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Investigating volcanic hazard in Cape Verde Islands through geophysical monitoring: network description and first results

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Abstract

We describe a new geophysical network deployed in the Cape Verde archipelago for the assessment and monitoring of volcanic hazards, and the first results from the network. Across the archipelago, the ages of volcanic activity range from ca. 20 Ma to present. In general, older islands are in the east and younger ones are in the west, but there is no clear age progression and widely-separated islands have erupted contemporaneously on geological time scales. The overall magmatic rate is low, and there are indications that eruptive activity is episodic, with intervals between episodes of intense activity ranging from 1 to 4 Ma. Although only Fogo island has experienced eruptions (mainly effusive) in the historic period (last 550 yr), Brava and Santo Antão have experienced numerous geologically recent eruptions including violent explosive eruptions, and show felt seismic activity and geothermal activity. Evidence for recent volcanism in the other islands is more limited and the emphasis has therefore been on monitoring of the three critical islands of Fogo, Brava and Santo Antão, where volcanic hazard levels are highest. Geophysical monitoring of all three islands is now in operation. The first results show that in Fogo the seismic activity is dominated by hydrothermal events and volcano-tectonic events that may be related to settling of the edifice after the 1995 eruption; in Brava by volcano-tectonic events (mostly offshore), and in Santo Antão by volcano-tectonic events, medium frequency events and harmonic tremor. Both in Brava and in Santo Antão, the recorded seismicity indicates that relatively shallow magmatic systems are present and causing deformation of the edifices that may include episodes of dike intrusion.

1 Introduction: the distribution of volcanic activity in Cape Verde over geological time

The Cape Verde archipelago consists of ten major islands – nine of which are inhabited – and several small islets. Located in the NW Atlantic, about 500 km off the coast of

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Senegal (Fig. 1), the islands are volcanic, and form a broadly horseshoe-shaped array, opened towards the west and containing two diverging chains with older islands in the east and younger islands in the northwest and southwest. It sits over a ca. 2 km bathymetric swell of about 1000 km in diameter, which is correlated with other anomalies in sea-floor heat flow (Courtney and White, 1986), gravity (Ali and Watts, 2003; Pim et al., 2008) and the geoid (Monnereau and Cazenave, 1990). It has therefore been inferred that the magmatism is due to a hotspot. However, it is not clear whether the root of the plume that sustains the hotspot is deep-seated (Montelli et al., 2006; Pim et al., 2008; Doucelane et al., 2003; Vinnik et al., 2012) or is in the upper mantle (Helfrich et al., 2010). In contrast to other hotspot oceanic island volcano archipelagoes, in Cape Verde there is no clear age progression with geographic location, and widely separated islands erupted simultaneously in the geological time scale (Plesner et al., 2002). The geological and geochronological evidence also shows that volcanic activity in the islands tends to be intermittent, with long periods of quiescence (up to a few million years) separating eruptive phases (Holm et al., 2005; Holm et al., 2006; Duprat et al., 2007).

In the historic period since the first settlement around 1460 AD, and perhaps for some thousand of years prior, eruptions have occurred only in Fogo island. However, fresh volcanic vents, lavas and pyroclastic deposits indicate geologically-recent activity in other islands, and signs of geological unrest such as island uplift occur in many parts of the archipelago (Ramalho, 2009; Ramalho et al., 2010). Brava and Santo Antão islands display major sequences of morphologically fresh and geologically recent volcanic rocks, including evidences of infrequent but sometimes violently explosive eruptions (Plesner et al., 2002; Mortensen et al., 2009; Tarff and Day, 2013; Day, 2009; Madeira et al., 2010) and important seismicity. In view of these features, it is difficult to exclude a priori the possibility of a reawakening of the activity in any of the islands, but the probability of such an event is likely to be much lower in the eastern islands – where the main sequences of volcanic rocks are deeply eroded and more recent volcanic events are infrequent and small in volume – than in the western islands.

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The National Institute for Meteorology and Geophysics (INMG) deployed recently a seismic and geodetic network for the assessment and mitigation of volcanic hazard, with special emphasis on real-time monitoring in Fogo, Brava and Santo Antão. Fifteen seismic stations are currently in operation, covering five islands – Santo Antão, S. Vicente, Sal, Fogo and Brava. In this paper we review the structures of the volcanoes and what is known about volcanic hazards in the Cape Verde islands, describe the new monitoring network, and present some of the data already recorded, with a preliminary discussion of the implications for volcanic hazard.

2 Geological setting and main volcanic hazards of Fogo Brava and Santo Antão

2.1 Fogo island

Located in the SW of the Cape Verde Archipelago (Fig. 1), Fogo Island is an active stratovolcano, rising over 6 km from the 4000 m-deep seafloor to the Pico do Fogo summit at 2829 m above sea level (m a.s.l.). With an area of 471 km², Fogo has a population of ~37 000 inhabitants. With mean diameter of 30 km at a roughly circular base, the island has a nearly conical shape truncated at ~1700 m a.s.l. by a 9 km wide lateral collapse scar (Day et al., 1999) opened to the east. Partial infilling of the collapse scar has produced a nearly horizontal flat plateau known as Chã das Caldeiras, enclosed on the north, west and south by the collapse scar cliff – the Bordeira – which reaches 1000 m above the plain. A population of about 700 farmers lives in Chã das Caldeiras, and 11 000 live on the eastern coast, unprotected by the Bordeira cliff. On the eastern side of Chã das Caldeiras rises the summit cone, Pico do Fogo (Fig. 2). In addition to onshore evidence for the lateral collapse (Day et al., 1999), Masson et al. (2008) reported results of multibeam bathymetric survey to the east of Fogo which were interpreted as the avalanche debris of the lateral collapse. Foeken et al. (2009) dated pre-collapse and post-collapse flows at 123 Ma and 62 Ma, respectively, providing a time window for the lateral collapse.

