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Letter to Editor

On the Geological and Palaeontological Heritage of the Azores Archipelago and the Urgent need to Review the Geosites of the Azores UNESCO Geopark: A Comment on Lima & Meneses (2023), Geoconservation Research, 6: 114-127

Sérgio P. Ávila [1,2,3,4], Ana Hipólito [1,2,3,4], Patrícia Madeira [1,2,3,4], Lara Baptista [1,2,3,5,6], Samuel Arruda [1,2], Gonçalo Castela Ávila[1,7], Carlos Góis-Marques [2,4,7,8] , Rui Quartau [9,10]

[1] MPB – Marine Palaeontology and Biogeography Lab, University of the Azores, Rua da Mãe de Deus, 9501-801 Ponta Delgada, Açores, Portugal
[2] CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Pólo dos Açores, Azores, Portugal
[3] UNESCO Chair – Land Within Sea: Biodiversity & Sustainability in Atlantic Islands
[4] BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Vairão, Portugal
[5] Departamento de Biologia, Faculdade de Ciências da Universidade do Porto, Portugal
[6] University of Natural Resources and Life Sciences (BOKU), Institute for Integrative Nature Conservation Research, Gregor-Mendel-Straße 33 1180 Wien, Austria
[7] Faculdade de Ciências da Universidade do Porto, Portugal
[8] Madeira Botanical Group (GBM), Faculdade de Ciências da Vida, Universidade da Madeira, Campus da Penteada, 9000-390, Funchal, Portugal
[9] Departamento de Geologia, Faculdade de Ciências da Universidade de Lisboa, Campo Grande 1749-016 Lisboa, Portugal
[10] Divisão de Geologia Marinha, Instituto Hidrográfico, Lisboa, Portugal

Corresponding Author:
Sérgio P. Ávila
Marine Palaeontology and Biogeography Lab, University of the Azores, Portugal
Email: sergio.pa.marques@uac.p

Abstract

In a recent review article, Lima & Meneses (2023, Geoconservation Research, 6 (1): 114–127) reported on the Azores Geopark, introducing a new geosite for São Miguel Island. We here express our concerns regarding the data presented in this review article. In our commentary, we focus mainly on the use of older bibliographic sources and inaccurate age estimates for some islands, as well as the absence of important references, which results in a poor revision of the published literature on the geology and palaeontology of the Azores Archipelago. Furthermore, and over ten years since the successful application to UNESCO for the implementation of the Azores Geopark, we stress the urgent need to re-evaluate the list of geosites selected by the Azores Geopark team, a task that we suggest could be done involving the collaboration of an expert and multidisciplinary scientific team.

Keywords: Azores Geopark, Azores Archipelago, International relevant geosites, Geology, Palaeontology, Geoconservation.

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Introduction

UNESCO Global Geoparks are geographic areas that contain geosites of international relevance and that are managed within a holistic framework that combines conservation with sustainable development, aiming for the protection of the area and a state-of-the-art promotion of its landscapes (including the main geological and palaeontological aspects), while involving local communities. At present, there are 195 UNESCO Global Geoparks distributed in 48 countries (UNESCO Geoparks 2023).

We have read the paper by Lima & Meneses (2023) with great expectations. That work is presented by the authors as a review paper and arrives 12 years after the proposal submitted to UNESCO for the Azores Geopark (Nunes *et al.* 2011), which was innovative in the way it changed the definition of geoparks from a continuous territory to a discontinuous one, to accommodate archipelagic settings. In our view, this was a good opportunity to present new results from the scientific efforts made by many researchers who have published on the geology and palaeontology of the Azores Archipelago since 2011, and to review the Azores geosite checklist. This need for improvement of the first inventory and characterization of the 121 selected geosites, which are spread over the nine Azorean islands and surrounding seafloor, was already acknowledged by Nunes *et al.* (2011: 12): "Several researchers of the Region and national and foreigner scientists with assignments about the Azores in several areas have also contributed to this inventory, which has resulted in a sustained and wide approach, although it might be susceptible to improvements."

