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Ground motion and tectonics in the Terceira Island: Tectonomagmatic interactions in an oceanic rift (Terceira Rift, Azores Triple Junction)

F.O. Marques [a,*], J. Catalão [b], A. Hildenbrand [c,d], P. Madureira [e,f]

[a] *Universidade de Lisboa, Lisboa, Portugal*
[b] *IDL, Universidade de Lisboa, Lisboa, Portugal*
[c] *Université Paris-Sud, Laboratoire GEOPS, UMR8148, Orsay, F-91405, France*
[d] *CNRS, Orsay, F-91405, France*
[e] *Estrutura de Missão para a Extensão da Plataforma Continental, Paço D'Arcos, Portugal*
[f] *Centro de Geofísica de Évora and Dep. Geociências da Univ. de Évora, Évora, Portugal*

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ABSTRACT

The interpretation of high-resolution topography/bathymetry, GPS and InSAR data, and detailed structural geology indicate that: (1) Terceira developed at the intersection of two major volcano-tectonic lineaments: WNW-ESE (local TR's direction) and NNW-SSE (submarine chain of volcanoes, here firstly recognised and coined Terceira Seamount Chain). (2) Terceira is affected by four main fault systems: the ca. N165° (normal faults dipping to east and west, mostly across the middle of the island), the N140° (normal faults mostly making up the Lajes Graben), the N110° (faults with oblique striations – normal dextral, making up the main volcanic lineament), and the more subtle N70° (the transform direction related to the Nubia/Eurasia plate boundary). Seismicity, GPS data and faults displacing the topography indicate that all systems are active. (3) The whole island is subsiding at a rate of ca. 5 mm/yr, as attested by both GPS and InSAR data, which is exceptionally high for the Azores islands. Common explanations like thermal contraction, or bending of the lithosphere, or magmatic processes, or collapse of the island under its own weight likely cannot justify the observed subsidence rate. The estimated average of TR's subsidence rate is also not enough, therefore we conclude that the measured 5 mm/yr can be a peak. (4) The fault geometry and kinematics are consistent with the current direction of maximum extension in the Azores (ca. N65°), and the rotation of Nubia relative to Eurasia. (5) Given that the NE shoulder of the Lajes Graben is moving upwards at 5 mm/yr and sits directly on the TR's NE shoulder, we conclude that the TR's shoulder is moving up, most likely as a result of the elastic rebound associated with rifting. The elastic rebound in both NE and SW TR's shoulders is most likely responsible for the observed ridge morphology all along the TR.

1. Introduction

The location and evolution of volcanic islands inside active oceanic rifts are still matters of great debate. Here we use Terceira Island, which has developed inside the Terceira Rift (TR), to bring light to some relevant problems that still require explanation: (1) What is Terceira's current ground motion, and what information can we retrieve regarding internal deformation of the volcanic edifice, and meaning of the rigid body motion? (2) What is the meaning of the vertical component of Terceira's motion? (3) How are internal tectonics and volcanism organised, and what is their relationship to large-scale tectonics? (4) How can the internal deformation give relevant information regarding the external deformation and far field stresses? (5) Why has volcanism concentrated to form islands, like Terceira, inside the TR? (6) How does the island relate to the elongated volcanic ridges and islands subparallel to, and SW of the TR?

McKenzie (1972) showed that the Azores-Gibraltar plate boundary results from differential spreading rates of Eurasia (Eu) and Nubia (Nu) relative to North America (NA), thus transforming the Mid-Atlantic Rift (MAR) spreading into compression in the Mediterranean Alpide Belt. Based on the kinematics of Eu and Nu, and on earthquake fault plane solutions, McKenzie (1972) concluded that, presently, the western end of the Azores-Gibraltar plate boundary is dilatational from the MAR-axis to the Gloria Fault, whereas the Gloria Fault is dextral transcurrent, and close to Iberia the Eu/Nu boundary becomes compressional.

The current plate kinematics (DeMets et al., 2010) shows that the MAR is opening faster north (NA/Eu boundary) than south of the Azores Triple Junction (ATJ) (NA/Nu boundary) (Fig. 1). Moreover, there is also an angular difference, which induces extension in the Azores region, between the Gloria Fault and the MAR. The rotation of Nu relative to Eu

* Corresponding author. Tel.: +351 217500000; fax: +351 217500064.
E-mail address: fomarques@fc.ul.pt (F.O. Marques).

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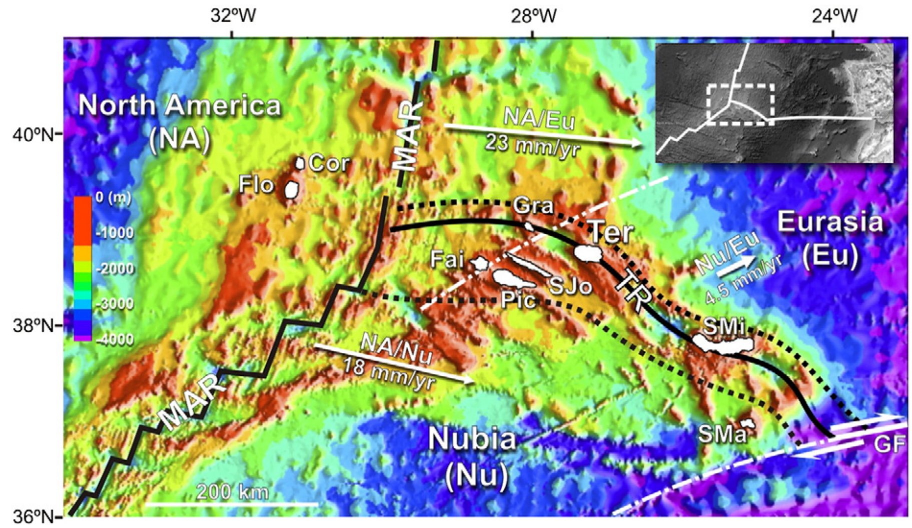

Fig. 1. Tectonic setting of the Azores Triple Junction. MAR and TR (thick black lines) are the Mid-Atlantic and Terceira rifts, respectively. The dotted black lines mark the Nu/Eu plate boundary in the Azores according to Marques et al. (2013a). Note that the TR's eastern half makes up a discrete Nu/Eu boundary, which becomes diffuse in the TR's western half and encompasses the Central Azores islands: Fai – Faial; Pic – Pico; SJo – S. Jorge; Gra – Graciosa; and Ter – Terceira. SMi, SMa, Flo and Cor are the islands of S. Miguel, Santa Maria, Flores and Corvo respectively. White arrows with underlying values represent the full plate velocities taken from DeMets et al. (2010). White half arrows indicate the strike-slip motion in the Gloria Fault (GF).

produces a transform direction that strikes approximately ENE-WSW along the TR, and is responsible for the dextral strike-slip in the Gloria Fault (Fig. 1). GPS velocities in Central Azores (Marques et al., 2013a, 2014a) indicate that the Nu/Eu boundary is discrete and made by the TR in the TR's eastern half, and is diffuse in the TR's western half (Fig. 1) (see also Miranda et al., 2014). From this, Marques et al. (2013a) concluded that the opening rate in the western segment of the TR is much smaller than previously thought, because it does not take up the whole deformation imposed by the motions of Nubia and Eurasia.

Using the bathymetry in Tolstoy (1951), and following the ideas of Agostinho (1931), Machado (1959) interpreted the linear succession of basins and islands stretching from the west Graciosa Basin to the S. Miguel Island as a rift belt of tectonic origin, which he coined the Terceira Rift (TR). Similarly to Agostinho (1931), Machado (1959) admitted that the TR could continue to the east until the Formigas Bank, close to the junction with the Gloria Fault. Vogt and Jung (2004) suggested that the TR is the world's slowest-spreading organized accreting plate boundary. Similarly to Machado (1959), Vogt and Jung (2004) interpreted the interisland basins simply as volcanically ‘unfilled’ rift valley segments. In contrast to previous studies, Vogt and Jung (2004) suggested an age of ca. 1 Ma for the TR.

The ultimate objective of this work is to integrate all data and interpret their meaning in the framework of the large-scale tectonics. Terceira Island is a key target for such purpose, as it sits within the TR, in an area characterised by the transition between discrete and diffuse behaviour of the western part of the Eu/Nu plate boundary. In order to accomplish this objective, we used the following methods: (1) analysis of a digital elevation model (DEM), in order to interpret the topography, in particular tectonic and volcanic lineaments, and also potential landslide scars. (2) GPS and InSAR data, to measure current ground motion, and estimate rigid body motion and internal deformation of the island. A GPS campaign was carried out in 2013 on the Terceira Island. This campaign followed on previous campaigns carried out in 2001, 2003 and 2006. The objective of this new campaign was to improve the precision of the estimated positions, time-series and related parameters. (3) Detailed structural/tectonic studies in the field in order to validate DEM interpretation, observe and measure tectonic structures at the outcrop, and infer the stress field. (4) Geochronology, to establish the correct succession of events, mostly of volcanic origin.

With the present study, we intend to improve the current knowledge by means of a much better GPS accuracy, new structural/tectonic data, and new interpretations of the subaerial and submarine topography.

2. Geological setting

Terceira lies inside the TR, at an inflection point where the TR's trend changes from ca. N110° (west of Terceira) to ca. N130° (SE of Terceira) (Figs. 1 and 2). Terceira Island is elliptical in plan view, with the greatest axis trending ca. N100°. The submarine edifice is apparently more complex, as shown in Fig. 2 and described in Section 4.

Terceira comprises five main volcanic complexes, with ages generally decreasing from east to west: (1) the Serra do Cume volcanic edifice, also referred to as Cinco Picos in more recent studies (e.g. Madureira et al., 2011), makes up the eastern third of the island. It is essentially composed of a succession of basaltic lava flows, which has been dated from the base to the top between 401 ± 6 ka, and 370 ± 2 ka (Calvert et al., 2006; Hildenbrand et al., 2014). This succession is affected by a graben in the NE and by a 7 km wide caldera elliptical depression in the SE. (2) The Guilherme Moniz edifice in the south-central part of the island is dominantly composed of differentiated volcanic products, including lava flows and pyroclastic deposits possibly derived from multiple vertical caldera collapses (Calvert et al., 2006). The Guilherme Moniz caldera has an elliptical shape and is roughly elongated NW-SE. Volcanic products exposed in its eastern and southern walls were dated between 270 ka and 110 ka (Calvert et al., 2006; Hildenbrand et al., 2014). (3) The Pico Alto volcanic complex comprises trachytic to comenditic lava domes and associated thick flows extruded dominantly on the northern slope of Guilherme Moniz, from which Self and Gunn (1976) deduced that Pico Alto is a younger continuation of Guilherme Moniz. These units have been dated around 120 ka (Calvert et al., 2006; Hildenbrand et al., 2014), suggesting that the Guilherme Moniz and Pico Alto share a common eruptive history. (4) The Santa Bárbara volcano makes up the western third of the island, and has been considered the youngest stratovolcano in Terceira (Calvert et al., 2006). Its evolution includes both effusive and explosive eruptions, which have been dated between ca 60 ka (Hildenbrand et al., 2014) up to historical time (Calvert et al., 2006). (5) The Fissural Complex consists of numerous monogenic strombolian cones roughly aligned along the WNW-ESE direction. They overly most of the previous complexes and thus were

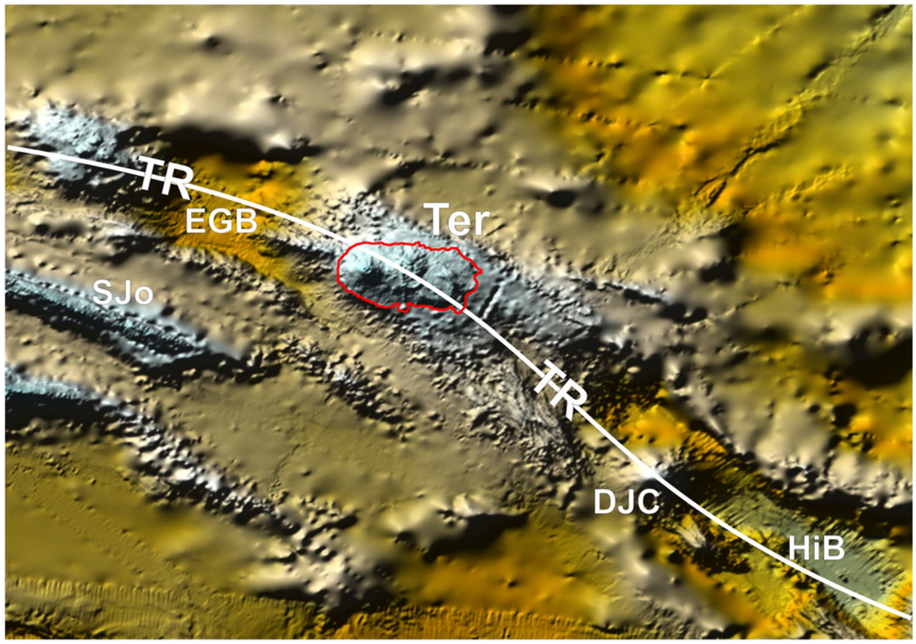

Fig. 2. Terceira (Ter) has developed inside the Terceira Rift (TR), where the TR's trend changes from ca. N110° (west of Terceira) to ca. N130° (SE of Terceira). EGB – East Graciosa Basin; SJo – S. Jorge Island; DJC – D. João de Castro Bank; HiB – Hirondelle Basin.

active very recently, up to historical times. The Fissural system also includes S. Sebastião on the SE edge of Terceira and offshore eruptions to the west.

