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10th IAG INTERNATIONAL CONFERENCE ON GEOMORPHOLOGY

COIMBRA - PORTUGAL

« GEOMORPHOLOGY AND GLOBAL CHANGE »

FIELDTRIP GUIDEBOOK
Cape Verde (Santiago and Fogo Islands)

06–09 September 2022

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Coimbra, 2022

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Edition notice:

Title: *10th International Conference on Geomorphology. Fieldtrip Guidebook – Cape Verde (Santiago and Fogo Islands)*

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Edition: *Universidade de Coimbra, Faculdade de Letras*

Fieldtrip and Guidebook Coordination: *António Vieira (University of Minho)*

Cover: *Perspective of Santiago Island (photograph by Vera Alfama)*

ISBN: *978-972-95222-8-4*

Introductory Note

The 10th International Conference on Geomorphology will take place in Coimbra (Portugal) from 12th to 16th September 2022, under the theme "Geomorphology and Global Change" and it is organized by the International Association of Geomorphologists (IAG) and the Portuguese Association of Geomorphologists (APGeom).

As in previous international conferences on Geomorphology, and as is the tradition in many geomorphological events organized around the world, the organizing committee of the 10th International Conference on Geomorphology proposed several fieldtrips to the participants, occurring before, during and after the main event.

These fieldtrips intend, above all, to show to geomorphologists from all over the world the diversity and richness of the geomorphological elements of the Portuguese territory (and also from Cape Verde) and to allow an exchange of experiences between the specialists that investigate these territories and the visitors, contributing for mutual scientific enrichment and for the valorization of this international conference.

The pre-conference fieldtrip is dedicated to the islands of Santiago and Fogo, in the Archipelago of Cape Verde. It will take place from 6th to 9th September and will be led by colleagues from the University of Cape Verde (Vera Alfama, Sónia Victória, Sílvia Monteiro, José Maria Semedo and Romualdo Correia). The volcanic geomorphology will dominate the visit (including well conserved structural volcanic forms such as cones, domes, craters and calderas), especially in the island of Fogo where recent volcanic activity has been registered.

The one-day mid-conference fieldtrips will take the visitors around the Portuguese mainland territory, the 14th September, allowing the visit of four different geomorphological realities.

In the Arouca UNESCO Global Geopark, internationally recognized territory since 2009, participants will be able to visit unique geological and geomorphological features (such as planation surfaces, bowl-shaped valleys and narrow river valleys) and witness the remarkable effort of protection and promotion of natural (abiotic and biotic) and cultural (tangible and intangible) heritage. The visit to the “516 Arouca” suspension bridge will be an excellent opportunity to observe the magnificent landscapes of this mountainous territory. This fieldtrip will be led by Artur A. Sá, António Vieira and Daniela Rocha.

The field trip to coastal areas of central Portugal will be led by Pedro Dinis and António Campar Almeida. Their proposal is to observe the different morphotectonic units of central west Portugal, namely the Coastal Mountain of Serra da Boa Viagem (revealing karstification features), the littoral plain (with aeolian dunes associated with some

reliefs with higher elevation), the Cértima subsiding area (structurally-controlled morphology), and the Buçaco region (with the Syncline of Buçaco).

The visit to the Schist Mountains of Central Portugal will be centered in the mountains of Lousã and Açor, and will be conducted by Luciano Lourenço and Bruno Martins. It is proposed the observation of the main contrasts of the landscape, especially in terms of its physical geography, translated into geological, hypsometric, geomorphological, and hydrographic differentiation, or the land use and occupation and evolution of vegetation cover, namely following the recurrent large forest fires and the subsequent erosive processes they caused.

The fourth one-day fieldtrip will be oriented to the Estrela UNESCO Global Geopark, and led by Gonçalo Vieira, Emanuel Castro and Fábio Loureiro. The main geoheritage significance of the Estrela UGGp is the extent and richness of the Late Pleistocene glaciation(s) landforms and deposits (with spectacular morphological features such as the Zêzere glacial valley or the glacial cirques, moraine boulders, erratics or *roches moutounnées*) as well as the peculiar long-term geological evolution (revealing a significant diversity of granite types and landforms).

The three post-conference fieldtrips include a visit to the Lisbon Region, Serra da Estrela and, finally, Minho and Galicia (Spain), and will take place from 17th to 19th September.

The fieldtrip to the Lisbon Region will be guided by José Luís Zêzere, César Andrade, Sérgio Oliveira, Jorge Trindade and Ricardo Garcia, and will cover topics related with slope instability and landslides that affect the region of Lisbon, the floods occurring in the area north of Lisbon, and the coastal dynamics, morphology, cliff instability and beach erosion at north and south of Lisbon.

The three days field trip to the Serra da Estrela is led by Gonçalo Vieira, Emanuel Castro and Fábio Loureiro. Participants will be taken to visit some of the Geopark's most inaccessible geosites and observe breathtaking landscapes during two hikes: one in the Zêzere valley and the other between Penhas Douradas and Lagoa Comprida. The different geosites to visit include features of glacial, periglacial, granite weathering, fluvial, hydrogeological, petrological and tectonic themes, and aspects related with the management of a UNESCO Global Geopark will be discussed.

The third three-days fieldtrip is destined to the northwestern part of Portugal and the Spanish region of Galicia. Guided by Alberto Gomes and Antonio Perez Alberti, will be mainly devoted to the coastal area and to the observation and discussion of issues related to coastal dynamics, marine terrace staircases, differential uplift of coastal blocks, coastal geoheritage, coastal geoarchaeology, coastal erosion and coastal land planning.

It is our expectation that these visits will please all participants and promote the scientific enrichment of all involved, allowing a better understanding of the topics covered in each one.

