ANNALS OF GEOPHYSICS, 56, 6, 2013, S0671; doi:10.4401/ag-6221

Special Issue: Earthquake geology

Paleoseismological evidence for historical surface faulting in São Miguel island (Azores)

Rita Carmo[1, *], José Madeira[2], Ana Hipólito[1], Teresa Ferreira[1]

[1] *Centro de Vulcanologia e Avaliação de Riscos Geológicos da Universidade dos Açores, CVARG, Açores, Portugal*

[2] *Universidade de Lisboa, Faculdade de Ciências, Departamento de Geologia, and Instituto Dom Luiz (Laboratório Associado)-IDL(LA), Lisboa, Portugal*

Article history
Received October 8, 2012; accepted May 10, 2013.
Subject classification:
Earthquake geology and paleoseismology, Seismic risk, Tectonics.

ABSTRACT

The Azores archipelago is located at the triple junction between the Eurasian, Nubian and North American lithospheric plates, whose boundaries are the Mid-Atlantic Ridge and the Azores-Gibraltar Fault Zone. São Miguel is the largest island of the archipelago and is located on the eastern part of the western segment of the Azores-Gibraltar Fault Zone. The Achada das Furnas plateau, located in the central part of the island, between Fogo and Furnas central volcanoes, is dominated by several WNW-ESE and E-W trending alignments of basaltic cinder cones. Two E-W trending scarps were identified by aerial photo interpretation. Transect trenches exposed two active normal faults-the Altiprado Faults – confirming the tectonic nature of the scarps. Several paleoearthquakes were deduced, most of which in historical times, producing 1.38 m and 0.48 m of cumulative displacement. Maximum expected magnitudes (MW) determined from slip per event range from 5.7 to 6.7. One of the events probably corresponds to the historical earthquake of October 22nd, 1522, the deadliest in the archipelago. Radiocarbon ages are in agreement with this interpretation.

1. Introduction

The population of Azorean islands faces significant geological hazard due to the geodynamic context of the archipelago, including frequent seismicity, active volcanism and landslides. Earthquakes claimed more than 6,000 victims in the six centuries since the beginning of settlement in mid-15th century. We present a paleoseismology study that revealed several events of surface faulting in the island of São Miguel during historical times, thus contributing to the seismic risk awareness in the most populated island in the Azores.

The Azores archipelago is located in a zone of anomalously shallow topography (the Azores Plateau), corresponding to the expression of the Eurasia, Nubia and North America triple junction (Figure 1). The Mid-Atlantic Ridge separates the North America from Eurasian and Nubian plates, while the Azores-Gibraltar Fault Zone (Terceira Rift (s.l.) and Gloria Fault) is the boundary between Eurasian and Nubian plates.

The archipelago comprises nine islands distributed by three groups. The western islands (Flores and Corvo) lie on the stable North American plate, while the central (Faial, Pico, São Jorge, Graciosa and Terceira) and eastern groups (São Miguel, Santa Maria and Formigas islets) are located along the western segment of the Azores-Gibraltar Fault Zone, the Terceira Rift (s.l.). This segment is bordered to the south by the inactive East Azores Fracture Zone and to the north by the São Miguel-Graciosa alignment (Terceira Rift (s.s.), Machado 1959). It corresponds to a diffuse and complex deformation zone, sheared by a dextral transtensive regime [Madeira 1998, Lourenço et al. 1998, Madeira and Brum da Silveira 2003] due to higher spreading rates at the Mid-Atlantic Ridge north of the triple junction [e.g. Laughton and Whitmarsh 1974, Fernandes et al. 2003, Argus et al. 2011] and to the obliquity relatively to the spreading directions [e.g. Madeira and Ribeiro 1990, Madeira 1998, Lourenço et al. 1998].

The fault pattern in the Azores islands is characterized by three-dimensional strain [Reches 1983, Reches and Dieterich 1983] and is represented by two main fault systems with oblique slip, each composed of two sets dipping in opposite senses: WNW-ESE to NW-SE normal dextral faults, and conjugated NNW-SSE to N-S normal left-lateral structures. This geometry and kinematics indicate a stress field with a horizontal maximum compressive stress axis (σ1) trending NW-SE, a horizontal minimum compressive stress axis (σ3) in the NE-SW direction and a vertical intermediate compressive stress axis (σ2); permutations between σ1

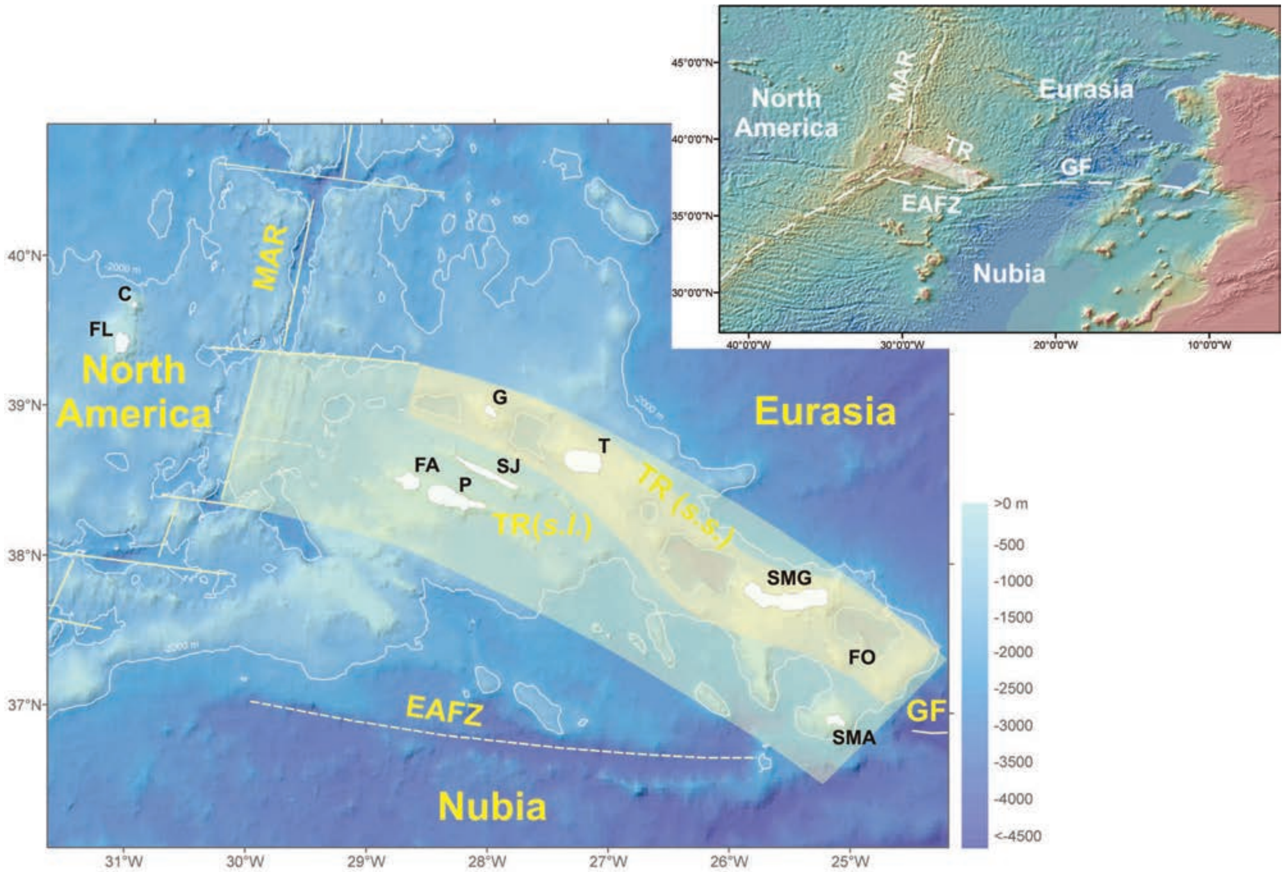

Figure 1. Tectonic setting of the Azores archipelago (adapted from Hipólito et al. 2010). The main morphotectonic features of the region are presented. The shaded area in both the inset and main figure TR (s.l.) represents the sheared western segment of the Eurasia-Nubia plate boundary, and TR (s.s.) corresponds to São Miguel-Graciosa alignment. Tectonic structures: MAR-Mid-Atlantic Ridge; TR-Terceira Rift; EAFZ-East Azores Fracture Zone; GF-Gloria Fault. Islands: C-Corvo; FL-Flores; FA-Faial; P-Pico; SJ-São Jorge; G-Graciosa; T-Terceira; SMG-São Miguel; FO-Formigas islets; SMA-Santa Maria. Azores bathymetry adapted from Lourenço et al. [1997], and World topography and bathymetry from GEBCO_08 database [2010].

and σ2 may originate from transtensive or tensile tectonic regimes [e.g. Madeira 1998, Madeira and Brum da Silveira 2003].

