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Journal of Volcanology and Geothermal Research 125 (2003) 39–56
Journal of volcanology and geothermal research
www.elsevier.com/locate/jvolgeores

Multiparameter monitoring of Fogo Island, Cape Verde, for volcanic risk mitigation

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Received 20 May 2002; received in revised form 14 January 2003

Abstract

Fogo Island in the Cape Verde Archipelago (North Atlantic) is a stratovolcano of nearly conical shape that rises 2829 m above sea level and ~6000 m above the surrounding seafloor. With a population of 40 000, the island has known intense historical volcanic activity since AD 1500, with an average interval between eruptions of the order of 20 years. Twentieth-century rates were more subdued, with only two flank eruptions in 1951 and 1995. Following the 1995 eruption, increased awareness of the volcanic hazard affecting the population of the island led to the deployment of the permanent VIGIL Network. Seismographic stations (both broadband and short-period), tiltmeters and a CO_2 sensor where installed in Fogo, together with a telemetry infrastructure to allow remote real-time monitoring. A broadband seismographic station was installed in neighbour Brava Island. The operation of the network was complemented by the introduction of routine geodetic and microgravity surveying and the operation of an automatic meteorological station. In this paper, we describe the methodology adopted to monitor the volcanic activity, combining real-time data analysis (volcanotectonic and volcanic earthquakes, volcanic tremor and tilt) with repeated surveying at intervals of several months (GPS, microgravity). Examples of data from the first years of operation are presented. In particular, the data pertaining to a period of anomalous activity in September–October 2000 are discussed, in the context of the risk mitigation strategy currently being developed.

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doi:10.1016/S0377-0273(03)00088-X

Keywords: Fogo Island; volcano; monitoring; eruption; forecast; hazard

1. Geological and structural setting

Fogo Island (15.0N, 24.5W), in the Cape Verde Archipelago, North Atlantic (Fig. 1), is an active stratovolcano rising 2829 m above sea level, surrounded by ∼3000-m-deep oceanic waters. The volcanic activity, located well inside the African plate, is due to hotspot magmatism under a broad lithospheric swell that reflects the low velocity of the plate relative to the mantle plume (Courtney and White, 1986; McNutt, 1988). The main structural characteristics of Fogo Island, which has an average diameter of 30 km, are the very steep slopes of its flanks and the presence of a lateral collapse scar (Day et al., 1999) forming a 9-km-wide hemicycle open towards the east at an average altitude of 1700 m (Fig. 2). The Bordeira scarp, that bounds the rim of the collapse structure to the north, west and south, rises sharply above the post-collapse sequence by as much as 1000 m. Although a date for the gravity-driven collapse is yet to be determined, a minimum age of 80 000 years can be roughly estimated (Day, in preparation), and post-collapse volcanic activity in Fogo has been restricted almost entirely to the interior of the caldera.

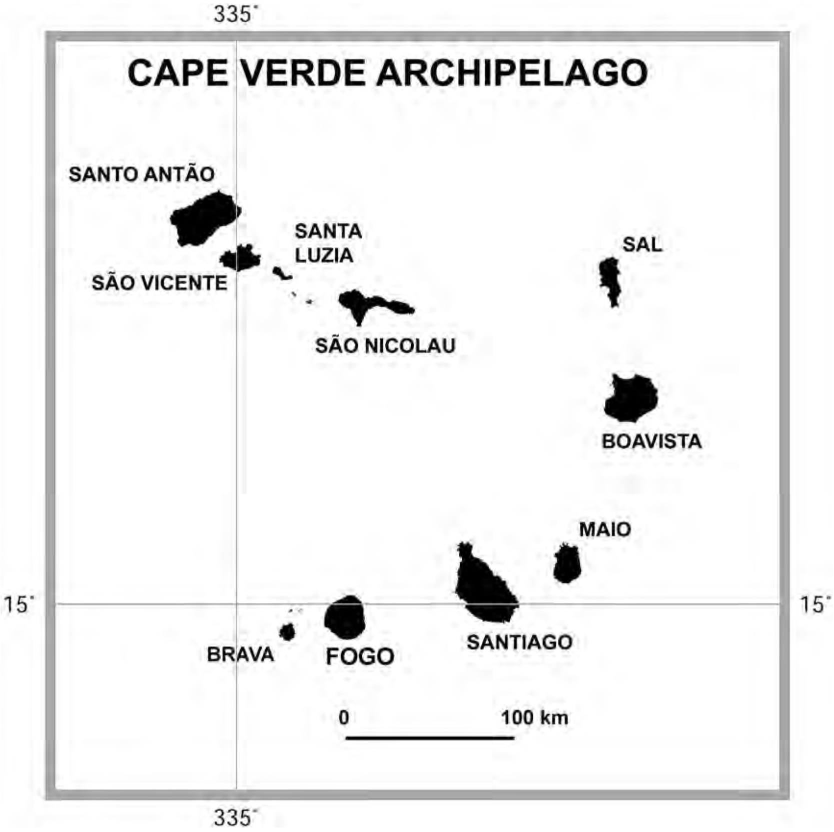


Fig. 1. The Cape Verde Archipelago, North Atlantic. Volcanic activity during the 500-year-long historical period is restricted to Fogo Island, whereas most of the seismic activity is concentrated in neighbour Brava Island.

