Geoheritage (2024) 16:34
https://doi.org/10.1007/s12371-024-00939-9

ORIGINAL ARTICLE

The Challenging Nature of Volcanic Heritage: The Fogo Island (Cabo Verde, W Africa)

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Received: 27 November 2023 / Accepted: 19 February 2024

Abstract

Many volcanic landscapes reflect the essence of volcanism and are particularly attractive to different kinds of visitors, featuring the concept of volcanic geoheritage. The expressiveness of volcanic processes is exacerbated in active volcanoes, which increasingly attracts geotourism, despite the natural hazards associated to such geological environment. This work reports how the 2014–2015 eruption of the Fogo volcano at Cabo Verde (West Africa) affected the geoheritage of the central part of the caldera, classified since 2003 as Natural Park, and which caused the destruction of several villages but enabled the occurrence of new geosites. Chã das Caldeiras is the only inhabited area within the perimeter of the park and the unique case of human settlement inside the crater of an active volcano. Besides agriculture, geotourism is an important economic activity for the local communities, and both were devastated after the eruption. However, after the 2014–2015 crisis and despite the eruption risk the local population decided to return to the affected villages and re-start their former life, including geotourism which has since recorded enormous growth. The volcanic geoheritage has dynamic nature that stand out from the majority of stable geosites, with periodic destruction of geosites and corresponding geotouristic infrastructures, and the emergence of new geosites. But despite the costs of rehabilitating, this type of geoheritage must be seen as an economic asset capable of attracting visitors to travel to destinations subject to the risk of eruptions, therefore contributing to foster the typical community-based tourism of normally inhospitable territories.

Keywords Volcanic geoheritage · Cabo Verde · Fogo eruption · Geotourism

Introduction

Volcanic eruptions are one of the most spectacular geological phenomena, and active volcanic fields engage geologists and the public both during and after their occurrence, as they form easily understandable landforms due to their geoheritage contents (Pena dos Reis and Henriques 2009). Volcanism is of particular interest to the public due to the human-scale duration of its operations and the highly visible impacts of both its generative and destructive parts (Németh et al. 2017), which gave rise to the emergence of a specific type of tourism: the volcano tourism (Erfurt 2022).

Volcanic regions have become increasingly attractive to tourists, who seek for adventure and fun in both active and extinct volcanic environments (Planagumà and Martí 2020). Because volcanoes represent extraordinary geoheritage sites, many of them are often included in protected areas (national parks, world heritage areas or global geoparks) and subject to very strict rules of use, particularly because of the volcanic hazards inherent to this type of territory (Texier-Teixeira et al. 2014; Erfurt 2022). However, volcanic regions receive more than 150 million visitors worldwide each year, a number that has likely increased over the past decade (Erfurt-Cooper 2010; Bidias et al. 2023). The demand for this type of tourism is increasing as it provides

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new experiences in a healthy environment linked with the natural environment, developed at the local level and away from mass tourism (Naranjo Llupart 2022).

Active volcanoes have higher levels of natural risk, which frequently limits the implementation of construction, infrastructure, or agricultural projects that could help to boost geotourism and, as a result, the sustainable development of regions. But the dangerous dynamic nature of volcanic geoheritage must be seen less as a hindrance to enjoyment and more as an opportunity to promote geotourism. This will help to justify public and private investment in high-quality infrastructure and accessibility in territories at high risk of eruption.

This work reports how the eruption of the Fogo volcano (Cabo Verde) in 2014–2015, despite being devastating for the communities that inhabit the Natural Park of Fogo (NPF) at the time, became an event that subsequently drove a clearly positive social and economic transformation (Silva et al. 2016; Jenkins et al. 2017). In fact, the great devastation caused to local communities estimated at US$28 million (PDNA 2015) made it doubtful that any significant resettlement would be possible after the eruption (Worsley 2015). However, new geosites have since emerged as disaster geosites (Migoń and Pijet-Migoń 2019), which have stimulated curiosity and interest among visitors, and greatly increased geotourism. Thus, the main objectives of the present work are:

- to describe the current geoheritage of the NPF, analyzing what existed and what was created as a result of 2014–2015 eruption;
- to evaluate economic and social indicators of the communities that inhabit the NPF before and after the 2014 eruption;
- to contribute to demystifying the idea that the vulnerability inherent to volcanic geoheritage should not be seen as a constraint to the design and implementation of valuation projects that are fundamental for the promotion of geotourism and local development.

Geotourism plays a crucial role in promoting inclusive and sustainable economic growth, make safe and resilient communities, and ensure sustainable consumption and production patterns (Jill 2017). The convergence of geoconservation with the objectives included in the 2030 Agenda, namely with ODS 8, 11 and 12, is clear. So, valuing and monitoring procedures fostering sustainable development through geoeducation and geotourism is a key issue for African countries, located in the continent with the richest geological, biological, and cultural heritage but which is certainly further away from achieving the objectives set out in the 2030 Agenda (Toteu et al. 2010).

This work is assumed to be a contribution to analyze and disclose the rich geodiversity outcropping in Africa that needs to be discovered, assessed, and used as a tool of sustainable development of local communities (Neto and Henriques 2022). But this requires innovative approaches to geoconservation by integrating natural and social and humanistic scientific knowledge with non-scientific and non-Western forms of knowledge, and by acknowledging that sustainable development can be achieved through culturally different pathways (Werlen et al. 2016).

Geographical and Geological Setting

The Cape Verde archipelago is located in the Central Atlantic, around 500 km off the west coast of Africa, 1,400 km SSW of the Canary Islands and 2,000 km east of the current rift of the mid-Atlantic ridge. It is made up of 10 islands and several islets, totalling 4,033 km^2. The islands are organised in the shape of a horseshoe open to the west, bounded by parallels 14° 48' and 17° 13' N and meridians 22° 42' and 25° 22' W. The islands are arranged according to their position relative to the prevailing northeast trade winds in two units: Windward and Leeward (Fig. 1).

Although there is no consensus on the existence of a "hotspot" in the area of Cape Verde, Davies et al. (1989) and Patriat and Labails (2006) indicate the origin of this archipelago from thermal plumes originating in the mantle. According to Stillman et al. (1982), Robertson (1984), and Pollitz (1991), Cape Verde is located in an elevated region of the current ocean floor, which is part of the "Cape Verde Rise" or "Swell" and which, due to the neighbourhood of the islands, corresponds to a dome around 400 km wide (Lancelot et al. 1977). The archipelago lies in the ancient oceanic lithosphere, which here has ages of 120–140 Ma (Williams et al. 1990; Müller et al. 2008), and a thickness of around 85 km (Cazenave et al. 1988). It is assumed that a dome of this size represents an important phenomenon, possibly related to decompression and partial melting that provided the source of the magmas that originated the islands through the "hot spot" mechanism (Stillman et al. 1982). The origin of this volcanism (characterised essentially by strongly alkaline magmas) is related to the presence of an oceanic "hot spot" within the African Plate, which is the surface expression of the "Cape Verde Mantle Plume" (White 1984; Courtney and White 1986). From a geodynamic perspective, this archipelago is located on the African plate, in a stable intra-plate environment, possibly marked by the presence of a mantle plume or other deep mantle processes, whose action on the surface is expressed by the seismic and volcanic activity that affects some of the islands, particularly Fogo, Brava and Santo Antão.

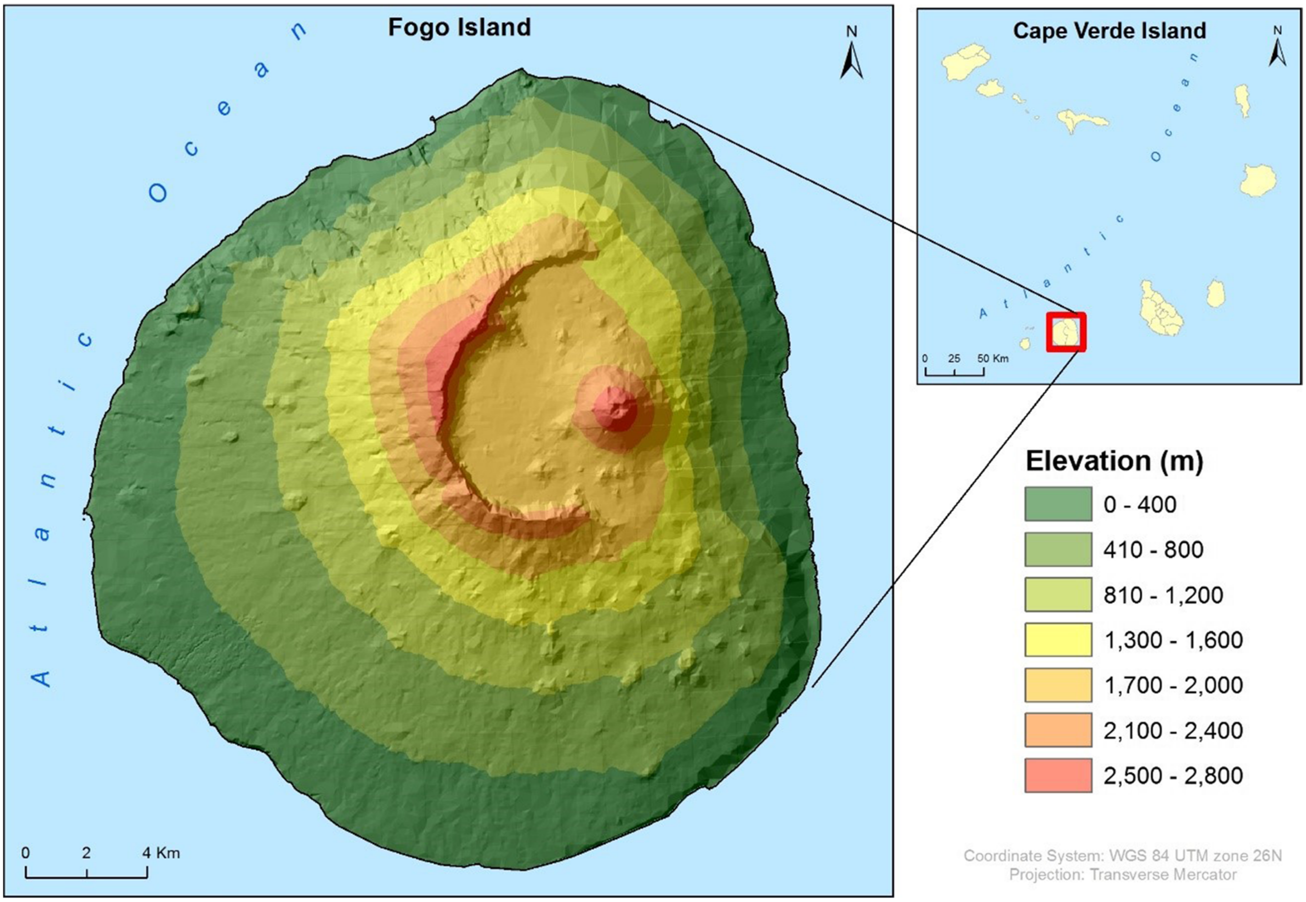


Fig. 1 Geographic location of the Cape Verde archipelago and Fogo Island (Credits: Patrick Silva)

The volcanic construction of the Cape Verde islands probably began in the Oligocene/Miocene period (Holm et al. 2008; Dyhr and Holm 2010; Ramalho 2011). Alkaline basaltic magmas are the most common, and their products (tephrite, phonolites, trachyte, etc.) are volumetrically residual (Kogarko 2008). According to Mourão et al. (2010), one of the striking features of Cape Verde's magmatism is the presence of intrusive and extrusive carbonatites on at least five islands.