Preliminary GPS results of Terceira were reported by Navarro et al. (2003), who used data from 10 stations and 2 campaigns (1999 and 2001). Their interpretation of the GPS data indicates a combination of bulk compression and clockwise rotation in the W half. However, the magnitude of the velocity field was close to the estimated precision, which hampered well-grounded inferences regarding intra-island deformation and relationship with the large-scale tectonics. Miranda et al. (2012) improved the previous GPS data by adding two more campaigns (2003 and 2006), and concluded that: (1) the Terceira Island mainly behaves like a rigid body with absolute NE motion that approximates Eurasia motion. (2) The magnitude of the internal horizontal deformation cannot be directly related to local processes because it is still below the observation precision. (3) The island is globally subsiding with an average rate close to 1 mm/yr, which could be the result of the volcanic processes that shaped the Serreta ridge NW of Terceira. We now have a longer observation period (12 years), which made the residual velocities greater than the observation precision. We also carried out new tectonic observations and measurements, and interpreted high-resolution topography/bathymetry and Interferometric Synthetic

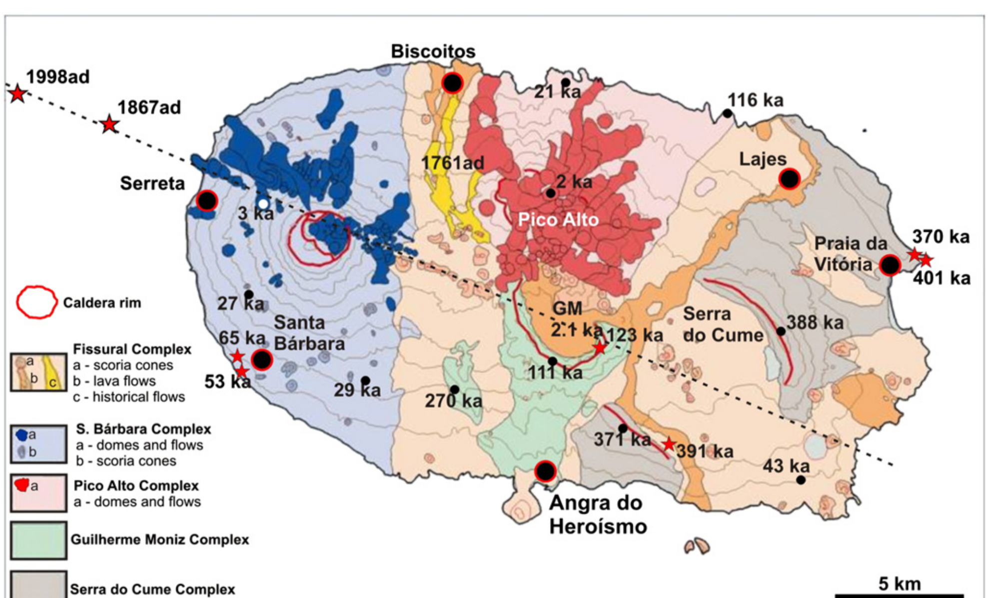

Fig. 3. Geological map of Terceira adapted from http://www.cvarg.azores.gov.pt/geologia-acores/terceira/Paginas/GA-Terceira-Carta-Vulcanologica.aspx. Black dots and red stars mark the locations of samples dated by Calvert et al. (2006) and Hildenbrand et al. (2014), respectively. Black dashed line added to show one of the most prominent and young volcanic lineaments.

Aperture Radar (InSAR) vertical displacement rates (from 2006 to 2009). Altogether, the new data sets allow us to discuss the GPS data with more confidence and in a broader context.

As recognised since very early in the study of the Azores, large to medium magnitude tectonic earthquakes (M > 4.0) do not occur inside the islands (e.g. Agostinho, 1931; Borges et al., 2007; Machado, 1959). In fact, no major intra-island tectonic earthquake has been recorded since earthquakes can be measured instrumentally. Therefore, it is not surprising that seismicity inside Terceira is of low magnitude (Fig. 4), and apparently along the main volcano/tectonic lineaments (e.g. Navarro et al., 2009). These include more specifically the N165° lineament in central Terceira, and the Lajes Graben in NE Terceira. The main shocks affecting Terceira occurred in the lithosphere surrounding the island, mostly associated with the TR. The largest and more recent event occurred on the 1st January 1980, with an epicentre ca. 50 km to the W of Terceira (TR's southern wall), a magnitude Mw = 7.2, and a maximum seismic intensity of VIII (EMS-98) in Terceira.

3. New GPS and InSAR data

3.1. GPS data processing and results

The GPS geodetic-geodynamic network in the Azorean central group of islands was established in 2001 in the framework of STAMINA and SARAZORES projects (Catalão et al., 2006; Navarro et al., 2003). It consists of 37 rock-anchored benchmarks on Faial, Pico and Terceira islands (14, 8 and 15 marks, respectively), with an average spacing of 5 km.

The data used for this study were acquired during four surveys from 2001 to 2013. In each survey, every benchmark was occupied for two-to-four 24 hour sessions with a sampling rate of 30 seconds and elevation mask of 15°. During each survey, at least six stations were observed simultaneously and one station was measuring continuously (TOMA). For this 12-year long time series, each station was visited at least four times and observed for at least eight 24-hour sessions. The GPS phase observations were analysed using GAMIT software version 10.4 (Herring et al., 2010). The processing and analysis were made using a two-step approach. In the first step, the GPS phase observations from each day were used to estimate loosely constrained station coordinates, tropospheric zenith delay parameters, and orbital and earth orientation parameters and associated variance-covariance matrices. We have included in the analysis 113 IGS continuous operating GPS stations in order to tie the regional measurements to the ITRF2008 (Altamimi et al., 2011). We have selected the closest IGS stations to Azores located on the Eurasia, North America, and Nubia plates and worldwide IGS stations working continuously since 2001. The GAMIT solution was computed using loose constraints on the a priori station coordinate (0.5 m), a priori hydrostatic and wet models from Saastamoinen (1972, 1973), and Global Mapping Functions (Böhm et al., 2006). The solid Earth tides were modelled according to the IERS conventions (Petit and Luzum, 2010). The ocean tidal loading was modelled from FES2004 ocean tide model (Lyard et al., 2006). The receivers and satellites antenna phase centre corrections were modelled using the IGS08 ANTEX files from IGS. We used SOPAC's final orbits generated under the scope of the IGS reprocessing analysis and coordinates for all the stations expressed in the ITRF2008 (Altamimi et al., 2011). In the second step, daily GAMIT solutions were used as quasi-observations in GLOBK to obtain the position time series for all sites. In this solution, the regional daily solutions were combined with the global daily solution from more than 100 IGS stations computed by SOPAC, the h-files (GAMIT interchange format). The position time series were analysed to detect and remove outliers, and detect possible vertical offsets caused by erroneous antenna height. After editing, the site coordinates and velocities were estimated with respect to ITRF2008 reference frame from a priori values of coordinates and velocities of IGS permanent sites. The final solution combines seven survey-mode GPS campaigns with IGS stations globally between 2001 and 2013. The weighted RMS of the residual velocity for the sites used to define the reference frame (IGS sites) are 0.56, 0.46, 1.97 mm/yr for east, north and vertical components, respectively. Table 1 gives the estimated velocities and 1-σ uncertainties for the GPS sites on Terceira.

All GPS sites exhibit similar behaviour, moving northeast with a mean velocity of 20 mm/yr (Fig. 5a), and moving down about 4.5 mm/yr (Fig. 5b). The only exception to the downward motion is the TCAP station, located at the top of the scarp of the master fault bounding Lajes Graben in the north, with no vertical displacement. This mark was observed 4 times in the last 12 years, and the estimated uncertainties are 0.42 mm/yr.

Estimated horizontal surface velocities were assumed to be representative of two main processes: a rigid body motion associated with the regional plate tectonics, and a residual displacement associated with the intra-island deformation. The rigid body motion was estimated using the Euler vector notation. The three vector components were

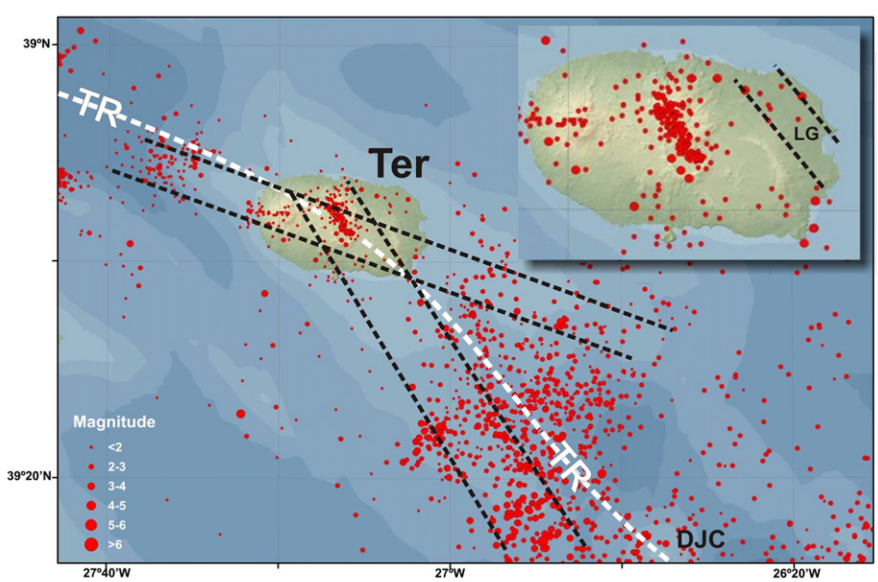

Fig. 4. Recent seismicity in the Terceira region. Note the concentration of shocks in the middle of the island, along azimuth N150° (inset at top right corner). LG – Lajes Graben; DJC – D. João de Castro Bank. Black dashed lines represent the main tectonic lineaments. Adapted from http://www.cvarg.azores.gov.pt/geologia-acores/terceira/Paginas/GA-Terceira-Sismicidade-Instrumental.aspx.

Table 1
GPS site velocities and 1σ uncertainties.

Name	Long. (°E)	Lat (°N)	V_E	V_N	V_u	σ_E	σ_N	σ_u
TPVT	332.94582	38.73359	13.31	16.03	−3.61	0.16	0.17	0.69
TPOM	332.94486	38.68715	13.67	15.09	−4.45	0.13	0.15	0.54
TPJD	332.89866	38.65635	13.59	17.06	−4.76	0.21	0.23	0.82
TCAP	332.89273	38.78465	12.59	15.44	−0.57	0.11	0.12	0.42
TSBR	332.86072	38.75664	12.79	15.59	−4.5	0.13	0.15	0.56
TCAB	332.85418	38.77781	13.56	14.76	−3.99	0.12	0.13	0.44
TSER	332.84397	38.64884	12.73	15.97	−5.16	0.19	0.22	0.79
TGOL	332.83961	38.72859	13.25	16.03	−4.68	0.17	0.2	0.77
TQRB	332.79388	38.78996	14.41	14.88	−4.43	0.11	0.12	0.38
TCAT	332.78926	38.79298	12.82	13.93	−0.01	0.27	0.32	1.17
TOMA	332.77669	38.65864	13.51	17.25	−4.27	0.09	0.09	0.31
TBIS	332.74793	38.79645	14.86	13.75	−4.59	0.1	0.11	0.36
TPBG	332.72534	38.72066	13.36	16.83	−6.87	0.27	0.3	1.16
TCCD	332.71397	38.6611	13.82	16.43	−4.81	0.12	0.13	0.47
TPFF	332.71134	38.70726	14.46	15.45	−5.29	0.24	0.25	1.06
TRAM	332.64861	38.77842	15.67	14.93	−4.82	0.15	0.18	0.63
TPTE	332.63582	38.73034	14.46	15.91	−5.47	0.18	0.2	0.75

The velocity unit is millimetres per year.

computed in the least square sense using the estimated GPS velocities and further used to compute the rigid body motion and the velocity residuals. Using these parameters, the velocity of the rigid body motion of Terceira Island is easting 13.7 mm/yr, northing 15.6 mm/yr. The residuals between the velocities obtained for each station and the rigid body motion are the consequence of local variations of the strain field and are within 5 mm/yr for the residual horizontal velocity. We plot the horizontal and vertical residuals in Fig. 6, together with the 95% confidence error ellipses for each station. The residual of the horizontal velocity shows a centripetal distribution, and the residual of the vertical velocity shows virtual zero velocity everywhere, except at TCAP on the NE shoulder of the Lajes Graben (upward displacement) and at TPBG (downward displacement).