Although we acknowledge the effort of Lima & Meneses (2023), in our opinion, this article has several issues that should be clarified:

1. First, and crucial in a review article, is to present a complete bibliography, but there were no papers after 2018. Several important references were omitted (e.g., Gaspar *et al.* 2003; Luis & Miranda 2008; Hipólito *et al.* 2013; Larrea *et al.* 2013; Marques *et al.* 2013; Meireles *et al.* 2013; Mendes *et al.* 2013; Hildenbrand *et al.* 2014; Larrea 2014; Miranda *et al.* 2014 2015; Quartau *et al.* 2014, Ávila *et al.* 2015a 2015b; Madeira *et al.* 2015; Pimentel *et al.* 2015; Genkse *et al.* 2016; Casas *et al.* 2018; Melo *et al.* 2018; Rijsdijk *et al.* 2020; Andrade *et al.* 2022; Beier *et al.* 2022), including key review papers/books (Pacheco *et al.* 2013; Gaspar *et al.* 2015; Kueppers & Beier 2018), and books describing internationally relevant geosites (e.g., Ávila *et al.* 2022).

2. The use of old references such as Laughton & Whitmarsh (1974) affects the quality of description of the complex geotectonic setting of the Azores Archipelago. For instance, Lima & Meneses (2023) write that "The Azores UNESCO Global Geopark is located in the North Atlantic Ocean, in a special geotectonic setting, corresponding to the triple junction of the lithospheric plates of Eurasia, Africa and North America (Laughton & Whitmarsh 1974), roughly crossed N–S by the Mid-Atlantic Ridge and by the GLORIA Fault, that integrates the Azores-Gibraltar Fault, with a general E–W trend." The Azores UNESCO Global Geopark includes nine islands and adjacent islets (Flores and Corvo Islands being located on the North American tectonic plate, west of the Mid-Atlantic Ridge), the channel between Faial and Pico Islands, the Formigas Islets, the Dom João de Castro and Dollabarat submarine banks, and the Mid-Atlantic Ridge and associate hydrothermal fields (Nunes et al 2011), its boundary defined by the 2,000 m bathymetric line. In fact, except for Flores and Corvo, most of those areas integrate the western segment of the Eurasia-Nubia Plate boundary (the "Azorean sector/segment"; e.g., Dias *et al.* 2007) which ends in a triple junction, where the North American plate

meets the Eurasia and Nubia plates through the Mid-Atlantic Ridge. The Azorean sector noted above corresponds to a diffuse plate boundary where the active Terceira Ridge and some main linear volcanic ridges, such as São Jorge and Pico-Faial Ridges, and the extinct Princesa Alice Rift (Miranda *et al.* 2018) make up the main volcano-tectonic structures. However, geographically and geologically, the Gloria Fault is outside the Azores region, extending from the eastern tip of the Azores Plateau towards the Madeira-Tore Rise (e.g., Laughton *et al.* 1972; Batista *et al.* 2017). Both the Azorean sector of the Eurasian Nubia Plate boundary and the Gloria Fault are part of the Azores-Gibraltar Fracture Zone (e.g., Grimison & Chen 1986; Luis & Miranda 2008; DeMets *et al.* 2010), the western segment of the Eurasia Nubia Plate boundary, that links the Mid-Atlantic Ridge to the Gibraltar Strait. Hence, most of the Azores UNESCO Global Geopark lies in the western sector of the Azores-Gibraltar Fracture Zone, but it is not crossed by the Gloria Fault (Fernandes *et al.* 2018; Vogt & Jung 2018).

3. The older references provide outdated age dating for the Azorean islands. For example, although the archipelago's youngest island is Pico Island, its oldest subaerial volcanics did not form about 270 ka ago (Chovelon 1982), but 186 ka (Costa *et al.* 2015). A more problematic inaccuracy is when Lima & Meneses (2023) report 6–8 Ma as the age of the oldest Azorean island, Santa Maria, citing Ramalho *et al.* (2017) as the source; however, these last authors clearly state that the oldest rocks found at Santa Maria (corresponding to the Cabrestantes Formation) yielded an age of 6.01 ± 0.14 Ma (Ramalho *et al.* 2017).

4. We noted further inaccurate information. For instance, as regards the evolution of the Azores Triple Junction, Lima & Meneses (2023), based on Searle (1980), state that "The Azores are oceanic islands of volcanic origin that started to form around 36 million years (My) ago." However, Luis & Miranda (2008) concluded that "the establishment of the Azores triple junction occurred between chrons C6c (ca. 24 Ma) and C11–C12 (ca. 30 Ma) following the welding of Iberia to Eurasia, at ~27 Ma ago." Moreover, Miranda *et al.* (2018) state that "(…) After more than four decades of research, a few questions have been clarified concerning the different phases of development of the Azores triple junction and allowing the design of the following interpretation sketch: ~27 Ma ago there was a major rearrangement of tectonic plates and microplates in the Atlantic amalgamating Iberia to Eurasia and developing a new plate boundary along the Azores-Gibraltar Fracture Zone, here comprising the Gloria Fault and the East Azores Fracture Zone. (…)" Thus, ~27 Ma, not 36 Ma, is the most recent date for the beginning of the history of the Azores Triple Junction, a premise for the magmatic/volcanic formation of the Azores Plateau (Krause & Watkins 1970; Beier *et al.* 2022), the submarine geomorphological feature defined by a bathymetric swell roughly delimited by the 2,000 m isobath, from which the islands rise. Regarding the formation of the islands, Miranda *et al.* (2014, 2015, 2018) re-evaluated the magnetic anomaly patterns, by magnetic reconstruction, together with high-resolution bathymetry analyses, in light of present scientific knowledge on the Azorean segment of the Eurasia-Nubia plate boundary, and the authors are consistent in attributing a span of less than 3 Ma for the development of most of the islands (except for Santa Maria Island).