We also hope that this set of fieldtrip guidebooks can help in the understanding of the themes discussed and that they can be a testimony of the commitment and dedication shown by all the scientific responsible for the several visits, to whom the organizing committee of the International Conference on Geomorphology expresses its greatest recognition and gratitude.

have a good fieldtrip!

Lúcio José Sobral da Cunha
António Vieira

on behalf of the ICG2022 Organizing Committee

ITINERARY AND SCHEDULE

Itinerary

Day 1: Santiago Island
Plateau of Praia; Monte das Vacas; Ribeira de São Domingos; Ribeira Seca (Poilão Dam) - Orgãos; Mountainous massif of Pico de Antonia; Santa Catarina Plateau; Mountainous massif of Serra Malagueta; Tarrafal - Baía Verde (Lunch break); Tarrafal- Monte Graciosa; Biscainhos (S. Miguel).

Day 2: Departure for the island of Fogo (Fig. 1)
Praia de S. Filipe; Ponta de Salina; Monte Sambango (Mosteiros); Corvo's lava; Valley of Ribeira de Caiada; Alto Espigão viewpoint; entrance to Fogo's Natural Park.

Day 3: Fogo Island
Trail in the area of Chã das Caldeiras (within the boundaries of the Natural Park)

Option 1: Visit at Chã das Caldeiras

1. Entrance to the Natural Park of Fogo (PNF)
2. Crater of explosion, Curral de Asno
3. Lava flows from the 2014 eruption, Lantisco
4. Slag cone from the 2014 eruption
5. Bordeira
6. Lava field
7. Main façade of the old winery, Boca Fonte
8. Contact between the lava flows of 1995 and those of 2014, Cabo Nhô Ernesto
9. Villages of Chã das Caldeiras
10. Monte Preto volcanic cave
11. Hornitos, north of the volcano, Monte Preto
12. Monte Velha Forest Perimeter

Option 2: Climb to Pico do Fogo (those who want to go will have to get up at 4am to make the climb and can be back before 12am) – need to contract a local guide Pico do Fogo Volcano: For those more inclined to physical activity, you can make a climb to the volcano, duly accompanied by one of the local guides, from where you can observe a unique and unforgettable landscape.

Option 3: Climb to the Peak of the 2014 eruption (those who want to go will have to get up at 7am to make the climb and can be back before 11am) need to contract a local guide Slag cone from the 2014 eruption.

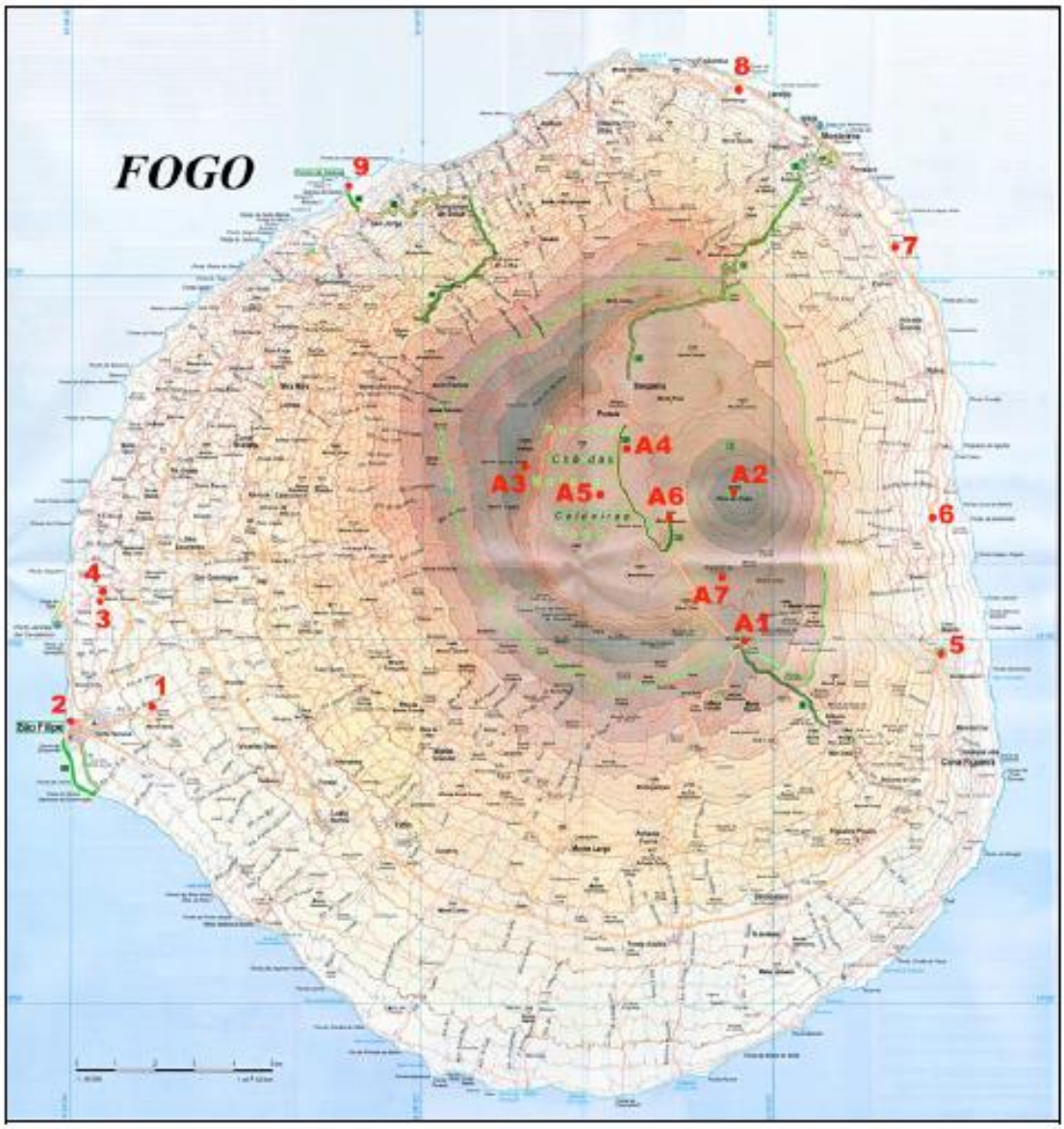

Figure 1. Itinerary of the field trip in Fogo island (Source: Alfama, 2007).

