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ORIGINAL ARTICLE

The Palaeontological Heritage of Santa Maria Island (Azores: NE Atlantic): a Re-evaluation of Geosites in GeoPark Azores and Their Use in Geotourism

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Abstract The application of geoconservation concepts and methodologies to the Azores archipelago led to the implementation of the Geopark Azores, recognized as such by the European and Global Geoparks Network. The current work re-evaluates and stresses the scientific and touristic value of the palaeontological sites of Santa Maria Island. Two new geosites (the Ponta do Castelo tempestite deposit and the Pedra-que-pica coquina) are proposed for classification as 'Regional Natural Monuments' by the Regional Government of the Azores, due to their international relevance. The tempestite deposit of Ponta do Castelo was overlain by a contemporary coastal lava delta, which enables the inference of the precise water depth of the geosite at the time of deposition, a very rare condition worldwide; and Pedra-que-pica is the most extensive multispecific fossiliferous coquina ever reported in the literature from the shelf of any of the ~20,000 known volcanic oceanic islands in the world. Relevant geosites reported for this island are increased from 15 to 26. Additional palaeontological heritage contributions to the sustainable tourism of Santa Maria are suggested, with a focus on two recent projects: the 'Fossil Trail' and the future 'PalaeoPark Santa Maria'.

Keywords Geoconservation · Geosites · Palaeontological heritage · Tourism · PalaeoPark Santa Maria · Azores

Introduction

The Azores islands are renowned for their geodiversity and important geological heritage (Lima 2007; Ávila and Rodrigues 2013). In March 2013, these remote islands located in the northeastern Atlantic were the first archipelago to be included as such in the European and Global Geoparks Network, recognized by UNESCO, with a very distinctive and unifying slogan '9 Islands, 1 Geopark' (Lima et al. 2014). Located in a complex oceanic magmatic and tectonic setting (Fig. 1) (25–32 ° W, 37–40 ° N), about 1500 km from the shores of mainland Portugal and almost midway between Europe and North America, this archipelago is composed of nine volcanic

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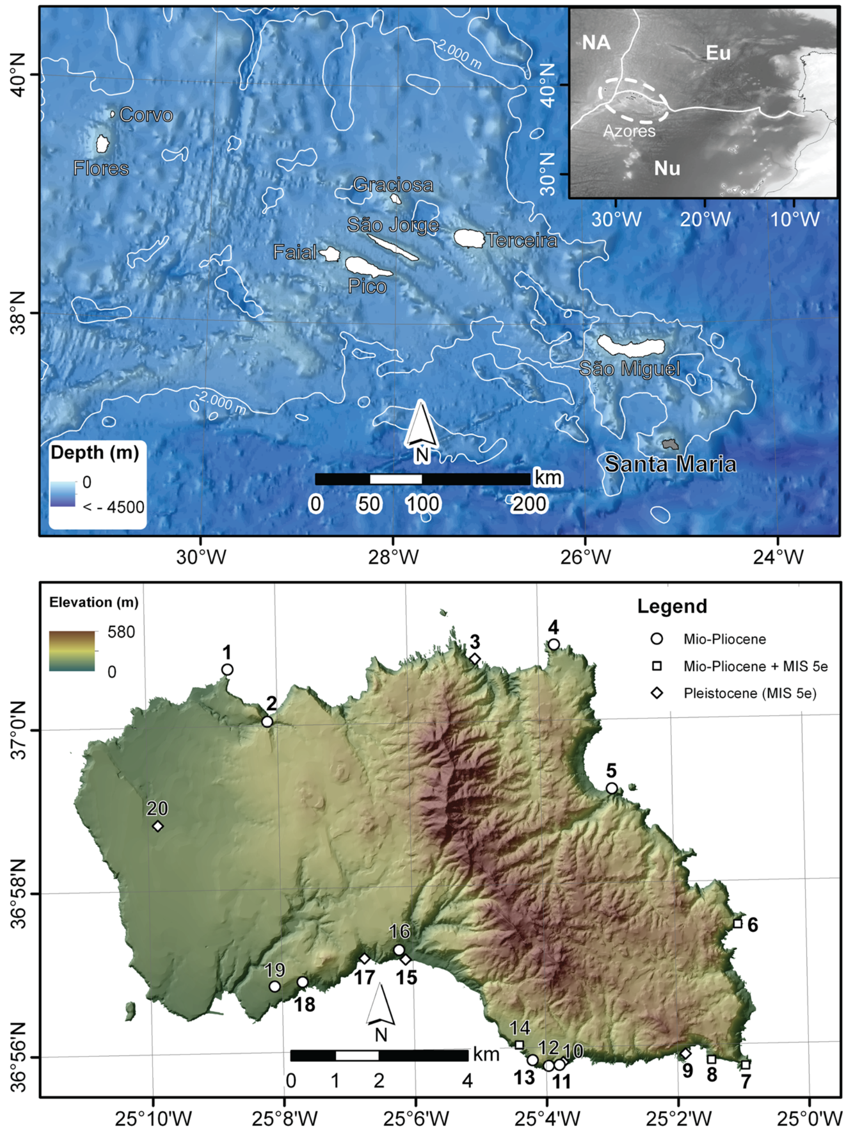

Fig. 1 **a** Location maps. Insert: location of the Azores archipelago in the Northeast Atlantic, in the triple junction between the North American (*NA*), Eurasian (*Eu*) and Nubian (*Nu*) tectonic plates; *MAR* Mid-Atlantic Ridge. Location of Santa Maria Island within the Azores Archipelago. **b** Map of Santa Maria with the location of the most important Mio-Pliocene and Pleistocene (MIS 5e) outcrops. *1* Ponta dos Frades, *2* Cré, *3* Lagoinhas, *4* Ponta do Norte, *5* Ponta Negra, *6* Ponta do Cedro, *7* Ponta do Castelo, *8* Pedra-que-pica, *9* Vinha Velha, *10* Pedrinha da Cré, *11* Baía de Nossa Senhora, *12* Malbusca, *13* Malbusca West fault, *14* 'Ichnofossils Cave', *15* Praia do Calhau, *16* Macela, *17* Prainha, *18* Figueiral, *19* Pedreira do Campo, *20* Airport area

islands and a number of islets, with a WNW-ESE general trend and about 615 km separating the most distant of the islands (Flores and Santa Maria).

Santa Maria is the oldest island of the Azores archipelago, having emerged above sea level during the Late Miocene (Serralheiro 2003; Ramalho et al. 2014; Sibrant et al. 2015). The geological history of this island is quite unique: after its first emergence, it was probably completely eroded and thus submerged during the Late Miocene/Early Pliocene, and then it re-emerged during the Early Pliocene. From Early Pleistocene to present, the island's edifice has been uplifted and eroded (Serralheiro 2003; Ávila et al. 2012; Ramalho et al. 2014), with fossil raised beach conglomerates and uplifted shore platforms now located up to 200–230 m above present sea level. No evidence indicates any volcanic eruptions took place since the late Pliocene (Serralheiro 2003; Sibrant et al. 2015).

The island's present-day size of 97 km^2 consists of a relatively flat western older area and an eastern mountainous younger area where the maximum altitude of the island occurs at 587 m at Pico Alto. The coastline varies from abrupt cliffs reaching 342 m (Rocha Alta) to a few localized bays harbouring sandy beaches (Serralheiro 2003).

The aim of this paper is to assess the impact of the recent palaeontological discoveries in Santa Maria Island for the classification and relevance of geosites. For this, we review the geoconservation criteria used by previous authors, in order to better describe and rank fossiliferous geosites at Santa Maria Island according to methodologies adapted to its oceanic island nature (Lima 2007). We also show how the palaeontological heritage of Santa Maria can provide sustainable ecotourism through the island's natural resources.