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The flanks of Fogo outside the lateral collapse scar display numerous volcanic vents, concentrated in radial zones which according to Day et al. (1999) form a modified triple-arm rift geometry. The distribution of dikes in the Bordeira cliff replicates these preferential directions: NNE, SSE and a broader sector towards the West. Activity in the southwest of the island ceased about 11 ka ago (Foeken et al., 2009), but eruptions in the east of the island have continued especially within the collapse scar. Since settlement in the 15th Century, 27 eruptions were identified through analysis of incomplete written records (Ribeiro, 1960), with average time intervals of 20 yrs and average duration of two months. According to Ribeiro (1960), until 1725 most historic (i.e. post-dating 1500) eruptions occurred through the Pico do Fogo summit, although more recent mapping (S. Day, personal communication, 2013) indicates that some of these also involved eruptions on flank fissures in the northwest and southeast. In contrast, from after 1785 eruption until now the summit of Pico do Fogo has been inactive. The six subsequent eruptions occurred inside the collapse scar, mainly through N–S trending fissures, that are arranged in a pattern that suggests that the feeding dikes follow the trends of the NNE and SSE rift zones at greater depths. The exception is the most recent eruption, in 1995, which was fed by the western rift zone (Day et al., 1999; Heleno, 2001). The composition of erupted rocks varied through time, but the most common are ankaramites, nephelinites, basanites, tephrites and scarce phonolitic rocks (Foeken et al., 2009; Hildner et al., 2011; Hildner et al., 2012). The eruptions were mostly effusive (Hawaiian to Strombolian), with rare occurrences of highly explosive episodes including phreatomagmatic events (Day et al., 1999; Foeken et al., 2009).

Ash, lapilli, bombs and lava flows are the most frequent volcanic products in Fogo island (Torres et al., 1997), and the most significant hazard is associated with lava flows (Ribeiro, 1960; Torres et al., 1997), especially inside the collapse scar and on the very steep eastern coast, which hosts ~30% of the island's population. In 1951 a village was totally destroyed by lava flows on the eastern coast, and in 1995 another small village was destroyed by lava flows, this time inside Chã das Caldeiras. The 1995 lava

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flows also covered an economically important agricultural area with some of the best soils of the island. Lava flows hazard can be regarded as high in the caldera floor and very high in the eastern coast, in view of the high speeds that the flow can reach on the steep slopes (Day and Faria, 2009).

2.2 Brava

Brava, located to the west of Fogo and separated from it by an 18 km-wide channel, is the smallest inhabited island of the archipelago, with an area of 62.5 km² and a population of ~6000 inhabitants. It has a broadly circular shape and steep coastal slopes, cut by deep erosional valleys. The island has a central summit plateau, where it reaches the maximum amplitude of 976 m a.s.l. at the Fontainhas peak. Day (2009) proposed that this plateau was produced by the infilling with pyroclastic rocks of a wide central collapse caldera (7 km × 5 km), formed during a catastrophic explosive eruption. Phreatomagmatic craters are widespread in the summit plateau, perhaps due to interaction of rising magmas with a major aquifer in the postulated caldera fill sequence (Day, 2009). Some phonolitic lava domes are also found, both on the plateau and on the outer flanks of the island (Machado, 1968; Madeira et al., 2010; Day, 2009), as are rare subaerial carbonatite lavas and pyroclastic deposits (Madeira et al., 2010).

Rock dating (Hoernle et al., 2002; Madeira et al., 2010) and the juvenile aspect of several craters (Day, 2009; Mourão et al., 2010; Madeira et al., 2010) suggest that the most recent eruptive activity of Brava is Holocene in age. Volcanic hazards are mainly associated with phreatomagmatic eruptions, surge and pyroclastic deposits, and to a lesser extend with lava flows (Machado et al., 1968; Day, 2009; Madeira et al., 2010). The geologically recent volcanic activity appears to have been very explosive, and phreatomagmatic craters are distributed densely on the central plateau, where 82% of the population lives. Since there have been no historic eruptions in Brava, volcanic hazard awareness among the population and the authorities is very low.

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2.3 Santo Antão

Santo Antão, located in the northwest of the archipelago and with an area of 784 km², is the second largest island of Cape Verde, with a population of about 44 000 inhabitants spread widely across the island. The economy is based on cattle-raising and agriculture, which account for 35% of the total food production in Cape Verde. It is shaped roughly like a triangular prism, whose arcuate crest, at the mean altitude of 1400 m a.s.l., but rising to 1800 m in places, is formed by two plateaus (Fig. 3). One, the Planalto Leste, makes up the central part of the island, and the other, the Planalto Norte in the southwestern end of the island, hosts numerous scoria cones and the highest peak of the island, the strato-volcano Topo de Coroa (1982 m a.s.l.). The slopes of the island are made of thick lava flows covered by sediments and pyroclastics rocks, and have been deeply dissected by erosion that has formed deep canyons, valleys and basins (Tarff and Day, 2013, their Supplementary file 1; Plesner et al., 2002; Holm et al., 2006).