3.2. InSAR data acquisition, processing and results

The interferometric dataset consists of 47 ENVISAT-ASAR images covering Terceira, from March 2006 to November 2009 (Annex Table 1). 23 images were acquired along the descending pass, and 24 along the ascending pass. The perpendicular baseline ranges from −461 m to 660 m, with a mean value of 87 m. The master image was chosen to minimise both the temporal and the perpendicular baselines.

The DORIS software (Delft University of Technology, Kampes, 2006) was used for the processing. A mask over sea was applied to the original data improving considerably the co-registration and interferometric processing. In the Azores, the coherence of interferograms is relatively

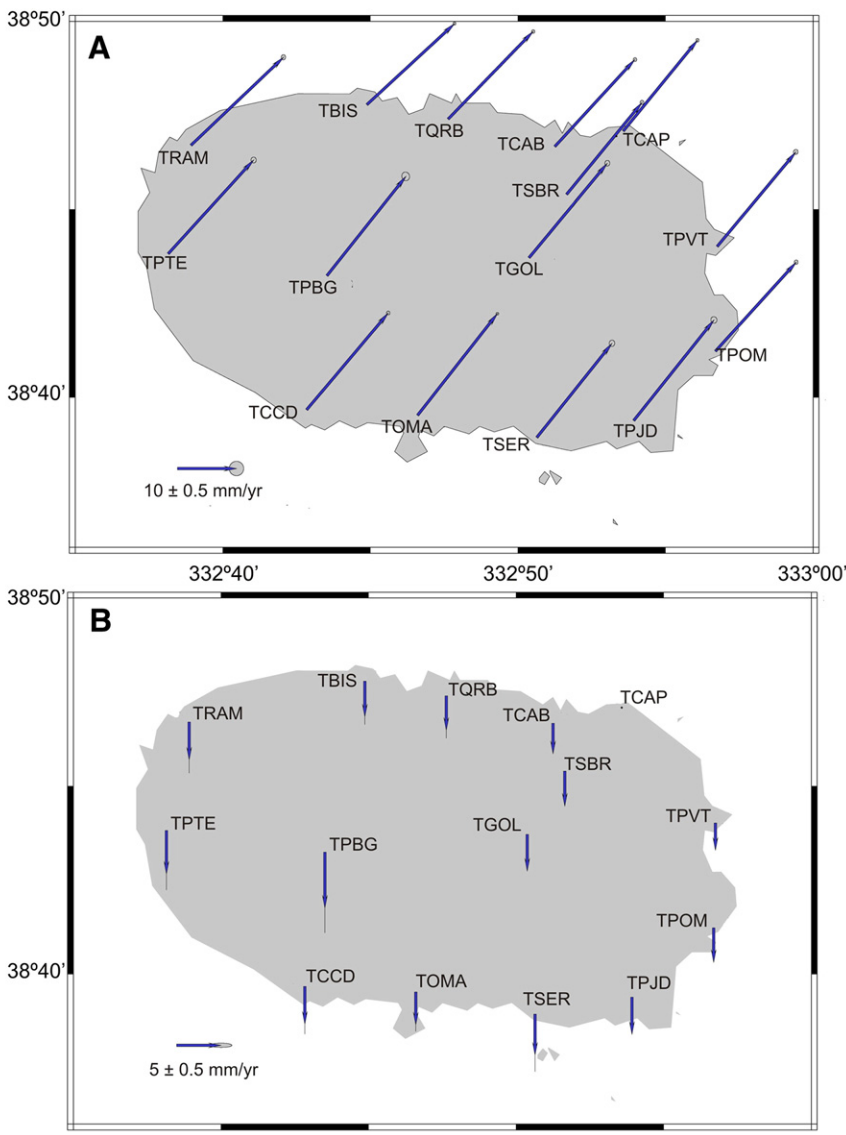

Fig. 5. GPS horizontal (A) and vertical (B) velocities with reference to ITRF08.

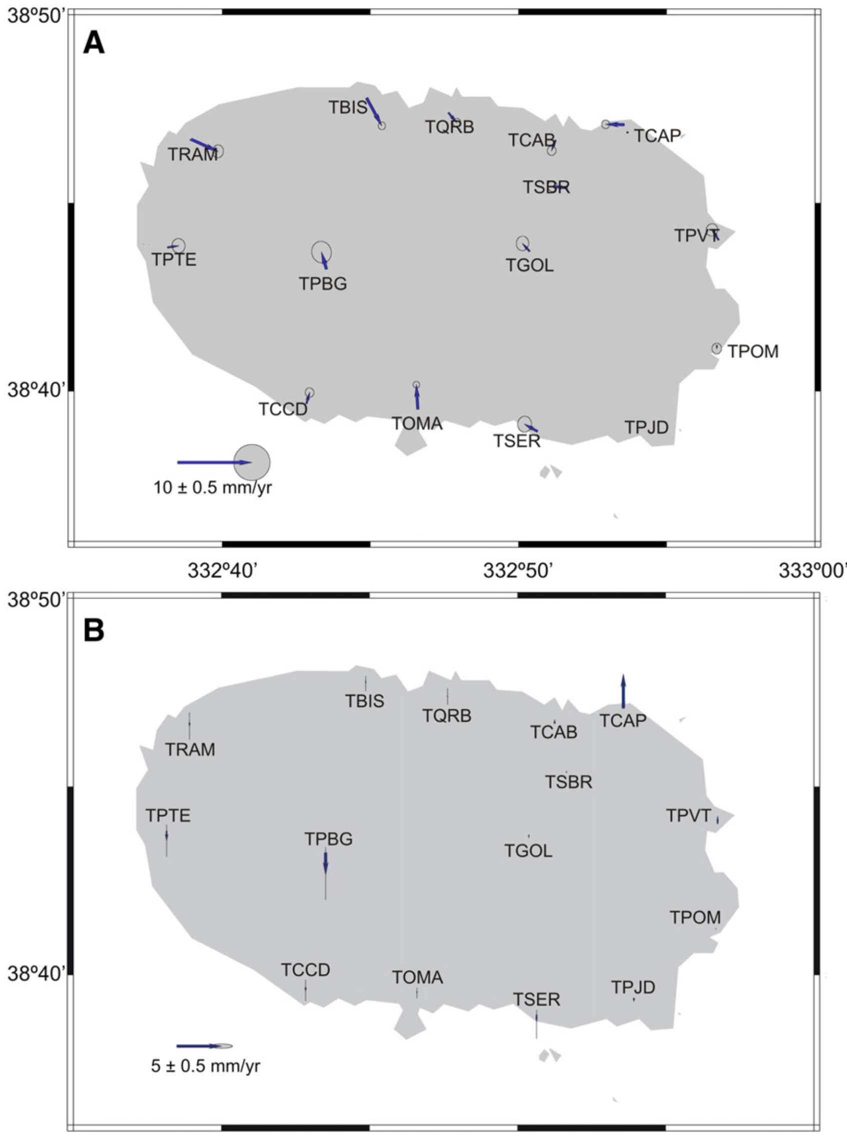

Fig. 6. Residual horizontal (A) and vertical (B) velocities obtained by extracting rigid-body motion from the velocities of the network. Error ellipses correspond to 95% confidence.

low and the Persistent Scatterers approach seems to be the only reliable technique to extract useful information from interferograms (Hooper et al., 2004; Ferretti et al., 2000). The STAMPS software (Hooper and Zebker, 2007) was used to determine the Permanent Scatterers using the stack of interferograms already processed for the ascending and descending passes. It is worth mentioning that 3-D terrain displacement is difficult to measure even in the case of InSAR measurements taken along both ascending and descending satellite passes. In fact, even in this case, there would be three unknown velocity components and just two independent InSAR LOS velocity measurements. For that, we have used a methodology to merge PSInSAR point-like velocities, from both ascending and descending passes, and GPS velocities to derive accurate maps of 3-D terrain displacement rate (Catalão et al., 2011). PSInSAR velocities computed from ascending and descending passes were integrated into a common solution resulting in a set of 3930 persistent scatterers with horizontal (east-north) and vertical velocities. A four-parameter trigonometric polynomial, representing a bias and a tilt, is computed by minimising an energy cost function of the residuals between GPS velocities and PSInSAR velocities. The accuracy of PSs vertical velocity given by the comparison with GPS vertical velocities is better than 0.5 mm/yr for a confidence level of 95% (Annex Table 2). The resulting PSs vertical velocities are unbiased and geo-referenced to ITRF08 (the reference system used for GPS processing). These values are then used to create the vertical deformation map of Terceira Island with considerably better resolution and accuracy than a single set of observations (Fig. 7).

The InSAR data show a generalised subsidence between 2 and 5 mm/yr on average, which is consistent overall with the GPS data. As the two datasets have been acquired on partly overlapping periods, this points to a steady subsidence rate during the last ten years. A few outliers in the INSAR data (orange to red spots in Fig. 7) show significantly higher subsidence rates (between 8 and 10 mm/yr), mostly associated with the alignment of young strombolian cones, and the young Pico Alto and Santa Bárbara volcanoes. We notice that the GPS station TPBG, located in the Santa Bárbara area, also shows higher downward displacement.

4. Topography and tectonics

The interpretation of the topography is shown in Figs. 8, 9 (submarine) and 10 (subaerial). It provides a critical basis for the tectonic study and fieldwork. From the shaded relief map in Fig. 8, it is clear that Terceira has developed inside the TR, at the intersection of two main volcano/tectonic lineaments: WNW-ESE (ca. N110°, yellow dash-dotted line) and NNW-SSE (ca. N140°, yellow dashed line).

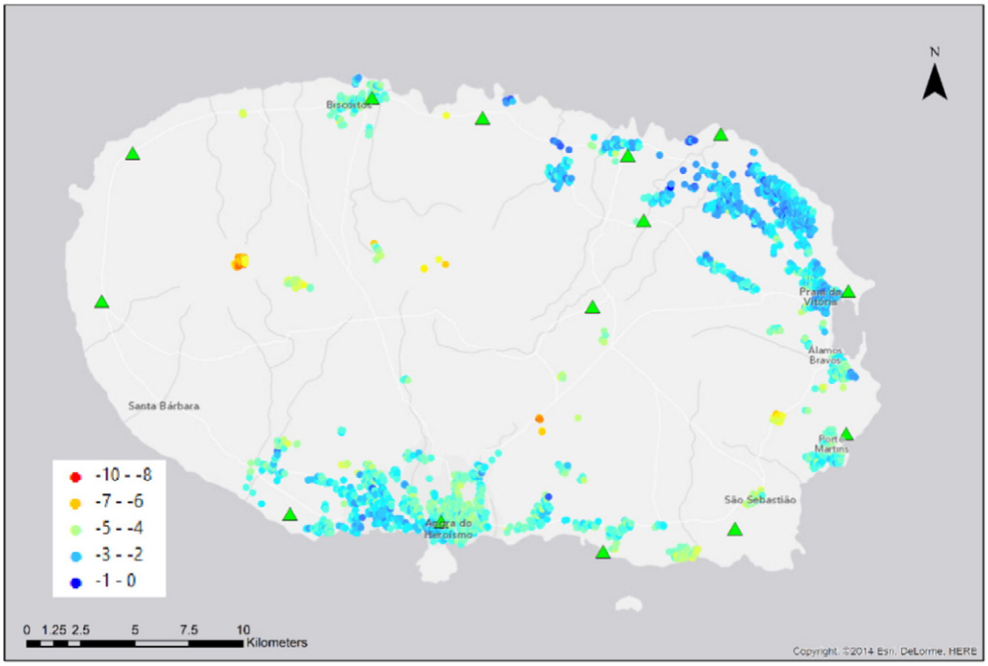

Fig. 7. InSAR persistent scatterers vertical velocity referenced to ITRF08 (mm/yr). For each class of values, the negative sign indicates downward movement. Note that the exceptionally high subsidence (yellow to red spots) rates are located in areas of young volcanism, including historical eruption sites.