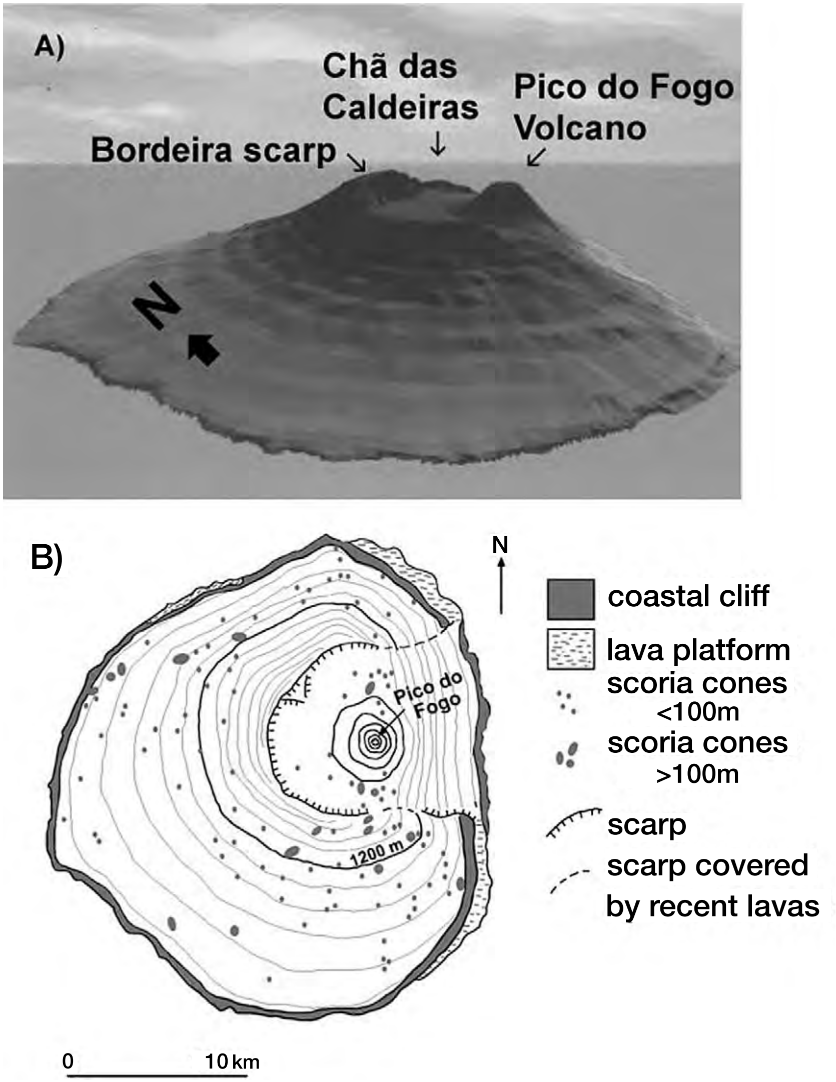


Fig. 2. (A) Digital elevation model showing the main structural features of Fogo Island. The Bordeira scarp reaches 1000 m above the flat Cha das Caldeiras plane (average altitude 1700 m). Pico do Fogo Volcano reaches 2829 m, the maximum altitude in the island. This geometry was interpreted as the result of a lateral collapse and subsequent eruptive activity by Day et al. (1999). (B) Structural sketch of Fogo Island, after Ribeiro (1960) and Day et al. (1999).

The few exceptions occurred along the rift zone that extends radially towards the SE (identifiable in Fig. 2 by the concentration of scoria cones), and more rarely in the NE and NW sectors of the island.

Brava Island, 20 km west of Fogo, shows geological evidence of Plinian volcanism, producing mostly phonolitic lavas and ashes, with a few basanitic scoria cones (Machado et al., 1968). Brava has higher seismic activity than Fogo and the level of magma differentiation indicates a shallow reservoir, but there are no reports of historical eruptions. Both islands are on top of the same submarine platform, made of alkaline intrusive rocks (nephelinic sienites and carbonatites), and there are grounds to admit that the two plumbing systems may have some degree of interconnection (Heleno and Fonseca, 1999).

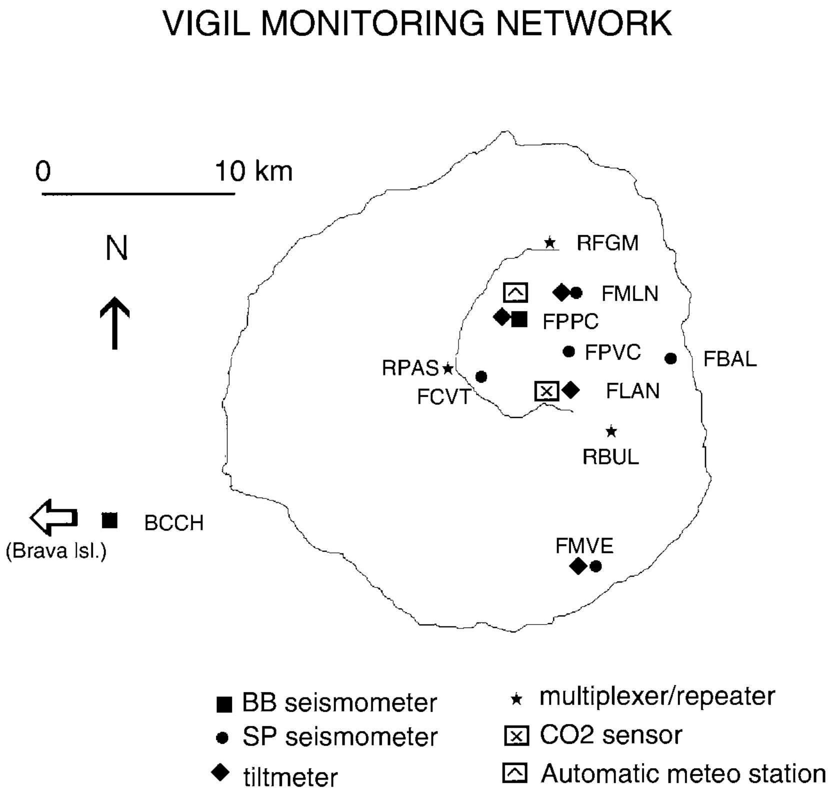


Fig. 3. Current configuration of the Fogo Volcano monitoring network.

2. Volcanic activity

Of the ten islands that make up the archipelago, only Fogo had eruptions after the arrival of the first settlers at the end of the fifteenth century. During the last five centuries, eruptions in the caldera, both through the summit of Pico do Fogo and through fissures near its base, have been reported with an average spacing of about 20 years (Ribeiro, 1960, Day et al., 2000). In the twentieth century events were more spaced, with only two strombolian flank eruptions in 1951 (Ribeiro, 1960) and 1995 (Heleno et al., 1999). Reports of summital eruptions were frequent until 1785, and since then the volcanic activity has consisted exclusively of fissure eruptions on the floor of the caldera. Erupted products are mainly basanites and nephelinites with almost no differentiation, and rare phonolites, tephrites and melilites (Assuncao, 1954; Machado, 1965a,b; Assuncao et al., 1967). Based on the abundance of pyroxene-rich xenoliths, Munha et al. (1997) propose a deep magma reservoir probably near the top of the mantle, with no significant shallow chamber.

Very little volcanotectonic seismicity is associated with the Fogo eruptions, and even lower levels are observed between eruptions. This is probably due to the lack of a shallow magma reservoir under Fogo (Day et al., 2000; Heleno, 2001). From twentieth-century evidence, the levels of seismic activity can remain extremely low up to the onset of eruptions, virtually without felt events, thus posing a major challenge to forecasting even at a very short time-range. In fact, both in 1951 and 1995 the initial explosions of the eruptions caught the population of the caldera by surprise. Assessing the evolution of pre-eruptive microearthquake activity is difficult because instrumental seismicity data prior to 1999 are only episodic. A temporary network deployed from January to April 1994 (Heleno and Fonseca,

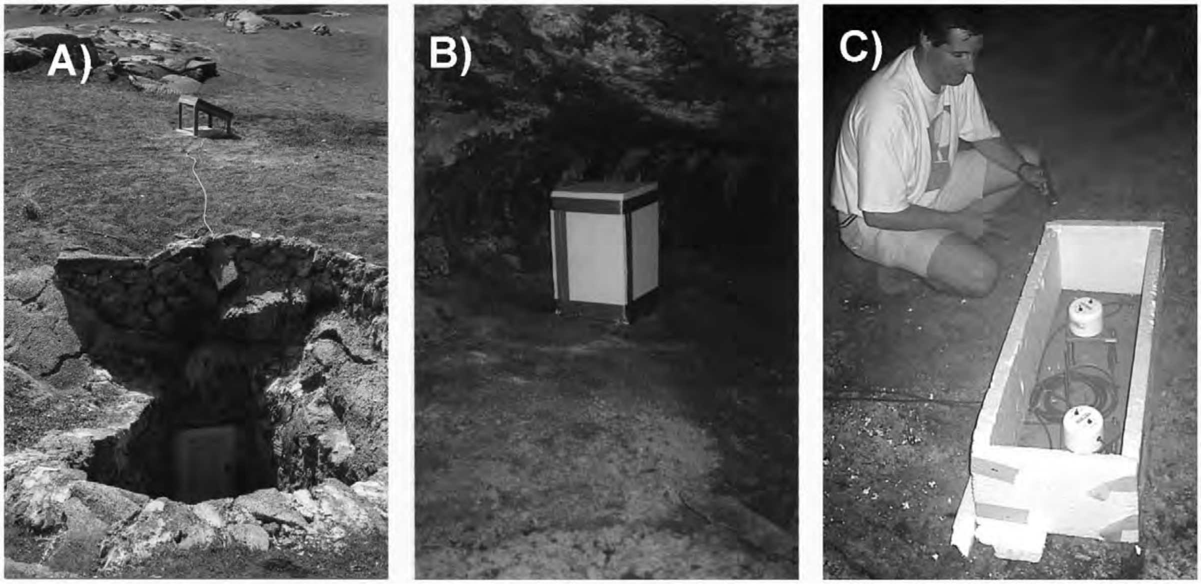


Fig. 4. (A) Entrance to the FPPC lava tunnel site. (B) Thermally insulated CMG-40T seismometer inside the lava tunnel. (C) A pair of bi-axial AGI701 tiltmeters installed inside the lava tunnel (in normal operation conditions the styrofoam box is closed).