Materials and Methods

For this work, we followed a geoconservation methodology designed with the purpose of preserving the rich palaeontological and geological heritage of Santa Maria Island. This methodology includes: (1) inventory and characterization of the geosites; (2) the use of numerical indices to evaluate the relevance and subsequent ranking of the geosites (see Appendix for further information); (3) implementation of a palaeontological and geological conservation strategy, including the promotion of the palaeontological assets for tourism; and (4) monitoring of the changes over time of selected geosites (Barettino et al. 2000; Cachão and da Silva 2004; Brilha 2005, 2006; Reis and Henriques 2009; Henriques et al. 2011; ProGEO 2011; Endere and Prado 2014; Joyce 2010; Lima et al. 2010, 2014).

Inventory and Characterization of the Geosites

All relevant scientific and other references related to the fossiliferous sites of Santa Maria Island were reviewed; a synthesis may be consulted in Madeira et al. (2007). This procedure allowed an initial assessment of potential palaeontological geosites. Interdisciplinary international scientific teams studied these geosites during the course of 11 meetings of the international workshops on 'Palaeontology in Atlantic Islands' (2002–2014). As a result, the entire island of Santa Maria (including its shores) was thoroughly examined for fossiliferous outcrops. The geographical position was determined using a handheld GPS (Fig. 2).

Although many of these fossiliferous outcrops were already mentioned in classical geological works (Berthois 1950, 1951; Ferreira 1952, 1955, 1961; Zbyszewski and Ferreira 1961, 1962a, b), they have never been systematically described. Thus, recent work has consistently produced general cross sections of the overall sequences and detailed composite columnar sections for each outcrop, displaying the most relevant body fossils and trace fossils, the internal sedimentary structures, and the contacts between volcanic and sedimentary units. This was done for the Late Miocene-Early Pliocene outcrops of Pedra-que-pica (Kirby et al. 2007; Habermann 2011), Cré (Janssen et al. 2008), Figueiral (Habermann 2010), Pedreira do Campo (Habermann 2010), Ponta do Castelo (Meireles et al. 2013), as well as the Pleistocene deposits of Prainha and Lagoinhas (Callapez and Soares 2000; Ávila et al. 2002, 2009a, 2009b, 2010, 2015; Amen et al. 2005) and Vinha Velha (Ávila et al. 2015). Work is also being carried out to provide a formal geological description for many other fossiliferous outcrops (e.g. Malbusca, Ponta do Cedro, 'Ichnofossils Cave', Ponta dos Frades, Pedrinha da Cré, Ponta da Baía de Nossa Senhora, Ponta do Norte, Aeroporto and Ponta Negra; Figs. 3 and 4).

Relevant publications were consulted concerning specific groups of fossils including the Mollusca, which is the most abundant fossil group on Santa Maria Island (Callapez and Soares 2000; Ávila et al. 2002, 2007, 2009a, b, 2010), Brachiopoda (Kroh et al. 2008), Crustacea (Winkelmann et al. 2010), Echinodermata (Madeira et al. 2011), Ostracoda (Meireles et al. 2012, 2014) and Vertebrata (Estevens and Ávila 2007; Ávila et al. 2012), as well as coralline algae (Amen et al. 2005; Rebelo et al. 2014; Johnson et al. in press).

Relevance and Classification of the Geosites

The geodiversity and palaeobiodiversity of 17 out of 20 fossiliferous geosites (Fig. 2) were assessed using numerical indices based on the methodology first proposed by Lima (2007: 80–84), which adapts the ideas and methods of Cendrero et al. (1996), Cendrero (2000) and Brilha (2005) to an archipelagic framework. These indices are a means to reduce the subjectivity of quality assessment for geosites and should be based on the opinion of experts. Accordingly, a team of geologists and palaeontologists with a strong expertise on volcanic oceanic islands evaluated selected geosites on the island. Three sets of criteria, related to the geological and palaeontological heritage of each outcrop, were used: (1) criteria related to the characteristics of the geosite (e.g. rarity or abundance, area (km^2), degree of scientific knowledge, utility of the geosite for illustrating geological processes, number of geodiversity elements present, presence of cultural elements associated with the geosite, relevant fauna and flora and pristine conditions of the geosite), coded as criteria **A**; (2) criteria related to the potential use of the geosite (for scientific, educational, tourism or recreational activities; good or bad viewing conditions; possibility of collecting fossil samples; accessibility; proximity to populations; attractiveness to the public; potential visitors (expressed as number of inhabitants per island as well as by the number of tourists per year per island); socio-economic conditions of the island), coded as criteria **B**; and (3) criteria related to the needs for protecting the fossils present at the geosites (e.g. actual or potential threats to the geosites; present legal status of the geosites; reasons for which the geosite was classified; interest in the industrial extraction of rocks; type of land owners (public or private); vulnerability to human activities; vulnerability to the natural changes operating on the geosite), coded as criteria **C** (see Appendix).

Each criterion was evaluated, and a table was constructed with all of them and the respective classifications. All geosites were then classified as to international or national relevance, or to regional or local relevance, according to the numerical values attributed to some criteria (see Appendix). The final results (Table 1) were obtained after applying the following Eqs. (1 and 2):