The deformation is accommodated by a large number of active faults along which significant seismic and volcanic activity occur. Since settlement, in the 15th century, the Azores islands have been severely affected by seismic activity, characterized by usually low to moderate magnitude isolated events or seismic swarms of tectonic and/or volcanic nature [e.g. Silveira et al. 2003]. However, high magnitude earthquakes (e.g. M 7.2; Hirn et al. [1980]) may also occur, causing thousands of deaths and severe damage [e.g. Machado 1949, Hirn et al. 1980]. Volcanic activity also occurred, both on land and at sea, sometimes with severe consequences [e.g. Chaves 1960, Weston 1964, Madeira 2006]. The temporal distribution of eruptions and earthquakes (at the archipelago scale) suggests alternating eruptive and tectonic phases. Volcanism would happen when the stress field becomes largely extensional, due to permutations between the maximum and intermediate stress axes [Madeira 1998].

In the Azores archipelago, surface faulting is well documented in all islands located along the Eurasia-Nubia margin (central and eastern groups) producing fault scarps of variable dimension. Most post-settlement earthquakes capable of producing surface rupture occurred off-shore with the exception of two events in Terceira Island in 1614 and 1841, for which there are coeval texts describing rupture on land. Earthquake magnitudes ranging from 6.9 to 7.1 were estimated from slip per event in the islands of Faial, Pico and São Jorge [Madeira and Brum da Silveira 2003]. However, this procedure should be used carefully because slip frequently overestimates magnitude as co-seismic, post-seismic and fault creep displacements are very difficult to discriminate in paleoseismological analyses.

At São Miguel, active faulting is represented by prominent fault scarps and linear volcano-tectonic structures with a main NW-SE to WNW-ESE trend and normal dextral slip. At Achada das Furnas area, aerial photo analysis identified the presence of two E-W trending scarps. Trenching across these scarps confirmed their tectonic nature revealing two previously unknown normal faults, hereafter named Altiprado Faults 1 and 2. This work presents evidence of surface faulting on these structures in historical (post-settlement) times.

2. Volcano-tectonic setting

São Miguel Island is located on the eastern part of the Terceira Rift (Figure 1). It comprises three active central volcanoes with summit calderas (Sete Cidades, Fogo and Furnas), characterized by basaltic (s.l.) effusive activity during the early subaerial stages followed by explosive trachytic volcanism in late Pleistocene and Holocene. These are linked by volcanic fissure zones (Picos region and Achada das Furnas plateau). Two older and inactive volcanoes (Povoação and Nordeste) form the eastern part of the island (Figure 2). Volcanism becomes younger westwards. The Nordeste mafic shield volcano is the oldest part of the island and its age ranges from 4 to 0.95 million years [Abdel-Monem et al. 1975]. Its southwest flank is cut by the Povoação caldera of unknown age. The 100,000 years old Furnas volcano [Moore 1990] is the easternmost of the three active central volcanoes of São Miguel and cuts the caldera of Povoação. Fogo volcano, located on the center of the island, started its subaerial edification more than 200,000 years ago [Muecke et al. 1974]. The western end of the island is dominated by Sete Cidades volcano whose formation began prior to 210,000 years BP [Moore 1990].

The main active fault system trends NW-SE to WNW-ESE. The surface expression of the faults is represented by fault scarps, forming large graben structures that truncate the flanks of the main volcanoes, and linear volcano-tectonic structures (Figure 2). The observable length of these structures is limited by the dimension of the island and by mantling by recent (mostly Holocene) volcanic deposits that locally conceal the faults. NNW-SSE and NE-SW trending structures are represented by volcano-tectonic alignments and lineaments (Figure 2).

Tectonic structures played a key role in the volcanic evolution of São Miguel, controlling the emplacement of major volcanoes and locally acting as conduits: central volcanoes were built at the intersection of the NW-SE to WNW-ESE and NNW-SSE to N-S conjugated fault systems, while monogenetic cones lie along them.

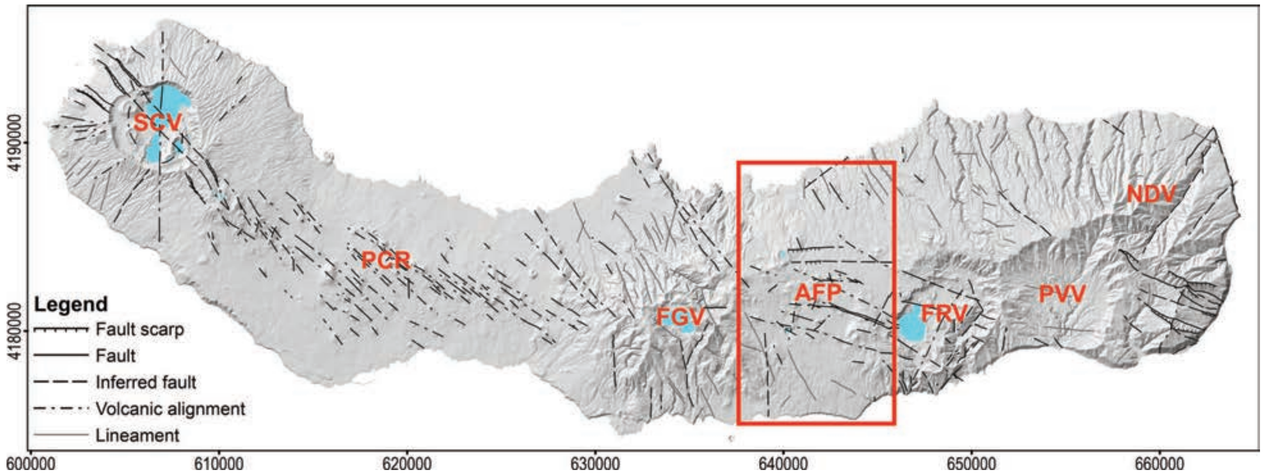

Figure 2. Volcano-tectonic map of São Miguel superimposed on a DTM of the island: SCV-Sete Cidades volcano; PCR-Picos region; FGV-Fogo volcano; AFP-Achada das Furnas plateau; FRV-Furnas volcano; PVV-Povoação volcano; NDV-Nordeste volcano. The red box indicates the area presented in Figure 3.

The Achada das Furnas plateau, located in the central area of the island between Fogo and Furnas volcanoes, is a flat area dominated by several basaltic cinder cones, occasional maars and trachytic domes, defining WNW-ESE and E-W alignments (Figure 3). The area is mantled by thick trachytic fall deposits produced by eruptions on the neighboring central volcanoes. Aerial photo analysis revealed the presence of two E-W trending scarps, related to the previously unknown Altiprado Faults 1 (south) and 2 (north), which interrupt the flatness of the plateau (Figures 3,4).

3. The Altiprado Faults

3.1. Altiprado Fault 1

The Altiprado Fault 1 (AF1) trace is marked by an 835 m-long, 3 m-high, south-facing scarp, trending N87°E (Figures 3,4). To the east and to the west its

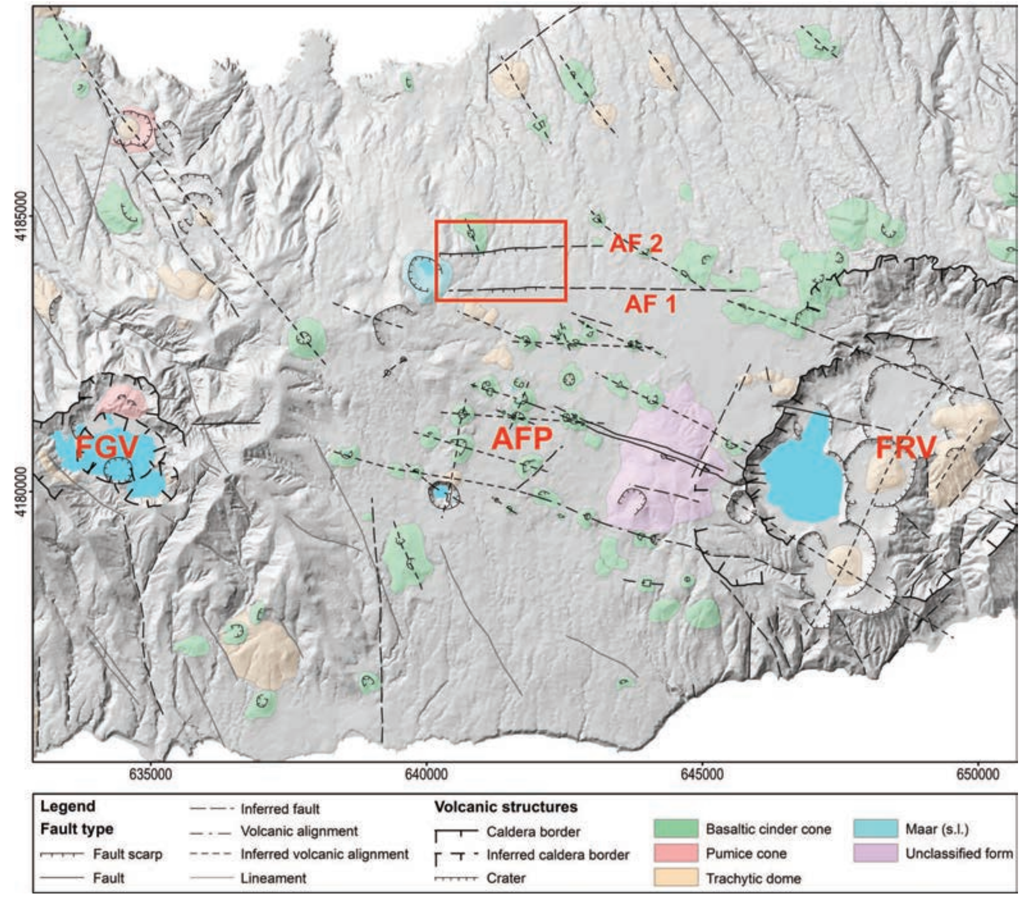

Figure 3. Main tectonic and volcanic structures of Achada das Furnas plateau: AF1-Altiprado Fault 1; AF2-Altiprado Fault 2; FGV-Fogo volcano; AFP-Achada das Furnas plateau; FRV-Furnas volcano. The red box indicates the area presented in Figure 4.

