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SITE CHARACTERIZATION OF A VOLCANIC CRATER IN TERCEIRA ISLAND - AZORES

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ABSTRACT

The Azores archipelago is located at the North America, Eurasia and Africa triple junction showing high seismicity and volcanism typical of an active plate boundary. Terceira Island has been affected by several damaging earthquakes and the 1980 January 1st earthquake (M= 7,2) was the strongest in Azores during the last century.

The São Sebastião volcanic crater, located at the SE end of Terceira Island (Azores), is characterized by an amplification of ground movements inside the crater with respect to the surrounding area. Inside this volcanic crater, with an average diameter of 1100m and a depth of about 50m, is located the village of São Sebastião that has shown an anomalous seismic behaviour in a more local expression during the last earthquakes. The local geology and geotechnical characteristics of the soil deposit play a strong role in the seismic ground shaking at the site.

Some previous studies were performed (geological and geophysical) but the information is merely qualitative, so it was not possible to have a rigorous and well-defined model of the crater.
The geological knowledge and interpretation of this volcanic area is a very important aspect in the detailed definition of the internal structure of the crater. A recent geological survey added new information that allows a better comprehension of the damage distribution during the earthquake of 1980. Also the detailed analysis of the accelerograms at some strong motion stations located within the São Sebastião Village (although induced by small earthquakes) show well-different site effects within the crater.

Keywords: Azores, volcanic crater, site characterization, geological interpretation, site effects

INTRODUCTION

The Azores archipelago is located in the middle of the Atlantic Ocean at the North America, Eurasia and Africa triple junction; the Mid Atlantic ridge separates the American plate from the others, while the Azores-Gibraltar fault zone is the boundary between Eurasia and Africa (Figure 1). The central group of the Azores islands, as the eastern, are on a broad sheared region, sometimes called Azores microplate, which absorbs the deformation induced by the eastward differential displacement of the Eurasia and African plates, east of the Azores triple junction (Figure 1). The deformation is represented by a widespread active faulting of the islands and surrounding seafloor (Madeira & Brum da Silveira, 2003). The high seismicity and volcanism of this area is due to its location on an active plate boundary.

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This paper focuses on the area of São Sebastião, located in the south-eastern side of Terceira Island in the central group of the archipelago (Figure 2).

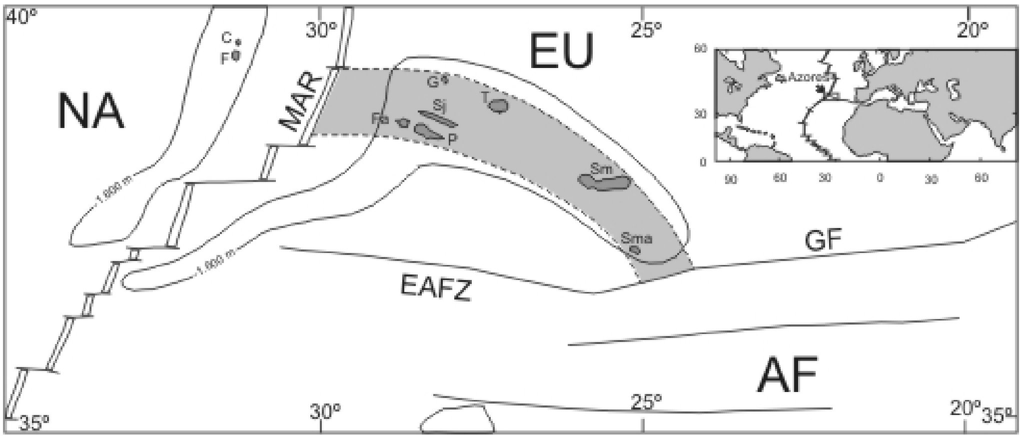


Figure 1. Location of the Azores Islands in the Atlantic Ocean and their tectonic setting (in: Madeira & Brum da Silveira, 2003): NA – North American Plate; MAR – Mid Atlantic Ridge; EU – Eurasian Plate; AF- African Plate; EAFZ – East Azores Fault Zone; GF – Gloria Fault. Azores Islands: C- Corvo; F- Flores; G- Graciosa; T- Terceira; Sj – São Jorge; Fa– Faial; P – Pico; Sm- São Miguel; Sma – Santa Maria

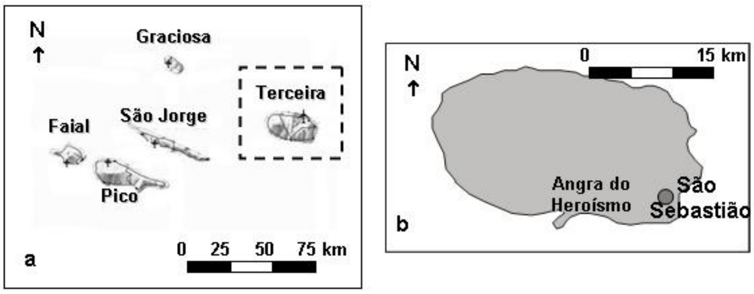


Figure 2. Location of São Sebastião area: a. Central Group of the Azores Archipelago; b. Terceira Island

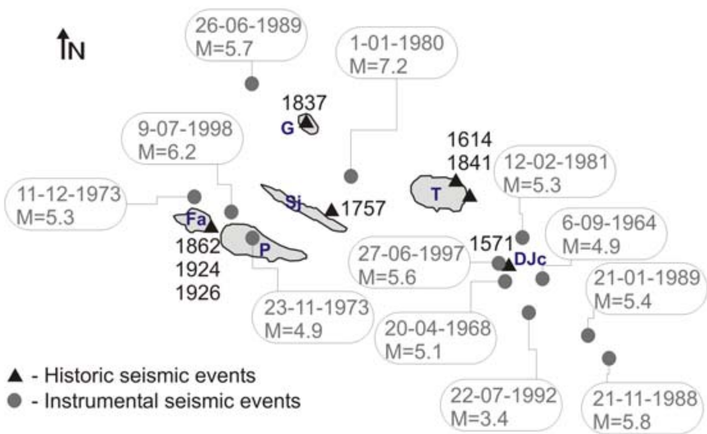


Figure 3. Schematic epicentral map for some of the main tectonic events in the central group of the Azores archipelago (adapted from: Madeira & Brum da Silveira, 2003; Nunes et al., 2004): G- Graciosa; T- Terceira; Sj – São Jorge; Fa– Faial; P – Pico; DJc – D. João de Castro bank