5. Some of the reported geosites are located on the coastline which represents a risk of their destruction by marine erosion. This is, therefore, a piece of important information that should have been reported in this review. A few studies tried to estimate long-term coastal erosion rates in the Azores (Quartau *et al.* 2010; 2015; 2016; 2018; Zhao *et al.* 2020) including one important geosite that will

likely disappear in the next 100 years (e.g., Capelinhos, Zhao *et al.* 2019).

6. We also expected to find a much-needed revision of the 121 geosites selected by the Azores Geopark team in their initial proposal (Nunes *et al.* 2011), as well as a thorough review of their status (international / national / regional interest). However, the review is limited to a description of Ponta da Ajuda, a new geosite for São Miguel Island (Lima & Meneses 2023), whose relevance was not evaluated.

Ponta da Ajuda is a hard rock coastal headland supported by massive basaltic (sensu lato) to intermediate lava flows. This geomorphic feature is developed on the northern flank of the Furnas polygenetic volcano, affecting its older sequences (the Lower Furnas Group; > 95 ka to <30 ka BP; Guest *et al.* 1999, 2015). The sea cliff exposure on Ponta da Ajuda includes units of volcanic acidic pyroclastic (ash and pumice) fall and flow (Fig. 1, II) interbedded between two lava flows (Fig. 1, I & III) emplaced into a subaerial palaeoenvironment. Nevertheless, at the base of the cliff, and extending laterally, a thick simple lava sheet flow exhibits (Fig. 1, I), in cross-section, transitional morphologies of columnar jointing suggesting progressively faster cooling rates towards the base. From the top to the bottom of the lava flow, poorly developed columnar jointing, composed of irregular wide columns, passes successively into right columnar jointing, where closely packed vertical narrow and long prisms, with slightly undulated fracture surfaces, form a plunging cliff. At sea level, wave-cut platforms cutting the lava flow expose closely packed polyhedral "jigsaw" jointing.

The current understanding of columnar joint formation from contractional cooling is coherent in recognizing that the cross-sectional area of basalt columns is inversely proportional to the cooling rate (Toramaru & Matsumoto 2004) and that the length of a polygon-bounding fracture segment is a function of the cooling rate, with slower cooling creating wider columns and faster cooling narrower columns (Hetényi *et al.* 2011). Transitional lava flow morphologies, between purely subaerial to purely subaqueous, have been widely observed in Santa Maria Island (Ramalho *et al.* 2017), and in the Cabo Verde Archipelago (Ramalho *et al.* 2010; Ramalho 2011). In São Miguel Island, the Ponta da Ajuda outcrop is the first to show those distinctive morphological characteristics of columnar jointing, a situation that can be explained by the presence of water at the base of the lava flow, promoting fast cooling. For instance, it is perfectly reasonable to assume this process when lava flows down into stream valleys cutting the volcano's flank.

Therefore, it should be emphasized that, in addition to the scientific and touristic (scenic value) interests of Ponta da Ajuda geosite, it has a remarkable pedagogical/ educational interest for the interpretation of distinctive surface and cross-sectional morphologies of basaltic (sensu lato) columnar joints.

Finally, we applied the methodology of Lima (2007), which is fully described in Ávila *et al.* (2016) and concluded that the Ponta da Ajuda geosite has a Q value of 25.00, meaning it is classified as a geosite of regional relevance.