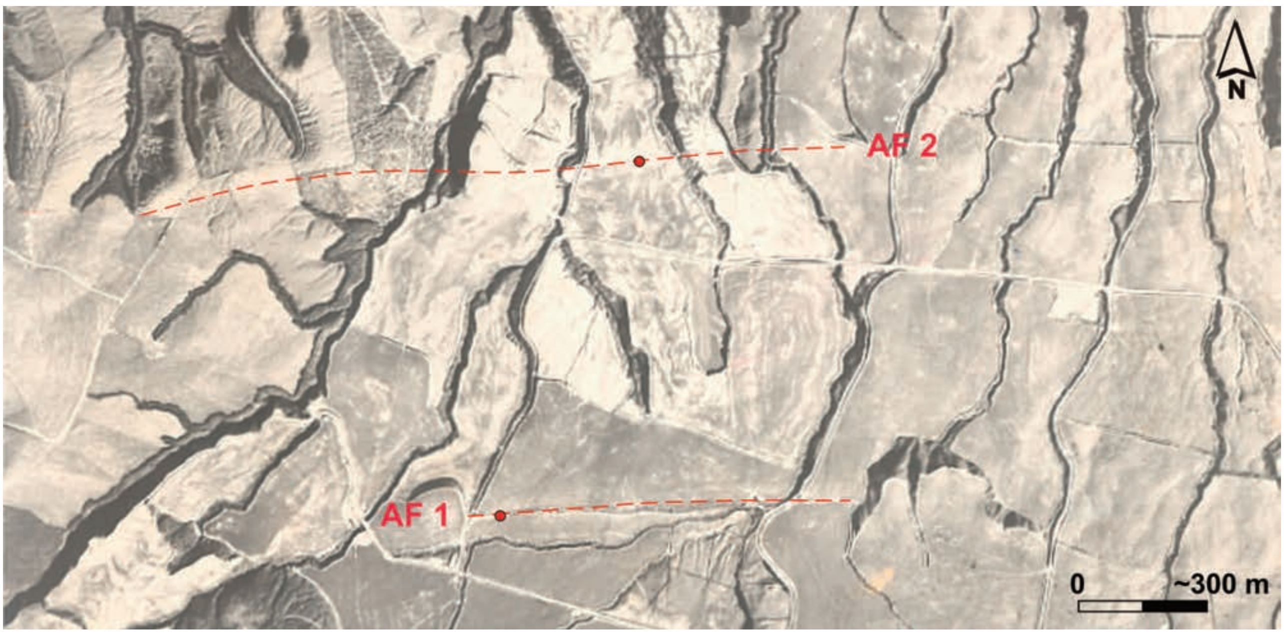

Figure 4. Vertical aerial photograph of Altiprado region, Achada das Furnas plateau, showing the geomorphic expression of Altiprado Faults: AF1-Altiprado Fault 1; AF2-Altiprado Fault 2; Red dots-location of trenches (Aerial photo from Direcção Geral de Planeamento Urbanístico 1974).

trace becomes uncertain.

An 18 m-long trench was open across the scarp, located at 37.79°N-25.396°W, exposing a N87°E, 65°S fault. The fault displaces a stratigraphic succession comprising six units separated by paleosols (Figure 5). Units 1 to 5 are pumice fall deposits produced by eruptions from Fogo and Furnas volcanoes and unit 6 is a sedimentary deposit (remobilized pyroclasts). The sequence is composed of: 1-olive brown paleosol developed on top of Fogo A deposit, produced by a major plinian eruption of Fogo volcano at about 4520±90 years BP [Wallenstein 1999; Table 1]; 2-pumice fall deposit composed of alternating yellowish fine grained lapilli and light olive brown ash beds, probably corresponding to Fogo C deposit, the product of a hydromagmatic eruption at Fogo volcano; 3-fall deposits, probably from Fogo D eruption, composed of three layers, from the base to the top: (3a) dark brown pumice ash fall deposit containing disseminated lapilli; (3b) yellowish lapilli pumice fall deposit; and (3c) brown ash fall deposit; 4-grey pumice ash layer corresponding to Furnas C deposit (1870±120 years BP; Guest et al. 1999], Table 1), which, in this trench, is completely altered to a very dark grey soil (410±30 years BP, 1440-1500 cal AD; Table 1); 5-stratified fall deposit of alternating beds of fine to medium greyish white pumice lapilli and ash (5a to 5d) containing sanidine crystals from 1563 AD Fogo volcano plinian eruption, topped by a very dark grey paleosol (5e) rich in coal fragments (160±30 years BP, 1660-1700 cal AD, Table 1); 6-sediment formed by remobilization of the underlying unit. The marked southward dip of all units suggests that they are draping a fault scarp produced by previous (pre 4520±90 BP) surface ruptures.

The AF1 affects all stratigraphic units, including the present-day soil, and the scarp is an intact free-face almost devoid of soil that corresponds to the projection of the fault plane to the surface, indicating its youth (Figure 5).

Lab. ref.	Trench	Field ref.	Unit	Material	Age	2σ calib. date	Author
-	AF1	-	1	Charcoal	4520±90 y BP	-	Wallenstein [1999]
-	AF/AF2	-	4	Carbonaceous layer from the base of deposit	1870±120 y BP	-	Guest et al. [1999]
295323	AF1/AF2	TR1-1	4	Paleosol	410±30 y BP	1440-1500 cal AD	This work
295337	AF1/AF2	TR1-2	5	Paleosol	160±30 y BP	1660-1700 cal AD	This work

Table 1. Radiocarbon ages of units trenched in Altiprado Faults.

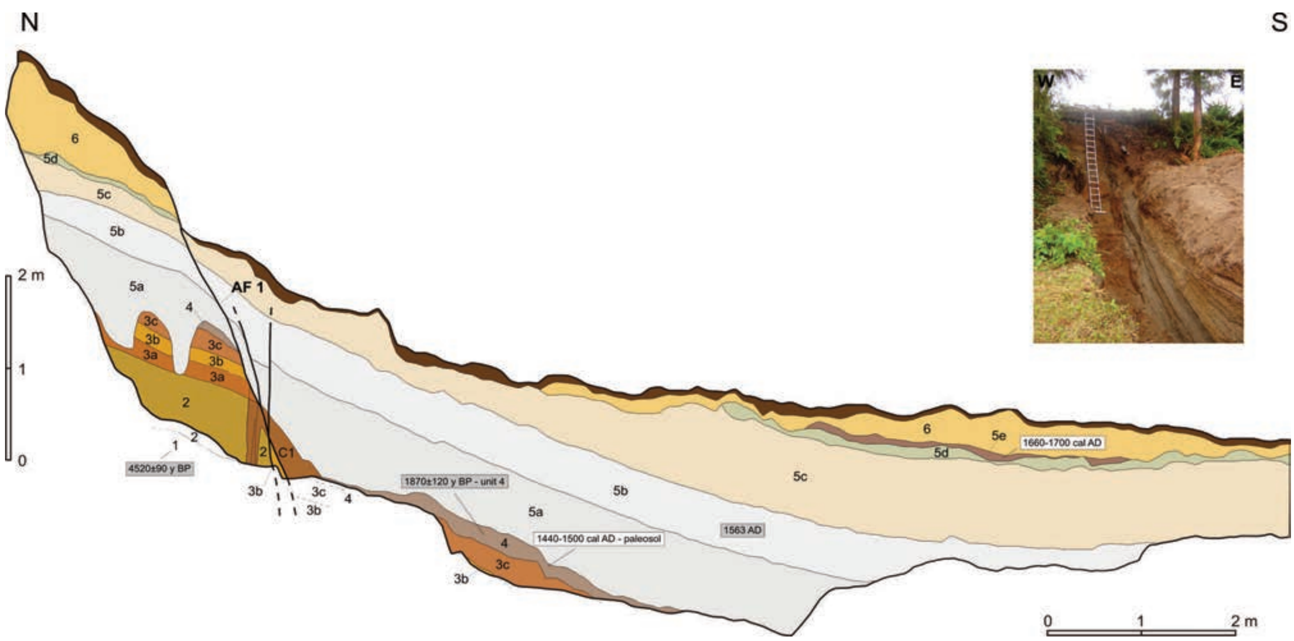

Figure 5. Map of the east wall of the Altiprado Fault 1 trench. Legend: 1-Fogo A; 2-Fogo C; 3a to 3c-Fogo D; 4-Furnas C; 5a to 5e-1563 Fogo volcano eruption; 6-remobilized deposit.