1999) allowed the detection of significant volcano-tectonic activity underneath Brava and under the channel between Brava and Fogo, but virtually no earthquakes in Fogo. On the other hand, volcanic tremor was recorded in the Fogo caldera during that period. With the benefit of hindsight, a few volcanic earthquakes under the channel recorded at that time might have indicated lateral transport of magma between the islands from a deep magma chamber under Brava to a network of dykes under Fogo, in preparation of the 1995 eruption (Heleno and Fonseca, 1999; Heleno, 2001). But a correlation between the seismic crises in Brava and the eruptions in Fogo (Silveira et al., 1995) is not supported by the available macroseismic reports for the twentieth century (Heleno and Fonseca, 1999).

3. Volcanic hazard in Fogo Island

Published studies of the volcanic hazard of Fogo Island are non-existent. Torres et al. (1997) provide a map of historical lava flows, and Quental (1999) proposes a model for lava-flow simulation given the eruptive source. However, a thorough study of the volcanic hazard and risk is still to be accomplished, and only a rough overview will be given here.

Due to the concentration of volcanic activity inside the caldera and the natural protection provided by the caldera scarp, villages outside the collapsed zone have low levels of volcanic hazard. Only in one occasion (following the explosive eruption of 1680) was the population forced to flee Fogo, after intense ash-fall rendered the fields improper for agriculture island-wide (Ribeiro, 1960). The main towns in the east (Mosteiros and Cova Figueira) are protected by the topography from the products of summital or flank eruptions of Pico do Fogo (while exposed to lava flows from less likely vents on the SE rift or on the NE sector). Accordingly, volcanic hazard is mainly an issue inside the caldera and on the collapsed sector of the Eastern coast.

A population of 800 dwell in two villages inside the fertile caldera (a third village having been destroyed by the lava flows in 1995, without casualties). Here, effusive or mildly explosive flank eruptions such as those reported since 1785 do not pose great threat to human life, since the lava flows progress slowly in the flat grounds and allow evacuation. Damage to property and loss of agricultural land are therefore the main threats in that scenario. Pre-1785 style eruptions through the summit of Pico do Fogo, however, are a direct threat to the population of the caldera due to ballistic projection of piroclasts. Settlement of population inside the caldera dates from the late-nineteenth century, and the local culture regarding volcanic activity is based on the experience of the 1951 and 1995 flank eruptions only.

Several small villages on the eastern coast between the two E–W collapse scars can be reached within a short time (typically a few hours) by lava flows coming directly from the summit of Pico do Fogo or from the overspill of the flat caldera floor, due to the extreme steepness of the eastern flank, which reaches a maximum of 28° average slope. These villages are highly exposed to both summital and fissure eruptions, making the hazard in this zone the highest of the island.

4. The VIGIL Network

Due to increased awareness of volcanic hazard in Fogo Island following the 1995 eruption, it was possible to install and operate a network of instruments to monitor the inter-eruptive volcanic activity and detect significant deviations from the background levels (Project VIGIL). The goal of the project is to monitor remotely and in real-time volcanotectonic and volcanic earthquakes, volcanic tremor, short-term ground deformations and CO_2 concentration. In addition to the real-time monitoring, a network of 23 geodetic monuments was built (Berberan, 1997) to conduct GPS and microgravity surveys with intervals of the order of eight months, to detect long-term ground deformation and mass changes (Lima, 2001).

Fig. 3 shows the equipment currently in operation in Fogo and Brava islands, consisting of:

- two broadband triaxial seismic stations (CMG-40T), at FPPC and BCCH;
- five short-period triaxial seismic stations, at FMLN, FPVC, FCVT, FBAL, and FMVE;
- four bi-axial tilt stations (AGI701), at FMLN, FPPC, FLAN and FMVE.

Fig. 5. Telemetry shelter on the rim of the Bordeira scarp. Note the dramatic drop in the topography (the shoreline is visible behind the standing person, 1800 m below).

A CO_2 sensor (Zirox) was installed at a later stage in station FLAN, but due to data recovery problems this component of the monitoring will not be discussed. Whenever possible, the sensors were installed inside lava tunnels or natural caves, to achieve good environmental protection. The network was complemented by an automatic meteorological station (Opus2), recording air and

Fig. 6. Detail of a monument of the Fogo Geodetic Network. Forced centring is achieved with a WILD thread on a steel plate imbedded in cement. The inner concrete pipe is filled with reinforced concrete with a 1-m^3 foundation, and is separated from the outer pipe by fibreglass for thermal insulation (Berberan, 1997). Special care was taken to select geologically stable sites to build the monuments.

ground temperature, humidity, solar radiation, rainfall, wind speed and direction, as well as air pressure. A telemetry infrastructure based on spread-spectrum radio-links with three separate repeaters was installed to transmit the data in real-time over a distance of ~100 km to the central laboratory in the capital (Praia, Santiago Island). Additional facilities in Fogo Island include a shelter in the caldera with capacity for a crew of seven, a 4WD vehicle and a private VHF network for voice communication. Figs. 4 and 5 show examples of the instrumentation setup, and Fig. 6 shows a detail of a geodetic monument. Fig. 7 is the record of a quarry blast by the VIGIL seismographic network, which was used to calibrate the crustal velocity model in use for hypocentral locations.

5. Monitoring routine and strategy

5.1. Data processing and analysis

In the central laboratory (LECV headquarters, Praia) the real-time data are routinely inspected both in time and frequency-domain, to detect significant deviations from background levels of activity rates, volcanic tremor episodes or unusual deformations. Next, the data are stored on CDs for backup. Recent data (last 15 days) are mirrored in a communications-dedicated Linux PC to allow remote access from other participating laboratories. Further processing and analysis – hypocentral locations and magnitude estimates – are conducted at SNMG (S. Vicente Island), using the SEISAN software package (Havskov, 1995). Tilt data are treated in depth at the ECGS (Luxembourg). In addition, broadband seismic data are made available in real-time to the ORFEUS Data Center (The Netherlands) for global seismological cover.