Introduction

The archipelago of Cape Verde is part of the group of islands called Macaronesia (Chevalier, 1935), which also includes the archipelagos of Madeira, the Canary Islands and the Azores and is in the Atlantic Ocean, about 500 km W of the coast of Senegal, between 14°N and 18°N latitude and 22°W and 26°W longitude. The archipelago is made up of 10 main islands and some islets (Fig. 2) that emerge from a topographic elevation with approximately 3 km of vertical extension and about 1,000 km in diameter known as Cape Verde Rise (McNUTT, 1988) and covers a total area of 4,033 km^2.

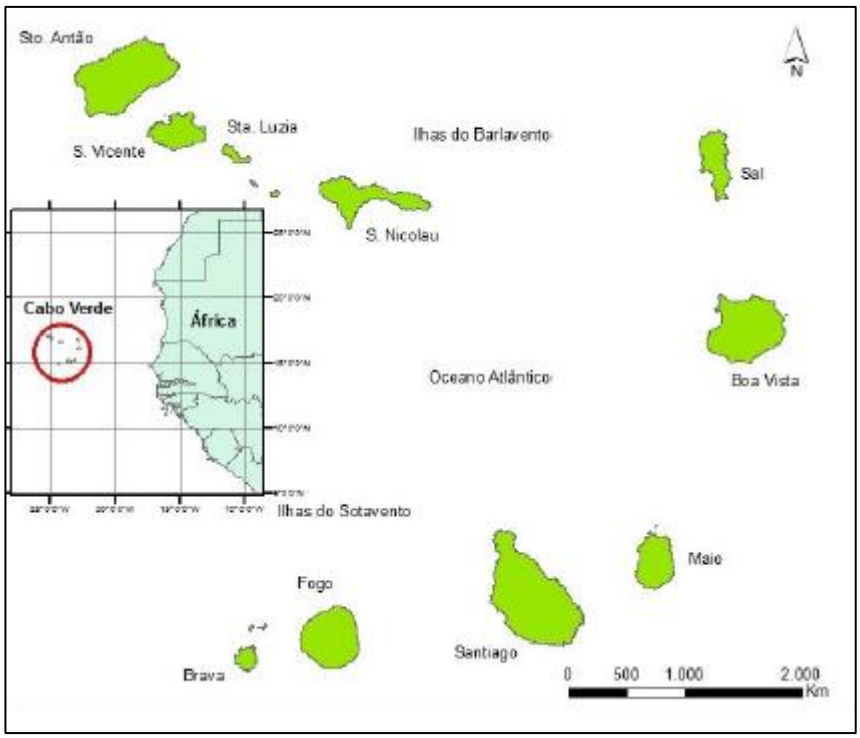

Figure 2. Localização geográfica do arquipélago de Cabo Verde (Alfama, 2016).

The group of islands forms an open arch facing west and is divided into two main groups: north and south, depending on the prevailing winds coming from the NE quadrant: Windward and Leeward. The first group is made up of the islands of Santo Antão, São Vicente, Santa Luzia, São Nicolau, Sal and Boa Vista and the leeward group is made up of the islands of Maio, Santiago, Fogo and Brava. The islands of Cape Verde are of volcanic origin, although there are also important sedimentary deposits on the islands of Sal, Boavista and Maio. They also exhibit distinct geological and geomorphological characteristics. The largest island, Santiago, is 991 km^2 and the smallest, Santa Luzia, is only 35 km^2.

The origin of the Cape Verde islands is associated with intraplate volcanism (Ernst & Buchan, 2003). According to some authors who defend its origin from mantle plumes

(hotspot), as is the case of Holm et al. (2008), they consider the existence of a crestal connection of the socle between the archipelagos of Cape Verde and Canary Islands, as well as an enormous similarity in the volcanic episodes as to its nature and composition. The hotspot type activity would have started about 19 to 22 Ma, which resulted in a large crustal uplift zone (Cape Verde Swell) in which the Cape Verde islands are embedded (Plesner et al., 2002), with volcanic activity remaining until the present day.

As for their morphological characteristics, the islands have very diversified relief forms, with each island having its own specificity. As they are volcanic islands, the relief is generally very rugged. However, in the oriental islands, also called shallow islands (Sal, Boavista and Maio), flattened forms and small elevations are predominant. There are numerous geoforms of volcanic, erosive and sedimentary origin whose study and characterisation are essential to help understand the geological history of the archipelago.

The original volcanic forms have been altered by erosive action, giving rise to a landscape dominated by deep and narrow valleys, peaks, narrow and elongated summits (locally called "*cutelos*") and wide plateau surfaces formed by basaltic flows: the "*achadas*" (tablelands). These often form true structural platforms and are found practically on all the islands well conserved structural volcanic forms such as cones, domes, craters and calderas. It is on Fogo Island that the most recent and best-preserved volcanic forms are found due to active volcanism.

The island of Santiago, much like the entire archipelago, is made up almost exclusively of morphologies, structures and rocks of volcanic origin, basaltic in nature, which were spilled by a main crater that occupies the site of the Pico de Antónia massif. The main structure of the island was formed in several phases, alternating with periods of greater quietness in the volcanic activity.

