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4th International Workshop on NATURAL HAZARDS

GEOTECHNICAL RISKS



FIELD TRIP
FAIAL ISLAND

GUIDE

João Carlos Nunes
Azores University
joao.cc.nunes@uac.pt

Carlos Faria
Regional Secretariat for
Environment and Climate Action
Carlos.e.faria@azores.gov.pt

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INTRODUCTION: Notes on the Geology and Volcanology of Faial Island

Faial Island is located about 120 km east of the Mid-Atlantic Ridge (M.A.R.), on the seismically active Faial-Pico Fracture Zone (FPFZ – Figure 1). This structure is a 350 km long leaky transform that extends from the M.A.R. with a ESE trend, and is considered by some (e.g. Luis et al., 1994) as the south border of the “Azores Block” (the third arm of the Azores triple junction) and therefore, the present boundary between the Eurasian and African plates.

In general terms, the geology of Faial island (21 km length and 173 km²) is dominated by two polygenetic central volcanoes and by a fissural basaltic ridge, the later subdivided in two main areas (Figure 2): i) the Capelo Peninsula, on the western part of the island, as a Holocene aged peninsula built by 20 scoria cones and related basaltic lava flows, and ii) the Horta Basaltic Zone, on the SE part of the island, with about a dozen of scoria cones emplaced along NW-SE trending fractures and associated basaltic lava flows (Figure 3), which are covered by pumice fall deposits from the Caldeira central volcano.

The Caldeira central volcano has a maximum altitude of 1043 m, average base diameter of 13,6 km (at sea level), area of 132,5 km², volume of about 48 km³ (Nunes et al., 2004)) and is built mostly by lava flows of basaltic to benmoreitic composition. However, its late eruptive history, e.g. during the past 10,000 years (Madeira, 1998; Pacheco, 2001), is characterized by explosive trachytic eruptions, accompanied by voluminous pumice fall deposits, ignimbrites and *lahar* deposits (Serralheiro et al., 1989). During those late explosive eruptions, a caldera 2 km wide and about 470 m deep was formed (Figure 2 and Table I).

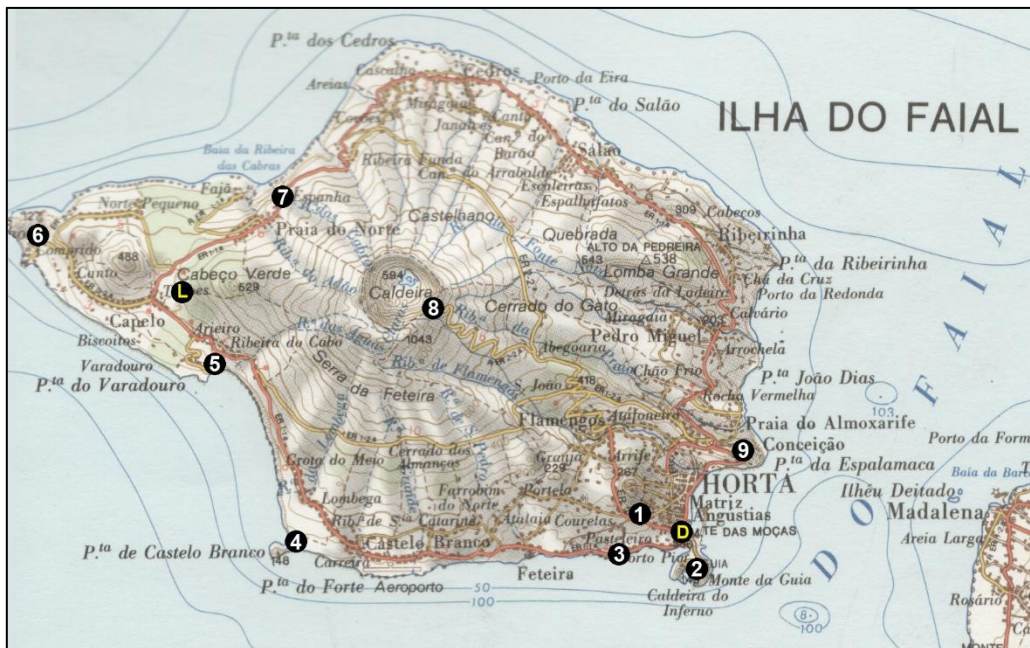
The eastern part of the island is characterized by the Pedro Miguel Graben, which has a N115°E average trend and width of about 7 km, between the Ribeirinha Fault (the NE border) and the Caldeira Fault (the SW border - Figures 2 and 4). In this eastern area, on the Espalamaca area outcrop the oldest rocks of Faial island dated about 0,85 My (Hildenbrand et al., 2012), as basaltic compound lava flows related to the old Ribeirinha shield volcano, centered east of Caldeira and covered by their younger trachytic products (Figures 2 and 5).