7. Lima & Meneses (2023: 118) state that there are six geosites of international relevance in the Azores: the Mid Atlantic Ridge, the Furnas volcano caldera (São Miguel Island), Pico Mountain (Pico Island), the Graciosa caldera volcano and Furna do Enxofre volcanic cave (Graciosa Island), the Capelinhos and Costado da Nau volcanoes (Faial Island), and Algar do Carvão (Terceira Island). They did not discuss the geology and palaeontology of Santa Maria, based on recent work by over 80 researchers in the last two decades. This easternmost and oldest island of the

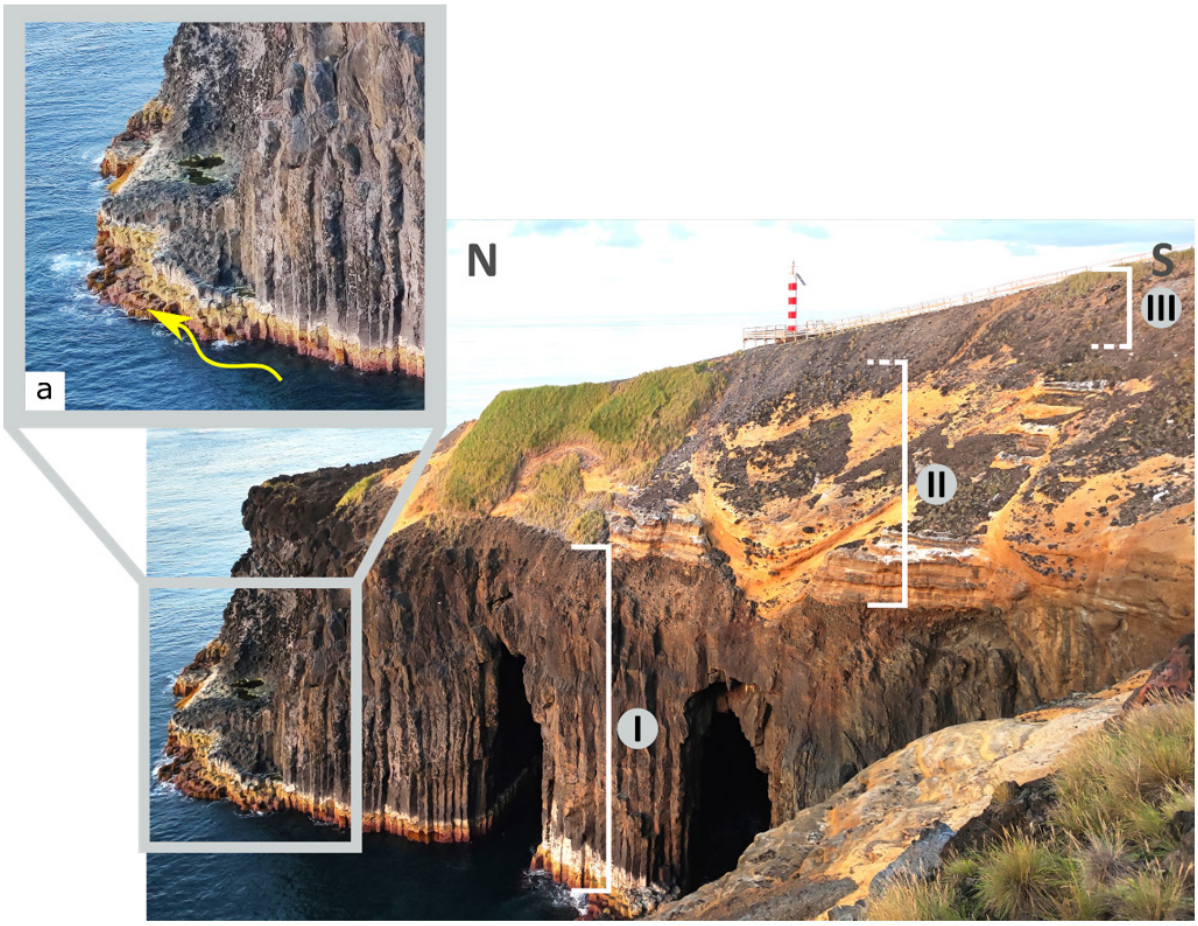

Figure 1. Ponta da Ajuda geosite seen from the west. A) Detail of the polyhedral jointing. Numbers indicate the units/set of units referred in the text: I – simple lava sheet flow (of intermediate composition) with distinctive morphologies of columnar jointing; II – sequence of units of volcanic acidic fall and flow deposits; III – basaltic (sensu lato) lava flow. Metric scale: lighthouse = 7 m high).