The island of Fogo displays important morphological aspects, the Chã das Caldeiras depression with 9 km of diameter, located at 1760 m of altitude, and whose base is surrounded by an escarpment (Bordeira) a 1000 m high. The highest point, the stratovolcano called Pico do Fogo, with 2829 m of altitude, reaches 1100 m of height. The current name of the island comes from the historical record of about 30 eruptions since its discovery in the 15th century.

1. Brief characterization of the area

a. Santiago Island

Santiago Island is the largest of the 10 islands of the Archipelago of Cape Verde with 991 Km^2 and the most densely populated with 273,988 inhabitants (INE, 2021). Its geological record is made up of volcanic materials, predominantly basalts and pyroclastic materials (breccias, lapilli, tuffs), which cover an area of 909 Km^2 and other basic lavas, such as limburgite, which cover 57 Km^2. With a long history of uplift (Ramalho, 2009), which led to the exposure of extensive sequences of volcanic seamounts and marine sediments, the presence of intrusive and extrusive carbonatites, a geomorphological evolution characterised by successive cycles of torrential flooding and valley filling by sequences of igneous rocks.

The island of Santiago displays a very fragmented morphology of volcanic origin evident from the coastal areas to the mountainous inland; it features diversified relief forms and large slopes of land, sometimes from large ravines and canyons to extensive tablelands (Ferreira, 1987). According to Assunção (1968) the intense erosion has affected the original forms resulting from the volcanic activity, so that many times it is not possible to identify in the island the old volcanic centres. The erosion acts with greater expression on the east-facing slope, the one that is more widely exposed to the action of the north-easterly trade winds; the water erosion is the process which affects more extensive areas. The average altitude of the island of Santiago is 278.5 m, with a maximum altitude of 1,392 m (Pico da Antonia Massif), to the South, and 1,063 m (Serra da Malagueta), to the North, separated by a plateau at an average altitude of 550 m, with cones and other reliefs in various states of evolution, known as the Assomada Plateau (Amaral, 1964).

To the South, there is a series of small tablelands spread out between sea level and 300-500m altitude. To the West, the coast is normally rugged, and, to the East, it is flattened and made up of tablelands. In the North of the island, Tarrafal stands out. It is an extensive region of tablelands with altitudes varying between 20 and 300 m, which develops from the northern foot of the Serra da Malagueta. This diversified relief includes a relatively dense temporary hydrographic network, which in most cases runs in embedded valleys with torrential longitudinal profiles (Marques, 1990, Gomes & Pina, 2003).

b. Fogo Island

Fogo Island belongs to the Leeward group of islands, located in the southwest of the archipelago, it has a circular shape, an area of 470 Km^2, and it is the fourth largest island of the Archipelago of Cape Verde. It has a population of 33,754 inhabitants (INE, 2021).

Chã das Caldeiras, where the Fogo Natural Park (PNF) can be found, the largest protected area in the country, is in the central area of the island of Fogo, Cape Verde, encompassing the Volcano, the Crater, Bordeira and the Monte Velha Forest Perimeter. It covers approximately 85 km^2 (Fig. 3) (Alfama, 2007).

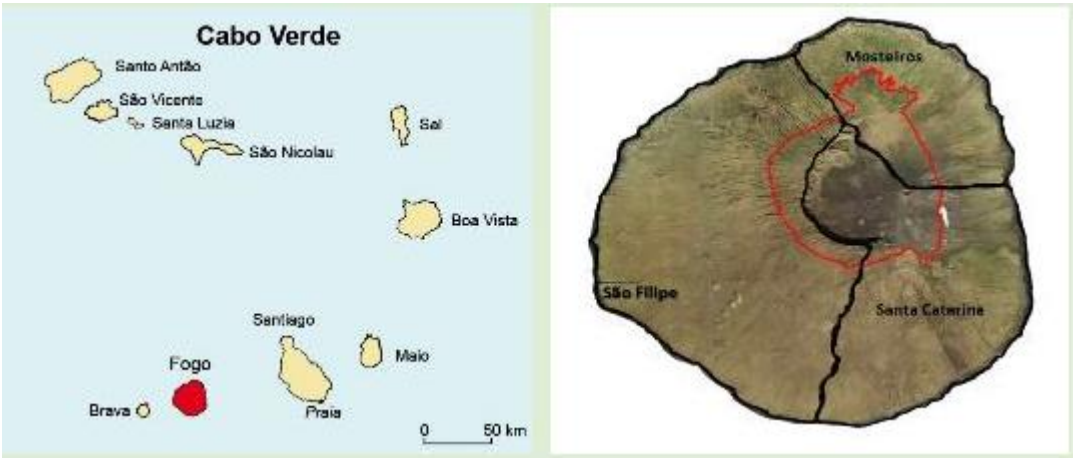

Figure 3. Location of the Chã das Caldeiras area.

The Fogo Island (476 km^2), located NW of Santiago Island, is one of the 10 islands that make up the Archipelago of Cape Verde. It has an eccentric trunco-conical shape, whose centre is displaced to the Northeast. Its flanks, particularly steep on the east side, are less steep on the west and south sides (Ribeiro, 1960), formed by recent lava flows interspersed with pyroclastics. An important morphological aspect is the Chã das Caldeiras depression (9 km in diameter) whose base is at about 1700 m of altitude, and which is bordered by a vertical wall (Bordeira) that reaches 1000 m. It is believed that the depression results from the collapse of the north-eastern flank of the island, which may have occurred in two stages. In the eastern side of Chã das Caldeiras there is a stratovolcano with 1100 metres of altitude and that reaches the maximum altitude of 2829 m, the highest point of the archipelago. The island owes its current name to the fact that 30 volcanic eruptions have occurred on it since its discovery in the 15th century, with recurrence periods varying between 1 and 98 years. The volcanic materials, alkaline mafic in nature and reflecting both explosive and effusive activity, represent most of the outcropping rocks. Also worth mentioning is the existence of carbonatite rocks integrated in the basal complex of the island, which have been dated at ages greater than 3.5 Ma. Among the rocks that outcrop on the island, the volcanic ones are worth highlighting. These are present in the form of flows, lodes and pipes, which correspond to the effusive phase, while the volcanic cones of pyroclastic material, also basaltic, correspond to the explosive phase of eruptions. One can also find sedimentary rocks such as beach sand and gravel, alluvium, slope deposits and torrential deposits.

