 6i). There are four different units from base to top. The lowest unit corresponds to a 10-cm-thick, internally massive pyroclastic surge deposit, which rests unconformably on a palaeosoil. The second unit consists of a poorly stratified, non-welded, highly vesiculated lapilli scoria deposit, up to 6-m thick, with a few lithic clasts, some of block size. The third unit overlies conformably the previous one and consists of a 1.5-m-thick, thinly laminated, well-sorted, fine-grained scoria deposit rich in lithic clasts of red Eocene sandstones of variable size (< 2–30 cm), with an interbedded ash layer in its upper part. The number of lithics increases gradually towards the top of this deposit,

which is sheared by the emplacement of the uppermost unit. This final unit is a massive dense PDC deposit (basaltic ignimbrite), up to 3-m thick, that contains abundant Eocene lithic clasts and scoria and highly vesiculated lapilli fragments, all contained in a lithic-rich, ash matrix that has been almost completely transformed into clay minerals, zeolites and iron oxides. The sequence of deposits displayed in this outcrop helps visualise the complex eruption dynamics of this monogenetic volcanism, in which magmatic and phreatomagmatic phases often alternated during the same eruption (Martí et al. 2011). This particular outcrop reveals how the explosive activity began with a short phreatomagmatic event, then changed immediately into a magmatic event (second and third units) and then changed back to a phreatomagmatic event (upper part of the third unit and fourth unit) during the course of the eruption.

Riera dels Arcs

This is another excellent outcrop for observing the full succession of a basaltic ignimbrite deposit (Martí et al. 2017). Located near Mas Carrer in Riera dels Arcs (Fig. 4), this outcrop is about 1.5 km from the vent of the volcano of Sant Jordi (Fig. 4). Two units are visible (Fig. 6j): the lower unit consists of fine scoria lapilli fall deposits that hug the irregular pre-existing topography in the bottom of the gully. It is well-sorted and thinly laminated and mostly composed of highly vesicular, juvenile basaltic scoria clasts. Its total thickness is about 25 cm. The upper unit consists of a brown, massive, 15-m-thick ignimbrite deposit composed of dense-to-highly vesiculated, large lapilli-to-bomb-sized juvenile scoria fragments that are sometimes flattened, together with lithic lapilli and blocks of Eocene sedimentary rocks and previous lavas, all supported by an indurated ash and fine lapilli matrix. The base of the upper unit is mostly planar and corresponds to a fine-grained layer that gradually grades into a lithic-rich horizon, about 0.4-m thick, composed of dense fragments of Eocene sediments and older lavas up to 50 cm in diameter that are irregularly distributed. In the rest of the deposit, the lithic content varies vertically and forms lithic-rich zones or lenses. Juvenile clasts tend to be concentrated towards the top. The top of the deposit has been partially eroded, reworked and transformed into a palaeosoil.

Torrent de Cal Bosquet

This outcrop is located to the north-east of the village of Santa Pau (Fig. 4).

It exhibits a succession of dilute PDC deposits (surges) emplaced during the final explosive episode originating from Croscat (Martí et al. 2011). This outcrop lies atop a former fluvial terrace; its lower part is characterized by a succession of levels of fine lapilli fall deposits, while its upper part, which is clearly differentiated, has grain-supported levels of ash affected by tractive structures and by erosive and/or canaliform morphologies. This outcrop is exceptional due to the visibility of a large number of erosive canaliform strata, with an abundance of Type A dunes (Fisher and Schminke, 1984) that cross at low angles and the presence of anti-dunes. These anti-dunes are eroded by reworked alluvial sediments that correspond to lahars provoked by the rainfall that accompanies this type of eruption.

AQ2

Quarry at Rocanegra

The quarry on the northern flank of the volcano of Rocanegra, located 1 km to the west of Santa Pau (Fig. 4), is an excellent site for studying the formation of a cinder cone composed of lapilli scoria and bombs formed during a pure Strombolian magmatic eruption. The outcrop has a well-stratified succession of fallout deposits, dipping in equilibrium with the slope, that corresponds to a small cinder cone (Fig. 6l). All the deposits are grain-supported and well classified, with grain size varying from block size to medium-sized lapilli, and all are clasts of vesiculated basaltic scoria. Some bombs are also visible in some layers in this succession. Another interesting characteristic of this particular outcrop, which distinguishes it from the other volcanoes in the area, is the presence of a large number of enclaves of pyroxenite and gabbros, as well as partially melted granitic rocks (Neumann et al. 1999).

Discussion

In order to preserve and disseminate the volcanological knowledge of an area, it is crucial to carry out a thorough study of its main geological and volcanological values (geodiversity) and accordingly identify its geoheritage and define and undertake appropriate conservation actions. Part of this management must consist of determining which sites are most interesting from a geological standpoint and which are the most suitable for visiting. To complete a full inventory of the outcrops to be protected, a full

analysis of the conservation status of each site of interest is essential: Is it geologically relevant? Can it be easily observed? Is it on public or private property? Is there good access? Might it become eroded due to over visiting? Thus, using the various proposed criteria (Table 2), it is possible to catalogue the sites of greatest geological interest in the zone that should be conserved and managed as key places for visitors.