Several WNW-ESE to E-W trending fractures and open cracks, sometimes filled with material from overlying units (3 and 4), and a colluvium (C1) composed of material from units 3 and 4 were also exposed in the trench (Figure 5).

The exposed geometry shows that units 2 to 4 are displaced by 1.38 m and units 5 (5a to 5e) and 6 by 0.38 m, indicating at least two surface rupturing paleoearthquakes. Although there is a time gap between the deposition of unit 4 and the development of the overlying soil, the presence of a single colluvial wedge on top of the soil indicates a major surface rupture producing a minimum displacement of 1 m. Units 5 and 6 are deeply eroded, so it is not possible to determine if the remaining 0.38 m of offset were produced by one or more earthquakes. Since unit 5 presents an over-thickening in the downthrown side when compared to the upthrown block and some branches of the fault apparently do not cut the entire deposit, part of the displacement may have occurred during the emplacement of unit 5, and the remaining displacement after the deposition of unit 6.

The 1.38 m accumulated dip-slip in 4520±90 years yields a minimum slip rate of 0.31±0.01 mm/year. If we take into account the age of the soil (410±30 years BP) a minimum slip rate of 3.37±0.25 mm/year is obtained.

3.2. Altiprado Fault 2

The Altiprado Fault 2 (AF2) trace is marked by an almost imperceptible 1690 m-long and ~40 cm-high south-facing scarp, trending N87°E (Figures 3,4). To the east its expression is lost.

A 29 m-long trench, located at 37.796°N - 25.392°W, exposed the same stratigraphic sequence observed in AF1 trench that is displaced by two N75-89°E trending subvertical faults (AF2-1 and AF2-2), which display frequent changes in dip direction (generally dipping 62-88°S), and an E-W trending paleo-channel (filled by unit 6) (Figure 6). A colluvium (C2), containing material of unit 3, is deposited at the base of AF2-1 fault scarp (Figure 6). Open cracks trending ENE-WSW to E-W were also filled by the colluvial material.

The faults produced different vertical offsets on units 2 and 3, and on units 4 (that in this trench is almost totally altered to soil) and 5. AF2-1 exhibits an accumulated dip slip of 33 cm, offsetting units 2 and 3 by 26 cm, and units 4 and 5 by 7 cm. AF2-2 displaced units 2 and 3 by 11 cm, and units 4 and 5 by 4 cm, resulting in an accumulated dip-slip of 15 cm. Displacement values of 26 cm, 7 cm, 11 cm and 4 cm are thus obtained. Assuming that AF2-1 and AF2-2 are branches of the same fault and that the ruptures in both planes were produced by the same earthquakes, displacement values of 0.37 m (0.26 m + 0.11 m) and 0.11 m (0.07 m + 0.04 m) are obtained, indicating two paleoearthquakes. An alternative interpretation is that four paleoearthquakes occurred in this tectonic structure, each offset corresponding to a separate event. The strong dip of the faults suggests dominant strike-slip component associated to down throw to south, indicating that the offsets may be significantly higher. A dominant strike-slip component could also account for the subdued geomorphic expression of this tectonic structure when compared to AF1. Considering both branches, the accumulated normal displacement in AF2 fault is 0.48 m (0.26 m + 0.07 m + 0.11 m + 0.04 m) in less than 4500 years, which yields a minimum slip rate of 0.11 mm/year.

The presence of a paleo-channel trending E-W, perpendicular to the general northward dipping slope and drainage direction, suggests that it may have been developed at the base of a previous fault scarp or along the trace of a fault plane that has not been exposed in the trench.

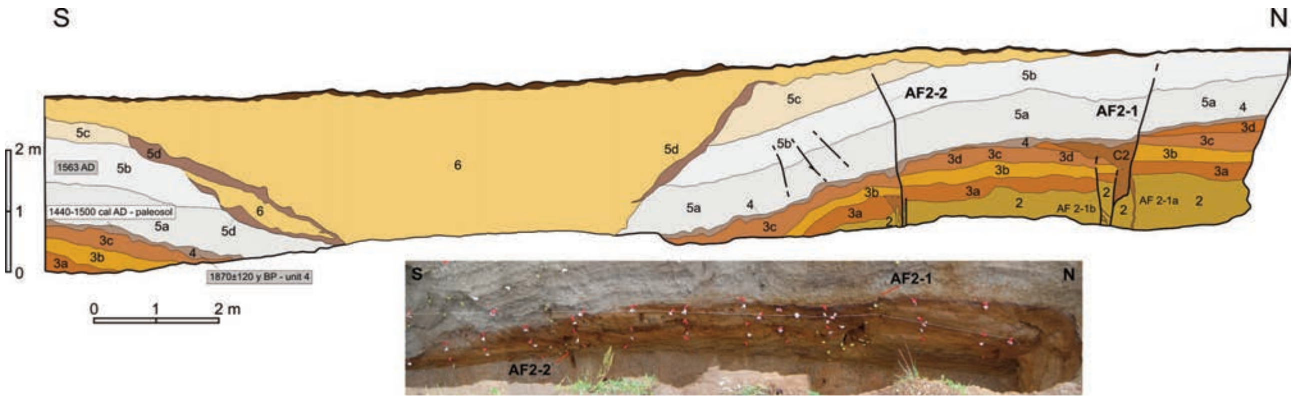

Figure 6. Map of the west wall of the trench across Altiprado Fault 2. Legend: 2-Fogo C; 3a to 3c-Fogo D; 4-Furnas C; 5a to 5d-1563 Fogo volcano eruption; 6-remobilized deposit.

3.3. Evolution of the Altiprado Faults

Geometric analysis of the trenches allowed the reconstruction of the sequence of deposition, faulting and erosion events. As the faults are less than 740 m apart from each other and affect the same stratigraphic succession the evolution of faulting, reconstructed for both locations in Figure 7, is the following:

a) Deposition of units 1 (4520±90 years BP) to 3;

b) Surface rupture(s) at AF2-1 and AF2-2 producing normal offsets of 26 cm and 11 cm, respectively;

c) Erosion truncating unit 3, with the formation of gullies in AF1 fault zone, and fault scarp retreat at

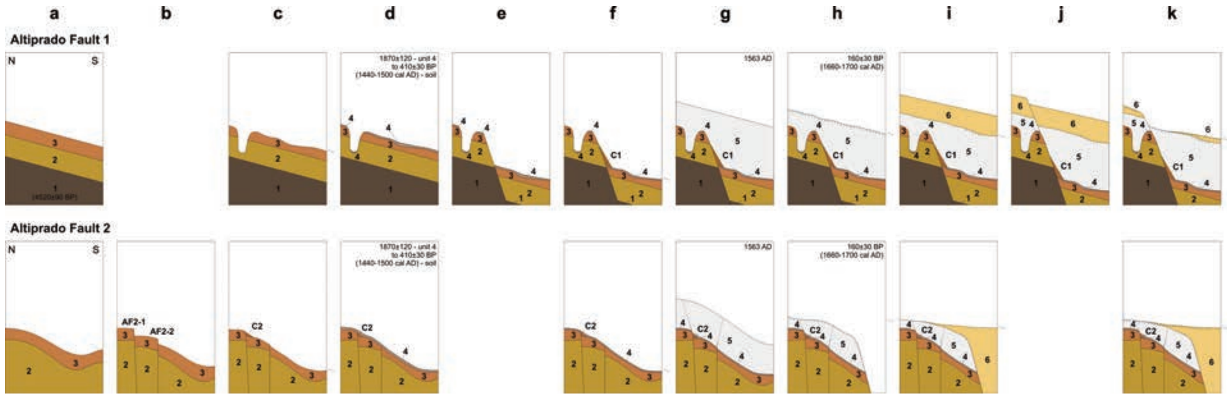

Figure 7. Sequence of depositional, erosional and tectonic events leading to present-day geometry exposed in Altiprado Faults 1 and 2 trenches. The first surface faulting event(s) is (are) related to AF2, generating an accumulated normal displacement of 0.37 m in AF2-1 and AF2-2 fault branches. It occurred between 4520 BP (unit 1) and 1900 BP (unit 4). The second surface rupture event occurred in AF1 after unit 4 paleosol formation (1440-1500 cal AD) and produced 1 m of normal displacement. The third rupture(s) produced an accumulated 0.11 m normal offset of unit 5 in AF2-1 and AF2-2 fault branches and probably occurred during the 1563 Fogo volcano eruption seismic activity. A last offset of 0.38 m of units 5 and 6 is related to AF1.