The roughly circular island of Fogo is located in the SW of the archipelago (Fig. 1). With an area of 476 km^2 and a diameter of 27 km, it belongs to the group of Leeward Islands and is situated between parallels 15° 03' and 14° 48' N and between meridians 24° 18' and 24° 31' W.

Fogo is the archipelago's most recent island and the only one with historical, post-population eruptions, with the last eruption occurring between November 23rd, 2014 and February 8th, 2015 (Silva et al. 2016; Bagnardi et al. 2016; Cappello et al. 2016; Richter et al. 2016; Mata et al. 2017). A Quaternary age has been indicated as the most probable for the island (Day et al. 1999; Ramalho 2011).

This island is a large complex volcano and has a more recent stratovolcano (Pico do Fogo) overlapping a previous volcanic edifice that collapsed (Ribeiro 1960; Day et al. 1999; Masson et al. 2008; Ramalho 2011; Mata et al. 2017; Martínez-Moreno et al. 2018). Pico do Fogo has contributed to shaping the entire island into a cone-like structure with a rounded base around 25 km in diameter and 2,829 m of maximum height above sea level (Fig. 1). At the base of Pico do Fogo there are two large calderas (about 10 km in N-S direction and 7 km in an E-W direction) located in the NE corner of the island. These are flanked by steep, almost vertical escarpments to the north, west and south (locally called Bordeira), open to the E to the sea as a result of the landslide of the volcano's eastern flank towards the ocean (Day et al. 1999; Brum da Silveira et al. 1997; Paris et al. 2011; Le Bas et al. 2007; Madeira et al. 2008; Masson et al. 2008), which is thought to have occurred in ~ 117 or ~ 73 ka (Eisele et al. 2015; Ramalho et al. 2015).

On Fogo Island, there is a predominance of rocks with a basaltic composition (sensu latu), generally represented by lithotypes that are more under-saturated in silica, such as basanites, limburgites and nephelinites (Mata et al. 2017), which are either effusive (more representative in terms of volume) or of an explosive nature. Occasionally, there are phonolitic rocks, which represent more evolved magmas, but are strongly undersaturated, and carbonatites, which stratigraphically represent the oldest rocks on the island, and which correspond to calciocarbonatites probably of a plutonic nature (Madeira et al. 2005; Mata et al. 2017).

On the October 28th 2021, the Fogo Island, together with the Maio Island, was classified by UNESCO as a World Biosphere Reserve. This distinction is due to the uniqueness of the volcanic landscapes, as well as the biodiversity and centuries of coexistence between nature and society.

The Natural Park of Fogo (NPF) was created by Decree-Law no. 3/2003 of February 24th and covers an area of 8,468.5 ha (PGPNF 2009). It occupies the central part of the island of Fogo and is elongated in an east–west direction. It is situated at the convergence of the island's three municipalities: S. Filipe (1,861 ha, 22% of the Park), Santa Catarina (4,237 ha, 50% of the Park) and Mosteiros (2 370 ha, 28% of the Park) (Fig. 2). The area has four small villages—Portela, Bangaeira, Cova Tina and Ilhéu de Losna—located at the base of the Fogo volcano (Santos 2017).

The NPF is home of a unique geodiversity in the national territory, as well as a very significant biological diversity. Chã das Caldeiras is the only settlement inside the park and is a popular tourist destination due to its geodiversity. According to the 2021 Census (INE 2022), Chã das Caldeiras has a population of 472 inhabitants, 262 men and 210 women, in a total of 151 households. These data indicate a decrease in population when compared to the 2010 Census and the demographic data from December 2014, obtained before the last eruption (Table 1).

The population of Chã das Caldeiras lives essentially from agriculture and livestock, agro-processing (especially the production of wine, cheese, jams, etc.), tourism services (touristic guides, accommodation and restaurants) and handicrafts (a complementary subsistence activity). In recent years, tourism has boomed in Fogo, particularly in Chã das Caldeiras, becoming one of the main sources of income for the local population.

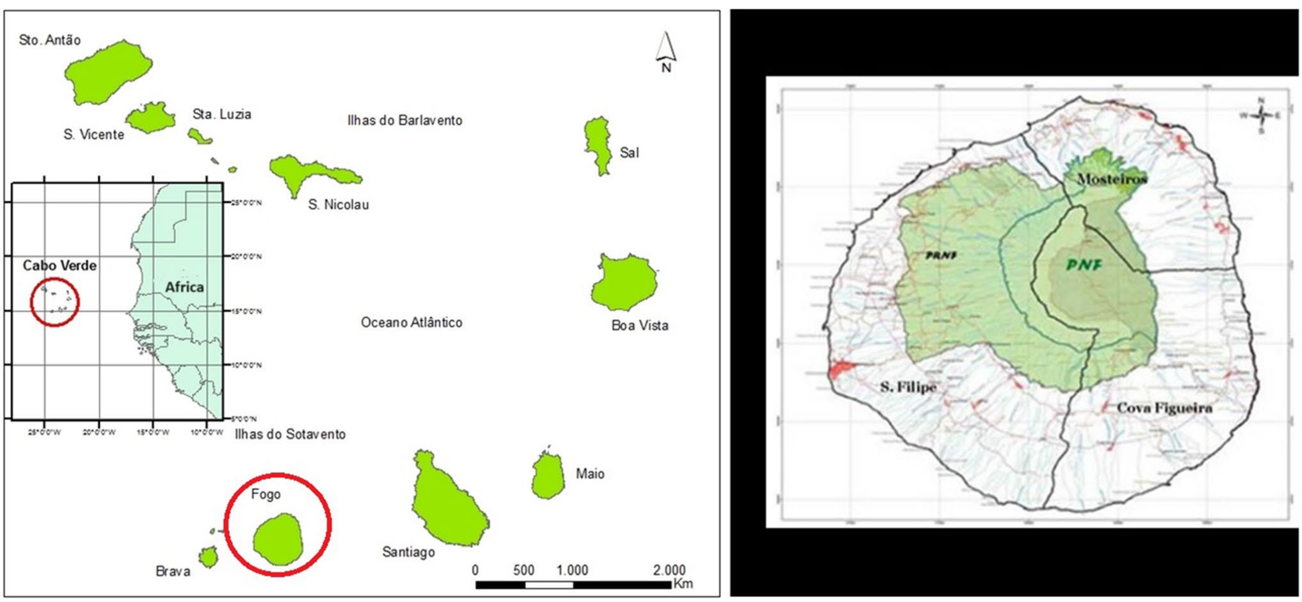


Fig. 2 Location and delimitation of the Natural Park of Fogo

Table 1 Data on the population of Chã das Caldeiras between 2010 and 2021: M – Male; F – Female

Locality	Population								
	Census 2010			December 2014			Census 2021		
	Total	M	F	Total	M	F	Total	M	F
Chã das Caldeiras	**696**	340	357	**964**	486	478	**472**	262	210

Sources: Census 2010 (INE 2011); Census 2021 (INE 2022) and PDNA (2015)

Geoheritage of the Natural Park of Fogo

As mentioned above, the island of Fogo is the only active volcanic island in the Cape Verde archipelago with a record of historical, post-population eruptions. Thus, there are records of around thirty eruptions since 1500 (Deville 1848; Ribeiro 1960), with the last two being the best documented: the 1995 eruption (e.g. Torres et al. 1997; Day et al. 2000; Heleno 2003; Hildner et al. 2011, 2012; Costa 2011; Silva et al. 1997, 1999) and the 2014–15 eruption (e. g. Carracedo et al. 2015). g. Carracedo et al. 2015; Silva et al 2016; Mata et al 2017; Cornu et al 2021; Bagnardi et al. 2016; Fernandes et al. 2015; González et al. 2015; Jenkins et al. 2017; Richter et al. 2016; Silva et al. 2017; Worsley 2015; Klügel et al. 2020; Cappello et al. 2016; Calvari et al. 2018) (Fig. 3).

Until the end of the eighteenth century, descriptions refer to prolonged explosive eruptions inside Chã das Caldeiras and in the Pico do Fogo crater, with lava flowing down the eastern flank of the island (Ribeiro 1960). The eruption of 1785 marked the end of activity in the Pico do Fogo crater and corresponds to the last observation of an eruption outside Chã das Caldeiras (Ribeiro 1960). The eruptions after 1785, with the exception of two in 1857 and 1799 on the east flank, occurred at the base of the main eruptive cone and inside Chã das Caldeiras, corresponding to predominantly effusive fissural activity, with the formation of cones of scoria and the production of lava flows which, in almost all cases, flowed down the east flank of the island to the sea (Torres et al. 1997; Day et al. 2000). With the exception of the 1995 and 2014 eruptions, which occurred on the SW flank of Pico do Fogo, the post-1785 eruptions within Chã das Caldeiras form an approximately N-S alignment on both sides of Pico do Fogo, through fissures that are also orientated close to N-S direction (Day et al. 1999, Brum da Silveira et al. 1997; Hildner et al. 2012; Worsley 2015).

So, the NPF displays a wide variety of forms resulting from different episodes of volcanism over time. The expressiveness, representativeness, and uniqueness of some of them allow us to identify them as geosites that constitute geological heritage of the magmatic type (Habibi et al. 2018). More recently Németh (2022) specify volcanic geoheritage as the record of volcanic processes, volcanic landforms and/or the eruptive products of volcanism that shape the geological architecture of a region. At the NPF, it is possible to identify geosites expressing volcanic activity prior to the last eruption, and geosites resulting from the last eruption dating from 2014–2015.

Geoheritage before the Last Eruption

The active volcanic activity of Fogo Island, with its historical eruptions, has contributed to the formation of a singular landscape with a rich and unique geological diversity, and shows high potential for the practice of nature tourism, especially geotourism. In order to identify, characterise, value and publicise the geotourism potential of this island, based on defined criteria, studies have been carried out on the local geodiversity and geological heritage which have made it possible to carry out inventories of the geosites formed during the structural evolution and after the historical eruptions of this island (a total of 22 geosites on the island of Fogo, 13 of which are in Chã das Caldeiras) (Fig. 4a and b) (Alfama 2007; Costa 2011; Dóniz-Páez et al. 2018).