The central group has felt in the historical times the effects of several seismic events, usually low to moderated events or swarms, but occasionally some with magnitude near 7 (Tables 1 and 2, Figure 3). The last large earthquake, named the Terceira earthquake, occurred on January 1st 1980 with magnitude M=7,2 (Hirn et al., 1980) and showed that the seismic response of the São Sebastião volcanic crater, is characterized by an amplification of ground movements inside the crater with respect to the surrounding area (Figure 4).

Table 1. Historical tectonic seismicity in the central group of the Azores archipelago (adapted from: Madeira & Brum da Silveira, 2003)

Date	Location	Intensity	Estimated Magnitude	Effects of the earthquake
June-July, 1571	D. João de Castro Bank	VI/VII		seismic swarm
May 24, 1614	Terceira	X/XI; VIII	>6,3	> 8km of surface rupture on Lages fault; 93 deaths
June 9, 1647	Terceira	V/VII		
March 29, 1960	Central group	V		alternative date is April 5, 1690
Nov. 15-25, 1698	Terceira	IV		seismic swarm
July 9, 1757	São Jorge	X/XI	7,1;7,4	deaths: 1034 in São Jorge; 11 in Pico. Small tsunami observed
Dec. 1759 to May 1760	Faial	VI		seismic swarm
August, 1791	Terceira	IV/V		
January 21, 1837	Graciosa	VIII; IX		probable rupture in Serra das Fontes Fault; 3 deaths
June 15, 1841	Terceira	X/XI; IX		> 1km of surface rupture in Cruz do Marco fault ; 5500 homeless
Sept. 21 to Dec.10, 1862	Faial	V/VI		seismic swarm
March 16, 1920	Faial	V		
February 9, 1924	Faial	V/VI		
August 31, 1926	Faial	VIII/IX; X		8 deaths

Table 2. Some of the more important instrumental seismic events for the last century (adapted from: Madeira & Brum da Silveira, 2003; Nunes et al., 2004)

Date	Location	Magnitude
Sept. 6, 1964	38.3N-26.6W	4.9
April 20, 1968	38.3N-26.77W	5.1
Nov. 23, 1973	38.52N-28.37W	4.9
Dec. 11, 1973	38.7N-28.7W	5.0
Jan. 1, 1980	38.82N-27.78W	7.2
Feb. 12, 1981	38.5N,26.7W	5.3
Nov. 21, 1988	37.9N-26.2W	5.8
Jan. 21, 1989	38.04N-26.28W	5.4
June 26, 1989	39.23N-28.34W	5.7
July 22, 1992	38.15N-26.65W	3.4
June 27, 1997	38.19N-26.84W	5.5
July 9, 1998	38.67N-28.52W	5.7

Inside this volcanic crater is located the village of São Sebastião that has shown an anomalous seismic behaviour in a more local expression, because some areas of the village have usually suffered more damage than others in the last earthquakes (Figure 5).

During the last years some efforts have been made to understand the different site-effects occurred in the village. Some previous geological and geophysical studies were performed, (Malheiro, 1998; Nunes, 2000; Senos et al., 2000; Montesinos et al., 2003) but the information is merely qualitative, so it was not possible to have a rigorous and well-defined model of the crater. The results obtained by Lopes (2005) identified some remarkable differences in the soil velocity profile within the crater.

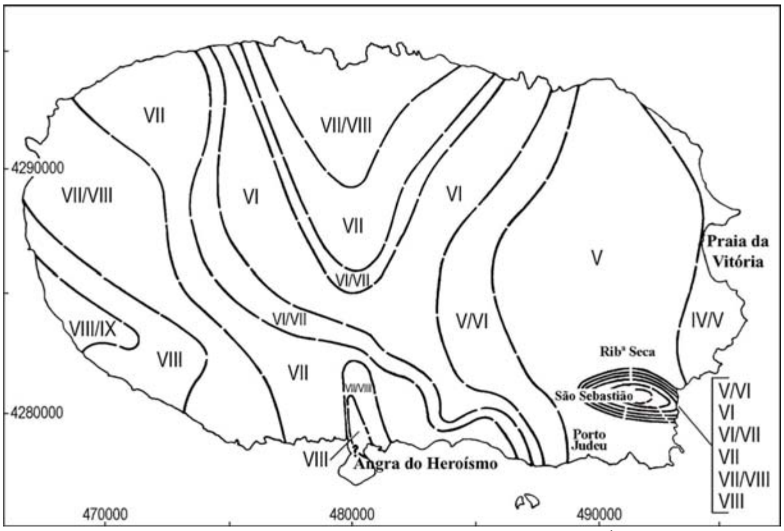


Figure 4. Isoseismic map of Terceira Island during the January 1st 1980 earthquake, showing the intensity anomalies (MM) in São Sebastião village (in: Montesinos et al., 2003)