Another regional scale lineament can be interpreted, the ca. N116° lineament, similar to the trend of the S. Jorge and Pico-Faial volcanic ridges (red dotted lines). Besides its position inside the TR, Terceira lies at the southern end of a ca. 260 km long, NNW-SSE trending chain of seamounts (Fig. 9), here recognised for the first time and coined the Terceira Seamount Chain.

Terceira is elliptical in plan view, with the greatest axis trending ca. N100°, and the NE quadrant of the island lies directly on the TR's NE shoulder (Figs. 2 and 8). The submarine edifice is seemingly more complex, because it comprises four volcano/tectonic ridges. However, the four ridges reduce to two, because they follow two main orientations, N140° and N110°, which intersect where the main volcanoes that

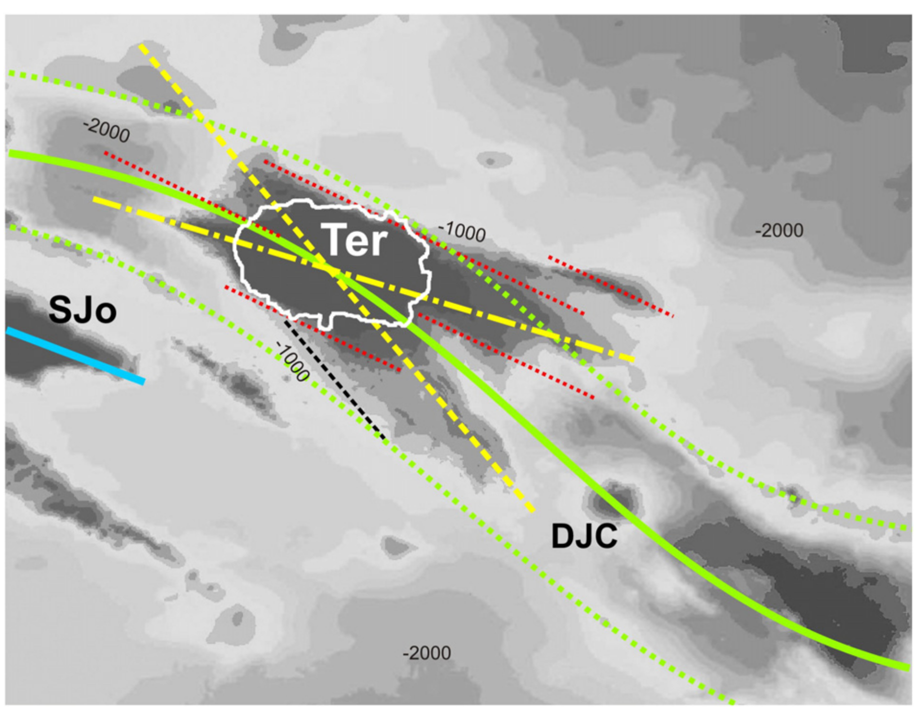

Fig. 8. Terceira Island has developed inside the TR, at the intersection of two main volcano/tectonic lineaments: WNW-ESE (ca. N110°, yellow dash-dotted line) and NNW-SSE (ca. N140°, yellow dashed line). Green full line through the middle of the TR. Green dotted line – TR's shoulders. Red dotted lines mark the ca. N116° lineament. Black dashed line marks a lineament parallel to the N140° lineament. Blue full line trends ca. N110°, and represents the direction of the S. Jorge (SJo) and Pico-Faial volcanic ridges. DJC – D. João de Castro Bank.

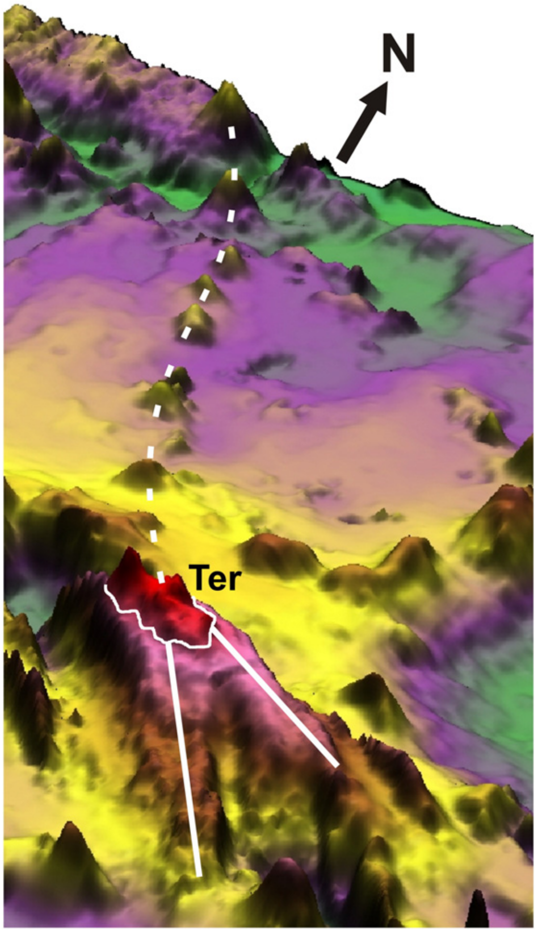

Fig. 9. 3-D surface view of a portion of the Azores Plateau. Note the chain of seamounts ending at Terceira in the south. This seamount chain (dashed white line, which is the continuation to the NW of the yellow dashed line in Fig. 8) is here recognised for the first time and coined the Terceira Seamount Chain. Terceira developed at the intersection of two major lineaments: the WNW-ESE (local TR's trend) and the NNW-SSE (Terceira Seamount Chain). Topographic data from Lourenço et al. (1998).

comprise the island have developed, thus masking the simple geometry of the ridges (Fig. 3). As shown by the bathymetry, both lineaments are oblique to the TR. The main intra-island lineaments, interpreted on the high-resolution DEM (Fig. 10), are volcanic and tectonic in nature. The main volcanic lineament strikes ca. N110° (red line in Fig. 10), and is defined, from W to E, by the historical submarine eruptions of Serreta, and the subaerial calderas of Santa Bárbara, Guilherme Moniz and Serra do Cume. Another volcanic lineament trends ca. N165°, and is made of the Guilherme Moniz and Pico Alto volcanoes. The main tectonic lineaments trend ca. N165°, ca. N140°, ca. N110°, and ca. N70°. As discussed below, there is an apparent relationship between the volcanic and tectonic lineaments.

Most of the main lineaments interpreted on the DEM have a tectonic origin, and could be characterised, in part, in the field. Like most of the islands in the Azores, Terceira is mostly covered by vegetation and thick soils, which cover most of the rocks and hamper observation and measurement of structural elements. Unlike other islands in the Azores, Terceira is not cut by deep canyons, therefore most outcrops occur on steep and high sea cliffs. These can be seen from the sea, and some of them accessed along the shore. The strike of many faults could not be measured directly on outcrop, because of the high risk of rock fall from the high (>50 m) and very steep sea cliffs. Therefore, we used the surface expression observed on the DEM to estimate fault strike. It is difficult to infer the age of faulting, but from the surface expression we infer that all faults are active and not rotated about a vertical axis. Terceira is affected by four main fault systems:

(1) The ca. N165°, which is made of normal faults dipping to east and west, and was observed mostly across the middle of the island (Figs. 10 and 11). They apparently delimit a graben, here coined the Angra do Heroísmo Graben.
(2) The ca. N140° normal faults mostly making up the Lajes Graben (Figs. 10 and 12). The master fault bounding the graben in the NE crops out at its NW end. There, we can observe that: (i) the master fault is not a unique structure, but comprises minor faults; (ii) the volcanic deposits (thin lava flows and pyroclasts) are tilted towards the core of the graben, and the older the more tilted, attesting to the continued subsidence of the graben and refilling with new volcanic products; (iii) normal fault kinematics can be deduced from the antithetic bookshelf minor faults, as a response

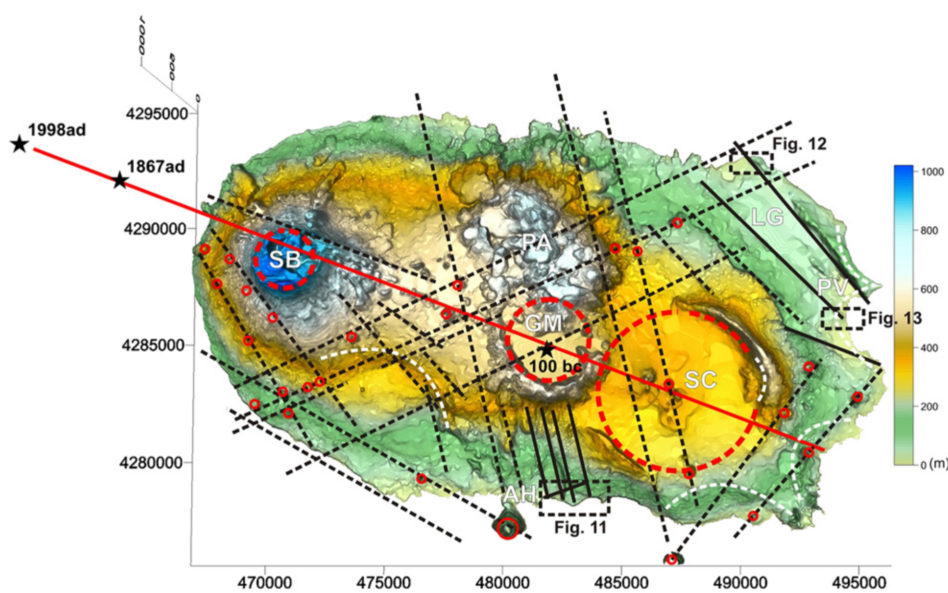

Fig. 10. Main lineaments interpreted on the high-resolution DEM. Solid and dashed black lines represent observed and interpreted faults, respectively. The full red line represents the main volcano/tectonic lineament, which strikes ca. N110°. Dashed red circles mark the calderas of three of the four main volcanoes: SC – Serra do Cume; GM – Guilherme Moniz; PA – Pico Alto; and SB – Santa Bárbara. Small red circles represent scoria cones defining main alignments. LG – Lajes Graben; AH – Angra do Heroísmo city; PV – Praia da Vitória village. Curved white dashed lines mark the location of interpreted landslide scars. Black stars in the west represent the last detected offshore eruptions.