AF2-1 with the formation of a colluvial wedge (C2) composed of material from unit 3;

d) Deposition of unit 4 (1900 years BP) and development of a soil (1440-1500 cal AD, 410±30 BP);

e) Surface rupture at AF1 producing a normal offset of 1 m;

f) Erosion with minor fault scarp retreat and formation of a colluvial wedge (C1) in AF1;

g) Deposition of unit 5 (1563 AD, Fogo volcano eruption) with probable sin-eruptive ruptures of 7 cm and 4 cm in AF2-1 and AF2-2 respectively, without surface expression and surface rupture of unknown offset at AF1?;

h) Erosion truncating the top of unit 5 and formation of a paleo-channel in AF2 fault zone; development of a soil (1660-1700 cal AD, 160±30 BP);

i) Erosion truncating unit 5 and deposition of unit 6, probably representing a major storm event that totally filled the gully exposed in AF2 trench;

j) Surface rupture(s) at AF1 contributing to an accumulated normal displacement of 0.38 m in units 5 and 6;

k) Erosion truncating units 5 and 6; development of the present topsoil.

4. Discussion

The trenches allowed the recognition of several surface rupture events at the Altiprado Faults, some of which post-date the settlement of the island.

In AF1, the first rupture (1 m) occurred after the development of a paleosol on unit 4 (1440-1500 cal AD) and before the 1563 AD eruption (unit 5). The presence of a colluvium above the paleosol developed on unit 4 indicates that the rupture occurred after the formation of the soil and has no relation to the underlying volcanic event. A second offset of 0.38 m is measured at units 5 and 6, but the available data are insufficient to determine the number of earthquakes that produced it and the temporal relation with the deposition of those units. Volcano-tectonic relations (see Villamor et al., 2011) suggest that part of the displacement may have occurred during the 1563 AD Fogo eruption, as there is a difference in thickness of unit 5 in both sides of the fault, or after the formation of unit 6 (1660-1700 cal AD).

In AF2, two hypotheses are possible. At least two earthquakes produced rupture in both branches (AF2-1 and AF2-2) of the fault zone, with an accumulated offset of 0.37 m (0.26 m + 0.11 m) in the first event, during the 4520 BP to 1900 BP interval, and 0.11 m (0.07 m + 0.04 m) in the second rupture, during the 1563 AD eruption or just after this event, as offsets do not propagate through all the thickness of unit 5. Alternatively, it ruptured at least four times. The two earliest earthquakes (0.26 m in AF2-1 and 0.11 m in AF2-2) occurred in the 4520 BP-1900 BP interval. The latest earthquakes (0.07 m in AF2-1 and 0.04 m in AF2-2) occurred during the 1563 AD Fogo eruption or after it.

4.1. Relation with historical seismicity

The first surface rupturing earthquake(s) is (are) associated to AF2, producing an accumulated dip-slip offset of 37 cm in AF2-1 and AF2-2. It occurred in pre settlement times, during the interval 4520±90 BP1870±120 BP (unit 4-Furnas C deposit).

The second surface rupture event occurred in AF1, after the development of the paleosol on unit 4 (410±30 BP, 1440-1500 cal AD) and before the deposition of unit 5 (1563 AD-Fogo historical eruption), producing 1 m of normal displacement. Considering that the settlement in São Miguel occurred in 1439-1443 AD, and taking into account the historical record of earthquakes in the island, this event probably corresponds to the October 22nd, 1522 Vila Franca do Campo earthquake. This was the deadliest and one of the most violent events recorded in the Azores, causing about 5000 deaths [Frutuoso 1522-1591]. Based on macroseismic analysis of historical records, using the European Macroseismic Scale 1998 (EMS-1998; Grünthal [1998]), Silveira [2002] and Silveira et al. [2003] inferred that the epicenter was located inland, NNW of Vila Franca do Campo (a few km southwest from the Altiprado Faults) and that the maximum intensity X was reached at the central part of the island (Figure 8). Silveira [2002] drew NW-SE trending elliptic isoseismal lines based on structural constraints. The earthquake produced severe damage and triggered numerous landslides mainly in the central-eastern part of the island, in an area located between Vila Franca do Campo, Ponta Garça, Furnas, Fenais da Ajuda and Maia [Mendonça Dias 1945] (Figure 8). A major landslide occurred on a slope above Vila Franca do Campo (the capital town of the island at the time), burying the village a few minutes after the main shock, destroying the houses that were still standing, and killing most of its inhabitants [Silveira et al. 2003]. Nevertheless, the historical records are not clear enough in what concerns the direct effects caused by the earthquake.

Although the paleoseismic data of AF1 reveals 1 m of surface rupture displacing the paleosol developed on unit 4 (1440-1500 cal AD), historical records do not account for surface ruptures. The documents reveal that "…in the earth entrails frightful noises sounded…" moving the earth "… with furious shakes" [Monte Alverne 1629-1726] and that there was no hill that did not collapse" [Maldonado 1644-1711]. However surface rupture phenomena could easily go unnoticed as the villages are preferentially located in coastal areas and, at the time (only 80 years since the beginning of settlement), the central part of the island was probably still covered by dense vegetation.

The third rupture(s) is (are) associated with AF2. As it is not clear if the last displacement (11 cm in AF2-1 and AF2-2) is affecting only the lower part of unit 5 (1563 AD) or affects the entire unit, these displacements could be associated to the intense seismic activity that accompanied the 1563 eruption of Fogo volcano. The earthquakes were felt in a wide region and caused severe damage in Ribeira Grande and Ribeira Seca villages [Frutuoso 1522-1591, Silveira 2002]. The earthquakes were distributed over a broad area, making it difficult to determine an epicentral location. Based in the damage levels reported in coeval records and using EMS-1998, Silveira [2002] deduced that the damage was similar to that caused by an

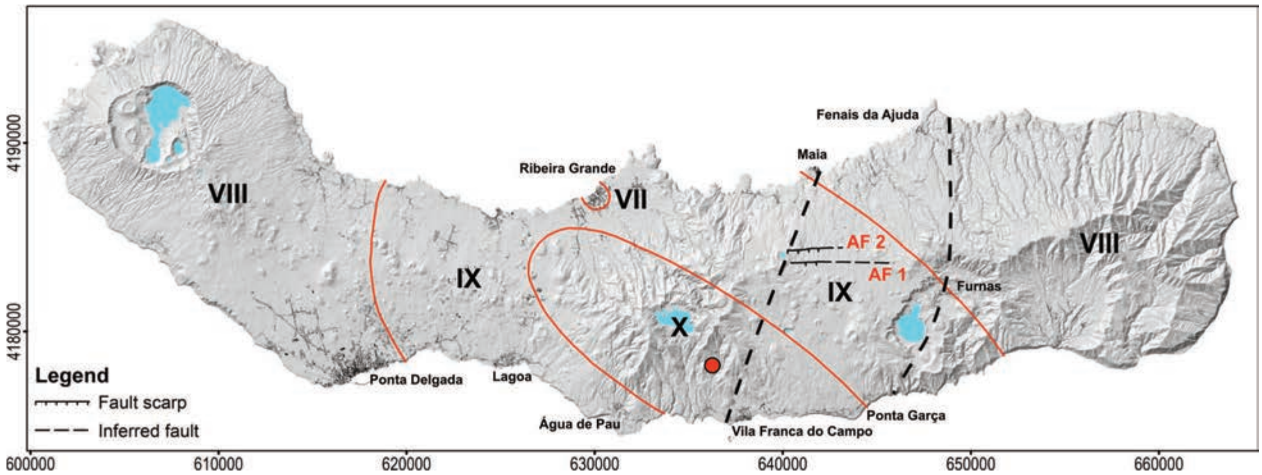

Figure 8. Isoseismal map for the 1522 earthquake (adapted from Silveira 2002): red dot-macroseismic epicenter; red lines-isoseismal lines; dashed black lines-area affected by landslides according to Mendonça Dias [1945].

earthquake reaching intensities X at Ribeira Grande and IX-X at Água de Pau, respectively. Historical documents do not describe the occurrence of secondary environmental effects related to seismic activity. On the other hand, other earthquakes occurred after this eruption that could be responsible for the observed offsets; possible candidates are the 1591 earthquake or the seismic activity associated to the 1630 eruption at Furnas volcano.

The July 26th, 1591 earthquake caused several deaths and produced severe damage in Vila Franca do Campo and Água de Pau. The lack of information does not allow inferring the epicentral location. Silveira [2002] considered intensity VIII (or greater) at those localities.

The 1630 eruption at Furnas volcano was also preceded and accompanied by seismic activity distributed over a wide area, and caused several landslides and a lot of damage, mainly in Povoação, Ponta Garça and Vila Franca do Campo [Monte Alverne 1629-1726], from which Silveira [2002] estimated an intensity VIII or greater.