Plesner et al. (2002) established the first timeline for the evolution of the island, and the results suggest that the older rocks are at least 7.5 Ma old. After a hiatus of 4.3 Ma the eruptive activity resumed at a lower eruption rate, and the last eruption occurred about 90 ka ago. Based on rock distribution, age and geochemistry, Holm et al. (2006) divided the evolution of Santo Antão in three main phases: from 7.5 to 2 Ma, composed mainly of basanite and phonolite rocks; from 2 to 0.3 Ma, composed mostly of basanite-phonolite, but also some incidence of nephelinite-phonolite, and from 0.4 to 0.1 Ma, composed mainly of nephelinite-phonolite rocks. Tarff and Day (2013) inferred the existence of three overlapping volcanic centres: Ribeira das Patas, Cova de Paúl and Topo de Coroa and proposed that Ribeira das Patas centre is the oldest, and largely extinct, whilst the other two are younger and both still active. Correlation of the distributions of rocks of these three centres with the dated rock location of Plesner et al. (2002) suggest that the activities of these three volcanic centers overlapped in time.

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Ribeira das Patas volcano, which is roughly in the center of the island (Fig. 3), is presently a basin produced by the erosion of hydrothermally-altered lavas, opened to the south, about 6 km in diameter and bounded by an arcuate cliff 900 m to 1000 m high (Tarff and Day, 2013; Plesner et al., 2002). The ages of Ribeira das Patas volcano lava flows range from 7.5 Ma to 1.1 Ma (Plesner et al., 2002). A particular feature of this volcano is a post-erosional scoria cone that formed inside the basin and whose lava is 0.22 Ma old, meaning that the eruption occurred about 1 Ma after the last eruption of Ribeira das Patas volcano and after it had been completely eroded. This feature highlights the intermittent eruptive activity in this island, with long periods of quiescence.

Cova de Paúl volcano, which forms most of the eastern half of Santo Antão, produced thick lava flows that overlap Ribeiras das Patas sequences (possibly infilling an east-facing collapse scar; Tarff and Day, 2013), and are now eroded by valleys up to 500 m deep. Tarff and Day (2013) argue that the activity of this volcano occurred along three rift zones, with WSW, NE and SE directions, respectively, extending radially from a summit area with many phonolite domes (Fig. 3). A prominent feature of this volcano is a 300 m deep crater at the western end of the summit area with a diameter of 1 km, caused by a violent phreatomagmatic explosive eruption that produced pyroclastic flow and surge deposits (Tarff and Day, 2013). Plesner et al. (2002) give an age of 1.35 Ma for the oldest dated lava in this volcano, and 90 ka to the youngest flows.

Topo de Coroa volcanic center corresponds to 20% of the surface of the island, towards its SW end (Fig. 3). It consists of numerous young fresh to very fresh scoria cones, phonolitic lava domes and spines. This volcanic center features a strato-volcano, also called Topo de Coroa (1982 m a.s.l.). According to Tarff and Day (2013) much of the activity of this volcano occurred along two rift zones both running from the east end of the Planalto Norte to the northwest and to the southwest, respectively. The Planalto Norte plateau was built by the infilling with young volcanic rocks of two escarpments opened to the southwest, which Tarff and Day (2013) attribute to two successive lateral collapses. Masson et al. (2008) used multibeam and acoustic backscatter images to map areas of blocky bathymetry offshore the island, which they interpreted

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hard rock. The tilt stations were installed in the seismic stations beside the seismometers (FGTT, FGMB and FGPP, Fig. 4) to take advantage of the infrastructure.

The locations of Brava seismic stations were chosen taking into account previous seismicity results from temporary networks (Heleno, 2001; Helffrich et al., 2006; Faria, 2010; Grevemeyer et al., 2010), the local geology and the requirement of line-of-sight to the radio repeaters installed in Fogo (see Fonseca et al., 2013).

3.2 Santo Antão sub-network

This sub-network, deployed in July 2010, consists of four stations (Fig. 5). Its geometry resulted mainly from the information obtained by questioning of the population, between 2000 and 2002, about felt earthquakes. This revealed the existence of intense seismic activity in the southwest and in the northeast, perhaps associated, respectively with the Topo de Coroa and Cova de Paúl volcanoes. The station vaults were dug 1.5 m deep in hard rock.

Line-of-sight requirements for data transmission were also a constraint in the network geometry. Data are transmitted using two RS-232 links (Fig. 5), each one consisting of three spread spectrum radios (FreeWave FGR-115RC): one in the acquisition lab, configured as master, one in the station/repeater (SACO and SAMO) configured as slave/repeater, which transmits data of two stations; and finally one at the “hidden” stations (SAAJ, SATA), configured as slave.

3.3 Sal and São Vicente

These two islands have a single seismic station each. The seismic station of Sal is installed in a 2 m deep well dug in a thick limestone layer. The data are recorded by an embedded computer in the station, which broadcasts the data using an ADSL Internet connection to a gateway in Santiago island (see Fonseca et al., this issue). In São Vicente, the seismic station is installed almost in the middle of the island, on the slope of a hill over a ~ 1 m thick basaltic dike. The data is telemetered using a RS-232 link,

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similar to those used in Santo Antão. This station has a particular relevance to the local seismic activity of Santo Antão as it provides key constraints on the locations of the larger recorded earthquakes.

4 First results and discussion

No seismic activity has been recorded to date from beneath the islands of Sal and São Vicente, so this discussion will focus on the activity in and near Fogo, Brava and Santo Antão.

4.1 Fogo

A variety of different classes of volcanic seismic events are recorded in Fogo. The most frequent are: cigar-shaped (Fig. 6), hybrid, long-period, volcano-tectonic events and spasmodic tremor (Fig. 7).