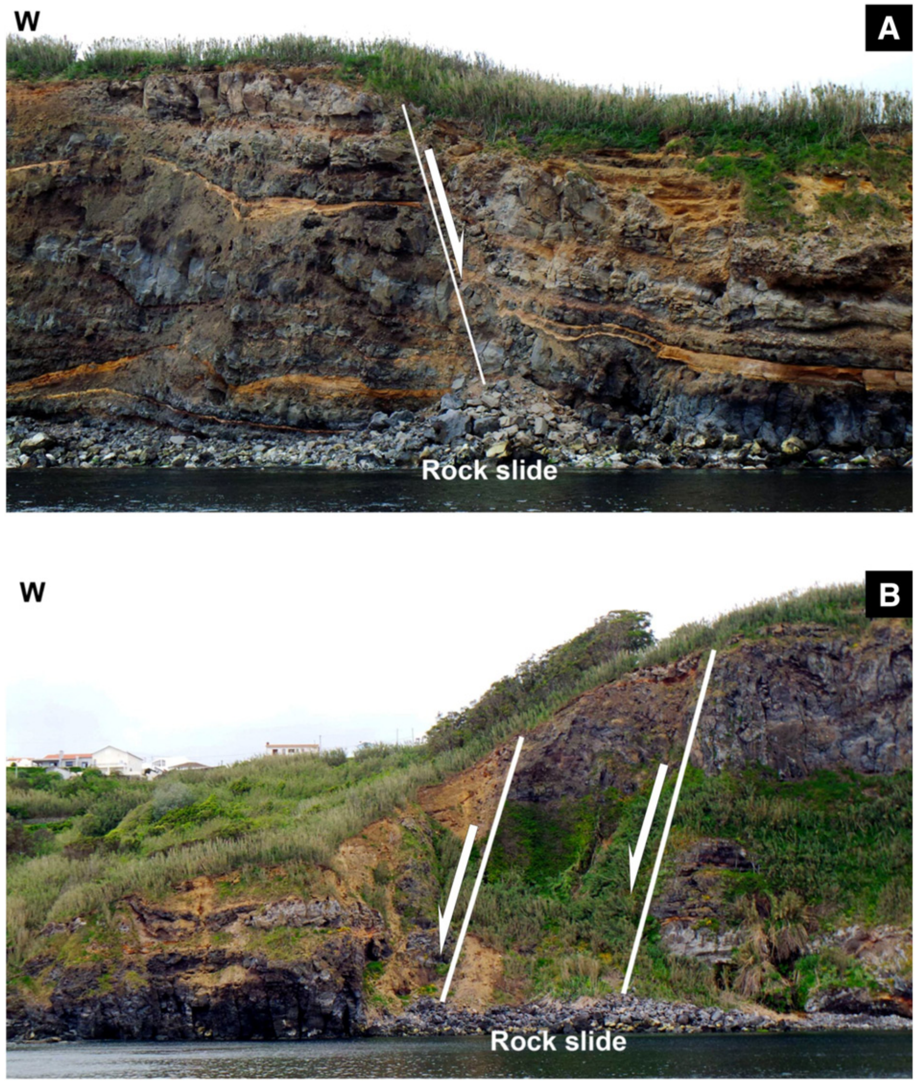

Fig. 11. Faults cropping out on sea cliffs east of Angra do Heroísmo. Note that rockslides concentrate at the base of the faults, which could be indicative of recent fault activity. See Fig. 10 for location.

to the clockwise synthetic normal fault displacement. Some of the graben fault planes strike N110° (Fig. 13), and the striations (inset) dip 66° to the east. From topographic surface displacement and striations, we deduce normal/dextral kinematics on the fault. The Terceira Seamount Chain strikes between N165 and N140.

(3) The ca. N110°, which comprises faults with oblique striations (normal dextral, Fig. 13), and makes up the main volcanic lineament.

(4) The more subtle ca. N70° strike-slip faults interpreted on the DEM from topographic lineaments and alignment of strombolian cones, have so far been directly observed in the field only on the sea cliff E of Angra do Heroísmo, but the kinematic characterisation was not possible.

Arcuate scars possibly generated by landslides could be interpreted on the DEM (white dashed lines in Fig. 10), but they are relatively small. One is associated with the caldera of the Serra do Cume volcano, and the other five are concave to the sea and lie close to the coast, except the one between the calderas of Guilherme Moniz and Santa Bárbara volcanoes. In contrast to other islands in the Azores, we did not find evidence of major flank collapses in Terceira, as also noticed by Mitchell (2003). The main volcanoes in Terceira are reasonably well preserved, which means that they have not undergone major flank collapses that can dismantle most of the original volcano, as reported in Hildenbrand et al. (2012a, 2012b) and Costa et al. (2014) regarding the Pico-Faial ridge, in Sibrant et al. (2014) regarding the Graciosa Island, and in Marques et al. (2013b) and Sibrant et al. (2013, 2015) regarding the Santa Maria Island.

4.1. Terceira offshore tectonics

Two main grabens (thick black dashed lines in Fig. 14), flanked by normal faults dipping to the NE and SW, sit at the top of the two main volcano/tectonic ridges. The one further north continues on-land into the conspicuous Lajes Graben, and the one further south continues into the Angra do Heroísmo Graben. Two main alignments of small cones trend ca. N105° (small red circles in Fig. 14a) and ca. N135° (small yellow circles in Fig. 14a). A well-preserved hemi-circular depression, most likely corresponding to a submarine caldera or a landslide scarp, can be interpreted on top of the southern volcano/tectonic ridge (red dotted circle at bottom right corner of Fig. 14). A lineament trending ca. N65° (black long-dashed line in Fig. 14a) can also be

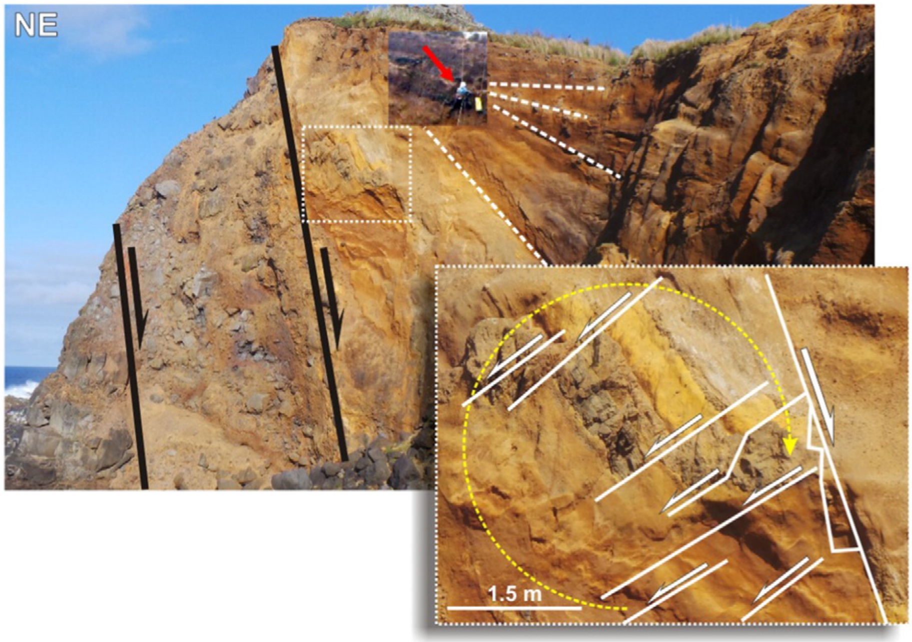

Fig. 12. Image of outcrop at the NW end of the master fault bounding the Lajes Graben in the NE. Note the presence of: (1) master and minor normal faults; (2) bookshelf antithetic normal faults zoomed on the inset and indicating the shear sense of the main normal fault; (3) gradual upward decrease in dip of the pyroclasts. Scale given by person marked by red arrow. See Fig. 10 for location.

interpreted that passes through the centre of the interpreted submarine caldera.

5. Discussion

Based on the previous and new data, and our own interpretations, here we discuss the possible meaning of most likely explanations to the problems posed in the rationale.

Terceira's GPS ground motion is given in Figs. 5 and 6. The GPS data relative to ITRF2008 show a horizontal rigid body velocity of ca. 20 mm/yr to the NE, and downward velocity of ca. 4.5 mm/yr. The residual velocity shows a centripetal velocity pattern. The horizontal velocities of Terceira relative to the volcanic ridges in the diffuse Eu/Nu plate boundary (S. Jorge and Pico-Faial ridges) have been reported and discussed in Marques et al. (2013a, 2014a).

In contrast to the limited (<1 mm/yr) downward velocity reported for Terceira in previous works (e.g. Miranda et al., 2012), the new GPS data indicate that the whole Terceira Island is subsiding at a rate of ca. 5 mm/yr, which is exceptionally high for the Azores. A couple of exceptions to this average are important to notice: (1) the GPS mark at the top of the NE shoulder of the Lajes Graben (TCAP) shows virtually zero vertical motion; and (2) InSAR is showing that the centre of the island is subsiding up to 10 mm/yr. The stability of the Lajes Graben's NE shoulder can be explained by the fact that it sits on the TR's NE shoulder. Therefore, it would be less susceptible to the fast subsidence of the rest of the island that lies inside the TR. However, the residual of the vertical velocity, which represents the actual internal deformation of Terceira, shows that the NE shoulder of the Lajes Graben is moving up at 5 mm/yr, consistent with the zero vertical velocity relative to the ITRF2008. Given that the NE shoulder of the Lajes Graben sits directly

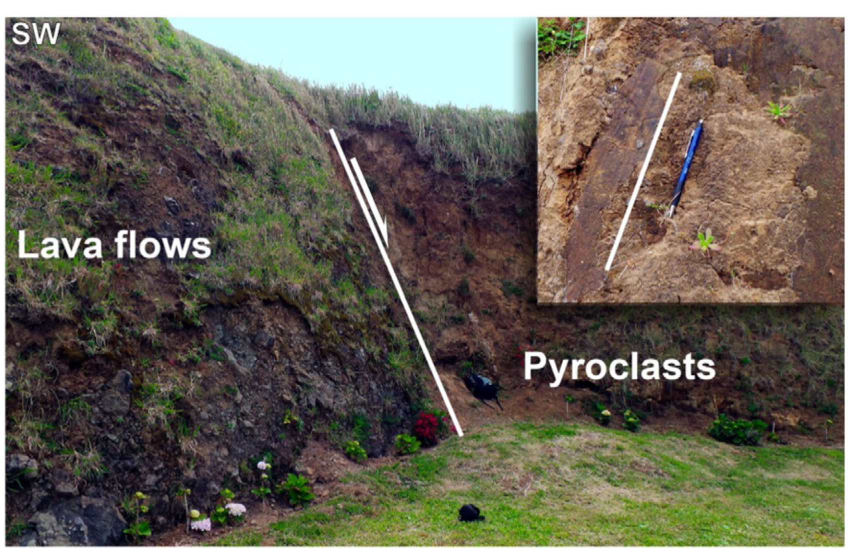

Fig. 13. Outcrop with fault of the Lajes Graben, south of Praia da Vitória village. The fault plane strikes N110°, and the striations (inset) dip 66° to the east. From topographic surface displacement and striations, we deduce normal/dextral kinematics on the fault. See Fig. 10 for location.

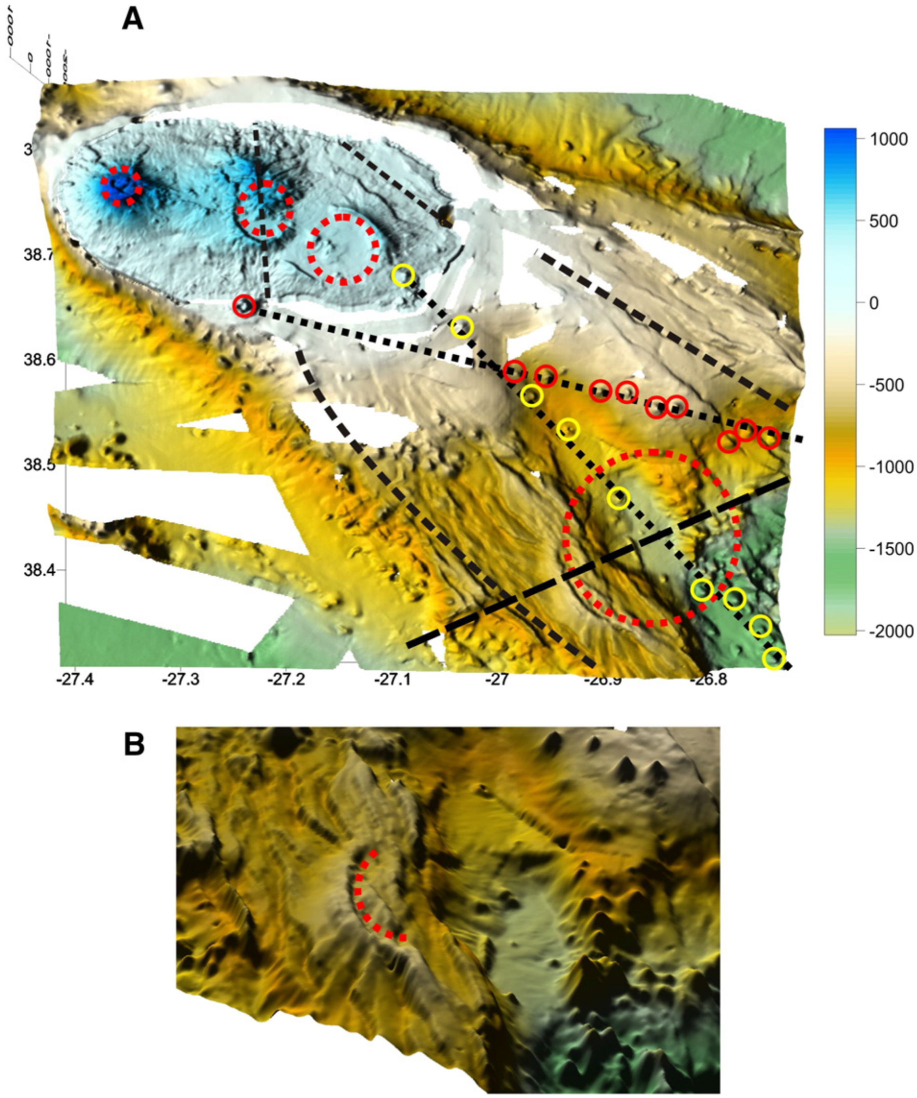

Fig. 14. Composite 3-D surface of high-resolution topography (Terceira Island) and bathymetry (SE Terceira Island). A – Vertical view with lighting from the W. Two grabens, with core marked by thick black dashed lines and flanked by normal faults, sit at the top of the two main volcano/tectonic ridges. Note that both continue onshore (thin black dashed lines), although with a trend closer to N-S. The one further north continues into the conspicuous Lajes Graben, and the one further south continues into the Angra do Heroísmo Graben. Red dotted circles represent calderas. Small red circles mark small cones aligned (black dotted line) ca. N105°. Small yellow circles mark small cones aligned ca. N135°. Black long-dashed line represents lineament trending ca. N65°. B – Oblique view from SE for better perception of the interpreted submarine caldera (dotted red arc).

on the TR's NE shoulder, we conclude that the TR's shoulder is moving up, most likely as a result of the elastic rebound associated with rifting. The elastic rebound in both NE and SW TR's shoulders is most likely responsible for the observed ridges all along the TR (dotted green lines in Fig. 8).