5.2. Seismicity

Sustained volcanic tremor, related to fluid motion at the source (Chouet, 1985, 1996), is frequently recorded in Fogo and plays an important role in the monitoring strategy. High-frequency tremor (Fig. 8), typically above 10 Hz, is the most common observation, frequently recorded

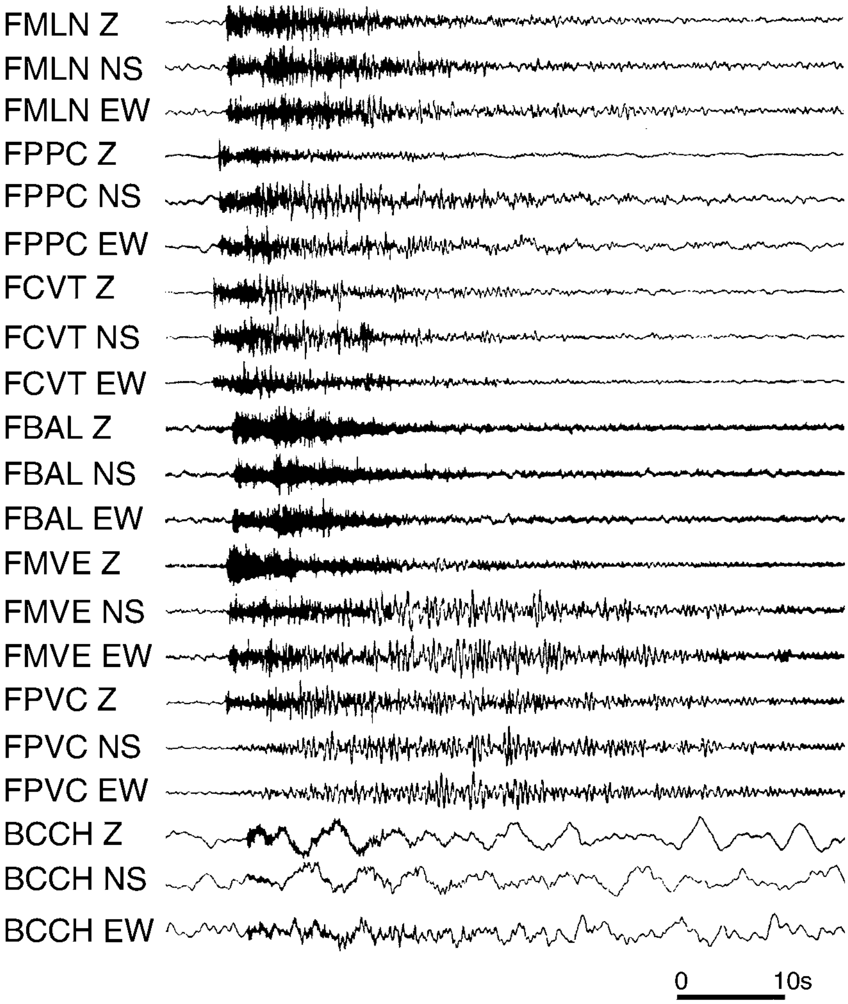


Fig. 7. Quarry blast (1.2 ton gelamonite) recorded in the VIGIL Network, which allowed the adjustment of the velocity model used for hypocentral location.

simultaneously at stations that are several (up to 15) km apart (Heleno, 2001). This is an unusual observation, since these frequencies are strongly attenuated in the crust and normally can only be recorded much closer to the source. For this reason, the mechanism of generation and propagation of this tremor is currently being investigated, and its monitoring is the object of particular attention. Sustained high-frequency tremor was observed also in 1994 (i.e. one year before the last eruption). While volcanotectonic earthquakes are extremely rare in Fogo (although frequent in Brava), long-period volcanic events with frequencies around 2 Hz are a common observation (Fig. 9). For the latter events, also associated with motions of fluids inside the conduits of the volcano (Chouet, 1996), source location is challenging due to the absence of clear phases. The wavelet transform (Chui, 1992) is being integrated in the analysis to circumvent this difficulty, with promising results. Taking advantage of the fact that the frequency content in seismic signals is not stationary in time and changes with the arrival of new phases, the wavelet transform of a volcanic earthquake record is inspected to identify changes in frequency that may be associated

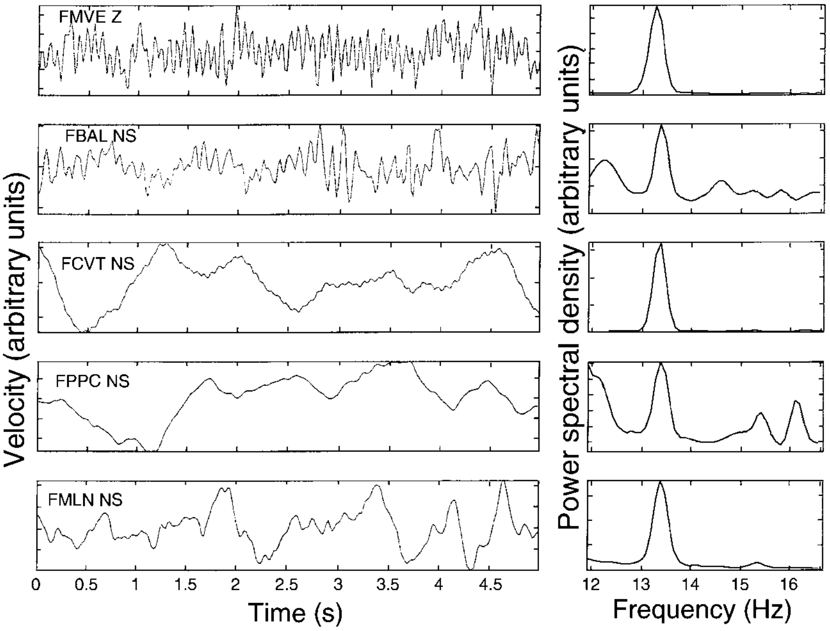


Fig. 8. High-frequency volcanic tremor recorded at several seismic stations of the VIGIL Network (maximum distance between stations of about 15 km). The power spectra on the right show a common peak at 13.4 Hz.

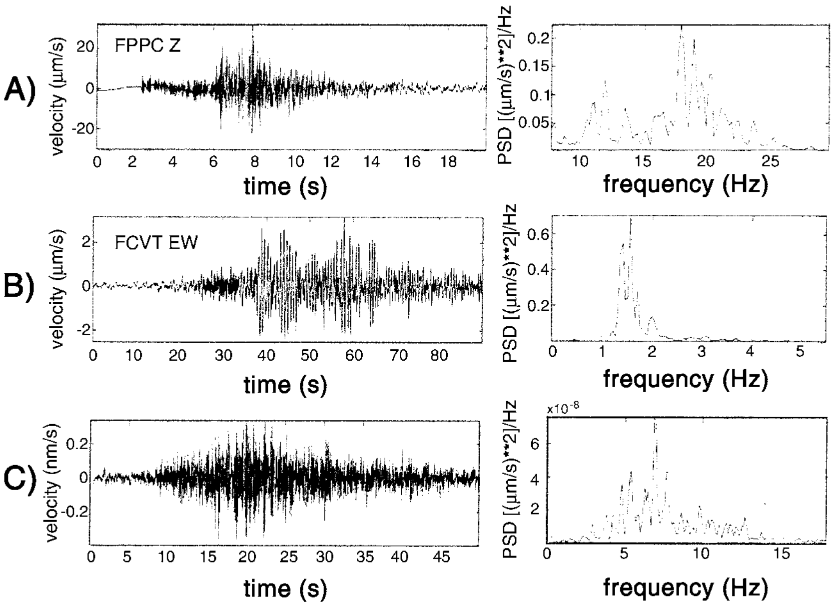


Fig. 9. Typical examples of seismic records from the VIGIL Network, and corresponding power spectra (spectral frequency resolution 0.008 Hz). (A) Volcanotectonic event near Brava Island, recorded at several stations of the VIGIL Network. (B) Long-period volcanic earthquake. A common observation in Fogo Island, these events are usually attributed to fluid motions at the source, hence their importance for volcanic monitoring. (C) Intermediate type of seismic event, sometimes described as 'cigar-shaped' in the literature (note different vertical scale).