In the archipelago of Cape Verde, the island of Fogo is the only one with historical eruptions, that is, with eruptions witnessed by the inhabitants. Since the discovery of Cape Verde (1460) about 30 eruptions have been recorded (Table 1) (Ribeiro, 1960;

Silveira et al., 1997; Silva et al., 2015). The first recorded eruption was in the year 1500, and the last was in 2014/15.

Regarding topography, it is the island with the most rugged relief, with a maximum altitude of 2829 m for a maximum diameter of only 25 Km. The basic shape of the island is an asymmetrical cone whose centre is displaced to the Northeast. The top of the conical edifice was shortened and in its place we can find a hemisphere-shaped caldera, locally referred to as the "Chã das Caldeiras", with a diameter of about 9 km and opening facing east. The escarpment that goes around the base of the caldera has a slope close to vertical, reaching about 1000 m at its highest point. In the inner side of the "Bordeira", as the escarpment is locally known, one can observe countless lodes that in some cases can be correlated with parasitic cones in its outer side (Ribeiro, 1960).

Table I. Record of eruptions that occurred in Fogo Island since its settlement.

Year			
1500	1683	1721 to 1725	1852
1564	1689	1761	1857
1569	1693	1769 and/or 1774	1858
1604	1695	1785	1909 (?)
1606 (?)	1697	1799	1951
1664	1699	1815/1816 (?)	1995
1675	1712	1817 (?)	2014/15
1680	1713	1847	

A remarkable geomorphologic feature is the absence of the eastern part of the Bordeira, as well as the presence of escarpments arranged in échelon and NW-SE direction (in the region of Cova Matinho) and a morphological step near the village of Corvo (Silveira et al., 1997). On the east flank of the island, in an area delimited by two scarps that appear in the continuation of the North and South "Bordeira" sections, no parasitic cones can be found, and both scarps coincide with the terminations of the two platform/cliff sets of the east zone (Ribeiro, 1960).

This zone is composed solely of materials emitted by the volcanic system that formed inside Chã das Caldeiras. From the interior of Chã das Caldeiras, with a flat bottom, only roughened by several scoria cones and lava flows, rises the main eruptive cone that, with about 1100 m of height, reaches the maximum altitude of 2829 m (corresponding to the highest point of the island and of the archipelago). The "Pico do Fogo" occupies, relatively to the surface of the island, an even more eccentric position than the caldera, and its eastern flank falls directly to the sea in an approximate slope of 32º (Ribeiro, 1960).

2. The geological constitution of Santiago Island

The geology of Santiago Island is essentially composed of volcanic materials, dominantly outcropping basalts, basanites, tephrites and limburgites, pyroclastic materials and lodes, basaltic dykes and limburgites. Phonolites, trachytes, gabbro, syenites, pyroxenites and sedimentary rocks can also be found in smaller extensions. The growth of the island is thought to have occurred first through a main emitting centre, later turning to fissures. The main volcanic activity must have occurred from the main crater of a volcano which would occupy the Pico de Antónia. Throughout the island there are recent and well-preserved craters. The oldest formations are observed in heavily exposed areas, usually in the bed of the most deeply excavated streams.

Tour around the Santiago Island

Stop 1. Praia Plateaus

The plateaus of Cidade da Praia lying between the altitudes of 0-200 meters, are made up of the Eruptive Complex of Pico de Antónia (PA), in which its rocks are responsible for the largest elevations and structural platforms on the island of Santiago. One can also find pyroclastic materials of explosive and effusive activities, subaerial (predominant) and submarine basaltic flows.

Stop 2. Monte das Vacas

Monte das Vacas is located near Ribeirão Chiqueiro (S. Domingos) and consists of a pyroclastic cone (tuffs, lapilli, scoria, bombs and blocks) intercalated with lava flows.
It is part of the volcanic unit - Monte das Vacas Formation. The top of the volcanic cone is at about 437 m of altitude and its inclination ranges from 25°-35°. It is often easier to observe the materials that constitute the cone, due to the collapse of the flanks, resulting from the erosive action of the water lines, or from the subsidence of the cornice on which they stand.

Stop 3. Ribeira de São Domingos

The São Domingos valley is very open and eroded, with vast cultivated fields, presenting quite weathered materials of the basaltic (base) series. One can also find in this valley quite fractured and weathered lodes from the Old Eruptive Complex (CA). Usually, we may find at the top of the sequence the basaltic series of the Pico de Antónia (PA), of subaerial facies. Monte Chaminé stands out in the landscape.

Stop 4. Ribeira Seca (Poilão Dam) – Órgãos

Embedded in the valley formed by the pillow lavas of the PA and the Órgãos Formation (CB) at the base of the sequence, basaltic in nature with flows, pyroclasts and hyaloclasts, this geological unit represents an important period of erosion. The Poilão Dam is a gravity dam, made of masonry, with reinforced concrete in the central core; it is intended for water storage for irrigation. With the construction of the dam, the area currently irrigated downstream of the dam is about 100 hectares.

Stop 5. Pico de Antónia Massif

Where the highest altitude of the island is reached, (1392 m), it extends in a SE-NW direction and is located facing south and west. It extends northeastwards, through the João Teves spur and southwards through the Boca Larga spur.