The high subsidence rate of Terceira can be due to a number of factors:

5.1. Lithosphere cooling from the MAR axis

At accreting plate boundaries, the first-order morphology and subsidence of oceanic lithosphere are mainly a function of its age. As the newly created lithosphere moves away from the ridge-axis, thermal contraction causes subsidence. As there is no evidence for appreciable spreading along the TR, the lithosphere under Terceira was born at the MAR axis. From the half-space cooling model, the predicted rate of thermal subsidence is only a fraction of a mm/yr, and probably closer to a tenth of a mm/yr, as discussed by Miranda et al. (2012). Such a small value cannot account for the ca. 5 mm/yr average rate of subsidence here reported.

5.2. Bending of the lithosphere due to island loading and rift opening

The possible bending of the lithosphere due to Terceira loading and elastic rebound following rift initiation cannot be calculated unequivocally, because the elastic thickness is not well constrained in the Azores. Whilst Luis et al. (1998) estimated a crustal thickness in the Azores Plateau between 9 and 12 km, Dias et al. (2007) estimated a crustal thickness of ca. 14 km in the Pico-Faial region. In turn, Silveira et al. (2010) estimated crustal and lithospheric thicknesses of ca. 20 and 80 km, respectively, below the Azores Plateau, whereas Luis and Neves (2006) estimated an average elastic thickness of 4 km in the Azores Plateau. It has been proposed that the lithosphere in the Azores region is underlain by a mantle plume-like anomaly, either thermal (e.g. Bourdon et al., 1996; Schilling, 1975) or chemical and volatile-rich (e.g. Asimow and Langmuir, 2003; Métrich et al., 2014). The extent and the dynamics of the inferred plume remain controversial, and dispersed fertile mantle domains at the regional scale may actually represent the remnants of an old plume responsible for the edification of the Azores plateau several Ma ago (Hildenbrand et al., 2014). From geochemical and geophysical data, one of these anomalous mantle domains seems to be centred in the Terceira region (Madureira et al., 2005; Moreira et al., 1999; Yang et al., 2006). Therefore, Terceira could be partly supported by the presence of buoyant low-density material under the lithosphere. However, inferred mantle upwelling in the Azores appears much less vigorous than in the case of Hawaii (e.g., Bourdon et al., 2005), and our data show that most of the island is presently subsiding fast, ruling out any significant role of active mantle upwelling (expected to produce uplift) on present vertical movements in Terceira. Hawaii, with a mass about 50 times greater than Terceira, is subsiding at a rate of ca. 2.5 mm/yr (Moore, 1987; Moore and Clague, 1992). Although Terceira could bend the lithosphere downward, depending on the rigidity of the underlying lithosphere, comparison between the Azores and Hawaii indicates that it is unlikely that loading by Terceira can bend the lithosphere at rates similar to the Hawaiian rate of 2.5 mm/yr.

5.3. Magmatic processes

The GPS data show a centripetal distribution of the horizontal residual velocity centred on the Pico Alto Complex (Fig. 15). This could indicate that Pico Alto is deflating, likely by shrinking of an underlying magma chamber, which can be due to (1) emptying by recent volcanism, and/or (2) magma migration to the W (e.g. Serreta submarine eruptions), and/or (3) loss of volume by crystal fractionation and degassing. The deflation could also be responsible for the seismicity concentrated in the same area (cf. Fig. 4). The occurrence of significant volumes of trachyte and rhyolite lava flows and pyroclastic deposits (pumice fall deposits and ignimbrites) has long been recognised in Terceira Island. More significantly, high-silica viscous lava flows (rhyolite and trachyte) from Pico Alto and Santa Bárbara volcanic systems account for more than 50% of the total volume of recently erupted rocks (Self and Gunn, 1976). Conversely, as noted by Mungall and Martin (1995), there is a compositional gap within the erupted lavas at the surface. The same authors showed that these trachyte and rhyolite magmas resulted from fractional crystallisation processes and concluded that large parts of the magmatic series remained as intrusive bodies. The latter can induce the escape of magmatic fluids promoting the local alteration of host rocks and the possible localization of deformation.

The volume of magma associated with the possible deflation is not possible to calculate, because we do not know where the magma chamber or magma source is (especially its depth). However, given the great difference between the whole island subsidence and the concentrated centripetal shrinking deduced from the residual velocities, the latter cannot justify the generalised subsidence of Terceira. Moreover, the shrinking/deflation discussed above, although compatible with the horizontal residual velocity, is not consistent with the vertical residual velocity, which is mostly virtually zero all over the island, with the exception of the station on the NE shoulder of the Lajes Graben. Therefore, the explanation of the estimated residuals is not trivial. A possible explanation might come from the balance between cooling of the recent volcanics at the surface and inflation at depth to counteract subsidence.

5.4. Island collapse due to its own weight

We have not found evidence of large-scale flank collapses in Terceira. However, it cannot be excluded that the island, as a whole, could be collapsing under its own weight, e.g. favoured by the presence of weaknesses at the base or the core of the edifice (e.g. Cecchi et al., 2004; Delcamp et al., 2012; van Wyk de Vries and Francis, 1997). However, such generalised collapse would produce a centrifugal distribution of the residual horizontal velocity, which contrasts with the residual presented in this work (centripetal, as shown in Figs. 6a and 15).

5.5. Subsidence in the TR

The TR's subsidence rate can be roughly estimated using the most likely age of the TR. From the ages of the islands inside the TR (the oldest age isotopically determined on an island inside the TR is ca. 850 ka in S. Miguel Island) and the lack of magnetic anomalies, we infer, as Vogt and Jung (2004), that the age of the TR is ≤ 1 Ma. Using an age of 1 Ma and a TR's depth of ca. 2000 m below Terceira (measured between the floor of the graben and the top of the graben shoulders), we conclude that the TR's average subsidence rate is ca. 2.0 mm/yr. This number is less than half the average GPS value, and can be interpreted in two ways: the GPS value is instantaneous and may thus represent an exceptional high, or it represents the average. In the latter case, further explanations are needed; however, the most likely solutions have been discussed above and seem to be not sufficient or even inconsistent with the present data. We cannot exclude that the present rate of downward

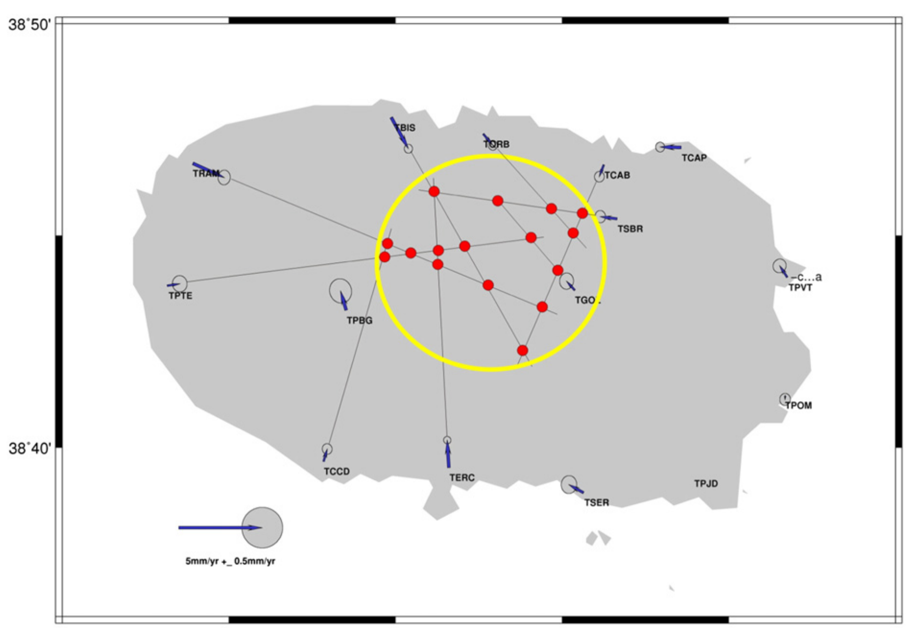

Fig. 15. Residual horizontal velocities obtained by extracting the rigid-body motion from the velocities of the network. The red dots mark the intersection points of straight lines drawn parallel to most GPS vectors. The yellow circle encompasses all intersections, and overlaps with the Pico Alto Complex (cf. Fig. 3) and the concentrated seismicity in central Terceira (cf. Fig. 4).

movement is due to fast "instantaneous" aseismic displacement along the TR's main NE wall.

Three groups of islands can be distinguished in the Azores based on the regional tectonic setting: (1) islands sitting on a lithosphere currently not affected by tectonics – Santa Maria (the oldest in the Azores, e.g. Sibrant et al., 2015) on the Nubia Plate, and Flores and Corvo islands on the North America Plate (Fig. 1); (2) islands sitting on the diffuse plate boundary defined in Marques et al. (2013a, 2013b) – Faial, Pico and S. Jorge islands; (3) islands sitting in the Terceira Rift (TR) – Graciosa, Terceira and S. Miguel islands. Therefore, Terceira subsidence cannot be directly compared to the linear volcanic ridges to the west (Pico-Faial and S. Jorge ridges), because they lie on distinct tectonic settings – diffuse plate boundary versus discrete plate boundary (the TR). Comparison of subsidence of the islands inside the TR is also not straightforward, because: (1) the TR does not show the same tectonic development on its whole length; the TR is deeper and wider in the ESE (SE of S. Miguel Island), and progressively becomes narrower and shallower towards the WNW (W of Graciosa Island). (2) The lithosphere becomes deeper in the TR towards the ESE, because the TR is approximately perpendicular to the MAR. Anyway, the three islands inside the TR are affected by common processes that can produce subsidence, as discussed above. S. Miguel is the biggest island and lies in the deepest and widest part of the TR, therefore one would expect the highest subsidence in S. Miguel, but its subsidence rate has been estimated at ca. 1 mm/yr by Muecke et al. (1974). This is an average over the past ca. 690 ka, therefore not directly comparable with the GPS data of Terceira. However, the GNSS station at Ponta Delgada, located away from the main volcanic centres, shows a subsidence rate of ca. 0.7 mm/yr in the last 10 years, therefore comparable to Terceira but much lower.