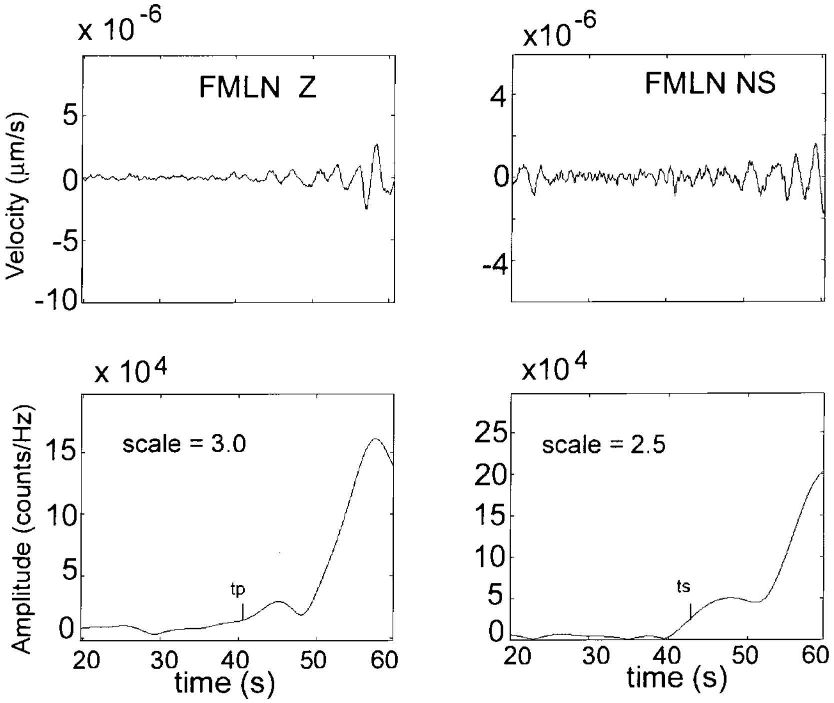


Fig. 10. The difficulty of identifying seismic phases in the emergent waveforms that characterise volcanic earthquakes may be attenuated with the use of the wavelet transform. Above are shown seismograms of a volcanic earthquake (vertical component to the left and N–S component to the right), and below the amplitude of the wavelet transform for a fixed scale, previously selected by inspection of the scalegram.

with the arrival of P (on the vertical component) and S phases (on the horizontal components). Once the frequency that best highlights a particular phase is selected, the amplitude of the wavelet transform for the corresponding scale is plotted as a function of translation, and the arrival is picked from the transformed trace (Fig. 10).

5.3. Tilt data

Bi-axial AGI701 tiltmeters with 0.005 µrad sensitivity were installed in pairs at each site, with a separation of the order of 1 m, to control the coupling between the instruments and the rock masses. Fig. 11 is an example of the quality control performed for the tilt data. Fig. 11A shows an example of data from a successful installation, with the parallel components of two separate sensors displaying the same behaviour over a period of 10 days (a similar agreement is also observed for seasonal variations). Fig. 11B shows a case of defective coupling: on the left side of the traces (3 first days) the two instruments show opposition of phase in the daily variation, but the teleseismic record shown in Fig. 11C (M7.1 New Zealand earthquake of 21 August 2001) does not show a reversal of polarity. On the right side of the traces (last 3 days) the daily variation is recorded in phase by the two sensors. As a result, this site was abandoned. Similar analyses were conducted for the long-term seasonal behaviour of the instruments. Besides signal quality control, current research is focused on the characterisation of environmental effects on tilt observations, using temperature, atmospheric pressure, rainfall and several other meteorological variables that are also recorded (D’Oreye, 2001). Fig. 12 shows several days of tilt data from a lava tunnel (two upper traces) in conjunction with meteorological variables. The fourth trace from the top is the temperature 40 cm below the surface (at the meteo station, ~1000 m from the tilt station), and