Basaltic volcanism dominates on the Capelo Peninsula, with about twenty Holocene eruptions, the last being the 1957-58 Capelinhos surtseyan eruption, located on its westernmost end. That eruption added 2.4 km² of new land to the island (nowadays reduced to only about 0.6 km² – Figures 5 and 6), and gave rise to 1.5 m maximum subsidence during the May, 1958 seismic crisis (Tazieff, 1959; Machado, 1958; Machado et al., 1962), as well as the opening of several tension cracks, namely in

Praia do Norte village, on the SE flanks of the Caldeira Volcano and also inside the caldera, the later triggering a small phreatic episode due to the drainage of the lagoon then existing. Besides the Capelinhos eruption, Faial island witnessed another historical eruption, in 1672/73 A.D., the “Mistério da Praia do Norte” eruption (Figure 5).

As mentioned, the Pedro Miguel Graben is the most prominent feature in the eastern part of Faial Island: its fault scarps face SW and NE, with maximum height of about 170 m, at the Lomba Grande Fault (Camacho et al., 2005). The lowest block of that structure is located near Pedro Miguel village (Figure 2), thus its name. Close to the Caldeira volcano summit the graben is mostly covered/filled by pumice and other Holocene pyroclastic deposits, but it can be traced again west of the caldera, namely as the Ribeira Funda Fault, even with a less clear topographic signature (Figure 5). Pedro Miguel fault scarps started developing during the last 73,000 (or 40,000) years, and channeled the pyroclastic flow deposits (e.g. *lahars* and ignimbrites) extruded during the Caldeira volcano explosive episodes (Madeira, 1998).

According to Tazieff (1959), Pedro Miguel Graben is merely a pure tectonic structure that influenced the volcanism on Faial Island. According to MacDonald (1972) the graben is either the result 1) of the removal of magma from an underlying magma chamber, 2) the result of stretching of the surface of the volcano, or 3) the result of stretching of the entire underlying crust, due to the spreading associated with the Atlantic Ocean. Present volcanological knowledge of the area indicates that, most likely the migration/removal of the magma (to West), from the “old” Ribeirinha Volcano to the “younger” Caldeira Volcano deep feeding systems, coupled with the Faial-Pico Fracture Zone interaction (e.g. its transtensional regime), favored the subsidence of the island’s surface and the development of the Pedro Miguel Graben.



Stop 2. Monte da Guia viewpoint

This site offers a privileged view over the Horta town, the Caldeira volcano – particularly its southwestern flank, with its gentle slopes composed mainly of pumice fall deposits – and the Horta Basaltic Zone.

This basaltic zone includes both submarine eruptive centres – as the Monte da Guia surtseyan tuff cone – and terrestrial/on-land eruptive centres, like the Monte das Moças, the Monte Queimado and the Monte Carneiro scoria cones, formed by strombolian-type eruptions. Monte Carneiro scoria cone – a cone dated less than 10,000 years old – is the eruptive centre of massive basaltic lava flows of *aa*-type, that are the geological basement of most of the Horta town buildings (cf. Figure 3).