Azores Archipelago is renowned for the abundant, well-preserved and diversified marine Pliocene and late Pleistocene (Last Interglacial) vertebrate (Estevens & Ávila 2007; Ávila *et al.* 2012, 2020) and invertebrate fossils (Kroh *et al.* 2008; Janssen *et al.* 2008; Winkelmann *et al.* 2010; Madeira *et al.* 2011; Ávila *et al.* 2012, 2015c; Meireles *et al.* 2012; Santos *et al.* 2015; Hyzny *et al.* 2021; Sacchetti *et al.* 2023), ichnofossils (Uchman *et al.* 2016, 2017, 2018; Dávid *et al.* 2021), and fossil algae (Rebelo *et al.* 2014, 2016, 2021). All this information allowed Ávila *et al.* (2016) to assess the relevance of the palaeontological locations on Santa Maria Island. Using numerical indices based on the same methodology adapted by Lima (2007), Ávila *et al.* (2016) concluded that two new palaeosites (the Ponta do Castelo tempestite deposit and the Pedra-que-pica coquina) had international relevance.

An interesting topic is whether Ponta do Castelo and Pedra-que-pica should be considered a single geosite or two independent geosites. Although the ages of these two outcrops are similar (4.78 ± 0.13 to 4.13 ± 0.19 Ma for Pedra-que-pica and 4.13 ± 0.19 to 3.98 ± 0.05 Ma for Ponta do Castelo; cf. Sacchetti *et al.* 2023), based on stratigraphic criteria, Ponta do Castelo is 104–106 years younger than Pedra-que-pica (Ávila *et al.* 2016), from which it is separated by approximately 60 m of

volcanic sediments with a lava delta on top of those sediments. Both are fossiliferous outcrops of international relevance, they are about 800 m apart (which is a considerable distance in such a small island as Santa Maria), and their accessibilities are quite different (Pedra-que-pica is best accessed by boat, whereas Ponta do Castelo is easily accessed by a pedestrian trail). Further, their geological histories are very different: Pedra-que-pica is a huge coquina deposited below storm-wave base, over 20,000 m2 in area (Ávila *et al.* 2015a, 2022), whereas Ponta do Castelo is a much smaller shelf tempestite deposit (less than 300 m2 in area) that resulted from a very large storm whose waves carved the bottom of the ocean at depths of ~55 m, producing a "wavy" bottom erosional topography about 4 m in height that was covered by sediments, colonized by marine organisms, and then buried by submarine lavas (Meireles *et al.* 2013). Thus, from a strict geological history/evolution aspect, we should consider these as two geosites. However, from a geoconservation point of view, the management of these two palaeosites is considerably easier if taken together as a single management unit, i.e., a single geosite. This opinion is also shared by José Brilha (personal communication, October 28th,2023). Therefore, we agree with the former Scientific Coordinator of the Azores UGGp that Ponta do Castelo and Pedra-que-pica are a single geosite for management purposes within the Geopark's holistic concept of protection, education and sustainable development. Ávila *et al.* (2016) also increased the number of relevant geosites indicated by the Azores Geopark team to Santa Maria, from 15 to 26. Thus, it has been known since 2016 that the total number of internationally relevant geosites within the Azores Geopark should be seven (considering Pedra-que-pica and Ponta do Castelo as a single geosite), not six.

Moreover, to the nine geosites indicated by Lima *et al.* (2014) on Santa Maria Island (five of national relevance and four of regional relevance), Ávila *et al.* (2016) added 17 palaeosites: two of international relevance (Pedra-que-pica and Ponta do Castelo, which we herein merge into a single geosite), six of national relevance, six of regional relevance and three of local relevance. As the geosites classified as of "local relevance" were excluded from the list used in 2011 by the Azores Geopark team on the establishment of the 121 Azores UGGp geosites, the total number of geosites currently reported for Santa Maria should be 22: one of international relevance, 11 of national relevance, and 10 of regional relevance.

8. Finally, although rarer and less studied than the marine ones, fossils of terrestrial species have also been reported for the Azores. Bird fossils of extinct taxa were described from sedimentary rocks deposited in volcanic caves on several Azorean islands (Rando *et al.* 2013; 2017; 2019; Alcover *et al.* 2015). Some of these fossils were found in recognized Azorean geosites (e.g., Algar do Carvão, Terceira Island), but the majority are not part of any geosite. Further, Holocene Azorean forests have also been redescribed based on plant fossils (Góis-Marques *et al.* 2015, 2019a, 2020; Góis-Marques 2020) and even reporting on the loss of a palaeobotanical geosite within the Azores UNESCO Global Geopark (Góis-Marques 2019b).

The discussion above illustrates our efforts to add an effective and valuable contribution to updating knowledge of the geoheritage and geosites of the Azores UNESCO Global Geopark. Finally, we would like to stress that, in our opinion, it is very important to re-evaluate the list of the geosites selected in 2011 by the Azores Geopark team, a task that should be carried out.

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