With altitudes above 700 m, it is overlaid by imposing peaks, besides Pico de Antónia (1392 m), Gambôa (1099 m), Tagarrinho (1035 m) and Grande (878 m). It is made up of subaerial mantles of the Pico de Antónia Formation. The massif features a dissymmetrical shape, strongly eroded, with jagged and pointed summits, to the east with the vigorous escarpment of the Pico de Antónia over the valleys of Orgãos and Picos.

Stop 6. Santa Catarina Plateau

Broad plain located at about 500 m of altitude, between the Pico da Antónia and Malagueta massifs, to the south and north, respectively; it features some volcanic cones (Monte das Vacas Formation), somewhat flattened by erosion. It leans slightly westwards, towards the coast, where it is limited by cliffs. To the West, the reliefs of Palha Carga, Monte Brianda and Pedroso are also prominent. The plateau is cut by some canyon valleys - the hydrographic basins of Águas Belas and Sansão, at the bottom of which there are irrigated areas.


Stop 7. Serra da Malagueta Massif

The Pico de Antónia and Serra da Malagueta massifs may represent the flanks of volcanic devices that had greater development in this complex, which must have covered the whole island. This massif is formed by layers of thick basalts, interspersed with pyroclasts, filled by a dense network of lodes. It displays a vigorous escarpment on the Santa Catarina plateau, broadly E-W oriented from Ponta Talho in São Miguel to the western coast of the island at Pontas Ruim and Água Doce, ending in cliffs.

Stop 8. Tarrafal - Baía Verde

Baía Verde consists of light-coloured beach sands of calcarenite and/or phonolitic nature. There occur deposits of phonolitic flows and pyroclasts from the Pico de Antónia (PA) Principal Eruptive Complex, which can be observed on the platform that forms the City of Tarrafal. The limestones, calcarenites and conglomerates of Pliocene age, constitute beach deposits, fossilised by the outflows of phonolitic flows from the PA overlying the calcarenites and conglomerates. In a section of Baía Verde, on the Presidente beach, one can observe from the bottom to the top, a sequence of conglomerates with rounded to subrounded basaltic pebbles, dispersed in a light-coloured cement of calcareous sandstone.

Stop 9. Tarrafal - Monte Graciosa

The northern side of the Serra da Malagueta massif slopes gently down towards Tarrafal, and is carved by deep ravines that enclose rows of hills in elongated ridges. The highest point of the Mountain (Serra) reaches 1064 m, and the central alignment has altitudes between 700 and 1000 m. Monte Graciosa (643 m) features a dome of phonoliths and trachytes formed by effusive and explosive volcanic phases, surrounded by basaltic mantles.

Stop 10. Biscainhos (S. Miguel)

A dense network of valleys that descend from the high areas of the Serra da Malagueta and Pico de Antónia massifs to the east of the island, ending in relatively lowlands that form flat-bottomed floodplains. Black sand or gravel beaches and relatively low cliffs. There is a predominance of high tablelands that descend gently to the sea, limited by vigorous cliffs. The valleys with subvertical slopes are numerous and deep. The coastline is quite indented with recesses and small coves.

A stop at Biscainhos allows one to observe pillow lavas outcrops from the Pico de Antónia Principal Eruptive Complex (PA) in an angular discrepancy of about 45° with subaerial flows from the PA.

3. The geological constitution of Fogo Island

On Fogo Island, specifically in the region of Chã das Caldeiras there is an active volcano that annually attracts many tourists, especially after the occurrence of the last two eruptions in 1995 and 2014. The island encompasses a complete series of geological and landscape phenomena that illustrate the formation of a landslide caldera and a pre-caldera explosive volcanic edifice, as well as a complete magmatic series with well-preserved volcanic materials, forms and structures such as lava flows of various types, varied pyroclastic materials, pyroclastic volcanic cones, etc. Visitors are attracted by the peculiarity of the landscapes, by the interest in observing an active volcano and by the magnificence and beauty of the site.

Tour around the Fogo Island

Stop 1. S. Filipe Beach

The black sands of S. Filipe beach easily giveaway the presence of basalts and other dark-coloured volcanic materials in the vicinity. In fact, on the cliffs surrounding the beach, one can observe a mixture of basalts and pyroclasts. Basaltic rocks, due to their particular nature of lava cooling, often show a columnar structure (prismatic disjunction). Sometimes basalts also display a structure resulting from their alteration (spheroidal disjunction), which causes scaling of the rock with an onion-shell appearance. This interlayering of basalts with pyroclasts represents changes in the type of volcanic activity (basalts: effusive activity; pyroclasts: explosive activity).

Stop 2. Ponta da Salina

Heading north, one arrives at Ponta da Salina, a place where the sea crashes vigorously against the cliffs formed by very old lava flows and with the typical columnar disjunction. The small beach has, however, one particularity that should be carefully observed.

The sand, although mostly black, has a "strange" greenish colour. A careful examination reveals the presence of small greenish grains of olivine, one of the minerals that form basalt and that are found in large quantities in the rocks on this part of the island. It is also possible to observe lava tunnels through which fluids flowed in the past.

Stop 3. Monte Sumbango (Mosteiros)

On the east side towards the town of Igreja, in Mosteiros, you reach the northern top of the island of Fogo, more precisely the village of Fajãzinha, built on a platform of coastal erosion (where the old Mosteiros aerodrome is located) and where there are also traces of pyroclastic deposits, as is the case of Monte Sumbango.

Mount Sumbango is a volcanic cone that is partially dismantled allowing to see the set of pyroclastic materials that form it and its internal structure. One of the main geological fault lines that cross Fogo Island from north to south runs along this point, which may possibly explain the dismantling of the volcanic cone. Coastal erosion may have contributed to the destruction of this edifice.

Stop 4. Corvo's Pahoehoe Lava Flows

Near the village of Corvo, along the road, we cross some lavas dating back to historic times, which can easily be identified by the few signs of alteration and the incipient vegetation. This stop, over one of these lava flows, allows us to contemplate magnificent examples of ropy structures. These structures develop during the cooling phase of quite fluid lavas (pahoehoe lavas), which are still moving as they slowly cool down.