On the eastern slopes of Monte Queimado scoria cone, partially dismantled by the sea erosion, it is possible to observe the pyroclastic materials that built this cone: volcanic ash, *lapilli* and bombs. On another hand, some cross-sections of the Monte da Guia road exhibit expressive examples of slumping marks, fold-like structures that originated due to plastic deformation of the water-saturated ash to lapilli deposits on the steep slopes of this tuff cone. The eruptive vent of this tuff cone is a double circular-shaped and coalescent crater, with a NW-SE general trend and opened to the sea (Figure 2), named as “Caldeirinhas”.



Stop 3. Littoral Ponta Furada – Feteira

The coastline between Ponta Furada and Lajinha sites is composed by very fluid basaltic lava flows of pahoehoe type, as rocky and plunging sea cliffs with several lava arch and littoral caves (including submersed ones) formed by sea erosion. In some cases, these littoral caves are affecting the main road stability, the reason why heavy traffic is conditioned on site.

Those pahoehoe lava flows were emitted from the area of Lameiro Grande scoria cone - Caminho das Tercas eruptive centres (Figure 3) and flowed towards south for about 2 km until reach the sea, and exhibit several structures and features typical of pahoehoe flows (or “lajidos”, the Azorean word for pahoehoe flows), as it is the case of ropy lavas.

As a result, the coast line is constituted by a pile of compound pahoehoe lava flows – known as “pancake-type lava pile” by the marine tour operators that promote coastal observations in the area – which contrast with the rough, irregular and clinkery morphology of the aa-type lava flows of Monte Carneiro cone, which outcrop to the east of Ponta Furada.



Stop 4. Castelo Branco Dome

Castelo Branco hill is an iconic landform in this area of Faial Island, which toponymy (meaning “white castle”) gives the name to the surrounding parish of Castelo Branco.

This imposing trachytic dome is covered by pumice deposits from the Caldeira Volcano and forms a peninsula of plunging cliffs that extend into the submerged area, the surrounding seabed being composed of sand and large rocky blocks, as a result of rockfall-type mass movements due to sea erosion.

In the uppermost part of the dome, the trachyte is highly weathered, displaying its typical whitish coloration (hence the dome's name) and its sugar-like texture.

The dome is emplaced on a radial fault of the Caldeira polygenetic volcano (Figure 2) and the nearby sea cliffs display a volcanic pile with basalt s.l. lava flows and pumice deposits associated with this central volcano.



Stop 5. Varadouro

In the Varadouro area there is a major geological contact between the pumice formations of the Caldeira central volcano, to the east, and the basaltic formations of the Capelo Peninsula volcanic ridge, to the west (Figure 2). This volcanic ridge, with 8 km length and Holocene age, is responsible by the increase of Faial Island area to the west. It corresponds to a volcano-tectonic lineament of about 20 cones, most of them scoria cones, extending from the Cabeco dos Trinta cone until the Capelinhos volcano, on the western end of Faial Island (Figure 2). The Strombolian and Hawaiian volcanic activity associated with this volcanic ridge took place along NW-SE general trending fractures and was responsible by the emission of basaltic lava flows that moved to north and/or south from that lineament.

This major geological contact has a clear morphological signature, as the high and steeply Varadouro fossil sea cliff (which marks the old shoreline of the island) that was surrounded by the young basaltic lava flows of the Capelo Peninsula, including those of the 1672/73 A.D. historical eruption, extruded from the Cabeço do Fogo and the Picarito scoria cones. The “Mistério do Capelo” area corresponds to the lava flows field associated with the 1672/73 A.D. eruption, which

started in April 1672 A.D. after seven months of earthquakes, and together with the associated seismic activity, caused the destruction of churches, about 300 houses, agriculture lands, and the death of 3 persons “who had gone to see the lava flows and got too close” (Machado, 1958).



===== LUNCH =====

Stop 6. Capelinhos Volcano

The Capelinhos eruption was the first submarine eruption in the world to be fully monitored and properly documented throughout its activity. Being so close to the shore and arousing the international scientific community’s curiosity, Capelinhos became one of the best-documented phreatomagmatic volcanoes of the World. For these reasons, this geosite was elected as one of the first 100 IUGS Geological Heritage Sites.