However, it should be emphasised that this geodiversity is subject to changes due to the island's active volcanism, particularly after volcanic eruptions. In fact, despite the destruction caused by these eruptions, new geosites have also been formed, which, in the case of the NPF, have become new tourist attractions relevant to the park. These new geosites have contributed to the return of people to Chã das Caldeiras after the eruptions (e.g. in the last eruptions, 1995 and 2014–15), who have used these new attractions to their benefit.

Geoheritage after the Last Eruption

The last volcanic eruption on Fogo Island began on November 23rd, 2014 and ended on February 8th, 2015. It originated in a NNE-SSW eruptive fissure, approximately 700 m long, at the SW base of the Pico do Fogo cone, between 2,200 m and 1,800 m above sea level, and about 200 m from the fissure that gave rise to the 1995 eruption (Worsley 2015; Silva et al. 2016; González et al. 2015; Vieira et al. 2016; Bagnardi et al. 2016; Jenkins et al. 2017; Mata et al. 2017; Calvari et al. 2018). This effusive event took place about 200 m SW of the eruptive fissure that caused the 1995 eruption.

Over a period of more than two months, the various eruptive phases recorded, from effusive to explosive, gave rise to various volcanic products (gases, ash, lapilli, bombs, lava fountains, lava flows), as well as different volcanic structures (cones, lava tubes). The lava flows covered a total area of around 4.5 km^2 at Chã das Caldeiras and a volume of ~ 46 × 106m^3 (Silva et al. 2016; Calvari et al. 2018). Lavas flowed from seven eruptive vents, together with the emission of ash and gases, all aligned along an eruptive fissure with a NNE-SSW direction (Calvari et al. 2018).

The lava flow moved partly conditioned by the access road to the villages of Portela and Bangaeira. In general, the

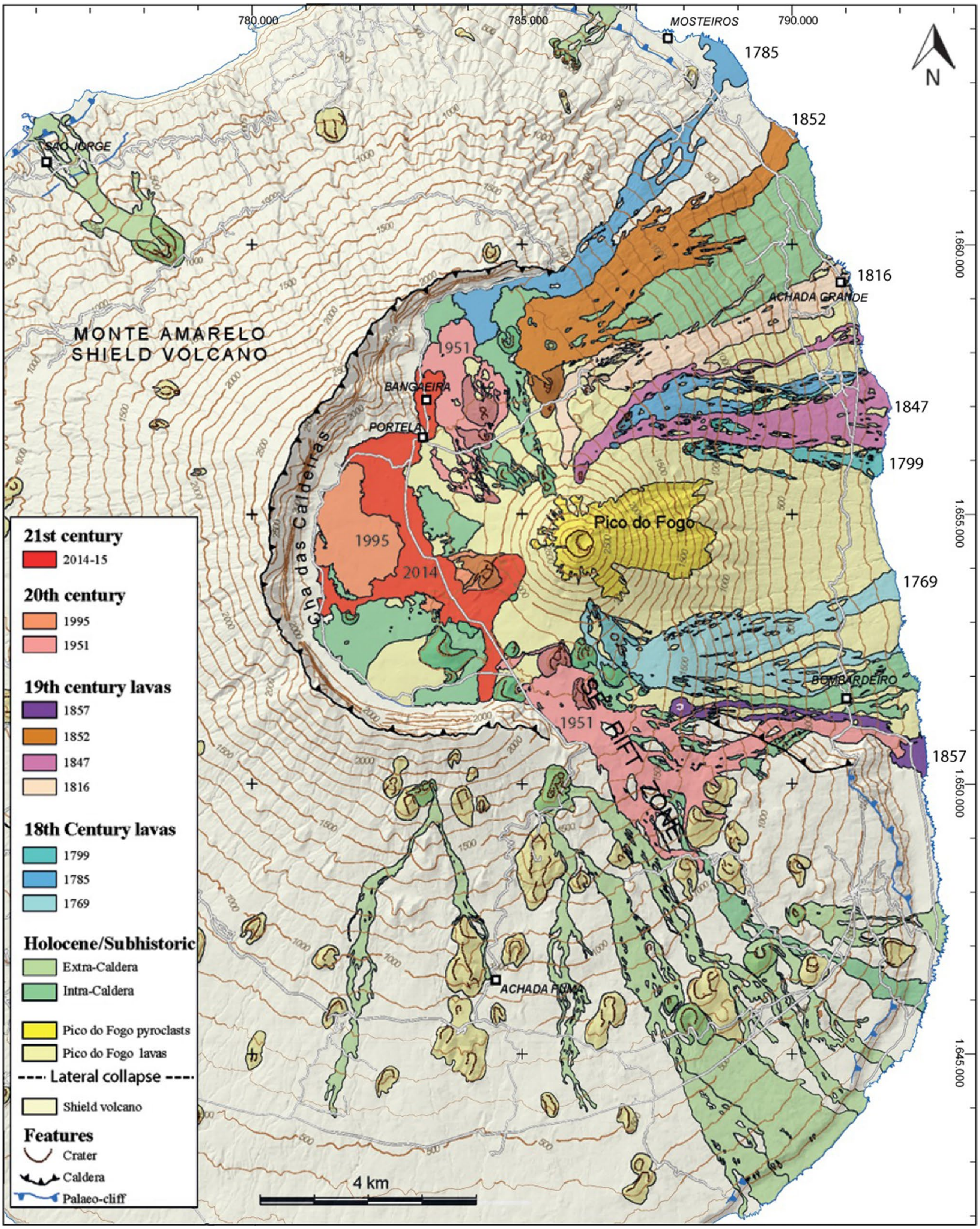


Fig. 3 Map of the prehistoric eruptions occurred on the island of Fogo (Carracedo et al. 2015)

lava spill was divided into three main arms, which flowed to the S, NW and W. The lava flows that moved to the NW were more important, both in terms of the area occupied and the damage caused by its progression through the terrain (Silva et al. 2016; Calvari et al. 2018). The flow that went to the W also destroyed the Ilhéu de Losna settlement, although the volume and extent of the lava were not as significant as the other flows produced during this eruptive event (Silva et al. 2016; Calvari et al. 2018). This flow is made up of aa and pahoehoe types, which formed at different times during the eruptive event, and destroyed several agricultural plots and infrastructures in the NPF.

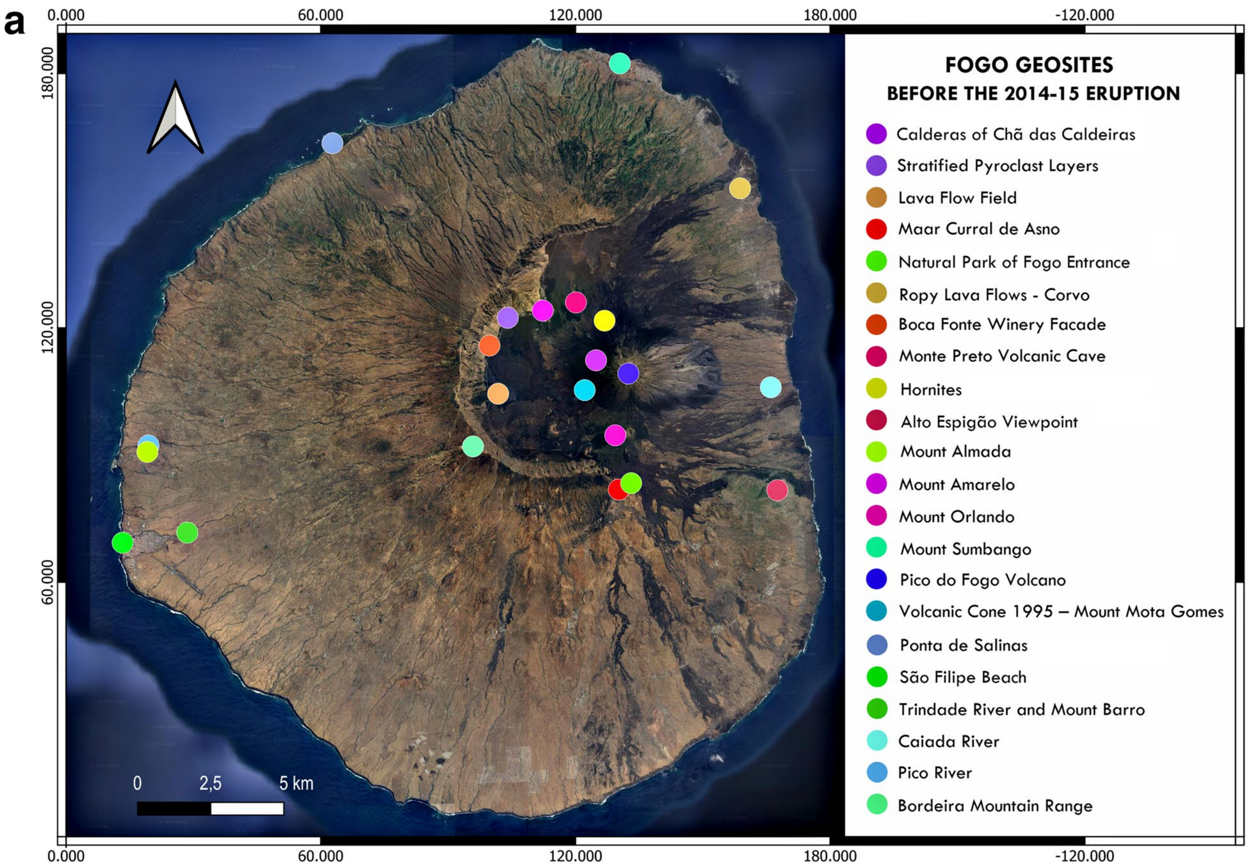
The 2014–15 eruption led to the formation of new geosites that were inventoried based on the methodology used by Alfama (2016), by carrying out a non-systematic inventory of geosites based on fieldwork, with campaigns during and after the volcanic eruption. For each of the new geosites, the aesthetic criterion was taken into account, due to their tourist, educational and scientific potential. The new geosites formed by the 2014–2015 eruption (Fig. 5) are listed and described below:

a) Lava flow fields (coordinates: 14° 55′ 52" N and 24° 21′ 17" W): the aa and pahoehoe lavas flowed from seven eruptive vents that were aligned along an eruptive fissure in a NNE-SSW direction, and gave rise to three main arms, which moved to the S, NW and W (Fig. 6) (Calvari et al. 2018) and progressed towards the base of Bordeira. Flow 1 is essentially formed by aa lavas, flow 2, the largest of all, is formed by both aa and pahoehoe lavas (Fig. 7), and flow 3 is dominantly pahoehoe.
b) Cinder cone (coordinates: 14° 56′ 40" N and 24° 21′ 13"W): it is a 138 m high monogenetic cone (the highest of the last eruptions) with basal diameter of 512 m, which resulted from the accumulation of lapilli, bombs, ash and lava (Teves 2018). It is located at the bottom of the western slope of the main cone and represents the most recent volcanic structure on the island and in the country. Its shape was moulded according to the NNE-SSW eruptive fissure direction. As a result, the cone presents a succession of craters, made up of sets of four to five aligned craters, displaying the complex morphologies of typical of fissural eruptions. A special feature of this cone is that it is located on the SE side of the cone formed in the 1995 eruption (Monte Mota Gomes) (Fig. 8). It is made up of dark-coloured pyroclasts with light tones on the crater side. During the eruption that formed this cone, four vents were formed simultaneously through which materials were expelled. Later, these vents merged to form the current cone crater, which is elongated (Fig. 9). At the base of this cone, a lava tube 2–3 m in diameter was formed, located approximately 20 m below the topographic surface (Calvari et al. 2018).
c) Ropy lavas (coordinates: 14° 57′ 03"N and 24° 23′ 8"W): there are several spills of pahoehoe lavas that have extended to the surface through the eruptive mouth, continuing the flows that went W towards the village of Ilhéu de Losna. These lavas must have travelled around 1.4 km until they reached the base of Bordeira, through a channel between 55 and 100 m wide (Calvari et al. 2018; Teves 2018). The slope deposits near the Bordeira escarpment caused the split into two flows, which inflected to the N and S. This flow is distinguished by the fact that it consists almost exclusively of pahoehoe-type lavas, with a shiny, bluish surface full of fractures along its entire length (Calvari et al. 2018). After consolidation, this flow gave rise to magnificent examples of ropy lavas (Figs. 10, 11, 12). These ropy lavas resulted from the cooling of relatively fluid pahoehoe lavas as they moved towards to lower zones. The samples of ropy lavas are found in series and are morphologically different from the surrounding lava structures, making them of great scientific, tourist and educational importance.
d) Contact between 1995 and 2014–15 flows (coordinates: 14° 57′ 41 "N and 24° 22′ 53" W): this geosite (Cabo Nhô Ernesto) shows the contact between the lava flows from the last two eruptions on the island. Both are dark in color, but the 1995 lava is less dark than the 2014–15 lava because it is more eroded. This geosite displays didactic interest as it contains aa type lavas from the 1995 eruption (in the form of broken blocks) and pahoehoe type lavas from the 2014 flows (with a softer appearance), besides good exemples of ropy lavas (Fig. 13).

Geotourism Dynamics at the Natural Park of Fogo

Chã das Caldeiras has biophysical and sociocultural characteristics of great scenic and scientific interest, in addition to the rich geodiversity and biodiversity, which led to the creation of the NPF. Community-based geotourism is the main tool for local economic development of the poor rural community that inhabit the park, besides agriculture and livestock production, although free grazing is not allowed, to preserve the biodiversity and the agricultural production (Costa 2011). Tourists are attracted by the great geodiversity of volcanic landforms scattered all over the park (Alfama 2007; Alfama et al. 2008) and for the uniqueness of Chã das Caldeiras, as the crater of an active volcano that is inhabited by several households.

The history of Fogo Island, particularly Chã das Caldeiras, is marked by an immense effort of human adaptation in relation to its volcanic nature, which made living in


a
FOGO GEOSITES
BEFORE THE 2014-15 ERUPTION
Calderas of Chã das Caldeiras
Stratified Pyroclast Layers
Lava Flow Field
Maar Curral de Asno
Natural Park of Fogo Entrance
Ropy Lava Flows - Corvo
Boca Fonte Winery Facade
Monte Preto Volcanic Cave
Hornites
Alto Espigão Viewpoint
Mount Almada
Mount Amarelo
Mount Orlando
Mount Sumbango
Pico do Fogo Volcano
Volcanic Cone 1995 – Mount Mota Gomes
Ponta de Salinas
São Filipe Beach
Trindade River and Mount Barro
Caiada River
Pico River
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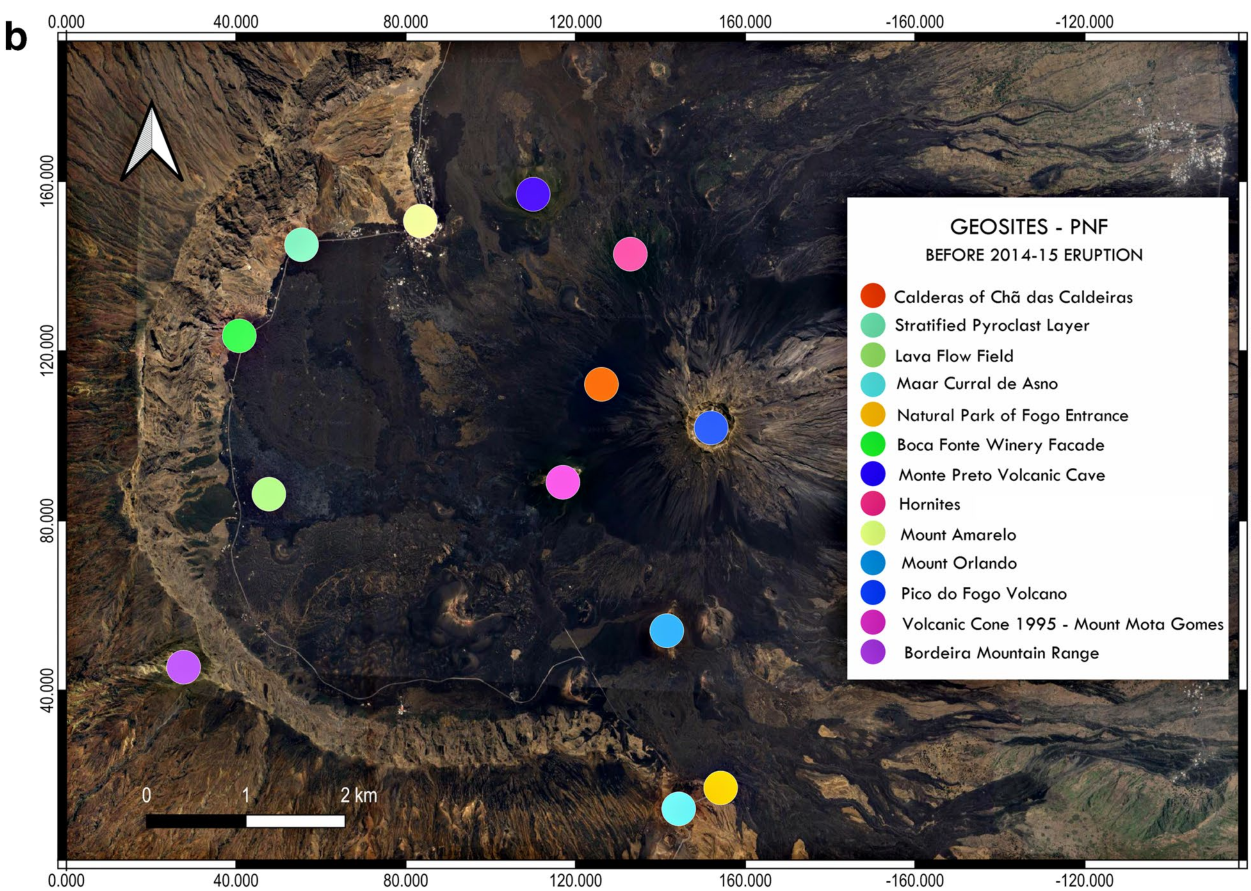
b
GEOSITES - PNF
BEFORE 2014-15 ERUPTION
Calderas of Chã das Caldeiras
Stratified Pyroclast Layer
Lava Flow Field
Maar Curral de Asno
Natural Park of Fogo Entrance
Boca Fonte Winery Facade
Monte Preto Volcanic Cave
Hornites
Mount Amarelo
Mount Orlando
Pico do Fogo Volcano
Volcanic Cone 1995 - Mount Mota Gomes
Bordeira Mountain Range
0 1 2 km
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◂**Fig. 4** Geosites inventoried before the 2014–2015 eruption: **a** Fogo Island; **b** Natural Park of Fogo, Chã das Caldeiras (based on Alfama 2007; Costa 2011; Dóniz-Páez et al. 2018)

continuous harmony with nature a very difficult task (Nascimento et al. 2016). Therefore, despite the physical damage and production losses caused by the various volcanic eruptions that occurred on the Fogo Island, particularly the last ones (1951, 1995 and 2014–15), the population of Chã das Caldeiras always returns there after their end, demonstrating the peculiar resilience of those who live in the crater of a volcano.

According to PDNA (2015), Chã das Caldeiras continues to be the main focus of the population's livelihood, which is always affected by eruptions, but this process also reveals the strong cultural link between the population and this part of the island, particularly with the volcano they consider as a friend and relative (Santos 2017).

The 2014–2015 volcanic eruption was responsible for the destruction of three villages in Chã das Caldeiras (Portela with total devastation; Bangaeira and Ilhéu de Losna with partial destruction), evacuation and displacement of 994 people and destruction of important infrastructure and equipment as well as as well as agricultural land (Table 2).

Fig. 6 Outlined photo of lava flow field (white line) comprising mainly lava flow surfaces (Credits: Got2globe.com)

Despite the damage and losses caused by the eruption and the PDNA's (2015) recommendation that the population should be resettled outside Chã das Caldeiras, less than a year after the end of the eruption, 1/3 of the former population returned to their volcanic environment and to the sites now occupied by the lava flows. This process