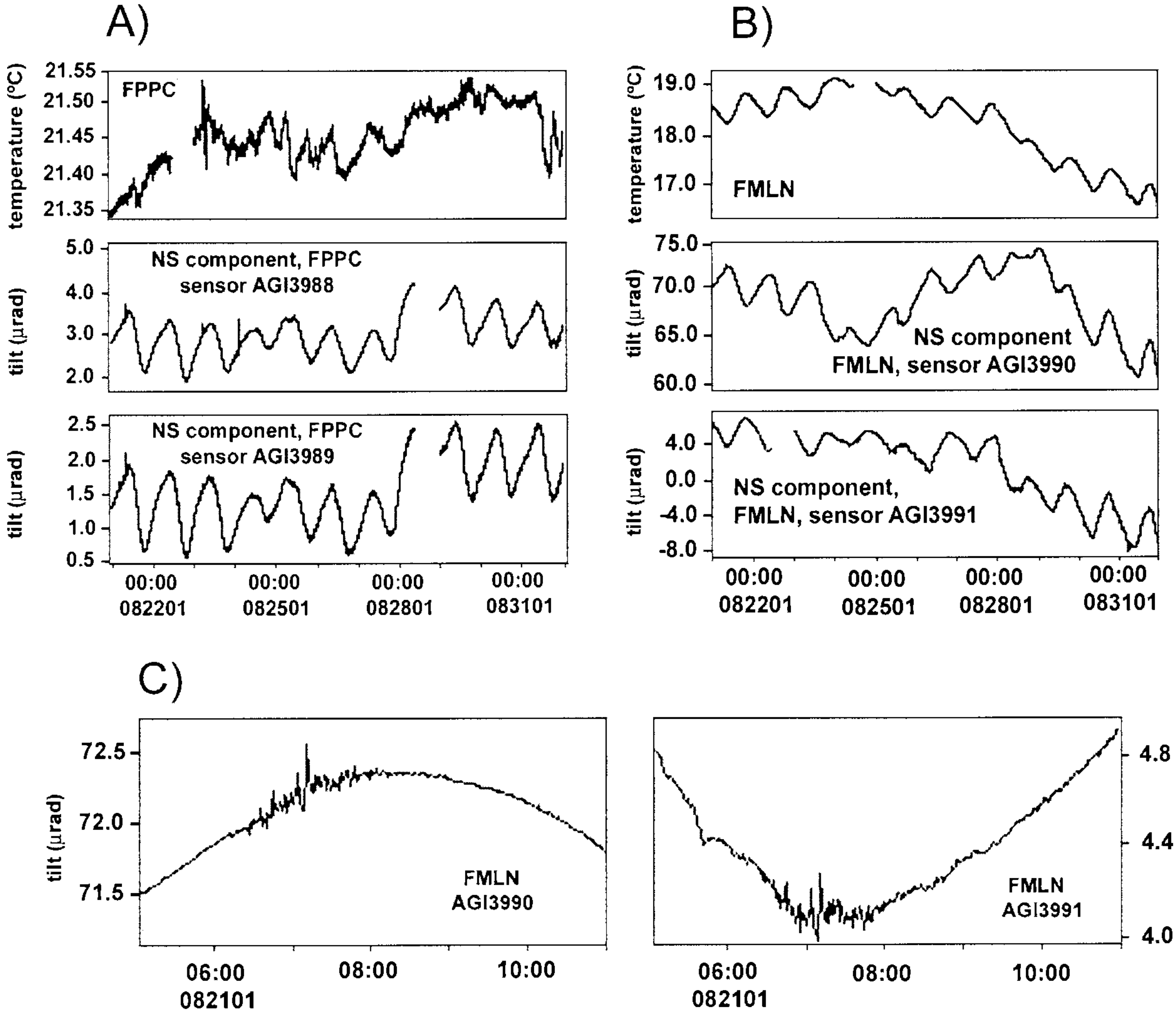


Fig. 11. Quality control of mechanical coupling between the tiltmeters and the bedrock, done by comparison of two time series acquired at close spacing (~1 m) by two sensors oriented in the same direction. (A) Adequate coupling, revealed by consistent signals from the two sensors. Temperature close to the sensor is shown in the top trace. (B) Deficient coupling between tiltmeter base and bedrock, evidenced by temporal changes in phase relation between adjacent and parallel sensors. During the first four days, the two traces are in phase opposition; during the last three days the traces are in phase. The change in response may be controlled by the temperature range (top trace). (C) The complexity of tilt recording is documented by this detail of the traces shown in (B): the long term behaviour of the signal shows opposition of phase, but the earthquake is recorded in phase.

shows the best correlation with the tilt. The lack of sunshine on 9 June 2001 allows the analysis of the phase relations between traces: the tilt signal lags behind the insolation, but is ahead of the temperature at 40 cm depth, despite the fact that the tiltmeters are a few metres deeper. The temperature inside the tilt station (third trace from top), on the other hand, is poorly correlated with the tilt signals. These observations show that the usual daily tilt variations are mainly driven by the thermoelastic stress (the thermal effect on the surrounding medium), although ocean loading is expected to play also a role. Finally, the important point that heavy rainfall on 9 August 2001 (bottom trace) had only a minor impact on the tiltmeter readings.

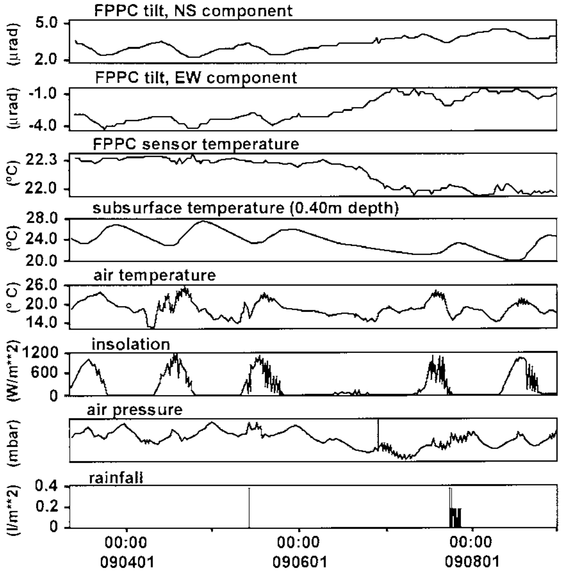


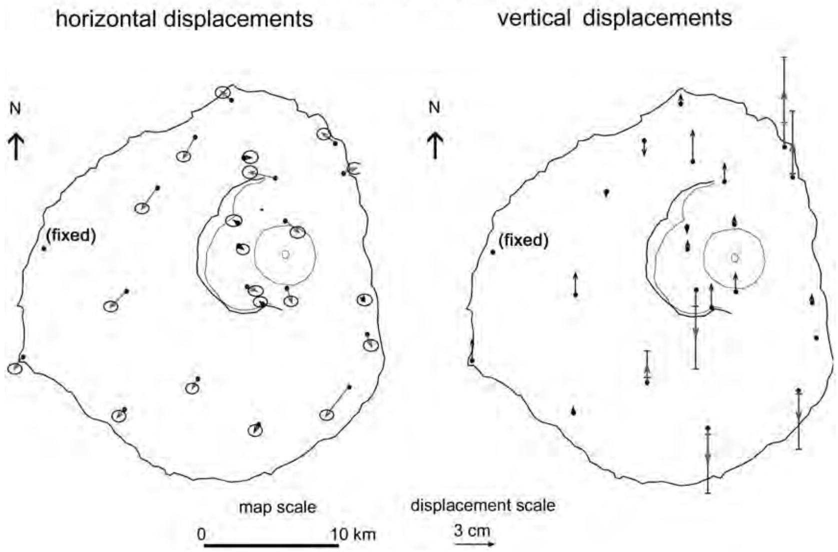
Fig. 12. The recording of meteorological data allows the characterisation of the effect of environmental parameters on the tilt data. Top two traces are N–S and E–W tilt at the FPPC site (Cha das Caldeiras), and the remaining traces are: air temperature inside the tunnel, soil temperature (measured 40 cm below surface), external air temperature, solar radiation, air pressure and precipitation. The lack of sunshine on 6 September 2000 allows the analysis of the phase relations between traces, showing that the tilt signals lag behind the solar radiation by several hours, but are ahead of the soil temperature. Intense rainfall on the 7 September 2000 (total of 16.2 l/m^2 in 3 h and 15 min) did not have a significant impact on the tilt data.

5.4. GPS and microgravity

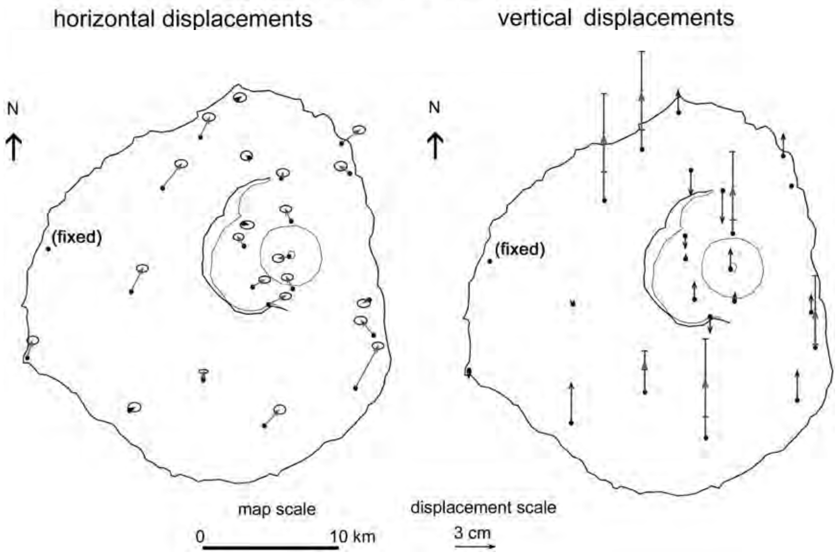
Whereas changes in level and type of seismicity and localised surface deformation detected with tiltmeters are useful for short-term eruption forecasting, deformation processes over broader space scales, which can be related to the inflation of magma reservoirs at depth, may predate the eruption by longer intervals of time, typically months. These can be conveniently studied with geodetic methods, and GPS surveying has become a common tool for long-term volcanic monitoring (Dvorak, 1993). Between September 1998 and January 2001 a total of five GPS campaigns were conducted in the Fogo geodetic network, each involving the use of seven Trimble 4000 receivers (Fonseca et al., 1998; Lima, 2001). Two monuments were surveyed continuously during the nine days of campaign, and the remaining stations were occupied three times each, with the duration of 2.5 h per session. Inter-survey displacement solutions were obtained with the Bernese IV software imposing a fixed station near the western coast (taken as more stable in view of the geology). The formal uncertainties were scaled up using the scatter of daily solutions.