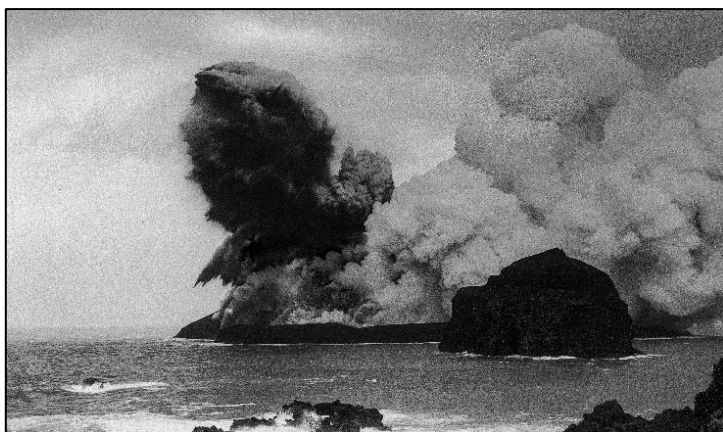
The eruption started on September 27th, 1957 as a submarine volcanic eruption only 1 km away from Faial Island, and continued for the next 13 months. The basaltic eruption started with the projection of volcanic ash – with the typical phreatomagmatic eruptions “cypress tree-like” ash jets – accompanied by high eruptive columns of steam and volcanic gases and the formation of pyroclastic surge deposits. The accumulation of the tephra created a small islet that in November 1957 connected to the island of Faial. In May 1958 the eruption evolved to a subaerial style, with the emission of scoria and lava flows, accompanied with an increase in the seismic activity, that

strongly affected the surrounding area and triggered a small phreatic eruption inside the Faial caldera.

During the eruption, the volcano expelled about 0.2 km³ of volcanic material, covering the agricultural fields and adding 2.4 km² to Faial Island – with only about a fourth of this area remaining today due to sea erosion.

The Costado da Nau fossil sea cliff – the westernmost coastline of Faial Island prior to the Capelinhos volcano – exhibits a didactic cross-section with the Capelinhos volcano tephra, as well as its “brother in arms” the Costado da Nau volcano geological formations, including its neck and feeding sill.

This eruption tells us the story of how volcanic islands are created and evolve, and it remains engraved not only in the landscape but also in the cultural, social and economic memory of Faial Island, that can be experienced visiting the underground Capelinhos Volcano Interpretation Centre.



Stop 7. Ribeira das Cabras – Praia do Norte

This viewpoint offers a good overlook to the “Mistério da Praia do Norte” that like the “Mistério do Capelo” is related to the 1672/73 A.D. eruption, as well as to the Praia do Norte old sea cliff, homologous to that observed in Varadouro. This fossil sea cliff is an extensive steep escarpment formed by a thick pile of basaltic lava flows, which are covered, in the upper part, by pumice deposits from the Caldeira volcano.

The deep valley of Ribeira das Cabras stream, has its general NW-SE trend conditioned by the Pedro Miguel Graben faults (Figures 2 and 5).



Stop 8. Caldeira

The Caldeira polygenetic volcano dominates all the central part of Faial Island, which summit is truncated by an almost circular shape caldera, a volcanic depression with average diameter of 2 km and 470 m depth. Inside the caldera there are a pyroclastic cone, a trachyte dome (the “Rocha do Altar”) and an intermittent wetland. This wetland once formed a lagoon, which was drained in 1958 during the seismic activity associated with the Capelinhos eruption, triggering a hydromagmatic eruption within the Caldeira. The highest altitude of Faial Island of Faial (at 1043 meters) is found at Cabeço Gordo, on the southern edge of the caldera rim.

The Caldeira volcano has an estimated age of about 400,000 years and its volcanic activity on the last 16,000 years is characterized by silicious and explosive eruptions (e.g. plinian-type eruptions), responsible by the emission of large amounts of pumice fall deposits and pyroclastic flows (e.g. *lahars* and ignimbrites). The nature of this tephra deposits (e.g. easily eroded) facilitated the installation of a dense superficial drainage network on the volcano flanks with a radial pattern, in certain areas as streams with deep valleys. Instead, the base of this central volcano consists primarily of basaltic to trachytic lava flows (including those of Castelo Branco dome), which are best visible along the coastal cliffs in the northern and southern parts of the island.