In the La Garrtoxa Volcanic Field, over the past two decades, most of the efforts aimed at conserving and describing the region's volcanic heritage have been centred on the outcrops described above. Currently, they are all well conserved and are easily visitable. Taking them as a whole, visitors can obtain a complete picture of the most important volcanic processes that have occurred in this volcanic zone. Each of these selected outcrops is now equipped with information panels in which the main features to be observed are outlined. In addition, these descriptions and detailed indications on how to reach each one, along with a general introduction to volcanism and to La Garrotxa Volcanic Field, are included in a field guide that helps visitors appreciate more fully the geoheritage of the area (Martí et al. 2000). This field guide has become an essential tool for raising awareness of these 12 sites of great geological interest and helps visitors interpret the volcanic features of the natural park through careful observation.

AQ3

The criteria to be considered for preserving the volcanic outcrops like those described here should include the following aspects: (i) the potential loss of sites of geomorphological interest and the difficulties in viewing geological processes due to changes in land use as forests encroach and swallow up pastureland and cropland; (ii) the potential loss of visibility of some outcrops due to landslips and rock falls that occur relatively frequently in this type of volcanic material; (iii) the potential impact caused by over-frequentation—i.e. the erosion of paths, increased noise levels, and the loss of the peace and quiet required for ensuring the quality of visits—that implies the need to regulate public access; and (iv) the potential loss and possible destruction of outcrops and volcanic morphologies such as blisters due to urban growth and the building of new lineal infrastructures such as roads.

Thus, it is essential to take into account the following principles when

attempting to restore, signpost and promote the protection of this type of geological outcrops: (i) good scientific knowledge of all relevant geological processes; (ii) all restoration work must blend in with the landscape and improve the possibilities of observing the geological processes; (iii) public use (i.e., car-parking, massification and interpretation) must be controlled; (iv) the risk of landslips and rock falls must be minimised; and (v) local bodies including town councils and citizen groups must be involved in all attempts to manage these outcrops.

These sites of geological interest are included in the La Garrotxa Volcanic Zone Natural Park management plan (*Pla Especial*), which is the main tool for territorial planning used in this protected area. A series of regulations has been established aimed at preserving and protecting the local geological heritage by prohibiting all activities that might either provoke or accelerate erosion and by forbidding any activity that might lead to the degradation and deterioration of the protected area, or hinder the study thereof. This plan bans any excavations or earth movements unless their aim is to improve access to the volcanoes for scientific or educational purposes; permission must always be granted beforehand by the park's management team. As well, the spaces created by past excavations must be kept free of all buildings and all other features that might hamper views of the volcanoes. The plan also states that these sites of exceptional geological interest should be actively managed, that agreements should be sought with landowners to facilitate the management of these volcanic features and that grants can be applied for if and when necessary (Table 4)

The relationship with local town councils and local people living in the park is one of the most interesting indicators of the correct management of these outcrops since in some cases they are co-managed by the Natural Park and local town councils. Of the 12 outcrops classified as 'of great interest', nine are actively managed by the park, of which six are co-managed by the park and local councils (Fig 8). This demonstrates how local authorities and local people are committed to the conservation of the geological heritage of the zone.

Fig. 8

Photographs before and after the restoration of the outcrop at Molí Fondo (platy and columnar jointing in lava flows)

Finally, it is worth mentioning that these selected outcrops are the reference points used for training the Park guides and where they study and learn about local volcanism. This training is important for the correct transmission to visitors of geological and volcanological knowledge and for making them more aware of the need to conserve the geological heritage of this area. This programme has been run since 2000 and to date 400 guides have been trained.

Conclusions

Sites such as La Garrotxa Volcanic Field harbour a great variety of volcanic features that illustrate a large number of eruptive processes, products and landforms. This makes them very attractive for geotourism and tourism in general, and they are often heavily visited due to their bucolic, easily accessible and gently rolling landscapes and as such are ideal places for raising awareness about the importance of volcanism. However, we should not forget that the volcanic materials present in these areas are often inherently fragile and easy to erode, which means that unchecked public access could lessen their value as heritage sites.

The use of this methodology in La Garrotxa Volcanic Zone Natural Park enabled the most important outcrops in the area to be identified, which crucially, enabled the park to (i) increase the efficiency of actions devoted to conserving the processes that characterize this type of volcanic activity for future generations; (ii) manage public use for those who come to visit the volcanoes; and (iii) ensure that the scientific knowledge of these sites

provides a service from a ecosystemic and cultural point of view. The correct management of all these aspects will contribute

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AQ4

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