The most recent displacement(s), producing an offset of 0.38 m, is (are) related with AF1. However, the data are insufficient to correlate deposition, erosion and faulting events. There is no evidence of a high-magnitude earthquake with epicenter inland in historical or instrumental records justifying the observed offset. Part of it could have been produced by the intense seismic activity that accompanied the 1563 AD Fogo eruption. Another possibility is that part (or the totality) of this offset may have been produced after the deposition of unit 6 (<160±30 years BP, <1660-1700 cal AD).

In the central region of São Miguel seismicity occurs mainly as shallow seismic swarms of low to moderate magnitude, with focal depths varying between 0 and 8 km [Silva 2011]. There is a long time record of seismic swarms in this area since the beginning of 20th century (e.g. 1922, 1967, 1983, 1985, 1989 and 2005).

The most recent seismic swarm started on May 10th, 2005 and continued until the end of the year, with more than 46,000 shallow earthquakes recorded (Figure 9), 170 of which were felt. The focal depth ranged from 1 to 7 km [Silva et al. 2012]. The strongest events occurred on September 20th and 21th and had M_L 4.1 and 4.3, respectively, causing several small landslides and E-W trending ground cracks. The larger fissure was 1 km-long and 15 cm-wide [Trota 2008]. The landslides were heterogeneously distributed over a 10 km^2 area around the epicentral zone, and some formed natural dams [Marques et al. 2007].

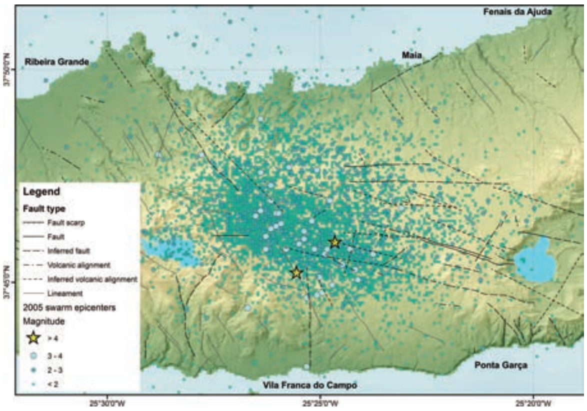

Figure 9. Epicenter distribution of the 2005 seismic swarm (May 10th to December 31st; data from CIVISA). More than 46,000 earthquakes, with focal depths between 1 and 7 km, were recorded. The most energetic events reached magnitudes 4.3 and 4.1 M_L and triggered several landslides and E-W trending ground cracks.

As the earthquakes were felt with intensity VI at Vila Franca do Campo, using the Mercalli Modified Scale 1956 (MM-56, CIVISA) which, in turns, corresponds to the same intensity value in EMS-1998 [Musson et al. 2010], intensity should have been higher (≥VII) at the epicentral zone. The region is unpopulated, but some farming support buildings suffered structural damage compatible with EMS-1998 intensity VII. Surface rupture could easily pass unnoticed as the main villages are located on coastal areas.

GPS monitoring data allowed Trota [2008] to verify that there was ground deformation associated with the seismic activity. Considering the seismicity pattern, the low seismic energy released, and the GPS data, this activity must have been related to a magmatic intrusion at 1.8 to 2.4 km depth. The previous seismic swarms were not geodetically monitored and the seismic network was limited at the time, so there are no evidences of previous episodes of crustal deformation. Thus, it is more realistic to consider that the 0.38 m displacement observed in AF1 trench could have accumulated as a consequence of several moderate shallow earthquakes during periods of increased seismic activity in this area, which may have produced crustal deformation. Azzaro [1999], Azzaro et al. [2000] and Ferreli et al. [2002] report surface ruptures and paleoseismological evidence produced by shallow moderate magnitude earthquakes (M^W 3.0-5.0) and creep in faults located on the eastern flank of Etna.

4.2. Slip rates and recurrence intervals

Normal slip rates range from 0.11 mm/year in AF2 to 0.31-3.37 mm/year in AF1. It should be noted that the minimum slip rate at AF1 may be overestimated, since a considerable time gap exists between the deposition of Furnas C tephra (unit 4) at about

1900 BP and the development of the overlying soil (410±30 BP). Some amount of displacement may have occurred before the formation of the paleosol. The slip rate in AF2 is a minimum value, since the age of the oldest rupture is unknown and because the geometry of the faults suggests that the strike-slip component could be significant.

Recurrence intervals were not estimated because the short period analyzed suggests clustering, as most of the events occurred in historical times and because, between the deposition of Furnas C (unit 4, 1900 BP) and the development of its topsoil (410±30 BP), there is a time gap of about 1500 years without any geological record.

4.3. Implications for seismogenic potential assessment

In the Azores, interactions between volcanism and faulting difficult seismic hazard assessment; besides coseismic ruptures, surface faulting can also occur during seismic swarms related to volcanic eruptions (such as during the 1957-58 Capelinhos eruption in Faial; Madeira and Brum da Silveira 2003).

The maximum probable magnitudes of the earthquakes generated by the Altiprado Faults were estimated based on Wells and Coppersmith's [1994] correlations between seismic moment magnitude (M_w) and surface rupture length [SRL; M_w=5.08+1.16log(SRL)], rupture area [RA; M_w=4.07+0.98log(RA)], and maximum displacement [MD; Mw=6.69+0.74log(MD)], considering the offset produced by each surface rupturing event (Table 2). However, one should be aware that the achieved numbers are approximate values, as we are dealing with a volcanic environment, where earthquakes may have non-double couple mechanisms.

Relatively to rupture area, we used a similar procedure to that used by Meletti et al. [2008] to estimate the thickness of the brittle crust (seismogenic crust) for Italian territory, by using the maximum depth at which earthquakes occur. According to Matias et al. [2007], the Moho is located at 12-13 km depth. Nevertheless, the majority of earthquakes of São Miguel central area are located at depths that do not exceed 8 km [Silva, 2011]. This is comparable with other volcanic regions, like the South Iceland Seismic Zone [Tryggvason et al. 2002, Gudmundsson and Brenner 2003] and the Taupo Volcanic Zone [Villamor et al. 2011]. Fault dip at depth is unknown, so we consider that fault dip does not change significantly. The rupture area was then calculated using a thickness of 8 km for the seismogenic crust and an average fault dip of 65°.

The maximum slip method frequently overestimates magnitude, since geological record does not allow distinguishing between coseismic, post-seismic and aseismic slip. On the other hand, the observed offsets may not represent the maximum offset produced by each rupture.

Considering the total observed length of Altiprado Faults (AF1, 0.8-5.5? km; AF2, 1.7-3? km), moment magnitudes in the order of 4.9-5.9 are obtained for surface rupture length and rupture area parameters, contrasting with magnitudes estimated from maximum displacement (5.7-6.7). However, in the two first cases, length and consequently area values are certainly underestimated as the total length of the faults is unknown. The faults must be longer but their traces may be concealed beneath thick fall deposits. For example, the deposits of the 1563 Fogo eruption reach a thickness of 2.5 m in Altiprado area. We must also considerer that, as this zone is prone to farming activities, morphological evidence may have been totally or partial destroyed by recent anthropic activities.

Although those magnitude values are usually considered as insufficient to generate surface rupture, in volcanic domains the magnitude threshold for surface faulting may be significantly lower due to existence of shallow seismogenic sources related to

Fault	SRL (km)	Mw(±0.24-0.28)	RA (km^2)	M_w	MD (m)	Mw
AF1	0.8 - 5.5	5.0 - 5.9	7.4 - 48.5	4.9 - 5.7	1	6.7
					0.38 (1)	6.4
AF2	1.7 - 3	5.3 - 5.6	15.0 - 26.5	5.2 - 5.5	0.37 (2)	6.4
					0.11 (2)	6.0
					0.26	6.3
					0.11	6.0
					0.07	5.8
					0.04	5.7

Table 2. Maximum expected magnitudes from surface rupture length (SRL), rupture area (RA) and maximum displacement (MD) of Altiprado faults using relationships by Wells and Coppersmith (1994). (1) Maximum displacement assuming a single paleoearthquake. (2) Maximum displacement assuming surface rupture in both branches of AF2 (AF2-1 + AF2-2) in a single paleoearthquake.

volcano-tectonic or purely tectonic mechanisms [Smith et al. 1996, Azzaro et al. 1998, Zobin 2012].

There is a long record of seismic swarms in the studied area, probably with features similar to that of 2005 that was related with a magmatic intrusion. Several authors [e.g. Rubin and Pollard 1988, Rubin 1992] suggest that a magmatic intrusion at shallow levels can induce brittle deformation of the surface. Gravimetric studies performed at São Miguel Island indicate that in this area, at about 8 km depth, a high-density region extending to shallower levels (still present at 1 km) exists and has been interpreted as an old basaltic shield or a partly solidified magmatic body [Camacho et al. 1997].