Stop 9. Espalamaca

This viewpoint offers an overlook of the Pedro Miguel Graben, with a clear morphological signature on the eastern sector of Faial Island, including on the Espalamaca Fault (Espalamaca “lomba”, on local designation), that extends to SE through the Faial - Pico sea channel (and its submarine fumarolic field), until the Madalena islets, the remaining of a submarine tuff cone.

To the southeast, the Horta town extends over the Monte do Carneiro cone basaltic lava flows, one of the scoria cones that makes the Horta Basaltic Zone and is emplaced on a NW-SE trend volcano-tectonic lineament (e.g. Figures 2 and 3).

Booth this lineament and the Pedro Miguel Graben tectonic structures are controlled by the regional Faial - Pico Fracture Zone, a 350 km long leaky transform fault that constitutes the present south border of the “Azores Block”, thus the present boundary between the Eurasian and African plates of the Azores Triple Junction (Figure 1).



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ANNEX

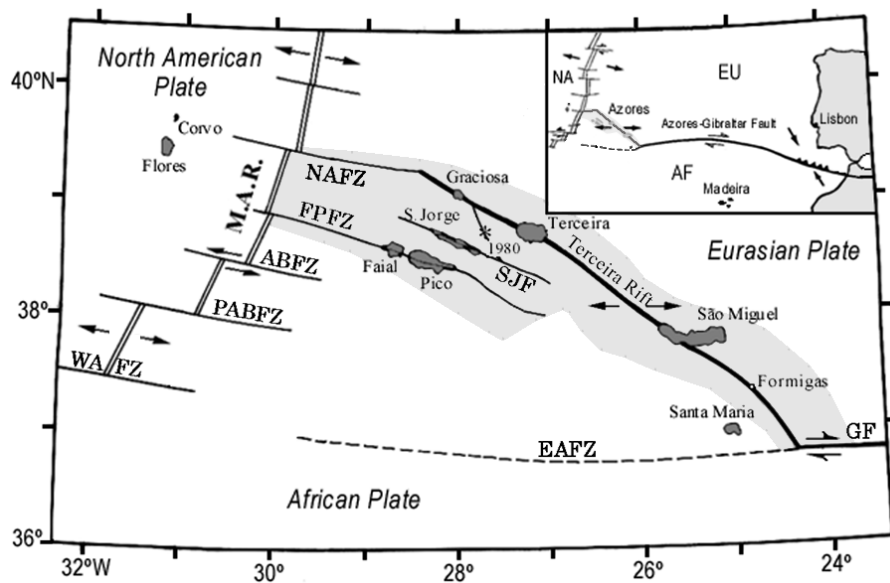


Figure 1. General geotectonic framework of the Azores archipelago, at the triple junction of Eurasian, North American and African plates. A star indicates the location of the 1980 January 1st earthquake. M.A.R.= Mid-Atlantic Ridge; EAFZ= East Azores Fracture Zone; WAFZ= West Azores Fracture Zone; NAFZ= North Azores Fracture Zone; FPFZ= Faial-Pico Fracture Zone; ABFZ= Açor Bank Fracture Zone; PABFZ= Princess Alice Bank Fracture Zone; GF= GLORIA Fault; SJF= São Jorge Fault; EU= Eurasian Plate; AF= African Plate; NA= North American Plate. Shaded area indicates the current EU/AF plate boundary, e.g. the “Azores Block”. Modified from Nunes *et al.* (2006).