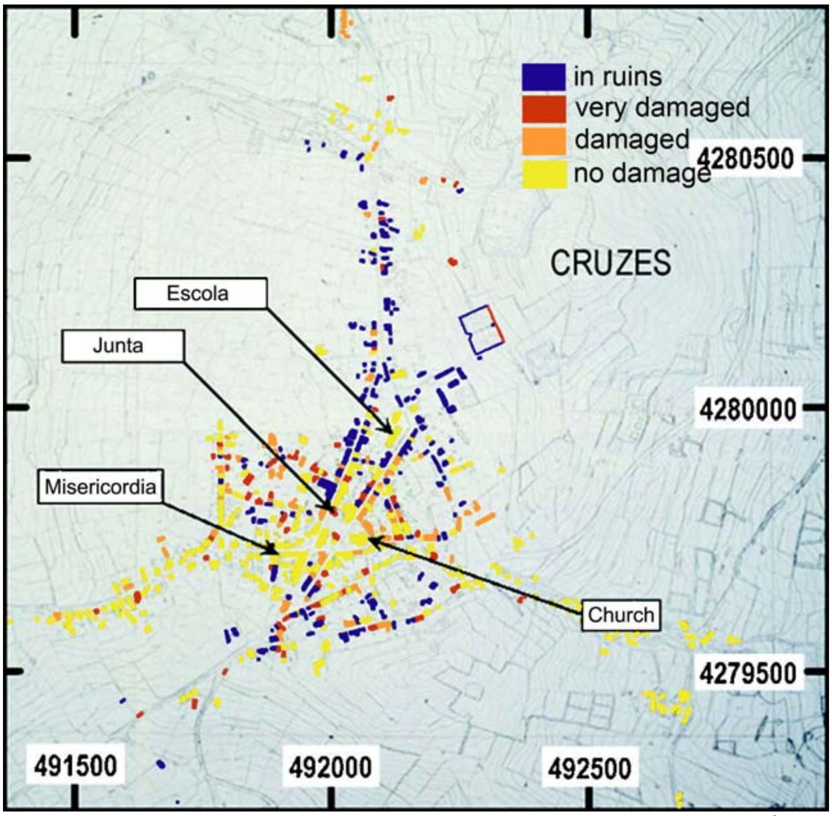


Figure 5. Distribution of damage in São Sebastião village for the January 1st 1980 earthquake, showing the location of the strong motion stations and of the church in the village main square (in: Montesinos et al., 2003)

The geological information and interpretation of this volcanic area is a very important aspect in the detailed definition of the internal structure of the crater, which will allow to study and to understand the site effects.

The comprehensive analysis of accelerograms recorded at 3 strong motion stations located within the São Sebastião Village, induced by small earthquakes felt in 1997 and 1998, show differences in behaviour within the crater compatible with the damage distribution of the 1980 earthquake.

Some new insights come from a recent geological survey that added information allowing a better comprehension of the damage distribution during the earthquake of 1980 and of the differences in amplification recorded within the crater.

SÃO SEBASTIÃO GEOLOGICAL SETTING

Terceira Island grew from E to W, starting during beginning to middle Pleistocene, and is composed by four major strato-volcanoes: the oldest structure is the Serra do Cume-5 Picos volcano, after in central position in the island it is possible to find the Guilherme Moniz and Pico Alto volcanoes and in the western area the Santa Bárbara volcano (Lloyd & Collis, 1981; Montesinos et al., 2003; Madeira, 2005). There is a basaltic fissure zone that crosses the island and that along with the Pico Alto and Santa Barbara volcanoes are thought to be still active (Madeira, 2005).

The volcanic products extruded are very variable and include ignimbrites, pyroclastic and pumice deposits, basaltic, andesitic and trachytic lava flows, scoria, tuffs, among others (Lloyd & Collis, 1981; Montesinos et al., 2003, Madeira, 2005).

São Sebastião crater has an average diameter of 1100 m and a depth of about 50 m. The detailed volcanological map of São Sebastião and surrounding area was made by Nunes (2000). A simplified version of the map is presented in Figure 6, which shows that the geological formations of the area have mainly basaltic composition. Nunes (2000) showed that in the northern side of the crater rim cuts basaltic lava flows while in the southern part is identified a *lahar* deposit. The eastern side of the crater shows a scoria cone (Monte das Cruzes) and inside (SE side) there is an outcrop of basaltic lavas, of the same nature as the ones that appear on the NW-W side. The depression is filled mostly by slope deposits of different nature and composition and by fluvial deposits.

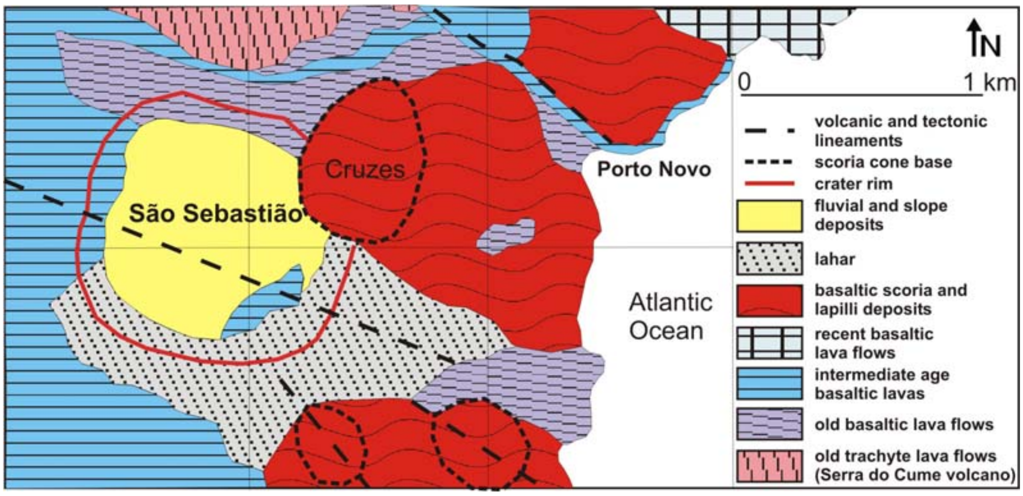


Figure 6. Simplified volcanological map of the São Sebastião area (adapted from Nunes, 2000)

While there is generally agreement on the type of the geological materials found in the São Sebastião area, the nature of depression is still under discussion. Montesinos et al. (2003) propose a pit crater structure for the area while Madeira (2005) agrees with the idea proposed by Lloyd & Collis (1981) of a phreatomagmatic nature. Lloyd & Collis (1981) had proposed this genetic nature for São Sebastião because such a large crater could only be formed by a very explosive event as the phreatomagmatic explosions. Madeira (personal communication, 2006) justifies that the *lahar* deposit is a phreatomagmatic flow deposit, resultant from the formation of the crater and couldn't be associated to other source because it doesn't appear anywhere else in the surrounding area.