Relocation and fault plane solution analysis of earthquakes that occurred between 2002 and 2008 in the area suggest the existence of a local heterogeneous stress field [Silva 2011]: in the upper 5 km depth, stress field is extensional, but at deeper levels (>5 km) fault plane solutions indicate a compressive stress field. According to Silva [2011], the extensional stress field may result from a compressive regime at larger depths, which promotes the ascension of thermal fluids to crustal lower levels, weakening pre-existing fault planes which, due to gravitational stress, become potential slip surfaces.

The role of hydrothermal fluids is well documented in São Miguel. Seismic tomography for this area relates the velocity anomalies to hydrothermal activity [Zandomeneghi et al. 2007]; the existence of a positive V_p anomaly with high V_p/V_s ratio suggest that this zone is characterized by low V_s due to fluids contained in fractures.

The possibility for creeping cannot also be disregarded, but the Altiprado faults were not subject to precise leveling measurements. For instance, aseismic creep due to volcanic-tectonic processes that cause gravitational instability is well documented in faults at Etna volcano [Ferreli et al. 2002].

Conversely, maximum displacement magnitudes may be overestimated. In AF1 there is a time gap between deposition of unit 4 and the development of the topsoil, so the separation of 1 m could be erroneously considered as the result of a single event. On the other hand, part of the displacement could be post-seismic or aseismic. For instance, after the 2009 L'Aquila earthquake, Boncio et al. [2010 in Wilkinson et al. 2012] observed widening in ground cracks. In the same way, in volcanic areas surface ruptures may occur related to moderate earthquakes, and in this case Wells and Coppersmith's [1994] correlations should not be used. Nevertheless, the correlation between magnitude and surface rupture length, deduced from aftershock distribution, for off-shore instrumental earthquakes in the Azores (the M 7.2, January 1st, 1980 and M_L 5.8, July 9th, 1998 earthquakes; Hirn et al. 1980, Dias et al. 2007) are in agreement with those obtained using the correlations from Wells and Coppersmith [1994], suggesting that they can be used in the Azores for tectonic earthquakes [Madeira and Brum da Silveira 2003]. However, the tectonic faulting origin for the observed offsets is not definitively proven.

5. Final remarks

Trenching across the two scarps observed at Achada das Furnas confirmed their tectonic nature and revealed the presence of two previously unknown normal faults, with a possible strike-slip component. The Altiprado Faults 1 and 2 trend E-W and cut a volcanic succession younger than 4500 years, the age of the well-known Fogo A deposit, undoubtedly showing that the faults are active.

The proximity of the two faults and their geometry suggests that they could be synthetic branches of a major fault dipping to the south. It is probable that such a fault would present oblique (normal dextral) slip so we can envisage some amount of strain partitioning between the two branches; the subvertical geometry of the fault planes in AF2 is compatible with this branch accommodating most of the strike-slip component, while AF1 would accommodate mostly normal slip.

AF1 exhibits an accumulated dip-slip of 1.38 m that may have been produced by at least two surface rupturing paleoearthquakes (1 m + 0.38 m). The radiocarbon age of the paleosol developed on unit 4 is compatible with the first rupture having been produced by the 1522 earthquake. The event that produced the second rupture remains unclear. Nevertheless, this area is subject to frequent seismic swarms of volcano-tectonic origin, and recent geodetic studies during periods of increased seismic activity showed the occurrence of crustal deformation. Thus, the normal offset of 0.38 m could be the result of displacements produced by several moderate magnitude events or swarms related or not with magmatic cycles.

AF2 presents an accumulated dip-slip of 0.48 m, but uncertainties remain about the exact number of paleoearthquakes. Assuming that both branches of AF2 ruptured during the same events, then two paleoearthquakes occurred (0.37 m + 0.11 m). On the other hand, four events may have occurred and, thus, each displacement be related to individual earthquakes (0.26 m, 0.11 m, 0.07 m and 0.04 m). In both cases, the older displacement(s) (0.37 m, or 0.26 m and 0.11 m) correspond to pre-settlement events, while the following ruptures (0.11 m, or 0.07 m and 0.04 m) occurred during the 1563 historical eruption of Fogo volcano or later.

Although there is some uncertainty about the seismic parameters, the Altiprado Faults have the potential to cause surface rupture either related to purely tectonic high-magnitude earthquakes (e.g. 1522 earthquake), or associated to volcano-tectonic seismic swarms of low to moderate magnitude, or even during surface deformation associated to eruptions, complicating seismic hazard assessment in the Azores due to the interaction between volcanism and faulting.

Data and sharing resources

Maps were made using ArcGIS 10.0 software, ESRI®.

World topography and bathymetry from GEBCO_08 database [2010], IHO UNESCO, General Bathymetry Chart of the Oceans, digital edition at http://www.gebco.net/data_and_products/gridded_bathymetry_data/.

Aerial photo of Achada das Furnas Plateau supplied by Direcção Geral de Planeamento Urbanístico, 1974.

Epicenter distribution of the 2005 seismic swarm and its macroseismic data was taken from CIVISA Database, Centro de Informação e Vigilância Sismovulcânica dos Açores, Centro de Vulcanologia e Avaliação de Riscos Geológicos da Universidade dos Açores.

Acknowledgments. Rita Carmo is supported by the Azores Regional Government, through a Ph.D. Grant from Fundo Regional da Ciência e Tecnologia (M3.1.2/F/016/2007), and through Serviço Regional de Protecção Civil e Bombeiros dos Açores in the scope of the scientific and technical protocols to guarantee the Azores Seismovolcanic Surveillance and the Emergency Planning Studies of Centro de Informação e Vigilância Sismovulcânica dos Açores (CIVISA). José Madeira's contribution to FCT project SHAAzores (PTDC/CTE-GIX/108637/2008).We also acknowledge the contribution of the reviewers (Emanuela Falcucci and Raffaele Azzaro) and associate editor Salvatore Barba to significant improvement of the initial version of the manuscript.

References

Abdel-Monem, A.A.; L.A. Fernandez and G.M. Boone (1975). K-Ar ages from the eastern Azores group (Santa Maria, São Miguel and the Formigas Islands), Lithos, 8, 247-254.

Argus, D.F., R.G. Gordon and C. DeMets (2011). Geologically current motion of 56 plates relative to the no-net rotation reference frame, Geochemistry Geophysics Geosystems, 12, Q11001, 13 p., doi:10.1029/2011GC003751.

Azzaro, R. (1999). Earthquake surface faulting at Mount Etna volcano (Sicily) and implications for active tectonics, Journal of Geodynamics, 28, 193-213.

Azzaro, R., L. Ferreli, A. Michetti, L. Serva and E. Vittori (1998). Environmental hazard of capable faults: the case of the Pernicana Fault (Mt. Etna, Sicily), Natural Hazards, 17, 147-162.

Azzaro, R., D. Bella, L. Ferreli, A.M. Michetti, F. Santagati, L. Serva and E. Vitttori (2000). First study of fault trench stratigraphy at Mt. Etna volcano, Southern Italy: understanding Holocene surface faulting along the Moscarello fault, Journal of Geodynamics, 29, 187-210.

Camacho, A.G.; F.G. Montesinos and R. Vieira (1997). A three-dimensional gravity inversion applied to São Miguel Island (Azores), Journal of Geophysical Research, 102(B4), 7717-7730.

Chaves, F.A. (1960). Erupções submarinas nos Açores. Informações que os navegantes podem prestar sobre tal assunto, Açoreana, v.5, nº 4, 50 p.

Dias, N.A., L. Matias, N. Lourenço, J. Madeira, F. Carrilho and J.L. Gaspar (2007). Crustal seismic velocity structure near Faial and Pico islands (Azores), from local earthquake tomography, Tectonophysics, 455(3-4), 301-317, doi: 10.1016/j.tecto.2007.09.001.

Fernandes, R., B. Ambrosius, R. Noomen, L. Bastos, M. Wortel, W. Spakman and R. Govers (2003). The relative motion between Africa and Eurasia as derived from ITRF2000 and GPS data, Geophysical Research Letters, 30(16), 1828.

Ferreli, L., A.M. Michetti, L. Serva and E. Vittori (2002). Stratigraphic evidence of coseismic faulting and aseismic fault creep from exploratory trenches at Mt. Etna volcano (Sicily, Italy), Geological Society of America, Special Paper 359, 49-62.

Frutuoso, G. (1522-1591†). Livro Quarto das Saudades da Terra, in Saudades da Terra, G. Frutuoso (Ed.), 2ª ed., Ponta Delgada, Instituto Cultural de Ponta Delgada, II, 1981.

Grünthal, G. (Ed.) (1998). European Macroseismic Scale 1998, Cahiers du Centre Européen de Géodynamique et de Séismologie, vol.15, Luxembourg.

Gudmundsson, A. and S. Brenner (2003). Loading of a seismic zone to failure deforms nearby volcanoes: a new earthquake precursor, Terra Nova, 15, 187-193.