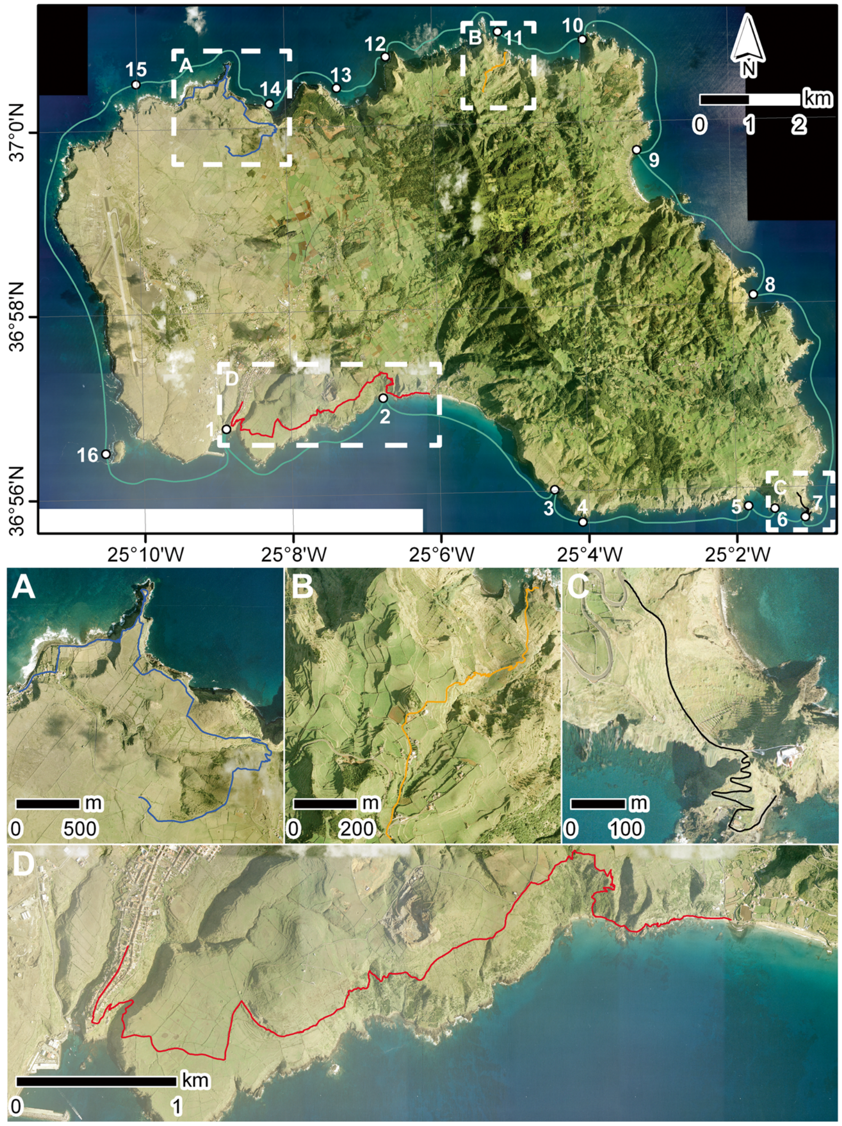

Fig. 2 Location of the designated hiking trails of Santa Maria. A-D: insert of the four terrestrial hiking tours. *Blue line* represents the marine tour around the island of Santa Maria. *White numbers* represent the consecutive stopping points of the marine tour. *1* Vila do Porto marina, *2* Prainha, *3* 'Ichnofossils Cave', *4* Malbusca, *5* Vinha Velha (Rocha Alta), *6* Pedra-que-pica, *7* Ponta do Castelo, *8* Baía do Cura, *9* São Lourenço, *10* Ponta do Norte, *11* Baía do Tagarete and Lagoinhas, *12* Ponta do Pesqueiro Alto, *13* Baía do Raposo, *14* Baía da Cré, *15* Anjos, *16* Ilhéu da Vila

1. For international/national relevant geosites:

$$Q = \left(\frac{2\,\Sigma A + \Sigma B + 1.5\,\Sigma C}{3}\right) \quad (1)$$

2. For regional/local relevant geosites:

$$Q = \left(\frac{\Sigma A + \Sigma B + \Sigma C}{3}\right) \quad (2)$$

where 'A' is the sum of nine different items, all related with geosite's own characteristics as explained above; 'B' is the sum of nine items, all related with the potential use of the geosite; and 'C' is the sum of six items, all related to the needs for protecting the geological characteristics of the geosite (cf. Appendix). According to Lima (2007), Eq. 1 is used if the values attributed to the following criteria are all accomplished: A1≥3, A3≥4, A6≥3, A9≥3, B1≥3 and B2≥3; in this case, geosites will have an international or national relevance. If any of the attributed values to criteria A1, A3, A6, A9, B1 or B2 is lower than the above-mentioned threshold values, then Eq. 2 is chosen and geosites will have regional or local relevance (for further information, please consult Appendix).

In order to validate the resulting *Q*-values, they were then compared with previous results obtained by Lima (2007) and Lima et al. (2014) (Table 2).

Results

Eight of the 17 selected geosites containing fossils were classified as having an international or national relevance; the remaining 9 were classified as of regional or local relevance (Table 1). Ponta do Castelo (*Q*=50.42), Prainha (45.83), Malbusca (44.25) and Pedra-que-pica (43.83) were the highest

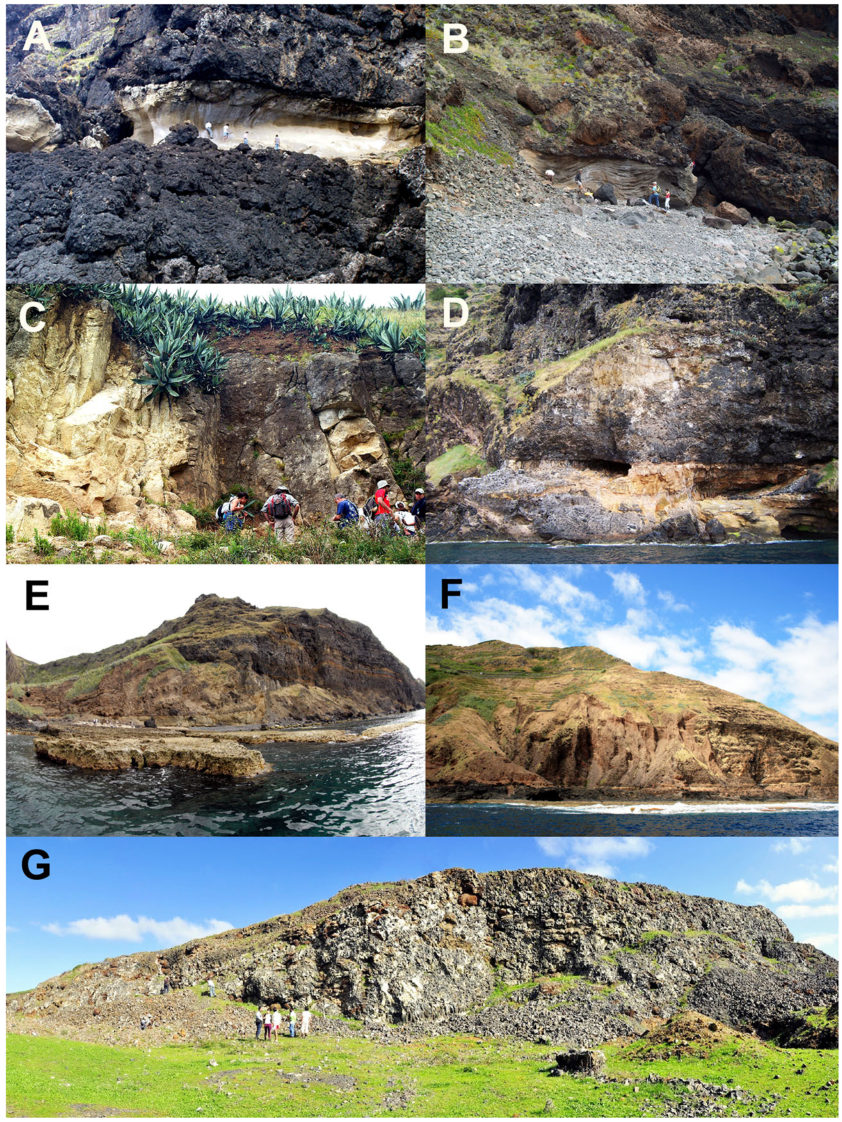

Fig. 3 Fossiliferous outcrops at Santa Maria. *A* Malbusca, *B* Ponta do Castelo, *C* Cré, *D* Ponta do Cedro, *E* Pedra-que-pica, *F* Lagoinhas, *G* Pedreira do Campo

ranked geosites with international or national relevance, and Lagoinhas (Q=41.42 and Cré (39.58) were the least relevant.

Ponta do Castelo and Pedra-que-pica (Fig. 3) were the only geosites considered to be of international relevance. The first represents a tempestite, seldom described from an oceanic island, which provides invaluable information on the processes of sediment remobilization, transport and deposition taking place on insular shelves during and after major storms. Moreover, this particular tempestite at Ponta do Castelo was overlain by a contemporary coastal lava delta, which enables the inference of the precise water depth of the geosite at the time of deposition, a very rare condition worldwide (Meireles et al. 2013). Pedra-que-pica was considered of international importance because it is probably the most extensive fossiliferous, multispecific coquina ever reported in the literature from volcanic oceanic islands.

The Q-values of the nine geosites considered of regional or local relevance range from 20.33 (the Last Interglacial deposits at Pedrinha da Cré geosite) to 26.83 (Airport area) (Table 1). The different Q-values assigned to the Figueiral outcrop by Lima et al. (2014) and by this work are explained by the fact that the former authors failed to consider the recently published literature on this geosite (e.g. Kirby et al. 2007; Winkelmann et al. 2010; Madeira et al. 2011; Ávila et al. 2012; Rebelo et al. 2014). For that reason, Lima et al. (2014) used Eq. 2 (with a resulting Q-value of 25.17, indicating regional or local relevance), whereas we used Eq. 1 (with a Q-value result of 43.25, indicating national relevance; cf. Table 2).