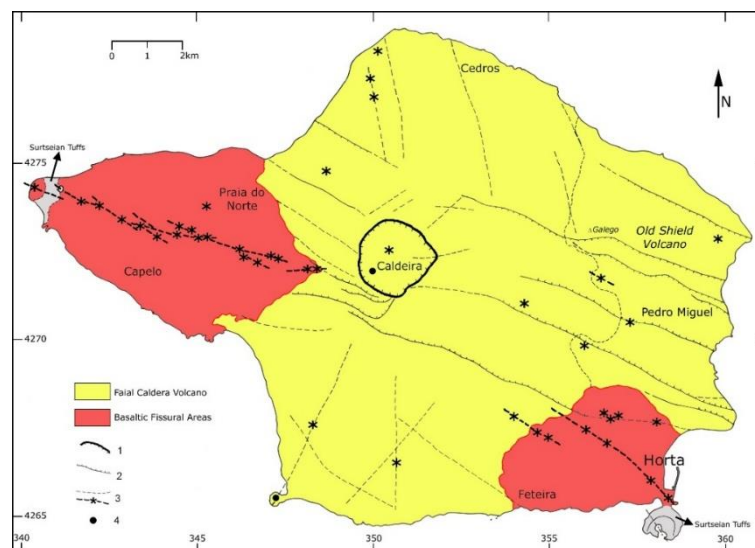


Figure 2. Main volcanic and tectonic features of Faial Island: 1- caldera rim; 2- Pedro Miguel Graben faults; 3- main volcanotectonic lineaments, including scoria cones vents (*); 4- Castelo Branco and Altar (at Caldeira) trachytic domes. In yellow: the Caldeira silicious volcano and the Ribeirinha old shield volcano. In red: the basaltic fissural areas of Capelo Peninsula and Horta. In gray: the surtseian tuffs of Monte da Guia (near Horta) and Capelinhos, at the westernmost part of the island. Modified after Serralheiro *et al.* (1989) and Madeira (1998).

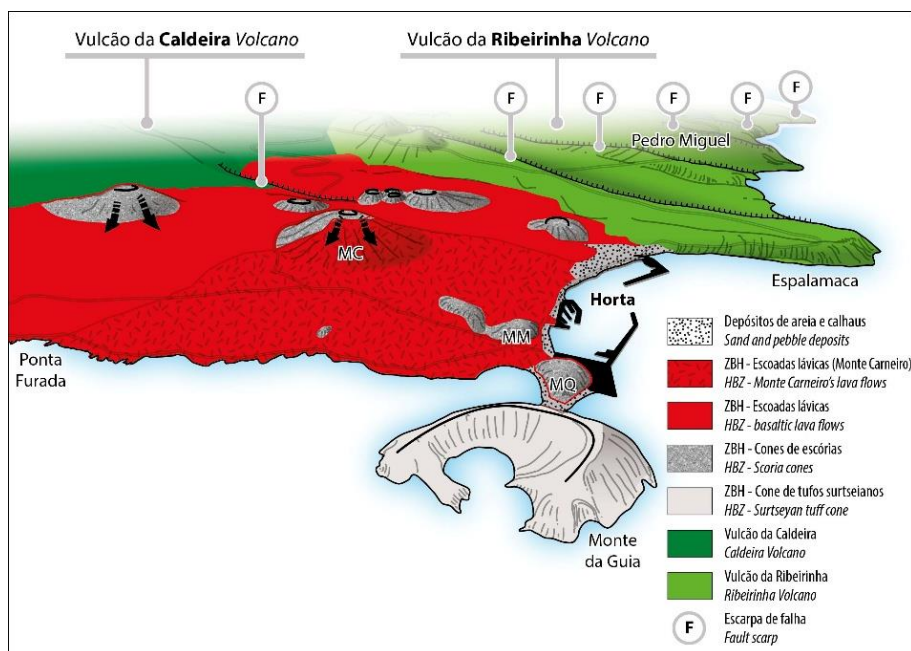


Figure 3. General geology of the Horta Basaltic Zone (©J.C. Nunes & C. Sousa).