The phreatomagmatic volcanoes, usually designated by maar, are low standing volcanoes with very wide bowl shaped craters that can range from a few hundreds of meters to about 3 km. They result from the contact of basaltic magma with water (the water level, an aquifer or the sea water) that produces a blast of fine-grained particles and a steam explosion. As they usually form holes in the surface, afterwards they get filled with water forming lakes (Cas & Wright, 1987; Francis, 1993; Fisher et al., 1997).

In the opinion of Madeira (personal communication, 2004) the soft shallow sediments of the actual São Sebastião crater are derived from the former existence of a lake, presently filled by sediments. Dependant on the understanding of the geological nature and evolution of the crater is the volcano-stratigraphic relation between the different geological materials and this is of primary importance for the comprehension of the site effects occurred in the village.

REVIEW OF PREVIOUS STUDIES ON THE CHARACTERIZATION OF SÃO SEBASTIÃO

One of the first interesting data on São Sebastião is a deep borehole (182 m) made in 1979, in the SE limit of the crater, for geothermal prospection (Lloyd & Collis, 1981). This borehole crossed until 34 m depth soft materials; a shallow deposit of brown sandy clay soil (4 m) followed by 30 m of fluvial/pyroclastic deposits described as “a mixture of angular to sub-rounded feldspar crystals, weathered fragments of scoria and aphyric basalt, minor volcanic glass and fine grained ash”. After this first layers, the borehole shows mainly intercalations between aphyric basaltic lavas, porphyritic basaltic lavas and weathered basaltic scoria. Between the 82 m and the 136 m there aren’t cuttings, so probably in that depth, the materials are also soft, maybe corresponding to very weathered basaltic scoria and/or weathered pyroclastic deposits.

After the 1980 earthquake, the geological and geophysical information gathered on São Sebastião resulted mainly from a research project dedicated to the study of seismic hazard and risk in the central group of the Azores archipelago (PPERCAS Project). One of the first works made in that project were 3 boreholes in the area of the crater (Malheiro, 1998), the volcanological map presented before (Nunes, 2000), noise (Senos et al., 2000) and gravimetric measurements (Montesinos et al., 2003). The boreholes were made with a rotation drill and had as objective to characterize in detail the filling deposits of the crater (Malheiro, 1998). The results were not as expected because the recovery ratio was very low (considering the 3 boreholes, the individual recovery ratio was less than 15%); the main causes are related to the type of materials, to the presence of the water level at 7 m, and to the water injection used as a circulation fluid for the drill. The first 6 to 7 m the soils are mainly silty to clayey with rock fragments and sand. Bellow 20 m the materials are mainly sand and rock fragments with a silty to clayey matrix.

A total of 130 noise measurements acquisitions of 10 minutes each were made in a quadrangular grid with 120 m between measurement points (Senos et al., 2000). The results showed that the site has a predominant frequency between 1-3 Hz and the higher damage occurred in the areas where the predominant frequency is 2 Hz.

Besides the volcanological map of the area, the more detailed study on São Sebastião that resulted from the PPERCAS project was the work by Montesinos et al. (2003). This work comprehends not only a description of the geological materials as the gravimetric study of the area. In this study were acquired 334 gravity sites in São Sebastião and surroundings with a 200 m spacing in the regional study and a 50 m spacing in the urban zone, inside the crater.

The results were obtained by a method of gravity inversion, constrained with the interpretation of the geology of the area to help removing inadequate density contrasts (Montesinos et al., 2003). From the regional study is important to notice some low density contrasts (Figure 7) that the authors associate mainly with the infillings of the crater and with the scoria cones in the vicinities. Noticeable is that the only low density contrast at a depth of about 500 m is inside the crater area. Montesinos et al. (2003), due also to the shape of the anomaly, interpret that it is directly related with the genesis mechanism of the crater.

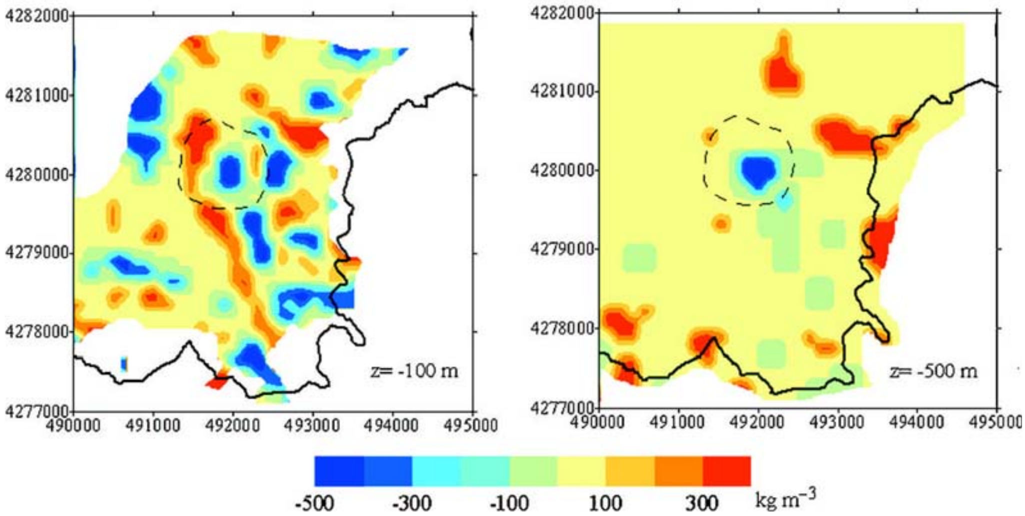


Figure 7. Deep horizontal sections of the density contrast 3-D regional model for the area of São Sebastião and surroundings, for -100 and -500m (UTM coordinates in meters) (adapted from Montesinos et al., 2003)

In the detailed study of the area those authors present 3 horizontal sections and 3 W-E cross-sections (Figure 8) located where were placed the strong motion stations that recorded the earthquakes that will be discussed further on. The shallower of the horizontal sections crosses at z=100 m (above the sea level) which is almost 50 m below the surface of the crater (≈150 m). Information on the first 50 m appears only in the cross-sections. In general two main high-density bodies can be identified and those authors associate with the presence of the basaltic lava flows that form the crater wall and define the collapsed area. These bodies are similar in all horizontal sections of the model seeming to characterize very steep walls that associate with the collapsed mechanism proposed. The negative density contrast present in the inner area corresponds to the post-generation soft sediments and infillings of the crater. Also, the conduit system is filled with breccia-type deposits, which are also identified as negative density contrast bodies (Montesinos et al., 2003).