Discussion

Inventory and Characterization of the Geosites

The pioneering scientific assessment of the relevance of Azorean geosites and the geoconservation of the Azores natural

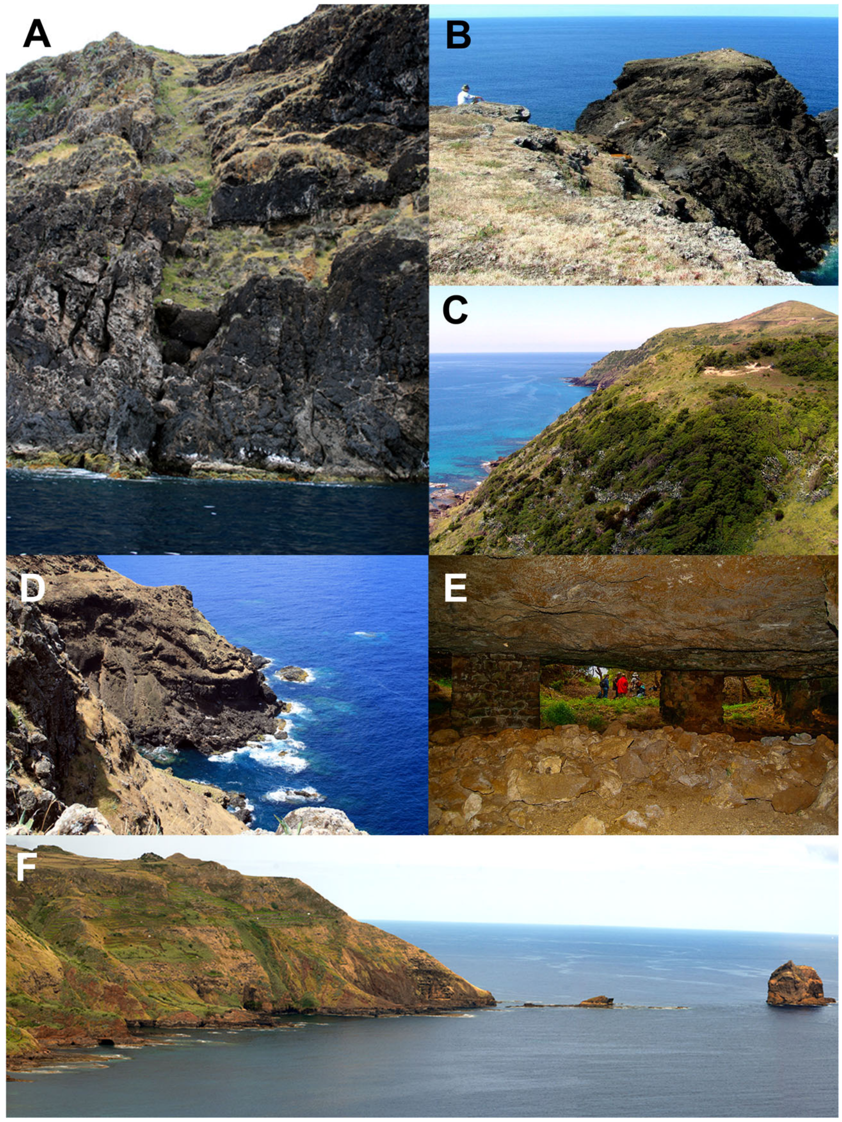

Fig. 4 Fossiliferous outcrops at Santa Maria. *A* Malbusca West fault, *B* Ponta dos Frades, *C* Macela, *D* Ponta do Norte, *E* Figueiral, *F* Lagoinhas and Tagarete Bay

patrimony made by Lima (2007) and those that formed the basis of the Azores Geopark application to the ENGG (European Network and Global Geoparks) summarized by Nunes et al. (2011,) were recently improved by Lima et al. (2014) with new data. The latter authors indicate a total of 121 geosites (117 terrestrial and 4 marine) for all Azores islands, six of which are of international relevance, 52 of national relevance and 63 of regional or local relevance.

The work by Nunes et al. (2007) is a good starting point for the description of the geodiversity of Santa Maria Island. For this island, the number of selected geosites has varied since the first account by Lima (2007), who identified 8 geosites: 5 with national relevance and with a *Q*-value ranging between 45.75 (Ponta do Castelo and Pedra-que-pica, then considered as a single geosite) and 38.00 (Cré); and 3 with regional or local relevance, with a *Q*-value ranging between 27.17 (Figueiral-Prainha, also considered then as a single geosite) and 24.00 (a north shore area comprising Lagoinhas islet, Tagarete Bay and Ponta do Norte).

After Lima et al. (2009a), the total number of Azorean selected geosites increased from the 59 reported by Lima (2007) to 106, of which 15 are located on Santa Maria (Nunes et al. 2008). The latter authors still considered Ponta do Castelo and Pedra-que-pica as a single geosite and, in a similar manner, Figueiral and Prainha were also grouped as a single geosite. However, in the present work, we show that these two geosites are, really, four different geosites, separated in time and space. Although Ponta do Castelo and Pedra-que-pica are both located on the southeastern tip of Santa Maria, besides being about 800 m apart, they represent distinct marine-shelf environments and are separated by thousands of years in age. Pedra-que-pica was dated by $^{87}Sr/^{86}Sr$ indicating an estimated age of 5.51±0.21 Ma (Kirby et al. 2007). Based on stratigraphical criteria, Ponta do Castelo is 10^4–10^6 years younger than Pedra-que-pica, from which it is separated by

Table 1 *Q*-value and relevance of the geosites at Santa Maria Island

Geosite	*Q*-value	Relevance	Author(s)
Ponta do Castelo[a]	50.42	International	This work
Prainha (MIS 5e)[a]	45.83	National	This work
Malbusca[a]	44.25	National	This work
Pedra-que-pica[a]	43.83	International	This work
Figueiral[a]	43.25	National	This work
Pedreira do Campo[a]	42.67	National	This work
Barreiro da Malbusca	42.17	National	Lima et al. (2014)
Barreiro da Faneca	41.83	National	Lima et al. (2014)
Lagoinhas (MIS 5e)[a]	41.42	National	This work
Poço da Pedreira	40.00	National	Lima et al. (2014)
Porto de Vila do Porto	39.67	National	Lima et al. (2014)
Cré[a]	39.58	National	This work
Ribeira do Maloás	39.33	National	Lima et al. (2014)
Cascata do Aveiro	28.83	Regional	Lima et al. (2014)
'Airport' area[a]	26.83	Regional	This work
Ponta do Cedro[a]	26.50	Regional	This work
Baía de São Lourenço	26.50	Regional	Lima et al. (2014)
'Ichnofossils Cave'[a]	26.33	Regional	This work
Baía do Raposo	25.83	Regional	Lima et al. (2014)
Baía dos Cabrestantes	25.50	Regional	Lima et al. (2014)
Ponta do Norte[a]	24.33	Regional	This work
Ponta da Baía de Nossa Senhora[a]	24.00	Regional	This work
Vinha Velha (MIS 5e)[a]	24.00	Regional	This work
Ponta dos Frades[a]	22.00	Local	This work
Ponta Negra[a]	21.17	Local	This work
Pedrinha da Cré (MIS 5e)[a]	20.33	Local	This work