Fig. 13 shows examples of inter-survey displacements, indicating that significant vertical and horizontal displacements are a common observation and occur in complex patterns. Both deflation episodes (April–November 1999) and inflation episodes (November 1999–June 2000) were interpreted. In general, it can be stated that the patterns of displacement reflect the major structural feature of the island, the Bordeira scarp, which appears as a zone of horizontal divergence when the vertical displacements are mainly downward (Fig. 13A), and as a zone of horizontal convergence when the upward displacements dominate (Fig. 13B). This supports the interpretation of the scarp as part of a weak detachment zone associated with the lateral collapse (Day et al., 1999). Since all observed displacements are relative (due to the fixed station condition), the statements on the dominant direction of vertical movement are based on the assumption that the western flank of the island is stable.

The interpretation of GPS displacements is easier when made in conjunction with microgravity variations, providing indication on subsurface mass and density changes. Fig. 14 shows examples of comparison between vertical displacements (relative to the westernmost station of the island) and variations of g between surveys. The two straight lines through the centre of the graph correspond to the free-air gravity gradient and Bouguer-corrected free-air gravity gradient. A variation of the height of the gravimeter between surveys causes a variation of g given by the free-air line, if only the change of distance to the Earth's centre is considered, or by the Bouguer-corrected line if the gravitational pull of the constant-thickness 'layer' added by the uplift or removed by the subsidence is also included in the calculation. Points plotting significantly away



A) April 1999 to November 1999



B) November 1999 to June 2000

Fig. 13. Examples of inter-survey displacements detected in the Fogo geodetic Network. A point close to the western coast was fixed arbitrarily.

from those lines and towards the up and right sides of the diagram indicate that mass was added or density increased in the region affecting the measurement; conversely, points deviating significantly towards the left and lower parts indicate loss of mass or reduction of density (Berrino et al., 1992; Williams-Jones and Rymer, 2002). The data in Fig. 14A) do not indicate significant mass or density variations. But Fig. 14B) documents a significant increase of mass or density in the shallow crust underneath the SE sector of the island and inside the caldera in the time interval between

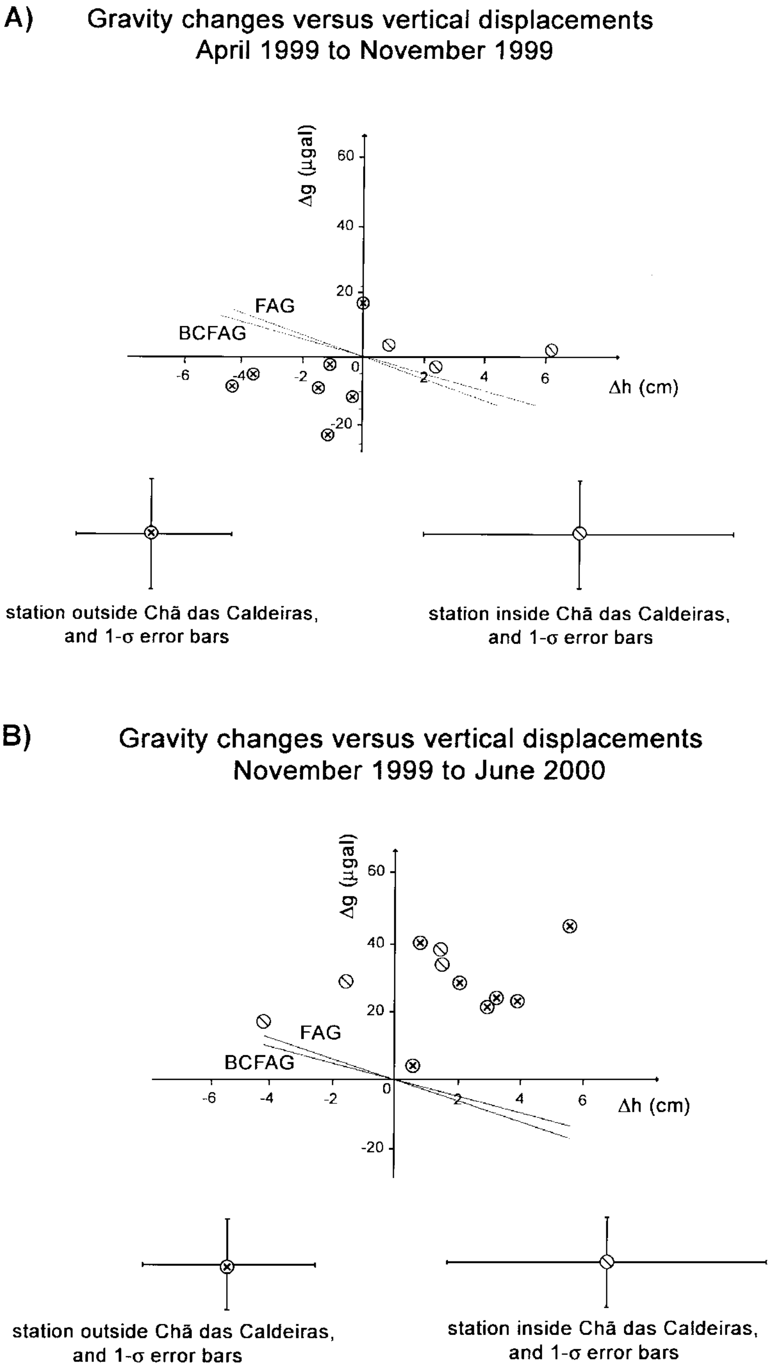


Fig. 14. The joint analysis of elevation changes and gravity changes between surveys allows a better insight into the mass or density changes taking place below the surface. Symbols with a cross and a diagonal correspond to geodetic monuments and (less reliable) levelling benchmarks, respectively. Only one pair of error bars is shown for each type of data point, for simplicity. (A) The points are within one error bar from the free air gradient line, and no significant mass or density change can be inferred. (B) Most points plot significantly above the free air gradient line, indicating an increase of mass or density under the surface.

the two surveys, adding a new meaning to the interpreted inflation.

5.5. Visual observations by local staff

LECV hires a supervisor and several guards who reside permanently in the vicinity of the volcano and report any unusual observations or occurrences to the central laboratory.

6. The September 2000 crisis

The methodology implemented to monitor Fogo Volcano was put to the test at the end of September 2000, when a series of anomalous signals were recorded in the VIGIL Network. The main observations were:

- anomalous surface deformation recorded in two tiltmeter stations, FPPC and FMLN, from 27 to 29 September 2000 (Fig. 15), the distance between the two stations being about 3 km;
- episodes of very strong sustained seismic signal recorded at station FBAL, in the east flank of

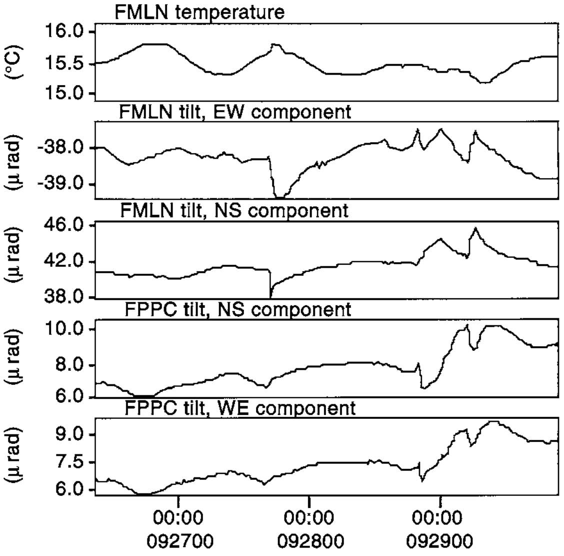


Fig. 15. Anomalous tilt and temperature data recorded at two separate sites in Cha das Caldeiras from 27 to 29 September 2000.