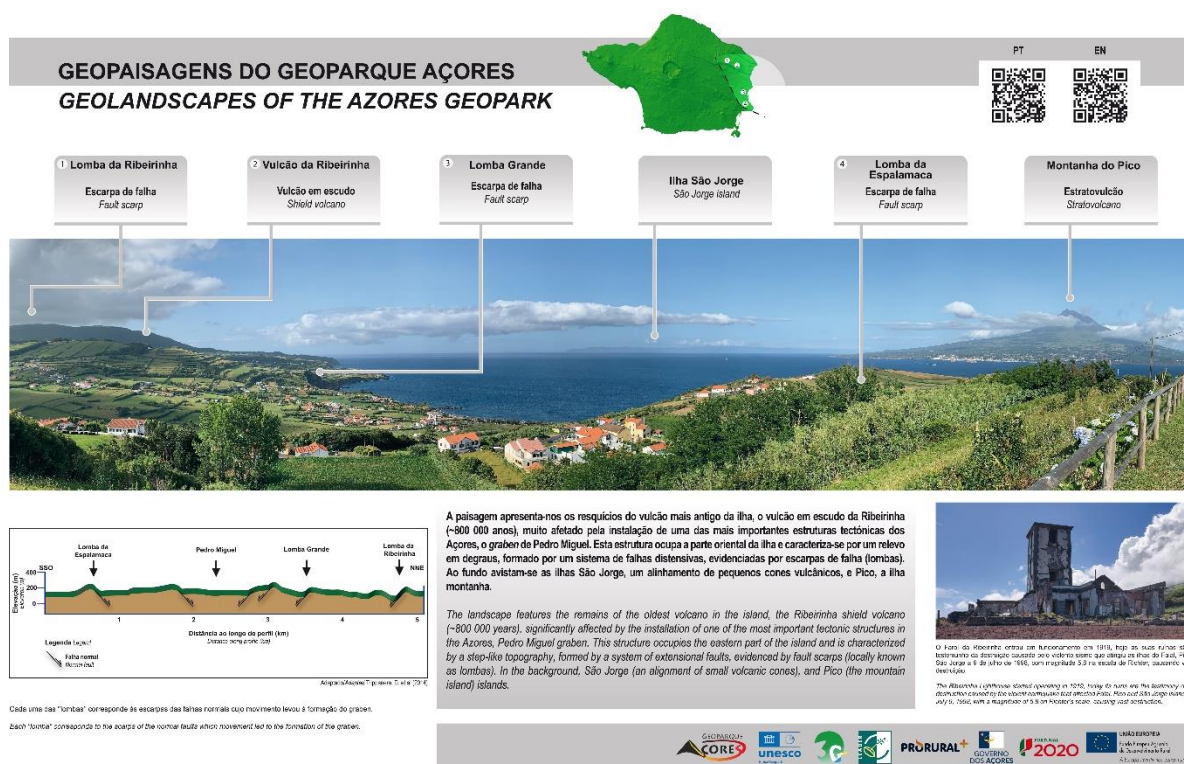


Figure 4. Overview of Pedro Miguel Graben landscape (©Azores UNESCO Global Geopark).

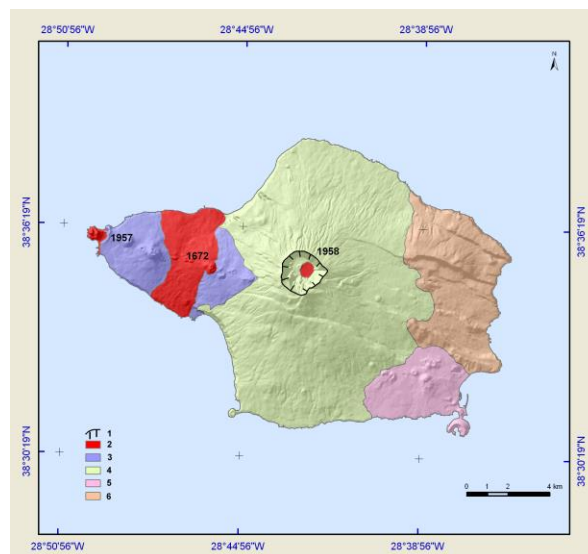
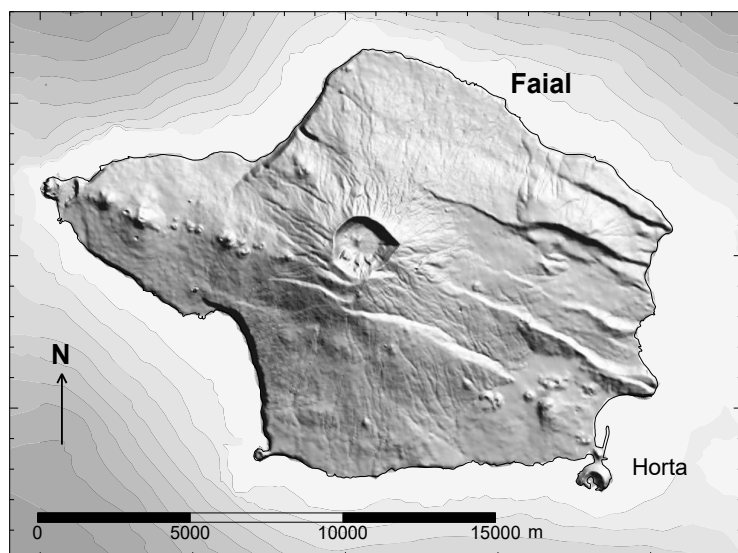