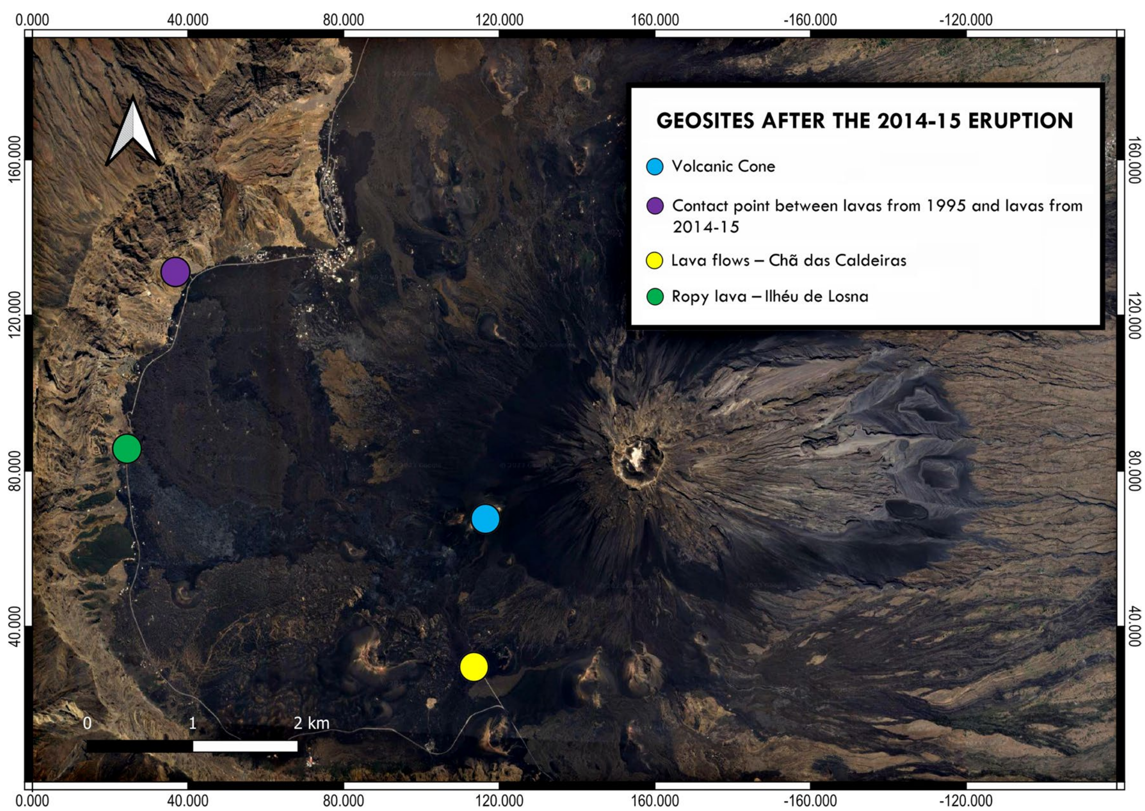

Fig. 5 Geosites formed after the 2014–2015 eruption

Fig. 7 Detail of the aa and pahoehoe lava flows in Portela during the eruption. (Credits: Vera Alfama)

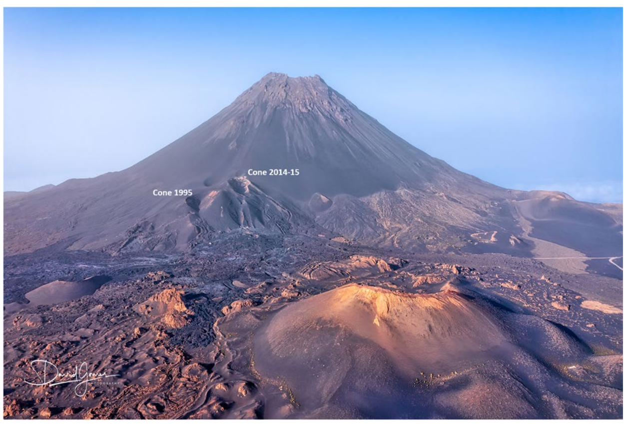

Fig. 8 Cone from 2014–2015, next to the 1995 cone, seen from Bordeira (Credits: David Gomes)

of self-recovery was aimed at restarting old economic activities and promoting new initiatives, thus proving their adaptability, tenacity, reorganisation and resilience.

The form of resilience of the population of Chã das Caldeiras, which faces volcanic risks, has been mobility, i.e. evacuation managed by the authorities at the time of eruptions and the private decision to return without observing all the rules after the eruptions are over. The return is driven by attachment to the place, the new opportunities opened up by the fertility of the land, with the availability of favourable soil to promote vine growing, and the attractiveness of the volcanic areas for tourism.

With this return, the towns destroyed by the eruption were rebuilt, in particular: the rehabilitation and construction of new buildings; the opening/construction of roads over the lava; the creation of new agricultural land; the establishment/reconstruction of new wine-growing facilities; and the re-establishment of tourist activity. For example, despite the lack of rainfall for four months after the end of the eruption, the vines grew enough to guarantee a good wine harvest for 2015. Only with the efforts of the local people of Portela and Bangaeira, and without any mechanical help, a new road was built over the lava, aptly named "Estrada da coragem" ("Road of courage"), linking Portela to the vineyard area of Montinho. Community efforts have led to the installation of a mini-market and a restaurant, and some houses have been prepared as guest houses to receive tourists. In other words, routine has returned to Chã das Caldeiras.

This voluntary and unregulated return of the population to Chã das Caldeiras was then accepted by the government authorities for political reasons. However, in 2018 the Cape Verdean government drew up a detailed plan (RPDCC 2018) for Chã das Caldeiras in response to the need to define a plan to organise construction and infrastructure as a result of the 2014–2015 volcanic eruption that affected the local population. The aim of this plan, which follows a model of sustainable, self-sufficient and environmentally-friendly development, is: to define the layout of rural settlements and building regulations, taking into account the need for evacuation and rapid response to volcanic risk; to guarantee the protection, conservation and enhancement of areas of

Fig. 9 View of the 2014–2015 cone (in the foreground, see the detail of the coalescing craters) and the lava field formed (in the background) (Credits: Eurico Montrond)

Fig. 10 Solidification of pahoehoe lavas into ropes during the eruption at Ilhéu de Losna (Credits: Vera Alfama)

landscape, geological and environmental interest, agricultural land and heritage elements with tourist, historical and/or architectural potential; and to encourage and strengthen compatibility and interconnection between housing and farming activities.

Today, Chã das Caldeiras has a higher level of development than before the last eruption, which has contributed significantly to improving the living conditions of the local population, who have been able to take advantage of this new dynamic and the existing landscape (Fig. 14).

A balanced combination of agriculture and tourism prevails there: new tour operators build establishments for tourists; new farmers promote vine growing; new farmers/tour operators share both specialisations; and new tour guides promote the tourist value of Chã das Caldeiras with an ever-increasing variety of activities. Statistical data for Fogo Island, which refers mainly to activities in the NPF, indicates 33 new tourist accommodations in the period from 2015 to 2022, representing an increase of 11.1 per cent, making Fogo the island in the country with the highest increase in this item (INE 2023a, b). Tourist conditions before and after the 2014–2015 eruption show significant development, particularly with regard to the increase and improvement of tourist offers, both in terms of tourist facilities (accommodation and restaurants) and in terms of diversification of tourist activities (Table 3).

Fig. 11 Panoramic view of the aa, pahoehoe and ropy lavas in Ilhéu de Losna (Credits: Eurico Montrond)

Fig. 12 Detail of the ropy lava in Ilhéu de Losna (Credits: Vera Alfama)

Fig. 13 Contact between the 2014–15 lavas and the 1995 lavas in Cabo Nhô Ernesto. (Credits: Alveno Barros)

This increase in the number of accommodations necessarily implies a greater number of tourists on the island after the last eruption. In addition to these tourist facilities, there has also been a considerable increase in the number of tour guides, and there is even an association of tour guides with 42 members and around twenty guides actively working in the sector.

Discussion

Volcanoes are among the three types of disasters that constitute substantial negative motivators for prospective visitors, which lead to a significant fall in tourism demand following an event (Rosselló et al. 2020). Besides the great devastation to the human environment, the 2014–2015 eruption at the NPF caused profound transformations in the landscape and the destruction of all infrastructures supporting geotourism in the area of Chã das Caldeiras.

Current geoheritage of the park includes 13 geosites that were not affected by the eruption, also resulting from older eruptions, and four geosites that emerged from volcanic activity that took place between 2014 and 2015. Rudimentary local infrastructure, which supported an important tourism activity for local communities, was destroyed, and the population was temporarily moved out of the park. The large-scale resettlement of Chã das Caldeiras after the crisis

Table 2 Impacts of the 2014–2015 volcanic eruption

Impacts of the 2014–2015 volcanic eruption	
Affected villages	Chã das Caldeiras (Portela, Bangaeira, Ilhéu de Losna).
Population—number of people affected	994 people evacuated.
Damage caused	Destruction and losses at various levels: social sector (housing, education, health and culture), productive sector (agriculture, livestock, agro-processing and tourism), infrastructure (electricity, water, sanitation and communications – roads) and in transversal sectors (environment, governance, risk reduction disasters and employment); Most social facilities were completely destroyed (e.g., NPF headquarters and interpretation center, health unit, school, municipal delegation, churches, sports equipment; domestic cisterns, tourist accommodation (1 hotel, 5 guesthouses and 5 hostels), In the productive sector, in addition to the material damage to properties and equipment, there were losses in terms of production flow, particularly in agriculture and tourism (the most affected activities)
Resettlement locations	Achada Furna, Monte Grande, São Filipe and Mosteiros.

Source: PDNA (2015)

Fig. 14 Current aspects of Chã das Caldeiras: **a** House invaded by lava repurposed into local tourist accommodation, Pedra Burkan Restaurant; **b** Current appearance of the village of Portela; **c** Harvest at Chã das Caldeiras. **d** Funco-shaped tourist accommodation (typical construction of Chã das Caldeiras) made with lava material (Credits: Eurico Montrond)

Table 3 Tourist facilities (accommodation and restaurants) in Chã das Caldeiras before and after the 2014–2015 volcanic eruption

Before the last eruption	After the last eruption
1 hotel (with restaurant)	**Hotels** (all with restaurant)
5 inns (with restaurant)	- Pensão Casa Mariza
5 hostels	- Pensão Casa Arlindo
	- Pensão Casa Zé e Sónia
	- Pensão José Dole/Doce
	- Pensão Ciza e Rose
	- Pensão Casa Lavra
	- Pensão Pedra Burkan
	- Pensão Casa Fernando
	- Residencial Adriano e Filomena
	- Residencial Escoral
	- Residencial Monte Amarelo
	Guesthouse (without restaurant)
	- Guesthouse Eco-Funco
	Housing tourism (without restaurant)
	- Casa Mana di Madona
	- Casa Celina
	- Casa Luzia
	- Casa Antonita
	- Casa Rio de Lava
	Restaurants
	- Casa Bebé
	- Restaurante Isabel
	- Bar-Restaurante Fefé

Sources: PDNA (2015) and Eurico Montrond (tourist guide in Chã das Caldeiras, oral communication on October 30th, 2023

seemed quite unlikely because the urban infrastructure was completely devastated, the arable land resources were significantly reduced and became insufficient to support previous levels of agriculture, and the government showed reluctance towards investments in reconstruction at a location with high eruption risk (Worsley 2015). But contrary to the theory that the evacuation experience had greatly altered the population's perception of risk, Chã das Caldeiras has since been repopulated and its tourism-related economic activity has significatively increased. Furthermore, and contrary to what Coratza and De Waele (2012) argue, visiting these disaster geosites does not appear to contribute to a better understanding the exposure to danger among visitors.

The research developed by Komorowski et al. (2016) revealed that eruption risk is not the major concern for the Chã das Caldeiras communities, who are particularly worried about the lack of basic services, drought and resulting food insecurity. The daily access to sources of livelihood overlaps the perception of local people of the risk on their lives and properties (Texier-Teixeira et al. 2014). So, after the 2014–2015 crisis and despite the risk on their lives and properties the local population decided to return to the affected villages and re-start their former life, i.e., resuming work (especially agriculture and tourism) and reconstruction of houses (Castro and Martins 2018).