After that work some seismic data in the São Sebastião crater were acquired, mainly by the Surface Wave Method (SWM) (Lopes, 2005). The seismic data is composed by 14 multichannel surface wave lines to determine an approximate shear wave velocity for the different materials in the area and also to get an idea on the distribution and thickness of the fillings within the crater. For the velocities 3 main groups were identified: for the basalts from the north area the shear wave velocity is around 1000 m/s; for the pyroclastic and scoria deposits from the Cruzes cone in the east the values varies between 250-450 m/s increasing with depth; and finally for the fillings of the crater the values are much smaller and between 90 and 200 m/s also increasing progressively with depth.

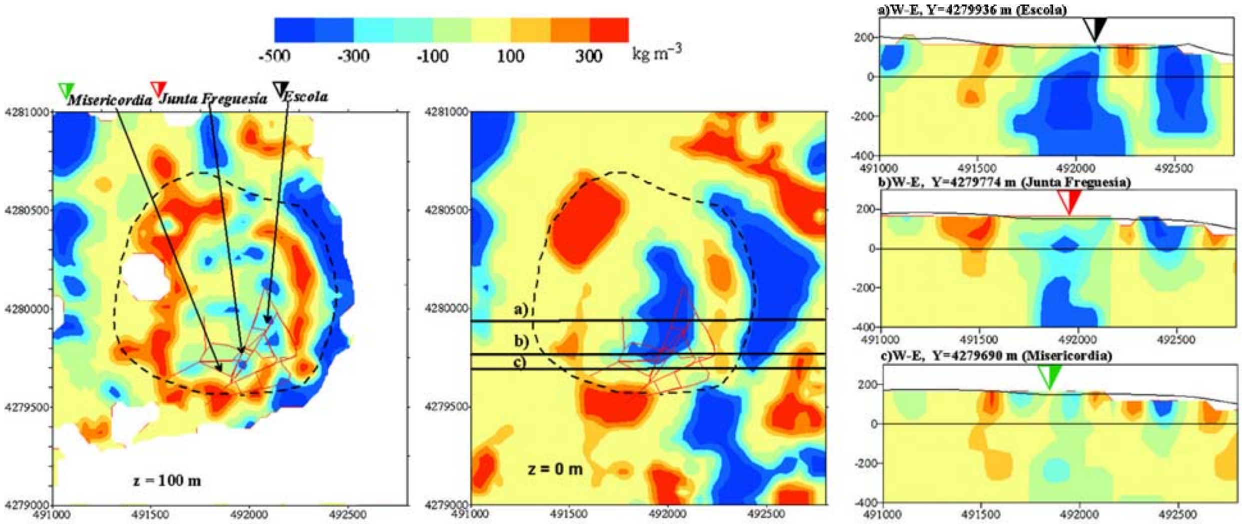


Figure 8. Horizontal sections of the density contrasts 3-D local model for 100 m (above the sea level) and to the sea level (z=0m) and the W-E profiles along the lines shown in z=0 m (UTM coordinates in meters) (adapted from Montesinos et al., 2003)

As the 1-D information obtained from the SWM was distributed in the area, Lopes (2005) made some maps to plot the velocity distribution at different depths. The isolines maps (Figure 9) show that in the area of Misericórdia and Junta the shear wave velocity near surface (z<50m) is higher than in the Escola area, justifying the differences observed in damage. Besides, high velocities in the western area of the crater were measured and the total thickness of the fillings was not possible to determine due to the low velocity of the surficial materials and intrinsic limitations of the method.