There seems to be an intimate relationship between volcanism and tectonics, because the respective lineaments are mostly coincident (see also Navarro et al., 2009). Apparently, tectonic fractures and faults have served as preferential conduits for the ascent of magma. Métrich et al. (2014) even suggested that the extensional tectonics in the Azores, in particular the TR, is likely responsible for the generation of magma by decompression melting. Given that Terceira has formed mostly inside the TR, there must be an intimate relationship between the island and the rift, because magma generation and ascent have preferentially occurred in grabens in central Azores, especially in the TR, but also in the S. Jorge and Pico-Faial grabens (Marques et al., 2013a, 2014a). From the spatial distribution of volcanoes and their age, we infer a main westward migration of trachytic volcanism (from Serra do Cume to Guilherme Moniz and Santa Bárbara, and more recently to Serreta furthest to the W), and a minor northward migration to the Pico Alto Complex. Two explanations are possible, one related to plate kinematics and the other to topographic stresses. The lithosphere where Terceira sits is moving eastwards from the MAR axis at a velocity of ca. 11 mm/yr. If the magma source is fixed (estimated at a depth of 80–90 km by Métrich et al., 2014) and the lithosphere moves (similarly to Hawaii), then we can use the plate velocity and the ages of the volcanoes (see Fig. 3) to estimate the displacement of the volcanic centres: taking the oldest ages of Serra do Cume (ca. 388 ka) and Guilherme Moniz (ca. 270 ka) volcanoes, we obtain $(388-270)$ ka $\times$ 11 mm/yr $\approx$ 1.3 km horizontal displacement, or taking the youngest age of the Guilherme Moniz Complex (ca. 111 ka) we obtain $(388-111)$ ka $\times$ 11 mm/yr $\approx$ 3 km of horizontal displacement. For the pair Serra do Cume (ca. 388 ka) and Santa Bárbara (ca. 60 ka) volcanoes, we obtain $(388-60)$ ka $\times$ 11 mm/yr $\approx$ 3.6 km of horizontal displacement. Similar computations can be made regarding the northward migration of volcanism to the Pico Alto Complex. These displacements are much smaller than the actual distances between the volcanoes, hence plate movement over a punctual magma supply is not a sufficient explanation. Kumar and Gordon (2009) concluded that newly created lithosphere (0.1 Ma old) is displaced by thermal contraction towards the older part of the lithosphere, with displacement rates of 0.1–1.0 km/Ma. In the case of the Azores, the lithosphere would be displaced to the east. However, the lithosphere below Terceira is significantly older than 0.1 Ma, and the island is younger than 0.5 Ma. Therefore, horizontal thermal contraction does not add much to explain the observed distances between volcanoes. Neves et al. (2013) modelled numerically the formation of linear volcanic ridges in the Azores, and concluded that the fractures where the volcanic ridges grow propagate from central portions towards the WNW and the ESE. This could in part explain the propagation of volcanism to the WNW, but Neves et al. (2013) do not give rates of propagation, hence we cannot compare with

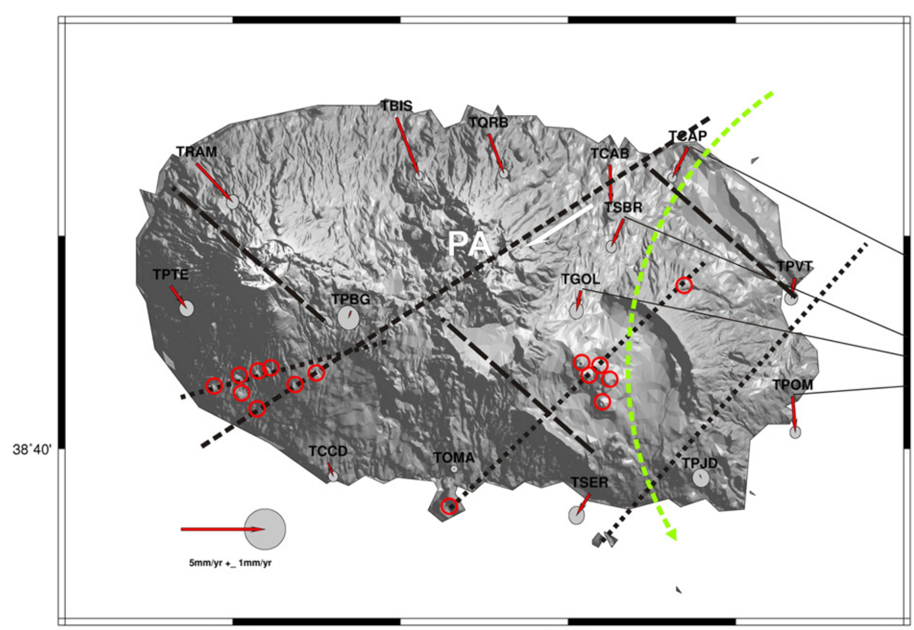

Fig. 16. Residual horizontal velocities with fixed TOMA station. Note the marked difference in velocity vector direction NW and SE of the ca. N60° tectonic lineament that cuts across the centre of the island (black dashed line). Thin black lines were drawn normal to the velocity vectors and converge to a small area in the east, which we used as centre to draw the green circle. Velocity vectors indicate a counter clockwise rotation of the SE block, from which we deduce dextral strike-slip. Small red circles mark the location of small scoria cones. Black dotted lines represent interpreted N50-60° volcanic lineaments. Black long-dashed lines represent interpreted and observed ca. N140° tectonic lineaments. Error ellipses correspond to 95% confidence.

the measured distances between volcanoes over time. We therefore propose that the westward displacement of volcanism be most likely the aggregate result of motion away from the MAR, horizontal thermal contraction and topographic (volcanic edifice) stresses. NE displacement of volcanism to Pico Alto Complex is likely due to SW motion of Terceira relative to Eurasia, and topographic stresses.

The island is affected by four main fault systems, whose geometry and kinematics should be consistent with the known plate kinematics (DeMets et al., 2010), which shows that the Terceira region is under extension along the ca. N60° direction. The N140° (normal faults mostly making up the Lajes Graben) should be almost pure normal faults, because they are almost perpendicular to maximum extension. The N110° faults show oblique striations, from which we deduce normal dextral displacement consistent with the direction of maximum extension. The subtler N60-70° fault system corresponds to the transform direction related to the rotation of Nubia relative to Eurasia, and should therefore be dextral strike-slip. We did not observe these faults in outcrop, but we use the GPS residual velocities to infer the position and kinematics of the N60-70° tectonic lineaments/faults. Fixing the TOMA GPS station (the station with best precision and a vertical residual velocity of zero), we obtain the horizontal residual velocities relative to that station (Fig. 16). The velocity vector pattern shows a marked difference in velocity vector direction between the blocks to the NW and SE of the ca. N60° tectonic lineament that cuts across the centre of the island (black dashed line in Fig. 16). Straight lines (thin black lines in Fig. 16) drawn normal to the velocity vectors in the SE block converge to a small area in the east, which we used as centre to draw the green circle in Fig. 16. The velocity vectors and their distribution indicate a counter clockwise rotation of the SE block, from which we deduce dextral strike-slip. The velocity vector orientation in the NW block is more complex, most likely because of the collapse of the Pico Alto volcano. The ca. N165° faults dipping to east and west, mostly across the middle of the island and defining the Angra do Heroísmo Graben, show at least a dominant normal fault component. However, its angular relationship with the direction of maximum extension should imply a minor sinistral strike-slip component, which was not observed in outcrop. The continuation of the N165° fault system into the Terceira Seamount Chain is still enigmatic, and we cannot put forward a well-grounded explanation for the seamount chain. Recent seismicity, GPS data, and faults displacing the topography indicate that all systems are active.

Currently, there is no evidence for spreading in the TR, in the sense of generation of new crust as observed in well-developed oceanic rifts like the MAR. Instead, volcanism in the TR has concentrated in four main volcanic edifices (see Figs. 1 and 2), three of which comprise the islands of Graciosa, Terceira and S. Miguel, and one is a seamount, the D. João de Castro Bank, the top of which is presently ~14 m below sea level. Based on our data, and on the fact that central-type volcanism typically occurs at fault intersections, we propose that volcanism has concentrated to form Terceira because three main fault systems meet where the island has developed (see Figs. 8 and 9): the N140°, the N110°, and the axis of the TR. There is also the possibility that a fourth fault system plays an important role, the ca. N70° (see Figs. 10 and 14), as proposed for the Faial Island by Marques et al. (2014b). Given the kinematics in the Azores (DeMets et al., 2010), the N60-70° faults are transforms, and therefore mostly transcurrent, and the downward displacement should be concentrated along the ca. N140-150° and N100-110° faults. As the TR's trend locally encompasses both directions, we cannot exclude that the present high displacement is mostly produced by movement along the TR's NE wall. We thus conclude that we cannot exclude fast "instantaneous" movement along the TR's NE bounding master fault.

6. Conclusions

The interpretation of high-resolution topography and bathymetry, GPS and InSAR data, detailed structural geology, and geochronology indicate that: (1) Terceira developed at the intersection of two major volcano-tectonic lineaments: WNW-ESE (local direction of the TR) and NNW-SSE (submarine chain of volcanoes, here firstly recognised and coined the Terceira Seamount Chain). (2) Terceira is affected by four main fault systems: the ca. N165° (normal faults dipping to east and west, mostly across the middle of the island), the N140° (normal faults mostly making up the Lajes Graben), the N110° (faults with oblique striations – normal dextral, making up the main volcanic lineament), and the more subtle N70° (the transform direction related to the Nubia/Eurasia plate boundary). Recent seismicity, GPS data, and faults displacing the topography indicate that all systems are active. (3) The whole island is subsiding at a rate of ca. 5 mm/yr, as attested by both GPS and InSAR data, which is exceptionally high for the Azores islands. Common explanations like thermal contraction, or bending of the lithosphere, or magmatic processes, or collapse under its weight likely cannot justify the observed subsidence rate. The estimated average of TR's subsidence rate is also not enough, therefore we conclude that the measured 5 mm/yr can be a peak. (4) The fault geometry and kinematics are consistent with the current direction of maximum extension in the Azores (ca. N65°), and the rotation of Nubia relative to Eurasia. (5) Given that the NE shoulder of the Lajes Graben is moving upwards at 5 mm/yr with respect to the rest of the island, and that it sits directly on the TR's NE shoulder, we conclude that the TR's shoulder is moving up, most likely as a result of the elastic rebound associated with rifting. The elastic rebound in both NE and SW TR's shoulders is most likely responsible for the observed ridge morphology all along the TR.

Acknowledgments

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Annex A

Annex Table 1
Ascending and descending SAR data set.

Ascending		Descending	
Date	Baseline (m)	Date	Baseline (m)
04-Mar-06	660	23-May-06	−378
13-May-06	−375	27-Jun-06	630
17-Jun-06	−276	05-Sep-06	495
26-Aug-06	−48	10-Oct-06	−383
13-Jan-07	479	19-Dec-06	190
17-Feb-07	−258	03-Apr-07	−345
24-Mar-07	451	08-May-07	0
28-Apr-07	−361	12-Jun-07	−50
02-Jun-07	−168	17-Jul-07	−39
07-Jul-07	168	21-Aug-07	154
11-Aug-07	166	30-Oct-07	160
15-Sep-07	555	08-Jan-08	−242
20-Oct-07	0	01-Jul-08	24
24-Nov-07	378	09-Sep-08	−461
29-Dec-07	−101	18-Nov-08	−287
02-Feb-08	307	23-Dec-08	−170
21-Jun-08	−30	03-Mar-09	360
08-Nov-08	312	07-Apr-09	−181
13-Dec-08	−194	21-Jul-09	−33
17-Jan-09	244	25-Aug-09	245
28-Mar-09	306	29-Sep-09	−156
02-May-09	−273	03-Nov-09	49
15-Aug-09	80		

Perpendicular baseline relative to the reference date.

Annex Table 2
Residuals between GPS vertical velocities and PS's vertical velocities (all values are mm/yr).

GPS station	Number of PSs	Residuals before		Residuals after	
		Mean	std	Mean	std
TPVT	6	−4.48	0.19	−0.13	0.23
TPOM	5	−4.29	0.19	0.38	0.42
TSBR	4	−4.15	0.72	−0.48	0.86
TCAB	10	−3.92	0.39	−0.12	0.41
TSER	4	−4.66	0.44	−0.05	0.45
TOMA	81	−4.72	0.64	0.03	0.62
TBIS	21	−4.56	0.50	0.11	0.52

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2015.02.026.