Since the deployment of the Fogo island stations (April 2011), the seismic rate of cigar-shaped, hybrid and long-period events and spasmodic tremor has shown a seasonal variation. It peaks between September and November, the rainy season, and then decreases to the background level (Fig. 8). This is similar to the pattern previously reported by Faria (2010) for data recorded in Fogo between 2001 and 2003. These events are characterized by a lack of clear phases, and as a result it is not possible to locate them by classical methods. To overcome this difficulty, the wavelet transforms (Vandergheynst et al., 2001) of the recorded seismograms were used to determine *P* phase arrival time, and by means of a grid search an approximate location of their source could be found. These locations are mostly below the crater of the 1995 eruption at focal depths ranging from 300 to 400 m below the surface of Chã das Caldeiras. Faria (2010) hypothesized that this seismicity, including the long-period events, is produced by the hydrothermal activity resulting from percolation of rainwater down to hot rocks in and around the conduit that fed the 1995 eruption. More recently (May 2012),

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that the swarm and harmonic tremor episodes were produced by magma intrusion underneath a submarine volcano. This hypothesis is reinforced by the previous occurrence of several high-frequency (> 5 Hz) harmonic tremor episodes recorded in Fogo and Brava between 1999 and 2002, which were interpreted as related to submarine volcanic processes (Heleno et al., 2006).

Day (2009), Madeira et al. (2010) and Ramalho (2009) propose that Brava is experiencing sustained uplift, which may be caused by crustal magmatic intrusions in form of sills or laccoliths. It is possible that part of the volcano-tectonic events, with focal depths between 5 km and 10 km, are produced by these processes.

4.3 Santo Antão

During the first three years of operation of the network on Santo Antão the seismic activity observed consists mainly of volcano-tectonic events, medium-frequency events and harmonic volcanic tremor episodes. The local magnitudes range from 0.1 to 4.5. The mean rate is 3 events per day, but as is the case with Brava the rate varies widely, mainly due to frequent seismic swarms.

The epicenters (Fig. 12) show a diffuse pattern, covering most of the island and extending offshore to the NW and SW. Despite the diffuseness of the picture defined by the offshore epicenters, Fig. 12 indicates that they are grouped in two main zones: one to the NW and the other to the SW of Santo Antão. The NW group is geographically correlated with Nola Seamount, and the SW with Charles Darwin Volcanic field, which was discovered recently (Masson et al., 2008). More recently, both Nola Seamount and Charles Darwin volcanic field were investigated in detail, by multibeam sonar bathymetric mapping and dredging (Hansteen et al., 2013). Charles Darwin volcanic field consist of a myriad of volcanic cones at more than 3000 m deep. Nola Seamount comprises two submarine peaks separated by a plateau at about 100 m deep. Young volcanic products were dredged from both, but no evidences of Holocene volcanic activity were found on these submarine volcanic structures (Hansteen et al., 2013). However, the

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occurrence of frequent seismic swarms may indicate that the activity is associated with intrusive processes.

An important feature of the seismic activity onshore Santo Antão, with focal depths between 3 and 13 km, is the frequent occurrence of swarms. A prominent one happened in December 2011, which lasted for the whole month (Fig. 13a), and reached a peak of more than 70 volcano-tectonic events in one day. Between 18:40 and 20:00 (UTC) of 13 December, more than 30 events (Fig. 14) were observed. It was only possible to locate the first of these, on the SW rift zone of Topo de Coroa Volcano (Fig. 12). All the stations recorded a low frequency (~ 2 Hz) harmonic volcanic tremor episode (Fig. 14), beginning about 10 min before the start of this swarm, and lasting for at least 10 min. Towards the end of this seismic swarm, the medium-frequency event rate increased and reached a local maximum in the first days of January 2012, when it decreased exponentially back to the background level (Fig. 13b).

The sequence: (1) low-frequency (< 5 Hz) volcanic tremor episodes, (2) volcano-tectonic events located on the volcanic rift zones and finally (3) medium-frequency events, suggests that the seismic activity recorded in the December 2011–January 2012 episode in Santo Antão, may have been associated with magmatic intrusion in the SW rift zone of Topo de Coroa.

5 Conclusions

The distribution of seismic activity recorded by the Cape Verde Geophysical Network in its first few years of operation is consistent with previous geological studies that indicate that, whilst infrequent volcanic activity may occur anywhere in the archipelago and may show long-term cyclicity, volcanic activity and volcanic hazards are presently concentrated in the western islands of Fogo, Brava and Santo Antão. In addition to significant numbers of events under these islands, offshore seismic activity probably related to submarine seamounts and volcanic fields was also recorded, indicating that these structures may be still active or are frequently subject to magmatic intrusions.

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Amongst the three western islands, Fogo displays the highest seismic rate, but it is dominated by seasonally-varying very shallow hydrothermal activity and by persistently low levels of volcano-tectonic earthquake activity, not associated with seismic swarms, that are linked to structural readjustments following the recent 1995 eruption.

5 The seismic activity onshore and nearshore Brava and Santo Antão does occur in discrete swarms and is probably associated with magmatic intrusions either within the deeper parts of the edifices or in underlying oceanic crust. This raises the possibility of eruptions on these islands in the near future. However, quantification of the probability of such eruptions as well as the assessment of the hazards that may result, requires

10 further investigation. Continued and extended monitoring, geophysical surveys of the subsurface structures of the volcanoes, and most especially detailed geological mapping and absolute age dating of the younger volcanic sequences, are required to establish the frequencies of occurrence of different types of volcanic activity on the different islands and hence the probabilities of occurrence of different volcanic hazards.