Guest, J.E., J.L. Gaspar, P.D. Cole, G. Queiroz, A.M. Duncan, N. Wallenstein, T. Ferreira and J.M. Pacheco (1999). Volcanic geology of Furnas volcano, São Miguel, Azores, Journal of Volcanology and Geothermal Research, 92, 1-29.

Hipólito, A., J. Madeira, J.L. Gaspar and R. Carmo (2010). Neotectónica da ilha Graciosa-uma contribuição para o enquadramento geodinâmico da junção tripla dos Açores, e-Terra, Revista electrónica de Ciências da Terra, 11, 3, ISSN 1645-0388.

Hirn, A., H. Haessler, P. Hoang Trong, G. Wittlinger and L. Mendes Victor (1980). Aftershock sequence of the January 1st, 1980, earthquake and present day tectonics in the Azores, Geophysical Research Letters, 7(7), 501-504.

Laughton, A.S. and R.B. Whitmarsh (1974). The Azores-Gibraltar plate boundary, in Geodynamics of Iceland and the North Atlantic Area, L. Kristjansson (Ed.), D. Reidel Publ. Co., Dordrecht, 63-81.

Lourenço, N., J.F. Luis and M. Miranda (1997). Azores triple junction bathymetry, Map edited by Lisbon and Algarve Universities.

Lourenço, N., J.M. Miranda, J.F. Luis, A. Ribeiro, L. Mendes Victor, J. Madeira and H. Needham (1998). Morphotectonic analysis of the Azores Volcanic Plateau from a new bathymetric compilation of the area, Marine Geophysical Researches, 20, 141-156.

Machado, F. (1949). O terramoto de São Jorge, em 1757, Açoreana, 4(4), 311-324.

Machado, F. (1959). Submarine pits of the Azores Plateau, Bulletin Volcanologique (sér. II), 21, 109-116.

Madeira, J. (1998). Estudos de neotectónica nas ilhas do Faial, Pico e São Jorge: uma contribuição para o conhecimento geodinâmico da junção tripla dos Açores, Ph.D. Thesis, Lisbon University, 428 pp.

Madeira, J. (2006). Erupções históricas nos Açores, in Enciclopédia Açoriana, edited by Centro de Estudos dos Povos e Cultura de Expressão Portuguesa da Universidade Católica Portuguesa e S.R. Educ. Cult. Centro do Conhecimento dos Açores, Presidência do Governo Regional dos Açores, Direcção Regional da Cultura da Região Autónoma.

Madeira, J. and A. Ribeiro (1990). Geodynamic models for the Azores triple junction: a contribution from tectonics, Tectonophysics, 184(3-4), 405-415.

Madeira, J. and A. Brum da Silveira (2003). Active tectonics and first paleoseismological results in Faial, Pico and São Jorge islands (Azores, Portugal), Annals of Geophysics, 46(5), 733-761.

Maldonado, Pe. M.L. (1644-1711†). Fenix Angrence, 1ª ed., Angra do Heroísmo, Instituto Histórico da Ilha Terceira, vol. 2, 717 p., 1990.

Marques, R., G. Queiroz, R. Coutinho and J.L. Zêzere (2007). Actividade geomorfológica desencadeada pela crise sísmica de 2005 no vulcão do Fogo (São Miguel, Açores): avaliação da susceptibilidade com recurso a regressão logística, Publicações da Associação Portuguesa de Geomorfólogos, V, 47-61.

Matias, L., N.A. Dias, I. Morais, D. Vales, F. Carrilho, J. Madeira and J.L. Gaspar (2007). The 9th of July 1998 Faial island (Azores, North Atlantic) seismic sequence, Journal of Seismology, 11, 275-298.

Mendonça Dias, A. (1945). O sismo de 1522 em São Miguel, Insulana, vol. I, nº 4, 490-500.

Meletti, C., F. Galadini, G. Valensise, M. Stucchi, R. Basili, S. Barba, G. Vannucci and E. Boschi (2008). A seismic source zone model for the seismic hazard assessment of the Italian territory, Tectonophysics, 450, 85-108.

Monte Alverne, A. (1629-1726†). Crónicas da Província de S. João Evangelista das Ilhas dos Açores, 1ª ed., Ponta Delgada, Instituto Cultural de Ponta Delgada, II, 520 p., 1961.

Moore, R. (1990). Volcanic geology and eruption frequency, São Miguel, Azores, Bulletin of Volcanology, 52, 602-614.

Muecke, G.K., J.M. Ade Hall, F. Aumento, A. MacDonald, P.H. Reynolds, R.D. Hyndman, J. Quintino, N. Opdyke and W. Lowrie (1974). Deep drilling in an active geothermal area in the Azores, Nature, 252, 5481, 281-285.

Musson, R., G. Grünthal and M. Stucchi (2010). The comparison of macroseismic intensity scales, Journal of Seismology, 14, 413-428.

Reches, Z. (1983). Faulting of rocks in three dimensional strain fields. II: theoretical analysis, Tectonophysics, 95, 133-156.

Reches, Z. and J.H. Dieterich (1983). Faulting of rocks in three-dimensional strain fields. I: failure of rocks in poliaxial, servo control experiments, Tectonophysics, 95, 111-132.

Rubin, A. (1992). Dyke-induced faulting and graben subsidence in volcanic rift zones, Journal of Geophysical Research, 97(B2), 1839-1858.

Rubin, A. e D. Pollard (1988). Dyke-induced faulting in rift zones of Iceland and Afar, Geology, 16, 413-417.

Silva, R. (2011). Evaluation of spatial and temporal seismicity patterns in the central region of São Miguel (Azores): implications for whole-island seismic hazard assessment, Ph.D. Thesis, Azores University, 236 pp.

Silva, R., J. Havskov, C. Bean and N. Wallenstein (2012). Seismic swarms, fault plane solutions, and stress tensors for São Miguel Island central region (Azores), Journal of Seismology, 16(3), 389-407.

Silveira, D. (2002). Caracterização da sismicidade histórica da ilha de São Miguel com base na reinterpretação de dados de macrossísmica: contribuição para a avaliação do risco sísmico, M.Sc. Thesis, Azores University, 149 pp.

Silveira, D., J.L. Gaspar, T. Ferreira and G. Queiroz (2003). Reassessment of the historical seismic activity with major impact on São Miguel Island (Azores), Natural Hazards and Earth System Sciences, 3, 615-623.

Smith, R., S. Jackson, and W. Hackett (1996). Paleoseismology and seismic hazards evaluations in extensional volcanic terrains, Journal of Geophysical Research, vol. 101(B3), 6277-6292.

Trota, A. (2008). Crustal deformation in São Miguel and Terceira islands (Azores). Volcanic unrest evaluation in Fogo/Congro area (São Miguel), Ph.D. Thesis, Azores University, 281 pp.

Tryggvason, A., S.Th. Rögnvaldsson and O.G. Flóvenz (2002). Three-dimensional imaging of the P-and S-wave velocity structure and earthquake locations beneath Southwest Iceland, Geophysical Journal International, 151, 848-866.

Villamor, P., K.R. Berryman, I.A. Nairn, K.J. Wilson, N.J. Litchfield and W. Ries (2011). Associations between volcanic eruptions from Okataina Volcanic Center and surface rupture of nearby active faults, Taupo rift, New Zealand: insights into the nature of volcano-tectonic interactions, Geological Society of America Bulletin, 123(7-8), 1383-1405, doi:10.1130/B30184.1.

Wallenstein, N. (1999). Estudo da história recente e do comportamento eruptivo do vulcão do Fogo (São Miguel, Açores). Avaliação preliminar do "hazard", Ph.D. Thesis, Azores University, 266 pp.

Wells, D.L. and K.J. Coppersmith (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area and surface displacement, Bulletin of Seismological Society of America, 84, 4, 974-1002.

Weston, F.S. (1964). List of recorded volcanic eruptions in the Azores with brief reports, Bol. Mus. Lab. Min. Geol. Fac. Ciências de Lisboa, 10(1), 3-18.

Wilkinson, M.W., K.J.W. McCaffrey, G.P. Roberts, P.A. Cowie, R.J. Phillips, M. Degasperi, E. Vittori and A.M. Michetti (2012). Distribution and magnitude of post seismic deformation of the 2009 L'Aquila earthquake (M6.3) surface rupture measured using repeat terrestrial laser scanning, Geophysical Journal International, 189(2), 911-922, doi: 10.1111/j.1365 246X.2012.05418.x.

Zandomeneghi, D., J. Almendrosa, J.M. Ibáñez and G. Saccorotti (2008). Seismic tomography of Central São Miguel, Azores. Physics of the Earth and Planetary Interiors, 167, 8-18.

Zobin, V. (2012). Introduction to volcanic seismology, 2nd ed., Elsevier B.V., Amsterdam, 482 pp.

*Corresponding author: Rita Carmo,
Centro de Vulcanologia e Avaliação de Riscos Geológicos da Universidade dos Açores, CVARG, Açores, Portugal;
email: rita.l.carmo@azores.gov.pt