[a] Geosites with fossils

approximately 60 m of volcanic sediments with a lava delta on top of those sediments. Moreover, they also differ in the processes (transport and deposition conditions) that formed the deposits. Their inherent characteristics make them distinctly important in different scientific contexts. Ponta do Castelo portrays a set of specific conditions which allowed the preservation of a shelf tempestite deposit for which its precise water depth could be inferred and additionally provides a good proxy for island uplift or subsidence reconstructions; Pedra-que-pica is probably the most extensive fossiliferous, multispecific coquina from the shelf ever reported in the literature of any of the ~20,000 known volcanic oceanic islands in the world. For instance, whereas the fossil fauna found at Pedra-que-pica is predominantly allochthonous and transported from shallower depths that found at Ponta do Castelo is a mixture of allochthonous and autochthonous elements (Meireles et al. 2013). Likewise, Figueiral and Prainha are considered as two different geosites, as they are located at very different elevations (Figueiral at about +90 m and Prainha at about +3/+4 to +5/+6 m), they have completely different ages (Figueiral is Early Pliocene (5.56–3.7 Ma), whereas Prainha corresponds to the Last Interglacial, and, consequently, their fossil faunas are almost totally different (Ávila et al. 2002, 2009a, 2010, 2015; Kirby et al. 2007;

Table 2 Changes over time of the *Q*-values assigned to some of the fossil deposits of Santa Maria Island

Geosite	Lima (2007)	Lima et al. (2014)	This work
Prainha	27.17[a]	48.00	45.83
Figueiral	27.17[a]	25.17	43.25
Pedreira do Campo	44.00	45.33	42.67
Ponta do Castelo	45.75[b]	44.67[c]	50.42
Lagoinhas	24.00	41.67	41.42
Pedra-que-pica	45.75[b]	44.67[c]	43.83
Cré	38.00	23.17	39.58

[a] Lima (2007) considered Prainha and Figueiral as a single geosite and of regional relevance

[b] Lima (2007) considered Ponta do Castelo and Pedra-que-pica as a single geosite of national relevance

[c] Lima et al. (2014) considered Ponta do Castelo and Pedra-que-pica as a single geosite of national relevance

Habermann 2010). Furthermore, they represent distinct marine palaeoenvironments (lower shore intertidal in Prainha versus inner to middle-shelf environment in Figueiral).

Lima et al. (2009b) added a new geosite (a small volcanic vent located on the southern shores of the island), therefore increasing to 16 the number of reported geosites from Santa Maria (from a total of 106 selected geosites in the Azores). In that paper, Prainha and Figueiral were considered, for the first time, as independent geosites. However, Ponta do Castelo and Pedra-que-pica were still classified as a single geosite, a situation that was followed by Lima et al. (2014), who reported again 15 geosites from Santa Maria, dropping from the list the latter geosite that had been added by Lima et al. (2009b).

Our work, with a special focus on the palaeontological heritage of Santa Maria Island, increases the total number of geosites reported for this island from 15 to 26 (Table 1). For many of these geosites, now classified as of regional or even just local relevance, their *Q*-values will rise as scientific knowledge about these deposits increases. This is especially true for the following geosites, where important discoveries have occurred over the last few years, but are not yet published: Airport area, Ichnofossils Cave, Ponta do Cedro and Vinha Velha.

Marine Palaeobiodiversity of Santa Maria Island

A total of 196 marine species from eight different phyla are reported from the fossiliferous Late Miocene-Early Pliocene geosites of Santa Maria (Table 3). This is a conservative number, as several new species (probably endemic to the island) are known but not yet described. Molluscs are the best-represented group with 105 species (53.6 %), followed by bryozoans with 38 species (19.4 %), arthropods with 16 species (8.2 %), chordates with 13 species (6.6 %), cnidarians with 11 species (5.6 %), echinoderms with 8 species (4.1 %) and brachiopods with 3 species (1.5 %). Although fossil sponges and foraminifers have also been collected, the species present in these samples have not yet been identified.

From the Pleistocene (MIS 5e) deposits, a total of 141 marine species from 4 phyla are reported. Sponges, cnidarians, arthropods and bryozoans have been collected but still wait proper scientific description, so their numbers are reported as '?' (Table 3). Molluscs are by far the best-represented group with 133 species (94.3 %), followed by algae with 4 species (2.8 %), echinoderms with 3 species (2.1 %) and chordates with 1 species (0.7 %). These numbers will increase shortly as a result of ongoing work (e.g. fossil marine birds, arthropods and bryozoans).

For such a small island, Santa Maria holds a diversified fossil fauna with some elements that are extremely rare in oceanic islands such as the fossils of cetaceans. In fact, for the entire Neogene and for the ~20,000 oceanic islands known in the present times, fossils of cetaceans have only been reported from the Mio-Pliocene of Santa Maria Island (Estevens and Ávila, 2007), the Pleistocene of Nauru Island (equatorial southwest Pacific; Fitzgerald 2011) and the Pleistocene of Santa Maria (work in progress). Moreover, on Santa Maria, the fossils of cetaceans are widely distributed, being reported from several Mio-Pliocene outcrops around the island [Cré (north coast), Figueiral and Pedra-que-pica (south coast) and Ponta Negra (east coast)]; and from the Pleistocene (MIS 5e) at Praia do Calhau (Fig. 2). Fossils of selachians are also uncommon in oceanic islands, but are relatively common at Santa Maria, from where seven species are reported (Ávila et al. 2012).

Palaeontological Conservation Strategy and Use of the Fossil Geosites

Recognizing the uniqueness and necessity to preserve the geological heritage of Santa Maria island, Cachão et al. (2003) proposed the classification of 'Pedreira do Campo' in what became the first Regional Natural Monument of the Azores, based on its scientific (geological and palaeontological), educational and tourism values. Since then, several other fossiliferous geosites have been scientifically studied and monitored by international teams accompanying yearly field trips since 2002. Calado et al. (2007) included the 'preservation and promotion of the fossil deposits of Santa Maria' as a specific goal of their study for the Coastal Zone Management Plan (CZMP) of the island. The final proposal of the CZMP included all fossiliferous outcrops of Santa Maria in a land use classified as 'Coastal Buffer' zone, with severe restrictions, as only conservation and protection measures were allowed (Calado et al. 2007).

In 2007, the Regional Government of the Azores reclassified the Regional Network of Protected Areas under a holistic framework, implementing a coherent management unit for each of the Azorean islands. This management unit was the 'Natural Island Park' concept. The Regional legislative Decree number 15/2007/A, dated the 25th of June, created the Natural Park of Santa Maria with two main objectives: to conserve nature and to protect biodiversity. In 2012, this legislation was changed by the Regional legislative Decree number 39/2012/A, dated the 19th of September, to also protect the fossil sites of the island and to clarify the procedures and rules for the study and sustainable use of this natural heritage.

This paper shows the need to establish similar classification and protection status by the Regional Government of the Azores for Ponta do Castelo and Pedra-que-pica outcrops, as additional Regional Natural Monuments, based on the rarity of tempestites and coquina deposits, respectively, on reefless volcanic oceanic islands, as well as on their geological and palaeontological values. Marine abrasion and weathering are fast eroding the rich fossil assemblage of Pedra-que-pica, with

Table 3 Number of species and percentage of the total number of species by phylum in the Pleistocene (MIS 5e) and Late Miocene-Early Pliocene fossiliferous outcrops at Santa Maria Island

Phyla	Pleistocene (MIS 5e)	%	Miocene-Pliocene	%
Proctotista (Algae)	4	2.8	?	?
Porifera	?	?	?	?
Cnidaria	0	0.0	11	5.6
Ctenophora	0	0.0	0	0.0
Brachiopoda	0	0.0	3	1.5
Sipuncula	0	0.0	0	0.0
Echiura	0	0.0	0	0.0
Annelida	?	?	2	1.0
Arthropoda	?	?	16	8.2
Mollusca	133	94.3	105	53.6
Bryozoa	?	?	38	19.4
Phoronida	0	0.0	0	0.0
Entoprocta	0	0.0	0	0.0
Echinodermata	3	2.1	8	4.1
Chordata	1	0.7	13	6.6
Total	141	100.0	196	100.0

Question mark indicates species that were collected but not yet classified

giant valves of *Gigantopecten latissimus* (Brocchi, 1814) (Fig. 5) and other macrofossils possibly being completely destroyed in less than 10 to 20 years. As this process continuously reveals previously unexposed fossils, the recommendation is made to the Regional Government of the Azores to promote regular surveys of this geosite to document the appearance of newly exposed rare species.