Figure 5. DEM- Digital Elevation Model for Faial Island (left) and Faial island general volcanostratigraphy (right). Adapted from Nunes (2004). 1- caldera rim; 2- Historical Eruptions (with year of occurrence); 3- Capelo Volcanic Complex; 4- Caldeira Volcano; 5- Horta Basaltic Zone; 6- Ribeirinha Shield Volcano and Pedro Miguel Graben.



Figure 6. Sketch of the westernmost sea shore cliff of Faial Island (e.g. Costado da Nau - CN) before Capelinhos Volcano (CV) eruption, with their tuff and scoria (sc) deposits and lava flows (lf). Scree slope deposits (sd) and Costado da Nau volcano main conduit (including feeding dykes and sill) are outlined. *In: Nunes et al. (2022).*

Table I. Morphometric parameters for the Faial Island central volcanoes (left) and the basaltic fissural areas (right). Adapted from Nunes et al. (2004).

PARAMETERS	CENTRAL VOLCANOES (including the Caldeira and the Ribeirinha shield volcanoes)
Distance to M.A.R. (km)	121
Maximum Elevation (above sea level) (m)	1043
High (above surrounding sea floor) (m)	2500
Average Base Diameter (at sea level) (km)	13.6
Area (km ²)	132.5
Volume (km ³)	48
Top Depression Maximum Diameter (km)	2.1
Top Depression Minimum Diameter (km)	1.8
Top Depression Average Diameter (km)	2
Top Depression Maximum Depth (m)	470
Top Depression Maximum Age (ka)	10.25
Maximum Known Absolute Age (My)	0.848 ± 0.012
Nr. Intracaldera Eruptive Centers	2
<i>Nr. Intracaldera Scoria Cones</i>	1
<i>Nr. Intracaldera Domes</i>	1
Nr. Flank Eruptive Centers	19
<i>Nr. Flank Scoria Cones</i>	18
<i>Nr. Flank Domes</i>	1
Total of Monogenetic Eruptive Centers	21
Nr. Historical Eruptions	1
Last Eruption (year)	1958 A.D.
Death / Injuries	0

PARAMETERS	BASALTIC FISSURAL AREAS (including the Capelo Peninsula and the Horta Basaltic Zone)
Minimum Distance to M.A.R. (km)	115
Maximum Elevation (above sea level) (m)	758
High (above surrounding sea floor) (m)	2200
Maximum Width (at sea level) (km)	5.5
Area (km ²)	41.2
Volume (km ³)	6
Maximum Known Absolute Age (ka)	1.86 ± 0.070
Maximum Inferred Age (ka)	15
Total of Monogenetic Eruptive Centers	32
<i>Nr. Scoria Cones</i>	29
<i>Nr. Surtseyan Tuff Cones</i>	3
Nr. Historical Eruptions	2
Last Eruption (year)	1957/58 A.D.
Historical eruptions deaths / injuries	3

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