In addition to these eminently pragmatic reasons, there are other relevant reasons of topophilic nature that also contribute to understanding the return of the population to an area of such high risk: the “spritu de burcan” or the spirit of the volcano in Creole (Henriques 2007). From the metaphysical point of view, the autochthonous communities make no distinctions between plants, volcanoes, humans, animals, that is, between society and nature, showing great respect for the existence of the other, that is, for otherness, in relation to the plants, the animals, the land, and even the volcano, which existence they try to understand, by sharing with this natural phenomenon anthropocentric and social qualities (Santos 2017). Tourism on Fogo Island converges with the concept of the typical community-based tourism, a tourism management model that put local communities (and their values, norms, beliefs, and attitudes) at the center of the process in which local people are given the opportunity to improve their standard of living (Rungchavalnont 2022).

The common tourist visiting this island, mainly with higher education, coming from European Union countries and the United States, claim to be satisfied with the services provided by community enterprises to the point of willing to repeat the experience (Lopez-Guzman et al. (2011). The volcano is the island´s major attraction, namely the experience of going up and coming down from its summit, named Pico do Fogo and rising to 2,829 m above sea level, and the physical effort and time needed to perform such activity (Oliveira et al. 2019). With the surrounding plateau it became Cabo Verde´s first national park on an inhabited island in 2003 (Gaudru 2010), being Chã das Caldeiras the only inhabited area within the perimeter of the park and the unique case of human settlement inside the crater of an active volcano.

Gotham (2015) assigns “disaster tourism” to situations where the tourism product is generated within, and from, the aftermath of a major disaster or traumatic event. Chã das Caldeiras has the potential for disaster tourism, offerig various opportunities to visitors to experience active volcanic environments (Göktekin and Şimşek 2023). With the 2014–2015 eruption, new volcanic forms appeared, some of them now identified as disaster geosites (Migoń and Pijet-Migoń 2019), that represent a new asset as a geotouristic product. This circumstance contributed decisively to the resumption of tourism activity and its growth to previously unreached levels, giving, in some way, substance to the local population’s cosmic vision about their "peaceful" exchanges with the volcano, i.e., "[what] the volcano takes away, the volcano gives back" (Castro and Martins 2018).

This highlights the importance of considering during all operations related to geoconservation, from inventory to valuation, the way in which the people inhabiting any region culturally interpret the surrounding landscape (Henriques et al. 2013). The intangible cultural elements that base the symbolic content of geosites (Pena dos Reis and Henriques 2009) are particularly relevant when dealing with the so diverse African socio-cultural contexts and represent a key factor to a successful community involvement in geoconservation (Tavares et al. 2015).

Moreover, assuming the role of local culture as a crucial tool to achieve global sustainability (Henriques and Brilha 2017) is the best way to avoid the recurring conflict between local communities and the NPF administration and the municipal officials regarding restrictions to land use within the central part of the caldera, including the so-far unsuccessful permanent relocation of people outside the caldera (Texier-Teixeira et al. 2014).

Conclusions

The last eruption of the Fogo volcano at Cabo Verde (West Africa) started at Ilha do Fogo on November 23rd, 2014 and finished on February 8th, 2015, and originated from a NNE-SSW eruptive fissure, approximately 700 m long, at the SW base of the Pico do Fogo cone. The eruption affected the central part of the caldera, classified since 2003 as Natural Park (the NPF), and it caused the destruction of several villages in Chã das Caldeiras area (Portela with total devastation; Bangaeira and Ilhéu de Losna with partial destruction), evacuation and displacement of 994 people and destruction of important infrastructure and equipment as well as agricultural land. At the same time, new geosites (four) were created, in adition to 13 geosites previously identified at the NPF as a result from older eruptions.

The large-scale resettlement of Chã das Caldeiras after the crisis seemed quite unlikely, but it has since been repopulated and its tourism-related economic activity has significatively increased particularly with regard to increasing and improving tourist offerings, both in terms of tourist equipment (accommodation and restaurants) and in terms of diversification of tourist activities.

Two main reasons can be identified to understand the return of Chã das Caldeiras communities inside the crater of an active volcano:

1. Volcanic regions are particularly attractive to tourists, who seek for adventure and fun in both active and extinct volcanic environments. Chã das Caldeiras has the potential for disaster tourism and for volcanotourism, therefore representing a valuable economic asset capable of attracting visitors.
2. The eruption risk is not the major concern for the Chã das Caldeiras communities, who perceive the volcano in a culturally differenciated way. Local communities make no distinctions between society and nature, including

the volcano, which existence they try to understand, by sharing with this natural phenomenon anthropocentric and social qualities.

The 2014–2015 eruption at NPF contributed decisively to the development of the Chã das Caldeiras villages through the increasing promotion of tourism (essentially geotourism) in the park up to previously unreached levels. New tourist guide services, restaurants and tourist accommodation or local products (e.g., wine production, which is known worldwide, jams fruit, goat cheese, lava stone crafts, etc.) were implemented with positive impact on local communities.

This case can contribute to look at the vulnerability inherent to volcanic geoheritage not as a limitation to the design and implementation of valuation projects that are fundamental for the promotion of geotourism and local development, particularly important for African countries. Moreover, its singularity regarding the harmonious relationship between resilient communities and natural hazards can contribute to assist United Nation's goals regarding Small Island Developing States and therefore contributing to achieve the Sustainable Development Goals of the 2030 Agenda.

Acknowledgements This study was developed in the frame of Santander Mobilidade CPLP Scholarship Program 2023, and it was supported by Portuguese funds by Fundação para a Ciência e a Tecnologia, I.P. (Portugal) through the UIDB/00073/2020 and UIDP/00073/2020 projects of I & D unit Geosciences Center (CGEO). The authors are grateful to David Gomes, Eurico Montrond and Got2globe.com for providing photography and relevant data to carry out the work. Thanks are also due to two anonymous reviewers.

Funding Open access funding provided by FCT|FCCN (b-on).

Declarations

Conflict of Interests The authors declare no conflict of interests.

References

Alfama VIB (2007) Património geológico da Ilha do Fogo (Cabo Verde): inventariação, caracterização e propostas de valorização. Unpublished MSc Thesis, Universidade do Minho, Escola de Ciências, Braga

Alfama VIB (2016) Avaliação dos Perigos Geológicos na Ilha Brava (Cabo Verde): implicações para o Planeamento de Emergência. Unpublished PhD Thesis, Departamento de Geociências, Universidade dos Açores, Portugal

Alfama VI, Gomes AM, Brilha J (2008) Guia geoturístico da Ilha do Fogo (Cabo Verde). Departamento de Ciências da Terra, Faculdade de Ciência e Tecnologia Universidade de Coimbra, Coimbra, Portugal (ISBN 978-989-95009-3-8)

Bagnardi M, González PJ, Hooper A (2016) High-resolution digital elevation model from tri-stereo Pleiades-1 satellite imagery for lava flow volume estimates at Fogo Volcano. Geophys Res Lett 43(12):6267–6275. https://doi.org/10.1002/2016GL069457

Bidias L, Kameni LHN, Moundi A, Kamgang P (2023) Geoheritage of the volcanic landscapes of Foumbot-Kououmboum region, Noun Plain, Cameroon: Geomorphological features and assessment of geomorphosites. Int J Geoheritage Parks 11(3):464–482. https://doi.org/10.1016/j.ijgeop.2023.08.002

Brum da Silveira A, Madeira J, Serralheiro A (1997) A estrutura da ilha do Fogo, Cabo Verde. In: Réffega A, Figueiredo M, Silva L, Costa F, Mendes M, Torres P, Silva T, Correia E (eds) A erupção vulcânica de 1995 na ilha do Fogo, Cabo Verde. Instituto de Investigação Científica Tropical e Ministério da Ciência e Tecnologia, Lisboa, pp 63–78 (ISBN: 972-672-869-0)

Calvari S, Ganci G, Victoria SS, Hernandez PA, Perez NM, Barrancos J, Alfama V, Dionis S, Cabral J, Cardoso N, Fernandes P, Melian G, Pereira JM, Semedo H, Padilla G, Rodriguez F (2018) Satellite and ground remote sensing techniques to trace the hidden growth of a lava flow field: The 2014–2015 effusive eruption at Fogo Volcano (Cape Verde). Remote Sens 10(7):1115. https://doi.org/10.3390/rs10071115

Cappello A, Ganci G, Calvari S, Pérez NM, Hernández PA, Silva SV, Cabral J, Del Negro C (2016) Lava flow hazard modeling during the 2014–2015 Fogo eruption, Cape Verde. J Geophys Res Solid Earth 121(4):2290–2303. https://doi.org/10.1002/2015JB012666

Carracedo JC, Perez-Torrado FJ, Rodriguez-Gonzalez A, Paris R, Troll VR, Baker AK (2015) Volcanic and structural evolution of Pico do Fogo, Cape Verde. Geol Today 31(4):146–152. https://doi.org/10.1111/gto.12101

Castro FV, Martins B (2018) The 2014 volcanic eruption in Fogo and the reterritorialization process: from risk to geographic resilience. Singap J Trop Geogr 39(1):149–168. https://doi.org/10.1111/sjtg.12218

Cazenave A, Dominh K, Rabinowicz M, Ceuleneer G (1988) Geoid and depth anomalies over ocean swells and troughs: evidence of an increasing trend of the geoid to depth ratio with age of plate. J Geophys Res 93:8064–8077. https://doi.org/10.1029/JB093iB07p08064

Coratza P, De Waele J (2012) Geomorphosites and Natural Hazards: teaching the Importance of Geomorphology in Society (2012). Geoheritage 4:195–203. https://doi.org/10.1007/s12371-012-0058-0

Cornu MN, Paris R, Doucelance R, Bachélery P, Bosq C, Auclair D, Benbakkar M, Gannoun AM, Guillou H (2021) Exploring the links between volcano lank collapse and the magmatic evolution of an ocean island volcano: Fogo, Cape Verde. Sci Rep 11:17478. https://doi.org/10.1038/s41598-021-96897-1

Costa FL (2011) Volcanic geomorphosites assessment of the last eruption, on April to May 1995, within the Natural Park of Fogo Island, Cape Verde. GeoJournal Tour Geosites 8(2):167–177

Courtney RC, White RS (1986) Anomalous heat-flow and geoid across the Cape- Verde rise — evidence for dynamic support from a thermal plume in the mantle. Geophys J Int 87(3):815–867. https://doi.org/10.1111/j.1365-246X.1986.tb01973.x

Davies GR, Norry MJ, Gerlach DC, Cliff RA (1989) A combined chemical and Pb-Sr-Nd isotope study of the Azores and Cape Verde hot-spots: the geodynamic implications. Geol Soc Publ 42:231–255. https://doi.org/10.1144/GSL.SP.1989.042.01.15