The palaeontological heritage of Azores constitutes an example of Upper Cenozoic marine palaeobiodiversity in the middle of the North Atlantic region with distinctive aspects that makes it unique in chronostratigraphic and palaeoceanographic terms. This heritage illustrates the connections with palaeobiogeographic provinces on either side of the Atlantic as well as helps to characterize climate change and related variations in the latitudinal gradients of dispersion of faunas and algae along this important ocean realm.

In the context of the Azores Geopark, Santa Maria's uniqueness lies mainly in its fossiliferous richness, palaeobiodiversity, sedimentological facies and profusion of subaerially exposed and easily accessible submarine volcanic morphologies related

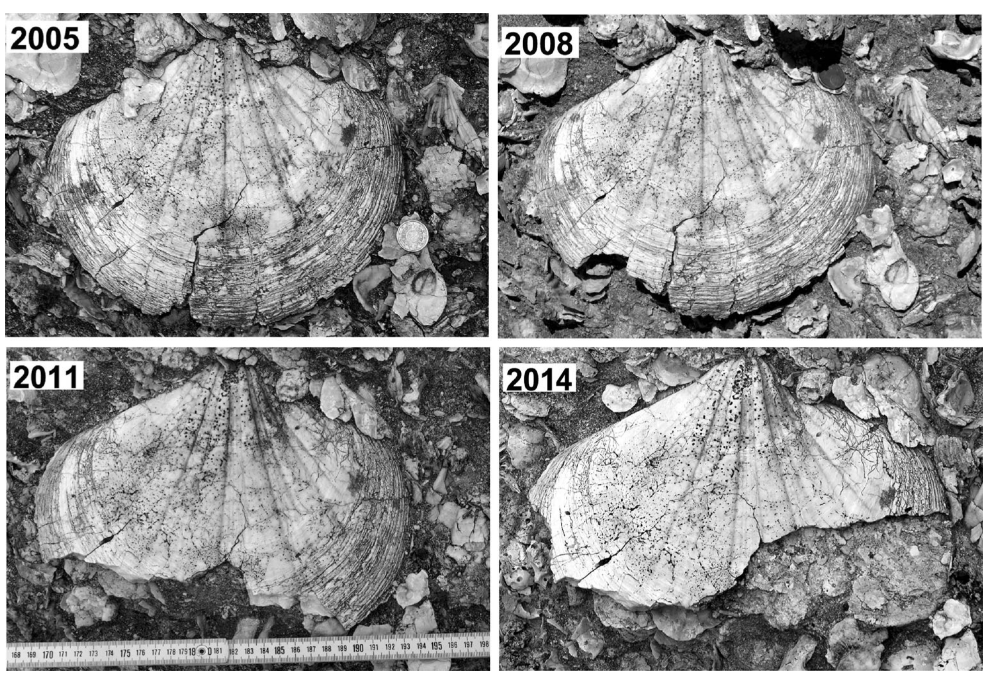

Fig. 5 Illustration of shell erosion on the giant bivalve *Gigantopecten latissimus* (Brocchi, 1814) during a 10-year time span

to different phases of the volcanic edifice construction. Thus, to reinforce and evaluate Santa Maria's palaeontological heritage is to strengthen arguments and provide new strategies for the continuous development and consolidation of the Geopark, as its implementation requires.

Interesting fossil assemblages of educational relevance are not common in volcanic oceanic islands. This makes the palaeontological heritage of Santa Maria Island particularly relevant for local school activities. In general, scholarly textbooks only provide examples of fossils from continental shelves and not from islands, so that Azorean teachers tend to approach universities on mainland Portugal to gain scientific support for field trips. Awareness of Santa Maria's palaeontological heritage could help to promote field trips by Azores middle and high school students. For instance, the Pedreira do Campo Natural Monument is a geosite that, by its accessibility and its already implemented infrastructures, will provide considerable opportunities for teaching activities with students of several ages.

Contribution of the Palaeontological Heritage to Small Island Sustainable Tourism

Tourism is a primary source of income in a growing number of archipelagos, sometimes exceeding the income from other sectors such as commercial fishing (Lutchman 2005). On the other hand, tourism sustainability in small islands is highly dependent on the maintenance of the quality of their marine and coastal environments, a balance sometimes difficult to achieve given an uncontrolled increase in the number of visitors to sensitive protected areas (Fonseca et al. 2011; Calado et al. 2014). In a study by Queiroz et al. (2014), the Azorean 'natural values', which included both its biodiversity and geodiversity that together provide a unique landscape, were actually considered to be the tourists' main reason to visit the archipelago, and in the end, they were mostly satisfied with the experience. Thus, tourism development in the Azores can and should be based mostly on the value of its wildlife, their unique environments, natural resources and landscapes (Queiroz et al. 2014).

The Fossil Trail was a project (2011–2014) funded by the Regional Government of the Azores (RGA) that created in Santa Maria Island four new terrestrial hiking trails: (1) a 7.21-km-long path (Vila do Porto-Pedreira do Campo-Figueiral-Macela-Prainha-Praia Formosa); (2) Lagoinhas (1.28 km); (3) Ponta do Castelo (0.92 km); (4) Paúl de Cima-Cré-Ponta dos Frades-Anjos (5.58 km)—and an innovative and quite exceptional marine touring route, the only one officially approved in the Atlantic islands, which consists of a counter clockwise tour by boat around the island that begins at the marina of Vila do Porto and includes disembarking on selected fossiliferous outcrops (Ichnofossils Cave, Pedra-que-pica, Ponta do Castelo and Ponta Negra) finishing at São Lourenço (mid-day tour) or at Vila do Porto marina (all-day tour, with a visit to the Vila do Porto Islet). According to Queiroz et al. (2014), hiking is the second most practiced activity by the visitors of the Azores, making the new fossil thematic trails an added value to bring people to the archipelago, particularly to Santa Maria Island. In the near future, certified nature guides will lead visits to these outstanding fossiliferous outcrops. Proper qualification for nature guides of the Fossil Trail was an important part of this project, and the first 3-day intensive course was held in November 2013. A total of 37 people participated in this course: 7 members of the Natural Park of Santa Maria; 18 people from 12 private companies related with nature tourism (both inland (e.g. hiking, climbing, canyoning) and maritime operators); 8 people were from local NGOs; and 4 teachers from the local school. Basic geological, palaeontological and biological concepts were given to participants, related to: (1) the geological history of the island from the seamount stage to the present, encompassing the last 6 Ma; (2) an overview of the fossiliferous outcrops of Santa Maria; (3) an overview of the most common fossil elements present in the outcrops that will be made available for tourist use; (4) and an overview of the patterns and processes of dispersal, colonization and speciation that usually operate in isolated oceanic islands such as the Azores. As most of the participants were inhabitants of Santa Maria Island, the economic revenue of the prospective nature guides will be mostly spent in the local economy. Future courses are planned on an annual basis for the period 2015–2017, as part of the 'PalaeoPark Santa Maria' project, also funded by the RGA. This has a considerable strength as a differentiating project for the development of Santa Maria as part of the Azores Geopark and, at a more regional scale, for the development of Azores as one region, stressing the educational, touristic and social relevance and value of its geological, palaeontological and natural heritage.