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25 the deployment of the seismic stations in Santo Antão. The authors are grateful to S. Day for his careful review of the manuscript, comments and suggestion, and the provision of geological information for Brava, which was fundamental for the seismic stations site selection there.

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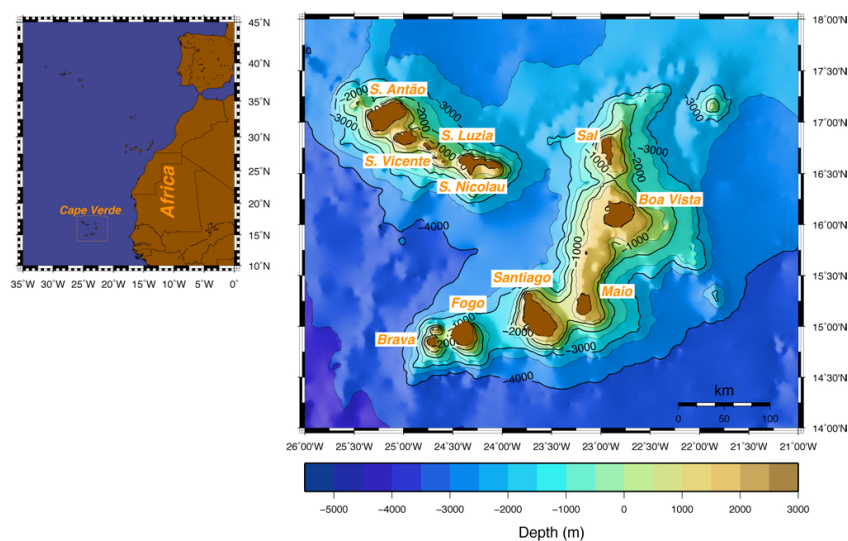


Fig. 1. Map of the Cape Verde Archipelago, North Atlantic.

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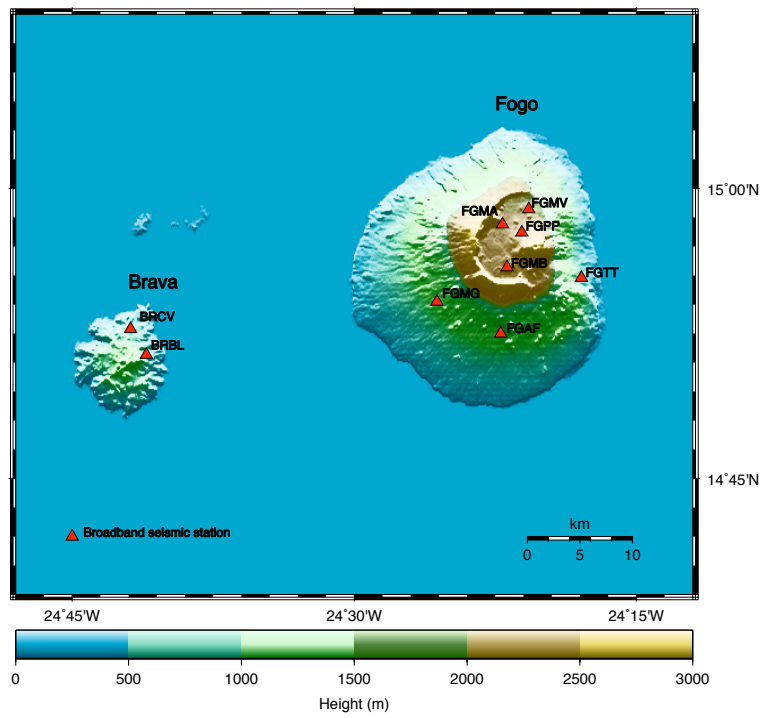


Fig. 4. Location of seismic stations of Fogo and Brava sub-network.

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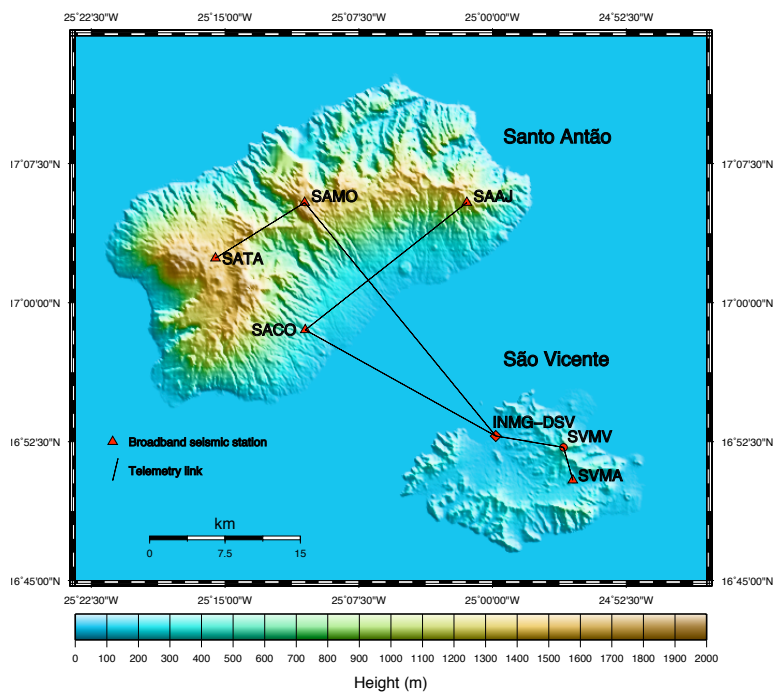


Fig. 5. The seismic sub-network of Santo Antão and its telemetry. Also shown is the location of the station of São Vicente – SVMA. INMG-DSV stands for the INMG Laboratory in São Vicente.