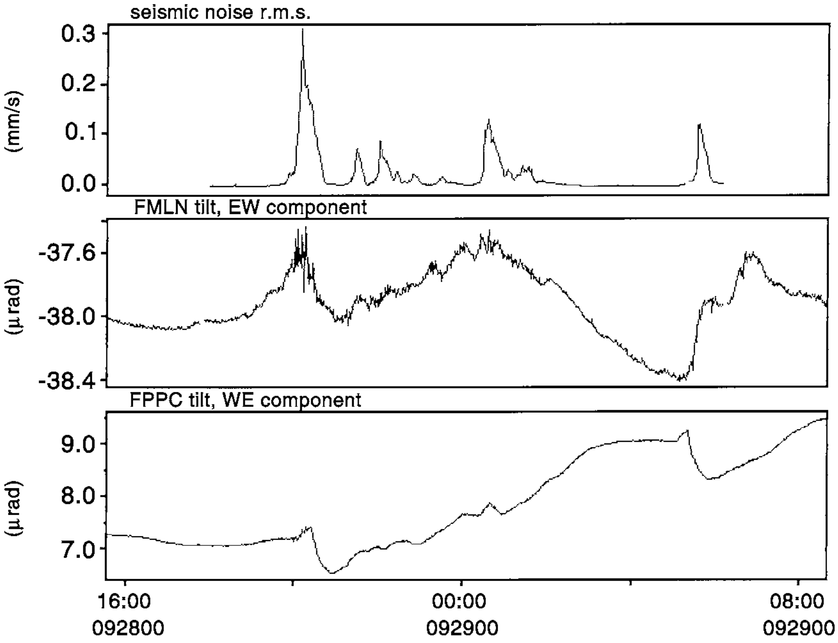


Fig. 16. Anomalous tilt data recorded on 28 and 29 September 2000 at two separate sites, and comparison with the r.m.s. seismic noise (top trace). The r.m.s. was computed on a 2-min-long window, moving with a time-step of 1 min.

the island, correlated with surface deformation at FPPC and FMLN (Fig. 16);

- on a longer time scale, the GPS-microgravity results for the period September 1999–June 2000, indicating that during that time interval magma had been stored at shallow levels in the plumbing system.

In addition, an earthquake was felt inside the caldera on 20 September 2000, and a questionnaire revealed a very localised felt area, suggesting a shallow focus (this event was not recorded due to a mains power failure at the central laboratory). Also, in mid-September 2000 an unusual sulphurous smell was reported on the SE rift zone (outside the caldera). Due to the convergence of independent indications pointing to shallow magmatic activity, a warning of increased probability of eruption was issued to the authorities on the 29 September 2000, according to the following chain: project coordinator > director of the Laboratory for Engineering of Cape Verde > Head of the National Civil Protection Service > Minister of Defence and Regional Civil Protection Service. The anomalous activity lasted until 30 September 2000, when all the observations subsided and eventually returned to the background values. On 2 October 2000, the crisis was interpreted as a shallow magma intrusion that had been accommodated without reaching the surface, and the warning to the authorities was withdrawn. The subsisting indications of magma storage given by the long-term GPS-microgravity observations correspond to a level of concern that is managed internally by the project's team, and the warnings to the authorities are issued only in the combined presence of short-term indicators such as anomalous tilt or increased long-period earthquakes or tremor.

7. Discussion

The experience gained in the first years of monitoring Fogo Volcano confirms the widely accepted idea that only through the integration of different types of data can some insight be gained about the evolution of a volcanic system. Broadband seismic data have proved very useful in the detection and study of sustained volcanic tremor and long-period volcanic events, important indicators of magma or gas movements under the surface. While tiltmeter observations provided an effective means of quickly detecting anomalous surface deformation, great care had to be exercised in the selection of sites and quality control of the data, due to mechanical coupling problems that are likely to occur in a heterogeneous medium such as a stratovolcano. Joint GPS and microgravity surveying can provide important information on the evolution of the volcanic system on the time scale of several months to one year. But ground deformation monitoring could be substantially improved by the introduction of continuous GPS and InSAR.

One of the main lessons from the operation of the VIGIL Network concerns the need to record meteorological data together with the geophysical data. In particular, the interpretation of tiltmeter data must be made in conjunction with meteorological data, because at 0.005 μrad sensitivity the variations of environmental parameters are reflected on the data. This corresponds to real deformations in the region around the site and not to the direct effect on the sensor, and therefore cannot be eliminated completely by the selection of well-insulated sites.

In hindsight, the inflation recorded by the GPS surveys from November 1999 to June 2000, and the accompanying mass/density increase recorded by the gravity surveys, may be regarded as a medium-term precursor to the September 2000 crisis. Whilst continued observation of the volcano over a period of years will be required to establish the true significance of these observations, the events pointed out the value of combining continuous-monitoring techniques with the long-term data provided by epochal geodetic and gravity surveys.

The anomalous observations of September 2000 coincided with the rainy season in Fogo Island, and in the absence of remotely-accessible information about the weather conditions (the meteo station having been installed in the Summer of 2001 only) the ambiguity subsisted as to whether a storm could be responsible for such signals. In particular, the episode of very strong seismic noise shown in Fig. 16, recorded on the steep eastern flank of the volcano, could be due to transient waterfalls near the seismic station. However, the anomalous tilt recorded simultaneously at FMLN and FPPC led us to dismiss that interpretation. Alternatively, the observations could point to an interaction between the gradually recharging aquifers and shallow magma.

Acknowledgements

This research was supported by the Portuguese government through FCT (Programme PRAXIS, Contracts PCNA/C/CTE/25/96 and P/CTE/12269/1998), and ICP. Further support was granted by the Gulbenkian Foundation (Lisbon), the ECGS (Luxembourg), the Ministry of Foreign Affairs and Cooperation of Luxembourg, and the NGO 'Amities Luxembourg Cap Verd'. S.I.N.H. acknowledges a post-doctoral grant from FCT, and B.V.E.F. acknowledges a Ph.D. grant from GRICES (Lisbon). Peggy Hellweg and Horst Rademacher (Geo Enterprises Orinda) assisted in site selection and instrument testing, and Gilles Celli (ECGS) provided informatics expertise. L. Fisher helped with the shot-point recording of the quarry blast in Fig. 7. Susana Vilanova and Paulo Rodrigues participated in the deployment. Two anonymous reviewers helped improve the manuscript, and Michele Soares assisted with the production of the figures. The authors are indebted to Teresa Leyens (Fogo Natural Park) for her continual support. Our thanks go also to the staff of LECV, Praia, for their support, and to the population of Cha das Caldeiras for their hospitality.

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