There are already good indicators of this relevance for the local development. Given its novelty, the marine touring route was received with strong interest from the maritime diving operators at Santa Maria Island, whose numbers have increased. Although mostly interested in diving with sharks, whale sharks and mantas, as these exotic large animals have been seen in increasing numbers through the archipelago, chiefly in Santa Maria warmer waters (see Bentz et al. 2014), the maritime diving operators foresee a market niche for their dive tourists that, for safety reasons, are forbidden to dive on their last day on the island, before flying home. For these people, the marine touring route provides an additional and unique opportunity to enjoy the sea. Moreover, it allows tourists to see and contemplate Santa Maria terrestrial landscapes from the sea, offering a different and wider perspective of the volcanic sequence where the fossiliferous sediments are found.

The fossil hiking trails, although mostly located in the coastal zone, are also placed throughout the island and can be used as alternative tours, less dependent on sea and weather conditions, than other sea-related activities like spear fishing, diving and whale watching. Thus, when rough sea conditions prevail, making those activities dangerous or even impossible, these high-quality thematic hiking paths will provide an attractive and interesting alternative to the usual inland trails. We expect positive socio-economic impacts such as an employment growth and increased value of local products, due to the increasing of the tourists in the activities available in Santa Maria Island.

Since Santa Maria is the only place in the archipelago where fossils are found, they ought to be preserved. Thus, the marine touring route will need infrastructure that will work as hiking paths for the visitors to the outcrops, and allow transportation between the land and the sea, with the necessary safety requirements. This is suggested, in particular, for the Pedra-que-pica coquina. These infrastructures must be mobile (removed during winter season to prevent destruction by rough seas) and are intended to avoid stepping on the fragile fossils. The cost associated with its implementation and maintenance is likely to be low.

Conclusions

This work increases the total number of geosites reported for Santa Maria from 15 to 26, of which 17 were evaluated according to their fossil content. Eight of the 17 selected geosites containing fossils were considered to have international (2 geosites) or national relevance (6 geosites), with Ponta do Castelo and Pedra-que-pica increasing the number of geosites to eight of international relevance in the Azores archipelago. We will recommend that these two sites be classified by the Regional Government of the Azores as additional Regional Natural Monuments, based on the rarity of tempestites and of coquina deposits on volcanic oceanic islands.

Our revision updates the number of Late Miocene-Early Pliocene marine taxa to 196 species and the number of Pleistocene (MIS 5e) marine taxa to 141 species. Of particular relevance is the presence of fossil cetaceans at Santa Maria Island, which are extremely rare on other oceanic islands.

Recent studies have shown that (1) different touristic activities, all related with 'Green Tourism', are the preferred choice of people visiting the Azores and (2) tourism sustainability in small islands is dependent on the maintenance of the quality of their marine and coastal environments. Moreover, these studies also point towards tourism development based in the preservation and promotion of island's wildlife, environment, natural resources and landscapes. As hiking was the second most practiced activity by tourists (Queiroz et al. 2014), we foresee great interest in the high-quality trails of the Fossil Trail, and especially, on the innovative and quite singular marine touring route, the only one officially approved in all the Atlantic and one that certainly will be an important alternative to other tourist marine activities such as spear fishing, diving and whale watching.

Finally, the involvement of local authorities, business people and inhabitants in the conservation of the fossils of Santa Maria and the educational projects that have been in place since 2002 are crucial factors in the sustainable management and tourist use of this unique palaeoheritage, which is likely to provide long-term revenues for the economic development of this small volcanic oceanic island.

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Appendix

Table 4 Description of the geoconservation criteria adapted to oceanic islands by Lima (2007) and quantification of their values

A. Intrinsic value of the geosite	
A1. Abundance/rareness (frequency of similar presences in the archipelago)	
Unique (only one example known from the archipelago)	5
2–4 examples	4
5–10 examples	3
11–20 examples	2
More than 20 examples	1

Table 4 (continued)

A. Intrinsic value of the geosite	
A2. Extension (surface area being evaluated)	
Larger than 1,000,000 m^2=1 km^2	5
100,000–1,000,000 m^2	4
10,000–100,000 m^2	3
1,000–10,000 m^2	2
Smaller than 1,000 m^2	1
A3. Scientific knowledge (number and type of scientific publications addressing the geology of the site which in turn reflects its relevance to the scientific community)	
More than one PhD/Master thesis and more than one scientific paper published in an international scientific journal	5
At least one PhD/Master thesis and/or more than one scientific paper published and/or several papers published in the country's scientific journals	4
At least one scientific paper published in a international journal or several papers published in the country's journals	3
Some research notes published in the country's journals or one paper published in local/regional journals	2
No scientific publications	1
A4. Educational suitability to illustrated geological processes (site potential to represent a certain geological process)	
Very useful	5
Useful	3
Of little use	1
A5. Geodiversity (diversity of relevant elements in terms of the geosite's geomorphology, mineralogy, petrology, stratigraphy, tectonics, hydrology, hydrothermal, volcanology, speleology and/or sedimentology)	
Five or more types of interest	5
Four types of interest	4
Three types of interest	3
Two types of interest	2
One type of interest	1
A6. Local-type (potential of the site to be considered as a reference in its category at the archipelago/regional level)	
Is recognized as the type locality (the best example/the most remarkable structure)	5
Is acknowledged as a secondary/reference type (a good example/a good reference)	3
Is not recognized as type	1
A7. Cultural and historical value (presence of elements classified as cultural or historical heritage—archaeological, historical, architectonic, artistic, etc.)	
Presence of relevant archaeological, historical and other types of elements	5
Presence of relevant cultural elements (architectonic, artistic, etc.)	3
No additional elements	1
A8. Other natural heritage elements associated to the geosite	
Remarkable fauna and flora, by its abundance, degree of development or the presence of species specially relevant	5
Presence of fauna and flora of moderate relevance	3
Absence of other natural elements of relevance	1
A9. Integrity (state of conservation of the geosite at the time of its characterization)	
Perfectly preserved, with no evidences of anthropic deterioration	5
With some degree of anthropic deterioration	4
With some degree of human intervention in the area of the geosite but do not prevent the observation of the site's essential characters	3
Numerous anthropic changes that have caused the deterioration of the important characters of the geosite	2
Very deteriorated	1
B. Criteria related with potential uses of the geosite	
B1. Potential to carry out scientific, educational, tourism and recreational activities without damaging the site geological characteristics	
Is possible to carry out scientific and educational activities	5
Is possible to carry out scientific or educational activities	3
Is possible to carry out other types of activities	1
B2. Observational conditions	
Excellent (relevant elements of the geosite can be observed and identified without any difficulty)	5

Table 4 (continued)