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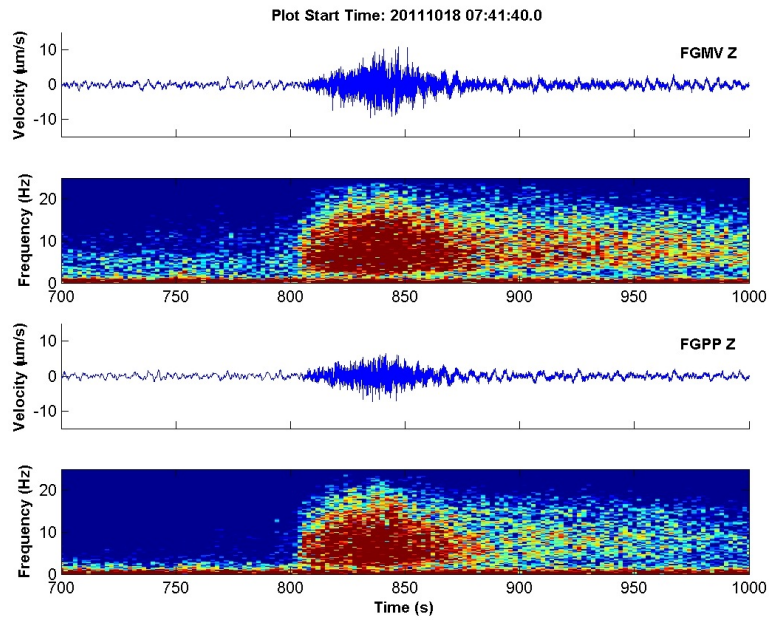


Fig. 6. Example of a seismogram and spectrogram of a cigar-shaped event recorded in Fogo on the 18 October 2011 at 07:30 UTC.

5023

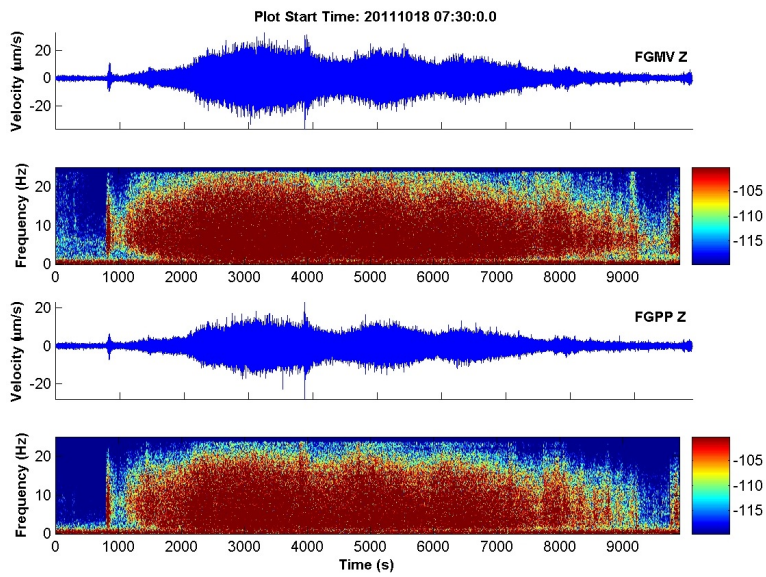


Fig. 7. Example of a seismogram and spectrogram of a spasmodic tremor episode recorded few minutes after the cigar-shaped event of the Fig. 6 and which lasted for about 2 h.

5024

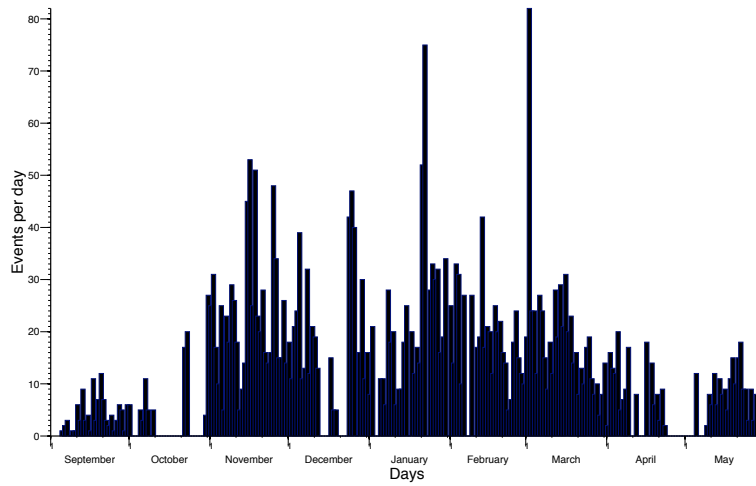


Fig. 8. Evolution of the seismic activity rate recorded in Fogo, between September 2011 and May 2012.