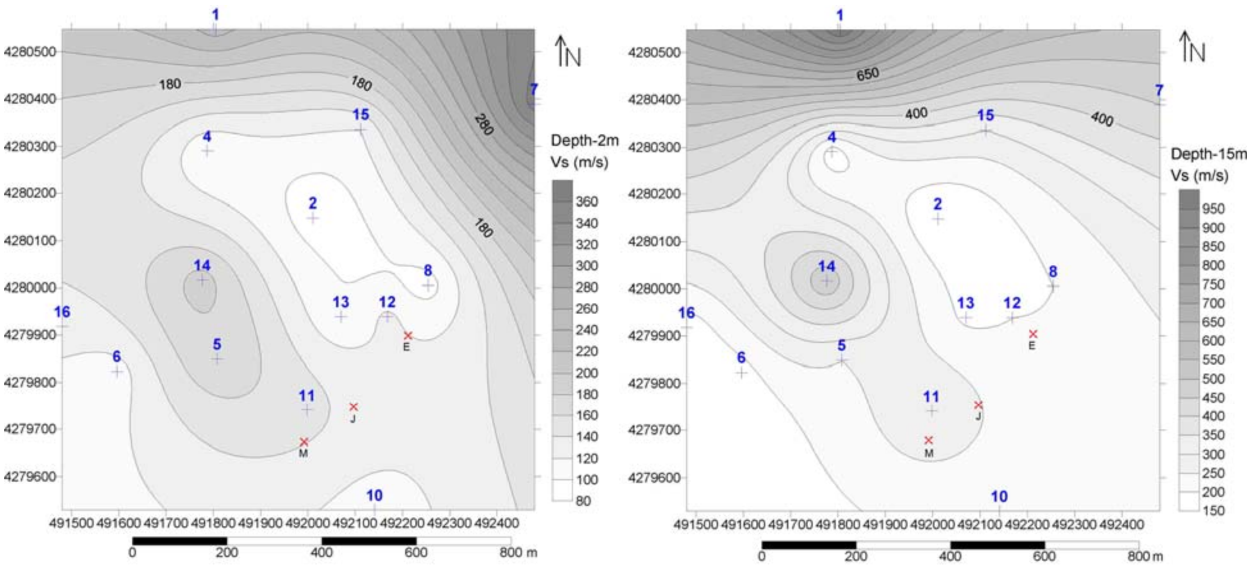


Figure 9. Horizontal sections of V_S (m/s) for different depths (2 m and 15 m from the topographic surface) with the Misericórdia (M), Junta (J) and Escola (E) location (adapted from Lopes, 2005)

SEISMIC MOTION ANALYSIS

The seismic motion analysis focused on two aspects. On one hand, according to the Isoseismic map related to the 1980 January 1st, the seismic records at the crater should have higher amplification than on other places at Terceira with more or less the same epicentral distance (Figure 4). On the other hand, as there was different damage inside the crater itself for the same event (Figure 5), one should detect differences between the records obtained by several stations placed inside the crater. During two seismic crises at the Azores Archipelago, one lasting from June 1997 to October 1997 (Oliveira et al., 1997) and the other from July 1998 to October 1998 (Oliveira et al., 1998), it was possible to measure seismic motions at different places not only at different stations placed at Terceira island, but also inside the crater, as there were three digital accelerometric stations at different locations at the São Sebastião village: Escola, Junta and Misericórdia. For the pretended analysis, this work focuses on four events. Table 3 contains their date, magnitude and locations where records were obtained (Nunes et al., 2004): These records have already been subjected to a preliminary treatment, and have been used in other studies (Oliveira et al., 1997; Oliveira et al., 1998; Montesinos et al. 2003).

Table 3. Date, magnitude and recording stations concerning the analyzed events (adapted from: Nunes et al., 2004)

Date (UTC)	M_L	Locations
1997/07/15 21:00	4,1	Escola, Junta, Misericórdia
1997/07/28 23:29	4,4	Escola, Junta, Misericórdia
1997/10/03 08:58	3,7	Escola, Junta
1998/07/09 05:19	5,7	Escola

The different records at each location for each event were corrected using a quadratic fit baseline correction and applying an acausal 4th order Butterworth high-pass filter with a cut-off frequency equal to 0,04Hz (Boore, 2002; Boore & Akkar 2003).

Comparison between the Crater and other sites on Terceira

Regarding the first referred aspect, comparison was made between the record at São Sebastião and a record obtained at Praia da Vitória town for the 1998/07/09 event, as this event had the higher magnitude, and the epicentral distance was such that it was unlikely there to exist near-source effects. These records fall on the definition of similar epicentral distance (Oliveira et al., 1998).

As far as the corrected Peak Ground Acceleration (PGA) is concerned, the record at São Sebastião contains higher PGA than the Praia da Vitória record (0,2215 m/s^2 vs. 0,1022 m/s^2). In terms of Fourier amplitude, the main difference between the records concerns the contribution of higher modes at São Sebastião. This effect is clearly shown at Figure 10, concerning the Transversal component (approx. N-S):

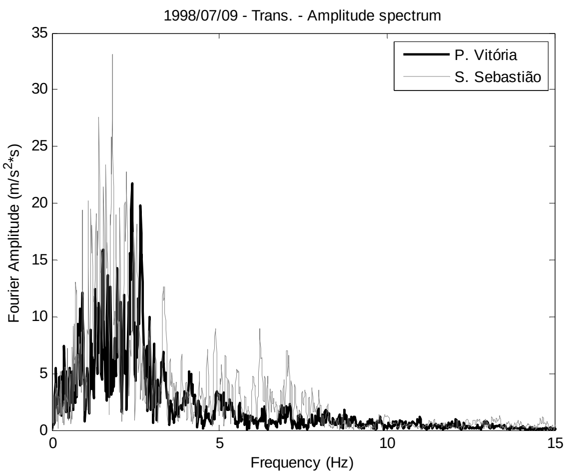


Figure 10. Fourier amplitude spectra for the transversal component of the records obtained at São Sebastião (sampling rate = 100Hz) and Praia da Vitória (sampling rate = 200Hz)

The power spectrum and the Arias Intensity for the transversal component of both records are presented in Figure 11.

Analyzing these results, there is a clear indication of site effects at the São Sebastião village.

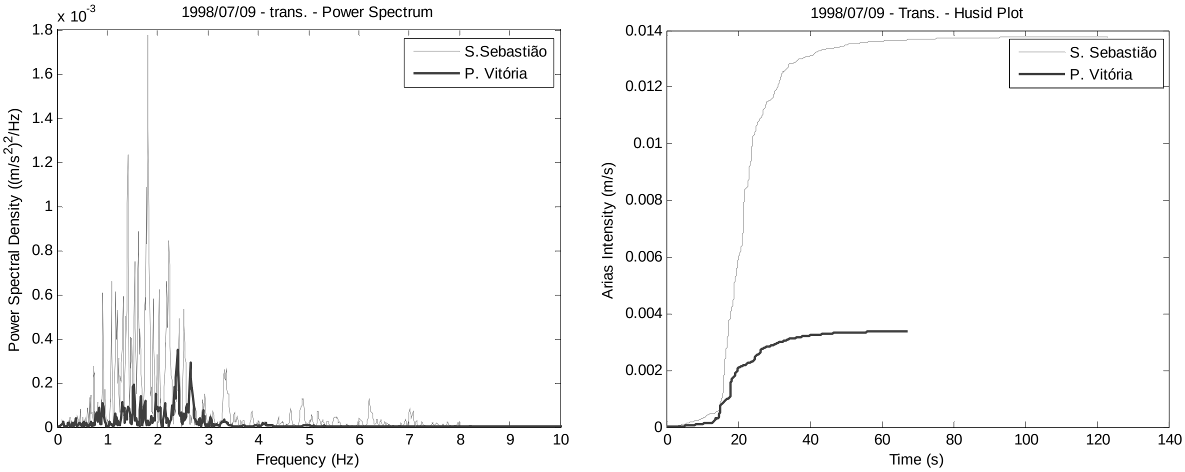


Figure 11. Power spectra and Husid plot for the transversal component of the records obtained at São Sebastião (sampling rate = 100Hz) and Praia da Vitória (sampling rate = 200Hz)

Comparison between different sites inside the Crater

The measured PGA at Escola station was consistently higher than on the other stations, as one can see on Table 4.