Day SJ, Heleno da Silva SIN, Fonseca JFBD (1999) A past giant lateral collapse and present-day flank instability of Fogo, Cape Verde Islands. J Volcanol Geotherm Res 94(1):191–218. https://doi.org/10.1016/S0377-0273(99)00103-1

Day S, Carracedo JC, Gillou H, Fonseca JFBD, Heleno SIN, Pais P, Badiola E (2000) Comparison and cross-checking of evidence for the location and type of historical eruptions in ocean island volcanoes. in Volcanoes, Earthquakes and Archeology, edited by W. McGuire. Geol Soc London Spec Publ 171:281–306. https://doi.org/10.1144/GSL.SP.2000.171.01.21

Deville Ch Ch S-C (1848) Études géologiques sur les iles de Ténériffe et de Fogo suivi d'une statistique abrégée des iles du Cap-Vert et d'une notice bibliographique. Gide, Paris, p 143

do Nascimento JM, Moreno-Medina C, Rodrigues NA, Dinis H (2016) The Human Mobility as Strategy Facing the Volcanic Risks: The Case of Ilha do Fogo (Cape Verde). In: Domínguez-Mujica J (ed) Global Change and Human Mobility. Advances in Geographical and Environmental Sciences. Springer, Singapore, pp 323–347. https://doi.org/10.1007/978-981-10-0050-8_17

Dóniz-Páez J, Becerra-Ramírez R, González-Cárdenas E, Escobar-La-hoz E, Dionis S, Alfama V (2018) Monte Preto monogenetic volcano (Fogo, Cape Verde) an exceptional volcanic heritage for the geotourism. In: Bolós X, Mar J (Eds), 7th International Maar Conference - Olot, Catalonia, Spain, 2018, Abstract Volume, pp 216–217. ISBN 978-84-09-01627-3

Dyhr CT, Holm PM (2010) A volcanological and geochemical investigation of Boa Vista, Cape Verde Islands. $^{40}Ar/^{39}Ar$ geochronology and field constrains. J Volcanol Geotherm Res 189(1–2):19–32. https://doi.org/10.1016/j.jvolgeores.2010.10.010

Eisele S, Reißig S, Freundt A, Kutterolf S, Nürnberg D, Wang KL, Kwasnitschka T (2015) Pleistocene to Holocene offshore tephrostratigraphy of highly explosive eruptions from the southwestern Cape Verde archipelago. Mar Geol 369:233–250. https://doi.org/10.1016/j.margeo.2015.09.006

Erfurt P (2022) Volcano tourism and visitor safety: still playing with fire? A 10-year update. Geoheritage 14:56. https://doi.org/10.1007/s12371-022-00691-y

Erfurt-Cooper P (2010) Introduction. In: Erfurt-Cooper P, Cooper M (eds) Volcano and geothermal tourism: sustainable geo-resources for leisure and recreation. Earthscan, London, pp 3–30

Fernandes R, Faria B, C4G Team (2015) FOGO-2014: Monitoring the Fogo 2014 Eruption, Cape Verde. EGU General Assembly 2015, Vienna, Austria, id.12709, available at: https://ui.adsabs.harvard.edu/abs/2015EGUGA.1712709F/abstract. Accessed 23 Nov 2023

Gaudru H (2010) Cape Verde Islands. In: Erfurt-Cooper P, Cooper M (eds) Volcano and geothermal tourism: sustainable geo-resources for leisure and recreation. Earthscan, London, pp 57–59

Göktekin Z, Şimşek AB (2023) Evaluation of the disaster tourism potential of countries. In: Sezerel H, Bryan Christiansen B (eds) Handbook of research on sustainable tourism and hotel operations in global hypercompetition. IGI Global, Hershey, Pennsylvania, pp 413–432. https://doi.org/10.4018/978-1-6684-4645-4.ch019

González PJ, Bagnardi M, Hooper AJ, Larsen Y, Marinkovic P, Samsonov SV, Wright TJ (2015) The 2014–2015 eruption of Fogo volcano: Geodetic modeling of Sentinel-1 TOPS interferometry. Geophys Res Lett 42. https://doi.org/10.1002/2015GL066003

Gotham KF (2015) Dark tourism and disaster tourism. In: Ritzer G. (ed), The Blackwell Encyclopedia of Sociology. https://doi.org/10.1002/9781405165518.wbeosd045.pub2

Habibi T, Ponedelnikb AA, Yashalova NN, Ruban DA (2018) Urban geoheritage complexity: evidence of a unique natural resource from Shiraz city in Iran. Resour Policy 59:85–94. https://doi.org/10.1016/j.resourpol.2018.06.002

Heleno S (2003) O vulcão do Fogo - estudo sismológico. Teses. IPAD, Lisboa, p 463 (SBN 972-99008-0-9)

Henriques MH (2007) Ilha do Fogo: o "spritu de burcan" (espírito do vulcão). Rua Larga. Rev Univ Coimbra 18:63–66

Henriques MH, Brilha J (2017) UNESCO Global Geoparks: a strategy towards global understanding and sustainability. Episodes 40(4):349–355. https://doi.org/10.18814/epiiugs/2017/v40i4/017036

Henriques MH, Tavares AO, Bala ALM (2013) The geological heritage of Tundavala (Angola): an integrated approach to its characterization. J Afr Earth Sci 88:62–71. https://doi.org/10.1016/j.jafrearsci.2013.09.003

Hildner E, Klügel A, Hauff F (2011) Magma storage and ascent during the 1995 eruption of Fogo, Cape Verde Archipelago. Contrib Mineral Petrol 162(4):751–772. https://doi.org/10.1007/s00410-011-0623-6

Hildner E, Klügel A, Hansteen TH (2012) Barometry of lavas from the 1951 eruption of Fogo, Cape Verde Islands: implications for historic and prehistoric magma plumbing systems. J Volcanol Geoth Res 217:73–90. https://doi.org/10.1016/j.jvolgeores.2011.12.014

Holm PM, Grandvuinet T, Friis J, Wilson JR, Barker AK, Plesner S (2008) An AR study of the Cape Verde hot spot: Temporal evolution in a semistationary plate environment. J Geophys Res 113:B08201. https://doi.org/10.1029/2007JB005339

Instituto Nacional de Estatística (INE) (2011) Dados estatísticos da Ilha do Fogo. Recenseamento Geral da População e Habitação (RGPH 2010), Praia, p 67

Instituto Nacional de Estatística (INE) (2022) Quadros Zonas e Lugares, Ilha do Fogo. Recenseamento Geral da População e Habitação (RGPH 2021), Praia, p 67

Instituto Nacional de Estatística (INE) (2023a) Estatísticas do Turismo: Inventário Anual de Estabelecimentos Hoteleiros – 2022. Praia, p 19

Instituto Nacional de Estatística (INE) (2023b) Estatísticas do Turismo: Movimentação de Hóspedes 2º semestre 2022. Praia, p 23

Jenkins SF, Day SJ, Faria BE, Fonseca JFBD (2017) Damage from lava flows: insights from the 2014–2015 eruption of Fogo, Cape Verde. J Appl Volcanol 6:6. https://doi.org/10.1186/s13617-017-0057-6

Jill JC (2017) Geology and the sustainable development goals. Episodes 40(1):70–76. https://doi.org/10.18814/epiiugs/2017/v40i1/017010

Klügel A, Day S, Schmid M, Faria B (2020) Magma Plumbing During the 2014–2015 Eruption of Fogo (Cape Verde Islands). Front Earth Sci 8:157. https://doi.org/10.3389/feart.2020.00157

Kogarko LN (2008) Characteristics of alkali magma diferentiation at the Cape Verde Islands. Geochem Int 46:1071–1080. https://doi.org/10.1134/S0016702908110013

Komorowski JC, Morin J, Jenkins S, Kelman I (2016) Challenges of volcanic crises on small Islands States. In: Fearnley CJ, Bird DK, Haynes K, McGuire WJ, Jolly G (eds) Observing the Volcano World. Advances in Volcanology. Springer, Cham. https://doi.org/10.1007/11157_2015_15

Lancelot Y, Seibold E, Cepek P, Dean WE, Eremeev V, Gardner J, Jansa LF, Johnson D, Krasheninnikov V, Pfaumann U, Rankin JG, Trabant P, Burky D (1977) Site 367: Cape Verde Basin. In: The Shipboard Scientific Party, David Bukry (eds) DSDP Volume XLI. U.S. Government Printing Office, Whashington, pp 163–232. https://doi.org/10.2973/dsdp.proc.41.103.1978

Le Bas TP, Masson DG, Holtom RT, Grevemeyer I (2007) Slope failures of the flanks of the southern Cape Verde Islands. In: Lykousis V, Sakellariou D, Locat J (eds) Submarine Mass Movements and their Consequences: 3 International Symposium. Springer, Netherlands, Dordrecht, pp 337–345

Lopez-Guzman T, Borges O, Castillo-Canalejo AM (2011) Community-based tourism in Cape Verde - a case study. Tour Hosp Manag 17(1):35–44. https://doi.org/10.20867/thm.17.1.3

Madeira J, Munhá J, Tassinari C, Mata J, Brum da Silveira A, Martins S (2005) K/Ar ages of carbonatites from the Island of Fogo (Cape Verde). Proceedings of the XIV semana de Geoquímica / VIII Congresso de Geoquímica dos Países de Língua Portuguesa (Portugal), 475–478, available at: https://biblios.ciencias.ulisboa.pt/detalhes/12878. Accessed 23 Nov 2023

Madeira J, Brum da Silveira A, Mata J, Mourão C, Martins S (2008) The role of mass movements on the geomorphologic evolution of island volcanoes: examples from Fogo and Brava in the Cape Verde archipelago. Comunicações Geológicas 95, 93–106, available at: https://www.lneg.pt/wp-content/uploads/2020/03/ComunGeol_V95_N1_Article_6.pdf. Accessed 23 Nov 2023

Martínez-Moreno FJ, Monteiro Santos FA, Madeira J, Pous J, Bernardo I, Soares A, Esteves M, Adão F, Ribeiro J, Mata J, Brum da Silveira A (2018) Investigating collapse structures in oceanic islands using magnetotelluric surveys: the case of Fogo Island in Cape Verde. J Volcanol Geotherm Res 357:152–162. https://doi.org/10.1016/j.jvolgeores.2018.04.028

Masson D, Le Bas T, Grevemeyer I, Weinrebe W (2008) Flank collapse and large-scale landsliding in the Cape Verde Islands, off West Africa. Geochem. Geophys Geosyst 9(7). https://doi.org/10.1029/2008GC001983

Mata J, Martins S, Mattielli N, Madeira J, Faria B, Ramalho R, Silva P, Moreira M, Caldeira R, Rodrigues J (2017) The 2014–15 eruption and the short-term geochemical evolution of the Fogo volcano (Cape Verde): evidence for small-scale mantle heterogeneity. Lithos 288–289:91–107. https://doi.org/10.1016/j.lithos.2017.07.001