The exceptional properties of these pahoehoe lava flows give them great scientific and didactic relevance, as their study allows us to understand how this phenomenon occurs. Occasionally, in this same place, some flows occur that, on account of having had a greater viscosity, gave rise to distinct structures, with a more fragmented appearance (aa type lavas). The presence of some small lava tunnels is noteworthy. In some of these tunnels the roofs have already collapsed.

Stop 5. Vale da Ribeira de Caiada

As the tour continues southeast, we cross several river valleys deeply carved by floodwater. The Ribeira de Caiada is an example of such streams, which occasionally carry water and sediment from the higher parts of the island (in the west) to the sea (in the east).

Although the climate on Fogo Island is predominantly dry for most of the year, occasional rains cause a remarkable water seepage at the surface, giving rise to violent

torrents with destructive effects that can lead, on occasion, to the cutting of roads and bridges. These relatively sinuous valleys are typical of this type of violent but short-lived phenomenon.

Stop 6. Alto Espigão Viewpoint

At an altitude of about 450m, this viewpoint is located a little south of the village of Cova Matinho, at a place on the road where a panoramic viewpoint has been built. From this spot, majestic black lava flows can be observed to the North, flowing down the slope of the volcano to the coast to the East. This lava flow dated 1951, having travelled along the eastern slope of the volcano, buried the village of Bombardeiro (built on a platform of coastal erosion known locally as "fajã") and reached the sea.

From here, one can easily distinguish, due to the difference in colour, the lava flows of the 20th century (black) and the preceding ones, already altered and, consequently, with brownish tones. From this viewpoint one can also observe slope deposits, quite thick, on the eastern flank of the volcano which overlies the entire island.

Stop 7. Entrance to the Fogo Natural Park

We continue west to the village of Achada Furna, where we head north, gradually overcoming the steep slope that leads us to the entrance of the Fogo Natural Park (PNF). Next to the wooden sign that announces the entrance to the Park, allow yourself to be fascinated by the landscape that surrounds you. From here we have a magnificent overview of the huge volcanic caldera with an area of about 60 km2 as well as of the various lava flows that completely fill the bottom of the caldera. These lava flows formed during volcanic eruptions that occurred over time, after the formation of the caldera, originate a flattened bottom from where the Pico volcano and two parasitic cones (Monte Rendall and Monte Orlando, both formed during the 1951 eruption) stand out. The caldera, locally known as "Chã das Caldeiras", was formed by the circular collapse of an old volcanic edifice, seemingly in two successive episodes of collapse. This collapse gave origin to a wall, almost vertical, that surrounds almost all the caldera. Locally, this wall is known as Bordeira and, in it, it is possible to observe the internal structure of the old volcanic edifice, which has since collapsed, namely sequences of lava flows and pyroclastic deposits, as well as lodes that intersect these materials.

<u>Option 1 - Tour inside Chã das Caldeiras - Fogo Natural Park</u>

Stop 1a. Entrance to the Fogo Natural Park

This point coincides with the last stop on the circular tour around the island. At this point, next to the entrance to the Fogo National Park, the visitor can enjoy a first glimpse of the magnificent landscape and geodiversity of Chã das Caldeiras.

Stop 2a. Explosion crater, Curral de Asno

On the west side of Chã das Caldeiras, a shallow and rounded scoria cone explosion crater may be observed in Curral de Asno. The crater may have been altered by erosion. On the way up the cone one may observe pyroclastics of different sizes (ash, lapilli and bombs) and black colour that were deposited during the 2014 eruption. From this point there is a panoramic view of the southern side of the Fogo Island, where one may observe numerous pyroclastic cones, lava flows from historical eruptions (e.g., the 1951 eruption).

Stop 3a. Lava flows from the 2014 eruption, Lantisco

This point is where one of the first lava flows of the 2014 eruption can be found. It was over 4 meters thick and cut the access road to the communities of Chã das Caldeiras. The lava flows started at 10 am and took two directions: one towards the southwest (Monte Beco) and the other towards the southeast (Cova Tina) having destroyed the road 3 hours after the eruption started. The lava flow observed at this site is dark in colour and stony in appearance. Blocks of variable shapes and dimensions can be found.

Stop 4a. Scoria cone from the 2014 eruption

This scoria cone is the most recent volcanic structure on the island and the country and was formed during the last eruption in 2014. Its shape was moulded in accordance with the direction in which the materials were expelled.

The cone lies to the west of the volcano and features an elongated crater 245 metres long and 109 metres wide. A distinctive feature of this cone is the fact that it is located next to (east) the scoria cone formed in the 1995 eruption. It is formed by dark-coloured pyroclasts that display light shades in the crater area.

Stop 5a. Bordeira

Once you enter the Fogo National Park, the sight of the Bordeira is constant throughout the entire tour of Chã das Caldeiras. Indeed, the caldera is surrounded by an extensive wall that can reach altitudes of around 1000m, which forms a semicircle since it is open on the eastern side. The missing of the eastern part of the Bordeira is thought to have been caused by a large landslide that, due to gravity, moved the volcanic materials towards the sea and caused a tsunami that hit the island of Santiago.

Stop 6a. Lava field

Throughout the tour one may observe several lava flows originated by eruptions of different ages, the most recent being in 2014. In this field of lavas several types of lavas can be observed, with different colours ranging from black to brown. As for the types of lavas, the aa lavas are predominant, and pahoehoe and ropy lavas can also be found.