Table 4. Peak Ground Acceleration for the different records

Event	PGA Escola (m/s^2)	PGA Junta (m/s^2)	PGA Miser. (m/s^2)
1997/07/15 21:00	0,0645	0,0266	0,0314
1997/07/28 23:29	0,0514	0,0283	0,0347
1997/10/03 08:58	0,0529	0,0243	-

In the frequency domain, the signals obtained at the Escola station have special features comparing to the signals recorded at the other stations. The amplitude for the predominant frequency (for the horizontal components) at the Escola station is higher than the amplitude obtained at the other stations for the first three events. The predominant frequency for the Escola station is also slightly higher. This effect is clear at Figure 12, concerning the longitudinal component for the first three events. At the same figure, one can also detect three main frequencies intervals where there is major amplification, especially at the Escola station: 2,5-3,0Hz, 4,5-5,5Hz and 7,0-8,0Hz. Comparison between Junta and Misericórida for the 1997/07/15 event shows little difference in terms of Fourier amplitude.

A global overlook at the obtained Fourier amplitude spectra indicates that at the Escola site there is an important contribution of higher modes, which can be attributed to the local site conditions or to the influence of the structure.

Regarding Vanmarcke’s central frequency (average of the horizontal components) and shape factor, there is no significant difference between the stations placed at the crater, as shown in Table 5.

Table 5. Vanmarcke’s Central Frequency for the different records

Event	Central Frequency Escola (Hz)	Central Frequency Junta (Hz)	Central Frequency Miser. (Hz)
1997/07/15 21:00	4,96	5,57	5,76
1997/07/28 23:29	4,64	4,46	4,75
1997/10/03 08:58	6,33	7,37	-

Considering the power spectrum and the signal energy, the records at the Escola station have significantly higher power and energy (and, subsequently, higher Arias Intensity). Considering the Trifunac & Brady (1975) energy-based duration, the records at Escola presents a much greater increase of energy along the significant duration. Figure 13 concerns the longitudinal component, but the same conclusions are also valid for the transversal component.

From the made remarks, one may conclude that there is a local amplification effect at Escola station. In fact, this conclusion is in line to the observed damage resulting from the 1980 January 1st earthquake.

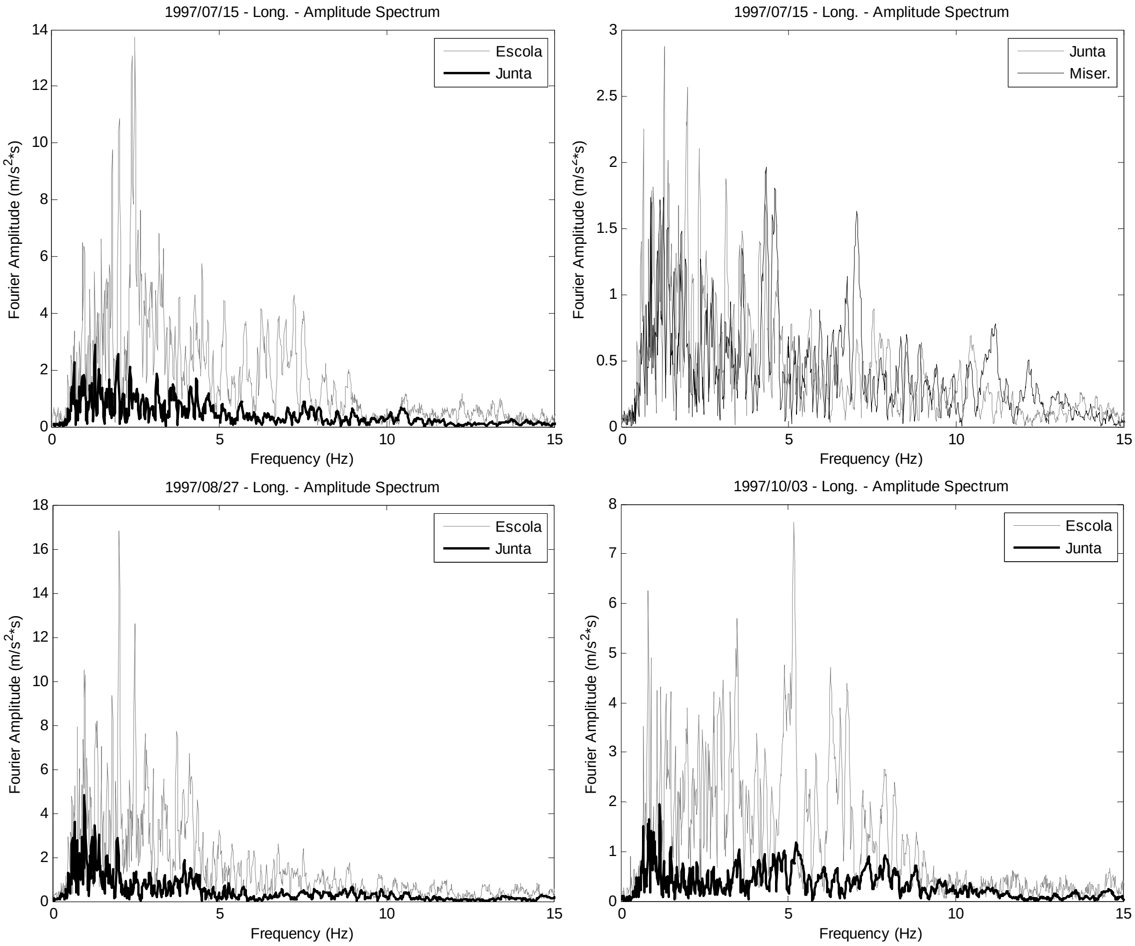
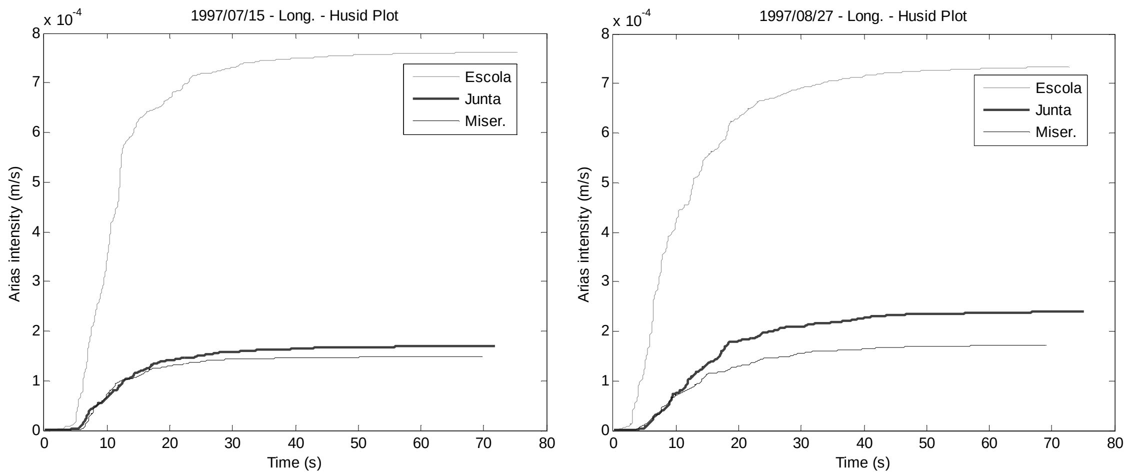