5025

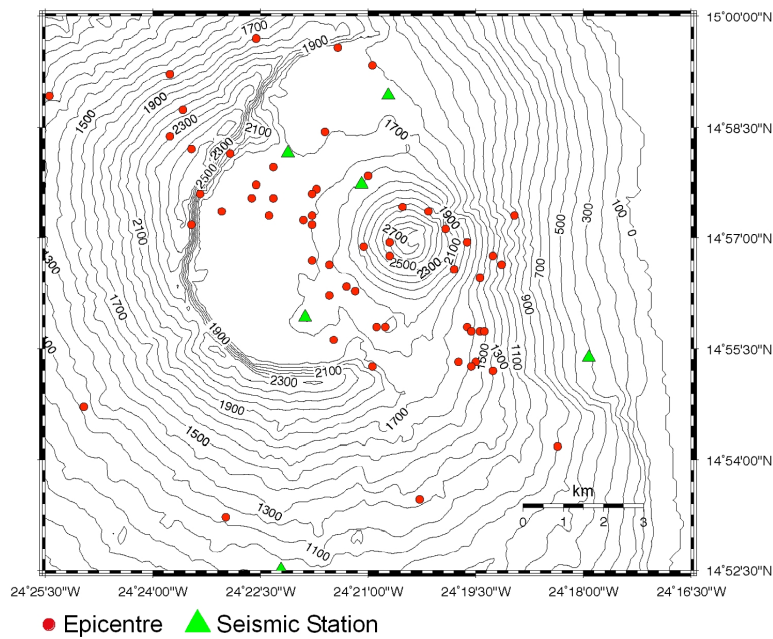


Fig. 9. Location of the epicentres of the volcano-tectonic events of Fogo.

5026

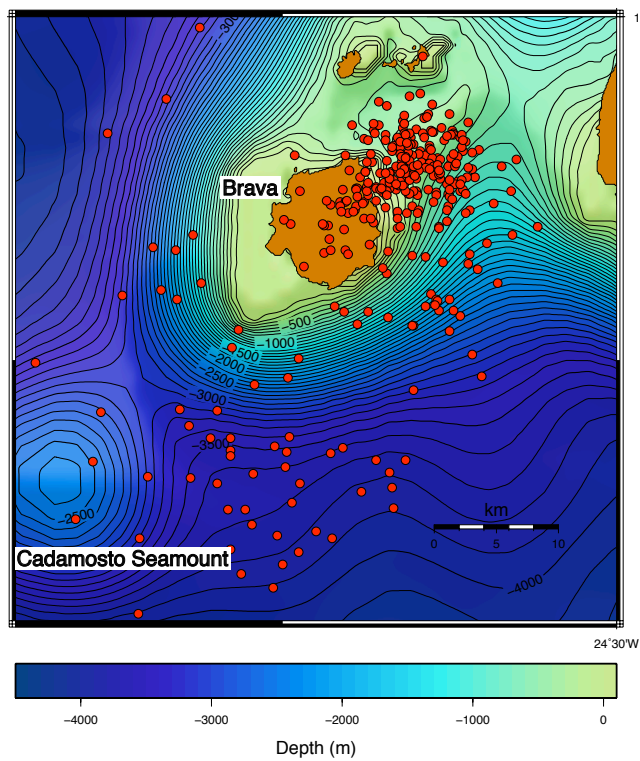


Fig. 10. Epicentral geographic distribution of the seismic events onshore and offshore of Brava. Cadamosto seamount is in the SW off Brava.

5027

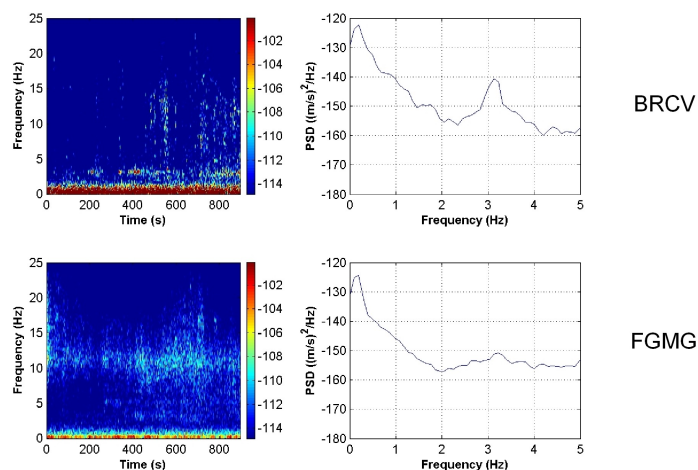


Fig. 11. Spectrogram (left) of 15 min windows of vertical component of ground velocity of a harmonic tremor episode recorded on 3 March 2012 at 08:00 UTC by BRCV (top) and FGGM (bottom) and the power spectra (right).

5028

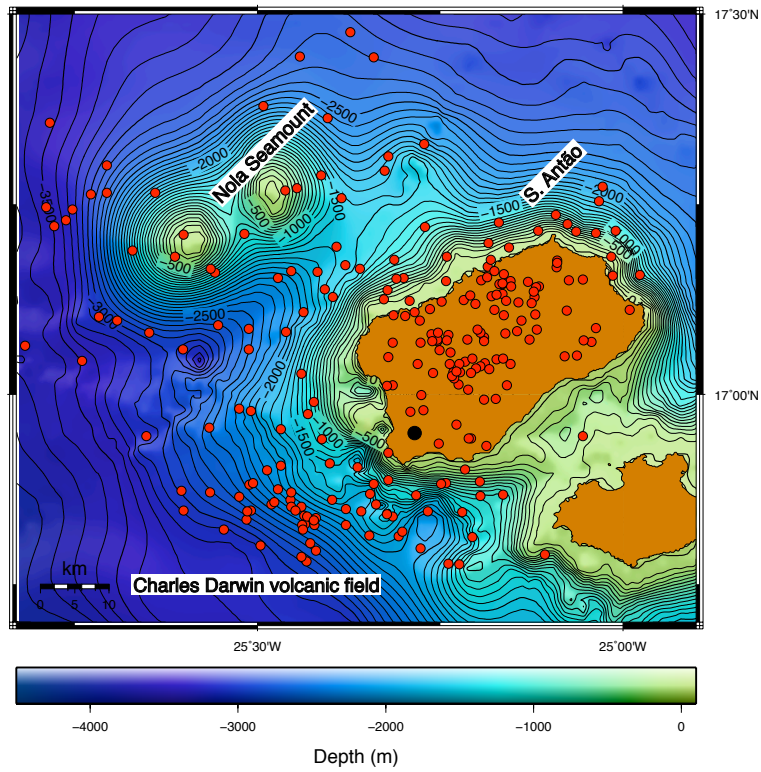


Fig. 12. Geographic distribution of the epicentres of the seismic events located both onshore and offshore of Santo Antão (red dots) and the epicentre of the first VT event of the 13 December 2011 crises (black dot).