Migoń P, Pijet-Migoń E (2019) Natural disasters, geotourism, and geo-interpretation. Geoheritage 11:629–640. https://doi.org/10.1007/s12371-018-0316-x

Mourão C, Mata J, Doucelance R, Madeira J, Brum da Silveira A, Silva LC, Moreira M (2010) Quaternary extrusive calciocarbonatite volcanism on Brava Island (Cape Verde): a nephenilite-carbonatite immiscibility product. J Afr Earth Sc 56:59–74. https://doi.org/10.1016/j.jafrearsci.2009.06.003

Müller RD, Sdrolias M, Gaina C, Roest WR (2008) Age, spreading rates, and spreading asymmetry of the world's ocean crust. Geochem Geophys Geosyst 9(4):Q04006. https://doi.org/10.1029/2007GC001743

Naranjo Llupart MR (2022) Theoretical model for the analysis of community-based tourism: contribution to sustainable development. Sustainability 14:10635. https://doi.org/10.3390/su141710635

Németh K (2022) Volcanic Geoheritage in the Light of Volcano Geology. In: Dóniz-Páez J, Pérez NM (eds) El Hierro Island Global Geopark. Geoheritage, Geoparks and Geotourism. Springer, Cham, pp 1–24. https://doi.org/10.1007/978-3-031-07289-5_1

Németh K, Casadevall T, Moufti MR, Marti J (2017) Volcanic geoheritage. Geoheritage 9:251–254. https://doi.org/10.1007/s12371-017-0257-9

Neto K, Henriques MH (2022) Geoconservation in Africa: State of the art and future challenges. Gondwana Res 110:107–113. https://doi.org/10.1016/j.gr.2022.05.022

Oliveira C, Brochado A, Moro S, Rita P (2019) Consumer perception of tourist experience through online reviews: The islands of the senses of Cape Verde. Worldw Hosp Tour Themes 11(6):696–717. https://doi.org/10.1108/WHATT-09-2019-0052

Paris R, Giachetti T, Chevalier J, Guillou H, Frank N (2011) Tsunami deposits in Santiago Island (Cape Verde archipelago) as possible evidence of a massive flank failure of Fogos volcano. Sediment Geol 239(3–4):129–145. https://doi.org/10.1016/j.sedgeo.2011.06.006

Patriat M, Labails C (2006) Linking the Canary and Cape-Verde hotspots, Northwest Africa. Mar Geophys Res 27:201–215. https://doi.org/10.1007/s11001-006-9000-7

PDNA (2015) Post-Disaster Needs Assessment. Fogo volcanic eruption 2014–2015. Government of Cabo Verde, available at: https://www.gfdrr.org/sites/default/files/publication/Cabo%20Verde%20PDNA_REPORT_EN.pdf. Accessed 10 Oct 2023

Pena dos Reis R, Henriques MH (2009) Approaching an integrated qualification and evaluation system for geological heritage. Geoheritage 1(1):1–10. https://doi.org/10.1007/s12371-009-0002-0

PGPNF (2009) Plano de Gestão do Parque Natural do Fogo (PNF). Ministério do Ambiente Desenvolvimento Rural e Recursos Marinhos (MADRRM) e Direção Geral do Ambiente (DGA), Praia, p 325

Planagumà L, Martí J (2020) Identification, cataloguing and preservation of outcrops of geological interest in monogenetic volcanic fields: the case of La Garrotxa Volcanic Zone Natural Park. Geoheritage 12:84. https://doi.org/10.1007/s12371-020-00508-w

Pollitz FF (1991) Two-stage model of African absolute motion during the last 30 million years. Tectonophysics 194:91–106. https://doi.org/10.1016/0040-1951(91)90274-V

Ramalho R (2011) Building the Cape Verde Islands. Springer Theses, Springer Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-19103-9

Ramalho R, Winckler G, Madeira J, Helffrich G, Hipólito A, Quartau R, Adena K, Schaefer J (2015) Hazard potential of volcanic flank collapses raised by new megatsunami evidence. Sci Adv 1(9):e1500456. https://doi.org/10.1126/sciadv.15004

Ribeiro O (1960) A Ilha do Fogo e as suas erupções. Mem. Sér. Geográfica 1, 2ª ed., Junta de Investigação do Ultramar, Lisboa, p 184

Richter N, Favalli M, de Zeeuw-van Dalfsen E, Fornaciai A, da Silva Fernandes RM, Pérez NM, Levy J, Silva Victória S, Walter TR (2016) A post-2015 lava flow hazard map for Fogo Volcano. GFZ Data Services, Cabo Verde. https://doi.org/10.5880/GFZ.2.1.2016.001

Robertson AHF (1984) Mesozoic deep-water and Tertiary volcaniclastic deposition of Maio, Cape Verde Islands: Implications for Atlantic paleoenvironments and ocean island volcanism. Geol Soc Am Bull 95(4):433–453. https://doi.org/10.1130/0016-7606(1984)95%3c433:MDATVD%3e2.0.CO;2

Rosselló J, Becken S, Santana-Gallego M (2020) The effects of natural disasters on international tourism: a global analysis. Tour Manag 79:104080. https://doi.org/10.1016/j.tourman.2020.104080

RPDCC (2018) Regulamento Plano Detalhado Chã das Caldeiras. Governo de Cabo Verde, Instituto Nacional de Gestão do Território (INGT), Câmara Municipal de Santa Catarina do Fogo (CMSCF) e Gesplan, available at: https://www.fogo.cv/index.php/projetos/272-plano-detalhado-cha-das-caldeiras. Accessed 23 Nov 2023

Rungchavalnont P (2022) Community-Based Tourism: Empowering Local Champions for Sustainable Tourism in Thailand. UNDP, available at: https://www.undp.org/thailand/blog/community-based-tourism-empowering-local-champions-sustainable-tourism-thailand. Accessed 8 Oct 2023

Santos FLGM (2017) O Parque Natural do Fogo: cosmologias e territorialidades. Etnográfica 21(3):509–525. https://doi.org/10.4000/etnografica.5005, available at: http://journals.openedition.org/etnografica/5005. Accessed 12 Oct 2023

Silva LC, Mendes MH, Torres PC, Palácios T, Munhá JM (1997) Petrografia e mineralogia das formações vulcânicas da erupção de 1995 na ilha do Fogo, Cabo Verde. In: Réffega A, Figueiredo M, Silva L, Costa F, Mendes M, Torres P, Silva T, Correia E (eds) A erupção vulcânica de 1995 na Ilha do Fogo, Cabo Verde. Instituto de Investigação Científica Tropical e Ministério da Ciência e Tecnologia, Lisboa, pp 165–170 (ISBN: 972-672-869-0)

Silva S, Alfama V, Cardoso N (2016) The volcanic eruption of 2014/15 on Fogo Island Cape Verde and the main effects. Revista Pos Ciências Sociais 13(26):49–61. https://doi.org/10.18764/2236-9473.v13n26p49-62

Silva S, Calvari S, Hernandez P, Pérez N, Ganci G, Alfama V, Barrancos J, Cabral J, Cardoso N, Dionis S, Fernandes P, Melian G, Pereira J, Semedo H, Padilla G, Rodriguez F (2017) Tracking the hidden growth of a lava flow field: the 2014–15 eruption of Fogo volcano (Cape Verde). 19th EGU General Assembly, EGU2017, proceedings from the conference held 23–28 April, 2017 in Vienna, Austria, p.14514, available at: https://ui.adsabs.harvard.edu/abs/2017EGUGA..1914514S/abstract. Accessed 23 Nov 2023

Stillman CJ, Furnes H, Le Bas MJ, Robertson AHF, Zileonka J (1982) The geological history of Maio, Cape Verde Island. J Geol Soc London 139:347–351. https://doi.org/10.1144/gsjgs.139.3.0347

Tavares AO, Henriques MH, Domingos A, Bala A (2015) Community involvement in geoconservation: a conceptual approach based on the geoheritage of South Angola. Sustainability 7:4893–4918. https://doi.org/10.3390/su7054893

Teves ASG (2018) Escoadas de lava históricas do Vulcão do Fogo (Cabo Verde): Cartografia e análise morfológica. Dissertação de Mestrado em Geografia Física e Ordenamento do Território. Unpublished MSc Thesis. Instituto de Geografia e Ordenamento do Território da Universidade de Coimbra, p 126

Texier-Teixeira P, Chouraqui F, Perrillat-Collomb A, Lavigne F, Cadag JR, Grancher D (2014) Reducing volcanic risk on Fogo Volcano, Cape Verde, through a participatory approach: which outcome? Nat Hazards Earth Syst Sci 14:2347–2358. https://doi.org/10.5194/nhess-14-2347-2014

Torres PC, Madeira J, Silva LC, Brum da Silveira A, Serralheiro A, Mota Gomes A (1997) Carta geológica das erupções históricas da Ilha do Fogo: revisão e actualização. In: Réffega A, Figueiredo M, Silva L, Costa F, Mendes M, Torres P, Silva T, Correia E (eds) A erupção vulcânica de 1995 na Ilha do Fogo, Cabo Verde. Instituto de Investigação Científica Tropical e Ministério da Ciência e Tecnologia, Lisboa, pp 119–132 (ISBN: 972-672-869-0)

Toteu SF, Anderson JM, de Wit M (2010) ‘‘Africa Alive Corridors”: Forging a new future for the people of Africa by the people of Africa. J Afr Earth Sci 58(4):692–715. https://doi.org/10.1016/j.jafrearsci.2010.08.011

Vieira D, Teodoro A, Gomes A (2016) Analyzing land surface temperature variations during Fogo Island (Cape Verde) 2014–2015 eruption with Landsat 8 images. Proceedings Volume 10005, Earth Resources and Environmental Remote Sensing/GIS Applications VII; 1000508 (2016), SPIE Remote Sensing, 2016, Edinburgh, United Kingdom. https://doi.org/10.1117/12.2241382

Werlen B, Osterbeek L, Henriques MH (2016) 2016 International Year of Global Understanding: Building bridges between global thinking and local actions. Episodes 39(4):604–611. https://doi.org/10.18814/epiiugs/2016/v39i4/103894

White RS (1984) Atlantic oceanic crust: seismic structure of a slow-spreading ridge. Geol Soc Lond Spec Publ 13(1):101–111. https://doi.org/10.1144/GSL.SP.1984.013.01.09

Williams CA, Hill IA, Young R, White RS (1990) Fractures zones across the Cape Verde Rise, NE Atlantic. J Geol Soc 147(5):851–857. https://doi.org/10.1144/gsjgs.147.5.08

Worsley P (2015) Physical geology of the Fogo volcano (Cape Verde Islands) and its 2014–2015 eruption. GeologyToday 31(4):153–159. https://doi.org/10.1111/gto.12102