Stop 7a. Main façade of the old wine cellar, Boca Fonte

In Boca Fonte next to the road that leads to Cabo de Nhô Ernesto, one can see the façade of an old wine cellar that was affected by the lava flows of the 1995 eruption. With the waning of the eruption the flow ceased and only the front part of the wine cellar remained. The wine cellar, which had been built and equipped by German cooperatives, was swallowed by aa type lava. Interestingly, the last two eruptions partially destroyed the existing wine cellars. The 2014 eruption partially destroyed the Portela wine cellar, leaving it unfit for wine production.

Stop 8a. Contact between the lava flows of 1995 and those of 2014, Cabo Nhô Ernesto

At this point, one may observe the contact between the lava flows of 1995 and those of 2014. Both have a dark colour, but you may notice that the ones from 1995 show a more eroded aspect (). This point is of didactic interest since it displays aa type lavas of the 1995 eruption (in the form of loose blocks) and pahoehoe type lavas of the 2014 flows (with a smoother surface).

Stop 9a. Villages of Chã das Caldeiras

Chã das Caldeiras is divided into 5 locations (Cova Tina, Ilhéu de Losna, Boca Fonte, Portela and Bangaeira). Although the communities of Ilhéu de Losna, Portela and Bangaeira were left completely destroyed by the 2014 eruption, since 2016 the local population, which was evacuated at the time of the eruption, is slowly returning to Chã das Caldeiras to develop their activities. This return reflects the resilience of these people in the face of adversity. The population is engaged in agriculture, livestock, tourism and handicrafts (using lava material).

Stop 10a. Monte Preto Volcanic Cave

Volcanic caves, while not common geological phenomena, are present in the territory of the Fogo National Park. This volcanic cave is found under the scoria cone of Monte Preto, formed in the volcanic eruption of 1951.

To access this cave, it is necessary to walk on top of the lava expelled during the eruption of 1951. The cave is about 50 metres long, 18 metres wide and 10 to 15 metres deep. Volcanic stalactites can be found inside. One may enter the cave by descending with the help of a steel cable ladder and walking in humid conditions for about 50 metres.

Stop 11a. Hornitos, north of the Volcano, Monte Preto

To the north of the volcano one can find 3 lined hornitos that are still well preserved, with a height of more than 4 metres (from the surface around them). These are cone-shaped with a small opening at the top. Hornitos are geological structures that result

from lava spills and are formed on the surface of a basaltic lava flow. "Hornitos" in Spanish means small horns.

Stop 12a. Monte Velha Forest Perimeter

The route to the Northeast, from the village of Bangaeira to the area of Monte Velha, allows the visitor to carry on enjoying the magnificent landscapes of Chã das Caldeiras, as well as enabling a more detailed observation of the materials that make up Bordeira and its volcanic structures. The Monte Velha area represents the only forest perimeter on the island, developed from forestry campaigns carried out in the 1950's that introduced, on a large scale, exotic trees to all the islands, to the detriment of the endemic highland flora. The 800-hectare Monte Velha Forest boasts an exuberant vegetation of trees and shrubs. Due to its altitude, humidity and fertile soil, it has the ideal conditions for the multiplication of several endemic species in the highest levels of the whole island. Of the 87 endemic species of higher plants existing in the archipelago, Fogo Island preserves 37 species, 5 of which are exclusive to the island.

<u>Option 2 - Climb to Pico do Fogo (between 5am and 12pm)</u>

Stop 1b. Pico do Fogo Volcano

The Pico or Fogo Volcano, as it is locally known, is the crowning jewel of both the archipelago and the island's geodiversity. It is the main cone of an active volcano that constitutes the highest point of the country (2829 m). This volcano represents a gigantic cone of volcanic ash and scoria interspersed with lava material. On its slopes there are some parasitic cones, smaller in size, resulting from various eruptions (including the last one in 2014), formed by accumulations of pyroclasts. For those more inclined to physical activity, it is possible to climb the volcano, duly accompanied by one of the local guides. From there, one can enjoy a unique and unforgettable landscape.

Option 3 - Climb to the Peak of the 2014/15 eruption (between 7am and 11am)

Stop 1c. Scoria cone from the 2014/15 eruption

This scoria cone is the most recent volcanic structure on the island and the country and was formed during the last eruption in 2014. Its shape was moulded in accordance with the direction in which the materials were expelled. The cone lies to the west of the volcano and features an elongated crater 245 metres long and 109 metres wide. A distinctive feature of this cone is the fact that it is located next to (east) the scoria cone formed in the 1995 eruption. It is formed by dark-coloured pyroclasts that display light shades in the crater area. During the eruption that gave rise to this cone there were as many as 4 vents through which the materials were expelled. Later these vents coalesced and formed the current crater of the scoria cone.

Final notes

This Guidebook allows to make geological tours to Santiago and Fogo islands located in the archipelago of Cape Verde, where the geology is made up of rocks of basic nature and composition (e.g., basalts and similar rocks) and evolved rocks (e.g., phonoliths and nepheline syenites) resulting from magmatic evolution and differentiation processes. The landforms in Cape Verde are quite diverse, with each island presenting a specific geodiversity. Santiago Island features 10 stops where it is possible to observe recent and well-preserved volcanic structures (mainly scoria cones and craters); original volcanic forms have been altered by erosive action, giving rise to a landscape dominated by deep and narrow valleys, or open and flat valleys, and wide plateau surfaces formed by basaltic flows (finds or plateau). In Fogo Island there are about 13 stops available to observe important morphological aspects of the geology and geomorphology. From the Chã das Caldeiras depression with 9 km of diameter, located at 1760 m of altitude and whose base is surrounded by an escarpment (Bordeira) with 1000 m of height and intersected by lodes, to the highest point, the stratovolcano, called Pico do Fogo, which reaches 2829 m of altitude. The record of 30 historic eruptions since its discovery in the 15th century is evidenced by the extensive aa and pahoehoe lava fields, in addition to numerous scoria and ash cones, and well-preserved craters.

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