A. Intrinsic value of the geosite	
Reasonable (relevant elements can be reasonable viewed and identified by its structure, size, distance from the observational point, etc.)	3
Deficient (it can be observed and identified with some degree of difficulty)	1
B3. Potential for collecting geological objects (capability of collecting small geological samples without loss of the site's integrity)	
Is possible to collect geological samples without destroying the geological characters of the site	5
Is possible to collect some geological samples, though damaging the geological characters of the site	3
Is not possible to collect geological samples without destroying the geological characteristics of the site	1
B4. Accessibility	
Direct access through the main roads	5
Access through secondary roads (unpaved roads possible to be used by any kind of motor vehicles)	4
Access through secondary roads (unpaved roads possible to be used only by off-road vehicles)	3
Access through tracks less than a 1 km from a road where it is possible to be used any type of motor vehicle	2
Remote location of difficult access by tracks, more than 1 km from a road where it is possible to be used any type of motor vehicle	1
B5. Distance from facilities	
Access to diverse facilities in the nearest town less than 5 km	5
Access to limited facilities in the nearest town less than 5 km	4
Access to facilities between 5 and 20 km	3
Access to facilities between 20 and 40 km	2
Facilities can be only access in the nearest town, more than 40 km	1
B6. Attractiveness	
High	5
Moderate	3
Null	1
B7. Number of inhabitants per island (potential visitors)	
More than 100,000 inhabitants	2.5
Between 50,000 and 100,000 inhabitants	2
Between 25,000 and 50,000 inhabitants	1.5
Between 10,000 and 25,000 inhabitants	1
Less than 10,000 inhabitants	0.5
B8. Number of tourists per island per year (potential visitors)	
More than 100,000	2.5
Between 50,000 and 100,000	2
Between 25,000 and 50,000	1.5
Between 10,000 and 25,000	1
Less than 10,000	0.5
B9. Socio-economic conditions (data related to the township)	
Per capita income and education above national average and unemployment rate bellow national average	5
Per capita income, education and unemployment rate are the national average	3
Per capita income and education bellow national average and unemployment rate higher than national average	1
C. Potential threats and protection needs	
C1. Current or potential threats (urban, industrial or other pressures that may compromise the integrity of the geosite)	
Area clear of urban-industrial development or projects for new infrastructures	5
Intermediate area with no immediate development projects though expected in the near future	3
Area with clear urban-industrial development	1
C2. Present legal status	
Area with no legal protecting status	2.5
Area classified	1.5
Area legally protected	0.5
C3. Classification factors	
Area classified only by geological criteria	2.5

Table 4 (continued)

A. Intrinsic value of the geosite	
Area classified by geological criteria, with reference to other factors (biological, ecological, cultural, etc.)	2
Area classified by geological criteria together with other factors	1.5
Area classified by non-geological factors, though being considered	1
Area classified only by non-geological factors	0.5
C4. Quarrying industry	
Area of no value for quarrying industry	5
Area with potentialities for quarrying industry activities, though no projects are known for the near future	4
Area with projects for quarrying industry	2
Area of high interest for quarrying industry with active and/or licensed quarries	1
C5. Land ownership	
Mainly of public land	5
Partially public and private property	3
Mainly private property	1
C6. Vulnerability to anthropic pressures	
Unlikelihood of geomorphological characteristics to be significantly affected by anthropic activities	5
Large geological structures can be affected by anthropic activities, though unlikely to be destroyed	4
Likelihood of damage or destruction by mild anthropic activities	3
Likelihood of destruction of geological structures by small anthropic activities	2
Likelihood of destruction of small geological structures by light anthropic pressures	1
C7. Vulnerability to natural processes (faunal activity, vegetation growth, natural hazards)	
geosite not affected by natural processes	5
geosite affected by natural processes without damaging its main features	3
geosite greatly affected by natural processes	1

Table 5 Geoconservation criteria adapted to oceanic islands by Lima (2007) and here used to rank fossiliferous geosites at Santa Maria Island (Azores: NE Atlantic)

Fossiliferous outcrops	A1	A2	A3	A4	A5	A6	A7	A8	A9	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2	C3	C4	C5	C6	C7	TOTAL	Total A	Total B	Total C	*Q* int/nac	*Q* reg/loc
Prainha	3	3	5	5	3	5	5	3	4	5	5	3	2	4	5	0.5	1	1	5	1.5	2.5	4	5	3	5	88.5	36	26.5	26.0	45.83	
Pedra-que-pica	5	3	5	5	4	5	1	3	4	5	5	3	1	4	5	0.5	1	1	5	1.5	2.5	5	5	2	3	84.5	35	25.5	24.0	43.83	
Pedreira do Campo	5	3	5	5	3	5	1	1	3	5	5	3	3	5	5	0.5	1	1	5	1.5	2.5	4	5	2	5	84.5	31	28.5	25.0	42.67	
Figueiral	4	2	5	5	2	3	5	3	3	5	5	3	2	5	5	0.5	1	1	5	1.5	2	4	5	3	5	85.0	32	27.5	25.5	43.25	
Ponta do Castelo	5	4	5	5	5	5	5	5	5	5	5	3	2	4	5	0.5	1	1	5	1.5	2	5	3	3	5	95.0	44	26.5	24.5	50.42	
Ichnofossil's cave	4	3	**1**	5	4	5	1	3	3	5	5	3	1	3	5	0.5	1	1	5	1.5	2	4	5	3	5	79.0	29	24.5	25.5		26.33
Malbusca	5	3	5	5	4	5	1	3	5	3	5	3	1	3	5	0.5	1	1	5	0.5	2	5	5	3	5	84.0	36	22.5	25.5	44.25	
Ponta do Cedro	3	2	**3**	5	4	3	1	3	3	5	5	3	1	4	5	0.5	1	1	5	2.5	2.5	4	5	3	5	79.5	27	25.5	27.0		26.50
Ponta dos Frades	3	2	4	1	2	**1**	1	1	5	3	5	3	2	4	1	0.5	1	1	5	1.5	2	5	5	2	5	66.0	20	20.5	25.5		22.00
Lagoinhas	3	2	4	3	4	3	3	5	4	5	5	3	1	4	5	0.5	1	1	5	1.5	2	5	3	3	5	81.0	31	25.5	24.5	41.42	
Pedrinha da Cré (MIS 5e)	3	1	**1**	1	3	**1**	1	1	5	3	5	3	1	4	1	0.5	1	1	5	0.5	2	5	5	2	5	61.0	17	19.5	24.5		20.33
Ponta da Baía de Nossa Senhora	3	3	**1**	3	3	3	1	3	3	5	5	3	1	4	3	0.5	1	1	5	0.5	2	5	5	3	5	72.0	23	23.5	25.5		24.00
Cré	4	2	4	5	4	3	1	3	3	5	5	3	3	4	3	0.5	1	1	5	1.5	2	4	3	3	5	78.0	29	25.5	23.5	39.58	
Vinha Velha	3	2	**3**	3	4	3	1	3	5	3	5	3	1	4	1	0.5	1	1	5	0.5	2	5	5	3	5	72.0	27	19.5	25.5		24.00
Ponta do Norte	3	3	4	3	3	**1**	1	3	5	3	5	3	2	4	1	0.5	1	1	5	1.5	2	5	5	3	5	73.0	26	20.5	26.5		24.33
Airport area	5	3	**1**	5	5	5	1	1	3	5	5	3	4	5	3	0.5	1	1	3	2.5	2.5	5	3	3	5	80.5	29	27.5	24.0		26.83
Ponta Negra	3	1	**1**	1	2	**1**	1	3	5	3	5	3	2	4	1	0.5	1	1	5	0.5	1.5	5	5	3	5	63.5	18	20.5	25.0		21.17
Maximum value	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	2.5	2.5	5	5	2.5	2.5	5	5	5	5	115.0	45	40.0	30.0		

The values in bold are those with values that obligate to use equation 2

P.S. 1 if any of the values attributed to A1, A6, A9, B1 and B2 is <3, then equation 2 is to be used (thus *Q*-values will have a regional/local relevance); *P.S. 2* if any of the values attributed to A3 is <4, then equation 2 is to be used (thus, *Q*-values will have a regional/local relevance)

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