References

Agostinho, J., 1931. The volcanoes of the Azores Islands. Bull. Volcanol. 8, 123–138.
Altamimi, Z., Collilieux, X., Metivier, L., 2011. ITRF2008: an improved solution of the international terrestrial reference frame. J. Geodesy 8, 457–473.
Asimow, P.D., Langmuir, C.H., 2003. The importance of water to oceanic mantle melting regimes. Nature 421, 815–820.
Böhm, J., Werl, B., Schuh, H., 2006. Troposphere mapping functions for GPS and very long baseline interferometry from European Centre Medium-Range Weather Forecasts operational analysis data. J. Geophys. Res. 111, B02406. http://dx.doi.org/10.1029/2005JB003629.
Borges, J.F., Bezzeghoud, M., Buforn, E., Pro, C., Fitas, A., 1998. The 1980, 1997 and, Azores earthquakes and some seismo-tectonic implications. Tectonophysics 435, 37–54.
Bourdon, B., Langmuir, C., Zindler, A., 1996. Ridge–hotspot interaction along the Mid-Atlantic ridge between 37°30′ and 40°30′N; the U–Th disequilibrium evidence. Earth Planet. Sci. Lett. 142, 175–189.
Bourdon, B., Turner, S.P., Ribe, N.M., 2005. Partial melting and upwelling rates beneath the Azores from a U-series isotope perspective. Earth Planet. Sci. Lett. 239 (1–2), 42–56.
Calvert, A.T., Moore, R.B., McGeehin, J.P., Rodrigues da Silva, A.M., 2006. Volcanic history and 40Ar/39Ar and 14C geochronology of Terceira Island, Azores, Portugal. J. Volcanol. Geotherm. Res. 156 (1–2), 103–115.
Catalão, J., Miranda, J.M., Lourenço, N., 2006. Deformation associated with the Faial (Capelinhos) 1956 eruption. Inferences from 1937-1997 geodetic measurements. J. Volcanol. Geotherm. Res. 155, 151–163.
Catalão, J., Nico, G., Hanssen, R.F., Catita, C., 2011. Merging GPS and atmospherically corrected InSAR data to map 3D terrain displacement velocity. IEEE Trans. Geosci. Remote Sens. 49 (6). http://dx.doi.org/10.1109/TGRS.2010.2091963 (Part: 2).
Cecchi, E., van Wyk de Vries, B., Lavest, J.M., 2004. Flank spreading and collapse of weak-cored volcanoes. Bull. Volcanol. 67, 72–91.
Costa, A.C.G., Marques, F.O., Hildenbrand, A., Sibrant, A.L.R., Catita, C.M.S., 2014. Large-scale flank collapses in a steep volcanic ridge: Pico-Faial Ridge, Azores Triple Junction. J. Volcanol. Geotherm. Res. 272, 111–125.
Delcamp, A., de Vries, B.V., James, M.R., Gailler, L.S., Lebas, E., 2012. Relationships between volcano gravitational spreading and magma intrusion. Bull. Volcanol. 74, 743–765.
DeMets, C., Gordon, R.G., Argus, D.F., 2010. Geologically current plate motions. Geophys. J. Int. 181, 1–80.
Dias, N.A., Matias, L., Lourenço, N., Madeira, J., Carrilho, F., Gaspar, J.L., 2007. Crustal seismic velocity structure near Faial and Pico Islands (Azores), from local earthquake tomography. Tectonophysics 445, 301–317.
Ferretti, A., Prati, C., Rocca, F., 2000. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. IEEE Trans. Geosci. Remote Sens. 38, 2202–2212.
Herring, T.A., King, R.W., McClusky, S.C., 2010. GLOBK Reference Manual Release 10.4. Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge.
Hildenbrand, A., Marques, F.O., Catalão, J., Catita, C.M.S., Costa, A.C.G., 2012a. Large-scale active slump of the southeastern flank of Pico Island, Azores. Geology 40, 939–942.
Hildenbrand, A., Marques, F.O., Costa, A.C.G., Sibrant, A.L.R., Silva, P.M.F., Henry, B., Miranda, J.M., Madureira, P., 2012b. Reconstructing the architectural evolution of volcanic islands from combined K/Ar, morphologic, tectonic, and magnetic data: the Faial Island example (Azores). J. Volcanol. Geotherm. Res. 241–242, 39–48.
Hildenbrand, A., Weis, D., Madureira, P., Marques, F.O., 2014. Plate re-organization at Triple Junctions: insights from new geochemical and geochronological data in the central Azores (Atlantic). Lithos 210–211, 27–39.
Hooper, A., Zebker, H., 2007. Phase unwrapping in three dimensions with application to InSAR time series. J. Opt. Soc. Am. 24, 2737–2747.
Hooper, A., Zebker, H., Segall, P., Kampes, B., 2007. A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers. Geophysical Research Letters 31, 16. http://dx.doi.org/10.1029/2004GL021737.
Kampes, B., 2006. Radar Interferometry, Persistent Scatterer Technique. Springer, The Netherlands.
Kumar, R.R., Gordon, R.G., 2009. Horizontal thermal contraction of oceanic lithosphere: the ultimate limit to the rigid plate approximation. J. Geophys. Res. 114, B01403. http://dx.doi.org/10.1029/2007JB005473.
Lourenço, N., Miranda, J.M., Luis, J.F., Ribeiro, A., Mendes Victor, L.A., Madeira, J., Needham, H.D., 1998. Morpho-tectonic analysis of the Azores Volcanic Plateau from a new bathymetric compilation of the area. Mar. Geophys. Res. 20, 141–156.
Luis, J., Neves, M.C., 2006. The isostatic compensation of the Azores Plateau: a 3D admittance and coherence analysis. J. Volcanol. Geotherm. Res. 156, 10–22.
Luis, J.F., Miranda, J.M., Galdeano, A., Patriat, P., 1998. Constraints on the structure of the Azores spreading center from gravity data. Mar. Geophys. Res. 20, 157–170.
Lyard, F., Lefèvre, F., Letellier, T., Francis, O., 2006. Modelling the global ocean tides: a modern insight from FES2004. Ocean Dyn. 56, 394–415.
Machado, F., 1959. Submarine pits of the Azores plateau. Bull. Volcanol. 21, 109–116.
Madureira, P., Moreira, M., Mata, J., Allègre, C.J., 2005. Primitive neon isotopes in Terceira Island (Azores archipelago). Earth Planet. Sci. Lett. 233, 429–440.
Madureira, P., Mata, J., Mattielli, N., Queiroz, G., Silva, P., 2011. Mantle source heterogeneity, magma generation and magmatic evolution at Terceira Island (Azores archipelago): constraints from elemental and isotopic (Sr, Nd, Hf, and Pb) data. Lithos 126, 402–418.
Marques, F.O., Catalão, J.C., DeMets, C., Costa, A.C.G., Hildenbrand, A., 2013a. GPS and tectonic evidence for a diffuse plate boundary at the Azores triple junction. Earth Planet. Sci. Lett. 381, 177–187.
Marques, F.O., Sibrant, A.L.R., Hildenbrand, A., Costa, A.C.G., 2013b. Large-scale sector collapses in the evolution of Santa Maria Island, Azores. Abstract Meeting AGU.
Marques, F.O., Catalão, J., Hildenbrand, A., Costa, A.C.G., Dias, N.A., 2014a. The 1998 Faial earthquake, Azores: evidence for a transform fault associated with the Nubia-Eurasia plate boundary? Tectonophysics http://dx.doi.org/10.1016/j.tecto.2014.06.024.
Marques, F.O., Catalão, J.C., DeMets, C., Costa, A.C.G., Hildenbrand, A., 2014b. Corrigendum to "GPS and tectonic evidence for a diffuse plate boundary at the Azores Triple Junction" [Earth Planet. Sci. Lett. 381 (2013) 177–187]. Earth Planet. Sci. Lett. 387, 1–3.
McKenzie, D., 1972. Active tectonics of the Mediterranean region. Geophys. J. R. Astron. Soc. 30, 109–185.
Métrich, N., Zanon, V., Créon, L., Hildenbrand, A., Moreira, M., Marques, F.O., 2014. Is the "Azores hotspot" a wetspot? Insights from geochemistry of fluid and melt inclusions in olivine of Pico basalt. J. Petrol. 55, 377–393.
Miranda, J.M., Navarro, A., Catalão, J., Fernandes, R.M.S., 2012. Surface displacement field at Terceira island deduced from repeated GPS measurements. J. Volcanol. Geotherm. Res. 217–218, 1–7.
Miranda, J.M., Luis, J.F., Lourenço, N., Goslin, J., 2014. Distributed deformation close to the Azores Triple "Point". Mar. Geol. 355, 27–35.
Mitchell, N.C., 2003. Susceptibility of mid-ocean ridge volcanic islands and seamounts to large-scale landsliding. J. Geophys. Res. 108, 2397. http://dx.doi.org/10.1029/2002JB001997.
Moore, J.G., 1987. Subsidence of the Hawaiian Ridge: U.S. Geol. Surv. Prof. Pap. 1350, 85–100.
Moore, J.G., Clague, D.A., 1992. Volcano growth and evolution of the island of Hawaii. GSA Bull. 104, 1471–1484.
Moreira, M., Doucelance, R., Kurz, M.D., Dupré, B., Allègre, C.J., 1999. Helium and lead isotope geochemistry of the Azores archipelago. Earth Planet. Sci. Lett. 169, 189–205.
Muecke, G.K., Ade-Hall, J.M., Aumento, F., MacDonald, A., Reynolds, P.H., Hyndman, R.D., Hyndman, J., Quintino, N., Opdyke, N., W., 1974. Lowrie Deep drilling in an active geothermal area in the Azores. Nature 252, 281–285.
Mungall, J.E., Martin, R.F., 1995. Petrogenesis of basalt comendite and basalt pantellerite suites, Terceira, Azores, and some implications for the origin of ocean island rhyolites. Contrib. Mineral. Petrol. 119, 43–55.
Navarro, A., Catalão, J., Miranda, J.M., Fernandes, R.M.S., 2003. Estimation of the Terceira Island (Azores) main strain rates from GPS data. Earth Planets Space 55, 637–642.
Navarro, A., Lourenço, N., Chorowicz, J., Miranda, J.M., Catalão, J., 2009. Analysis of geometry of volcanoes and faults in Terceira Island (Azores): Evidence for reactivation tectonics at the EUR/AFR plate boundary in the Azores triple junction. Tectonophysics 465, 98–113.
Neves, M.C., Miranda, J.M., Luis, J., 2013. The role of lithospheric processes on the development of linear volcanic ridges in the Azores. Tectonophysics 608, 376–388.
Petit, G., Luzum, B., 2010. IERS Conventions (2010). IERS Technical Note 36, Verlag des Bundesamts fur Kartographie und Geodasie, Frankfurt am Main.
Saastamoinen, J., 1972, 1973. Contributions to the theory of atmospheric refraction. In three parts. Bull. Géodésique 105, 279–298 (106, 383-397; 107, 13-34).
Schilling, J.G., 1975. Azores mantle blob: rare-earth evidence. Earth Planet. Sci. Lett. 25, 103–115.
Self, S., Gunn, B.M., 1976. Petrology, volume and age relations of alkaline and saturated peralkaline volcanics from Terceira, Azores. Contrib. Mineral. Petrol. 54, 293–313.
Sibrant, A.L.R., Hildenbrand, A., Marques, F.O., Costa, A.C.G., 2013. Volcano-tectonic evolution of Santa Maria Island: implications for Nubia-Eurasia plate boundary in the Azores. Abstract Meeting AGU.
Sibrant, A.L.R., Marques, F.O., Hildenbrand, A., 2014. Construction and destruction of a volcanic island developed inside an oceanic rift: Graciosa Island, Terceira Rift, Azores. J. Volcanol. Geotherm. Res. 284, 32–45.
Sibrant, A.L.R., Hildenbrand, A., Marques, F.O., Costa, A.C.G., 2015. Volcano-tectonic evolution of the Santa Maria Island (Azores): implications for palaeostress evolution at the western Eurasia-Nubia plate boundary. J. Volcanol. Geotherm. Res. 291, 49–62.

Silveira, G., Vinnik, L., Stutzmann, E., Farra, V., Kiselev, S., Morais, I., 2010. Stratification of the Earth beneath the Azores from P and S receiver functions, Earth Planet. Sci. Lett. 299, 91–103.
Tolstoy, I., 1951. Submarine topography in the North Atlantic. GSA Bull. 62, 441–450.
van Wyk de Vries, B., Francis, P.W., 1997. Catastrophic collapse at stratovolcanoes induced by gradual volcano spreading. Nature 387, 387–390.
Vogt, P.R., Jung, W.Y., 2004. The Terceira Rift as hyper-slow, hotspot-dominated oblique spreading axis: a comparison with other slow-spreading plate boundaries. Earth Planet. Sci. Lett. 218, 77–90.
Yang, T., Y., Shen, S., Solomon, C., 2006. Upper mantle structure beneath the Azores hotspot from finite frequency seismic topography. Earth Planet. Sci. Lett. 250 (12), 11–26.