5029

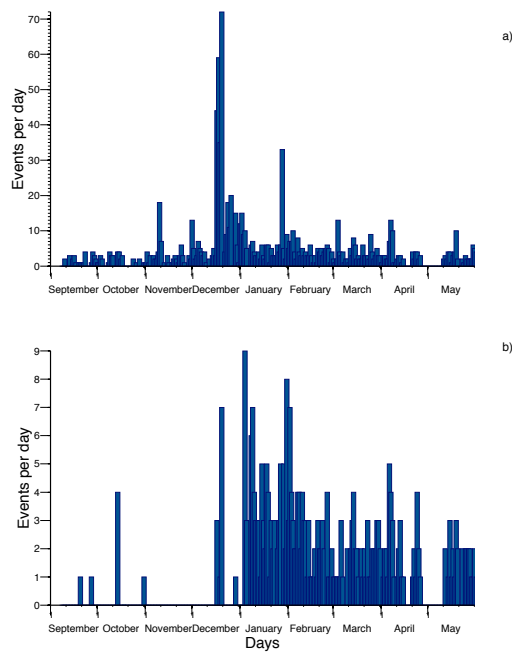


Fig. 13. Evolution of the seismic activity rate of Santo Antão: for volcano-tectonic events (a) and for medium frequency events (b).

5030

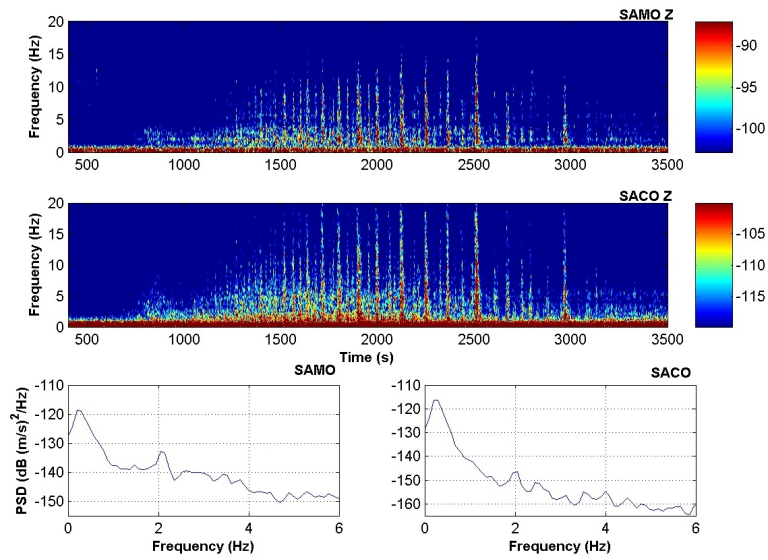


Fig. 14. Spectrogram (top) of 1 h windows of vertical component of ground velocity of seismic swarm recorded on 13 December 2011 between 18:40 and 20:00 UTC, and the power spectra (bottom) of 10 min time window before the swarm. It is visible a peak around 2 Hz.

5031

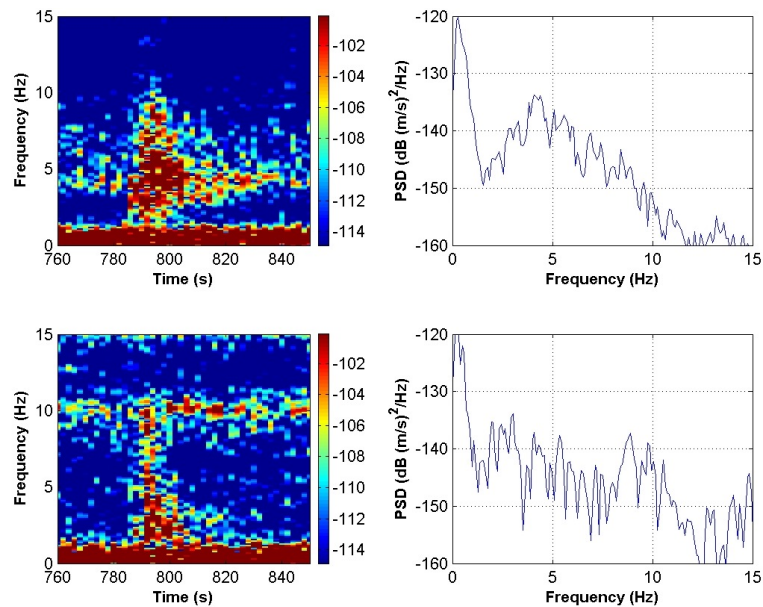


Fig. 15. Spectrogram (left) of vertical component of ground velocity of a medium frequency event recorded on 1 January 2012 at 00:12 UTC by SATA (top) and SAMO (bottom) and the power spectra (right) of the signal.

5032