Figure 12. Fourier amplitude spectra for the longitudinal component of the records concerning the 1997 events at Escola and Junta stations (sampling rates = 200Hz & 100Hz, respectively)



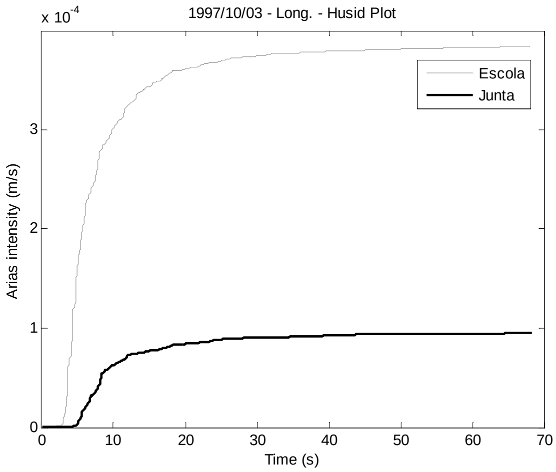


Figure 13. Husid plots for the longitudinal component of the records concerning the 1997 events

RECENT INFORMATION ON THE GEOLOGY OF THE CRATER

During 2006 a field trip to São Sebastião was planned with the main objective of acquiring new seismic data, mainly P seismic refraction, SH seismic reflection and a few more surface wave tests. Besides the seismic tests, the geological investigation included a visual inspection, in the North and in the Western areas of the crater, of fresh basalt from a quarry. The exposed rock is of basaltic composition, slightly vesicular, with a porphyric texture showing phenocrists of olivine, pyroxene and plagioclase.

According to the local information the basalt layer appears in a small area located in the N and W limit of the crater. This layer appears to have a thickness of about 4m flowing to the centre with subvertical configuration on the crater walls. Beneath this basaltic lava flow scoria deposits were found.

Crossing this information with the volcanological map (Figure 6) and the surface wave results (Figure 9) it will make sense that, at least, the intermediate lava flows are posterior to the formation of the crater. Considering this hypothesis, the outcrop of intermediate lava that appears in the SE limit can be the end of the lava tongue that flowed into the crater and outcrops in that area due to its lower altitude relatively to the surroundings. This altitude corresponds approximately to the altitude in which this lava flow appears in the middle of the sediments of the crater, corresponding to the base of the crater at the moment that the lava flow occurred. This flow doesn't cover all the crater area, can be irregular in shape and in thickness and probably occurred a long time after the formation of the crater as the latter has, at least, more than 30 m of deposits. This layer of basaltic rock that appears in the middle of the sediments is compatible with the surface wave tests results indicating the increase of V_S along the NW-SE direction (Figure 9). The presence of this layer can help to explain the differences in amplification felt in the strong motion stations.

CONCLUSIONS

Despite a significant amount of work done in order to characterize the crater and to understand the differences in behaviour, this geological setting is still an open issue. The information is still very qualitative not allowing to define a geological model with the necessary detail to perform the site effects modelling of São Sebastião volcanic crater. Further works are still needed.

The recent information on the geology of the crater allowed to identify areas where boreholes are needed. These boreholes with SPT tests are planned to be carried out in 2007. The isotope dating of the lava flows around the crater is also needed to understand the volcanostratigraphic relationships.

Also, the results of the seismic acquisitions will soon be available allowing to have a more detailed comprehension on the internal structure and the velocities of the sediment deposits inside the crater. Further work is also needed regarding the signal acquisition and processing. Nowadays, there is only one strong motion station available inside the crater (Escola station) and so, the accelerographic network within the crater needs to be improved. The soil-structure interaction can influence the acquired signals and needs to be checked in detail. The 1-D site-effects modelling based on the available soil velocity profiles is undergoing: a parametric study will allow the best possible fit between observed data and modelling results.

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