The structure of the Azores triple junction: implications for S. Miguel Island

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Abstract

The lack of reliable morphological and geophysical data for most of the Azores plateau has been up to now a major limitation to the understanding of tectonic and magmatic processes that shape the Eurasia-Nubia-North America triple junction and the Terceira Rift. This situation changed recently: for the first time both the Triple Junction area and the Terceira Rift are covered by high quality swath bathymetry surveys and marine magnetic data with GPS quality positioning. This provides a good description of the surface morphology, and also of magnetic chrons that give fundamental information for the timing of spreading processes on the geological time frame. There is also a large amount of data from continuous GPS stations, operating since 1997, which provides accurate estimations of present day velocities for most of the islands. It is shown that only two main rift systems can be found on the plateau, the oldest one matching the Princess Alice Basin, and the newest one matching Terceira rift; the shift between the two probably occurring close to ~3Ma. It is shown that extension is nowadays concentrated in Terceira rift, progressively attaching Graciosa and Terceira islands to Eurasia, while S. Miguel is being strained by rifting. It is also shown that no right lateral strike slip fault connects Terceira Rift to the Mid-Atlantic Ridge and that the differential motion between Eurasia and Nubia, west of Western Graciosa Basin, is accommodated within a wide right lateral transtension area.

The succession of basins and volcanic highs that runs from the Western Graciosa Basin, close to the Mid-Atlantic Ridge (MAR) up to Formigas islets, in the western tip of Gloria Fault (see figure 1 for locations), was interpreted by Machado (1959) as a rift belt of tectonic origin and referred to as the Terceira Rift. Krause and Watkins (1970) were the first to provide a plate tectonic interpretation of the genesis of the Azores, describing it as a secondary spreading ridge, based on the interpretation of coarse bathymetric and magnetic data. Its development was attributed to a sudden change in the direction and the magnitude of the Eurasia-North America and Nubia-North-America spreading rates, which would have occurred around 45 Ma BP.

McKenzie (1972) discussed the stability of such configuration, showing that it implies a northward migration of the Eurasia-North America-Nubia triple point. Searle (1980), based on additional shipborne magnetic data and a large amount of GLORIA side-scan sonar data acquired between the Azores plateau and the MAR, was able to define the Terceira Rift more fully. He proposed that the configuration change predicted by Krause and Watkins (1970) corresponded to a northward jump of the EU-NU plate boundary from the latitude of the East Azores Fracture Zones, to the vicinity of the North Azores Fracture Zone, which would connect Terceira Rift to the MAR (Searle, 1980).

Srivastava *et al*. (1990) analysed a large magnetic compilation in the North Atlantic and identified the main changes since chron M0 (~125 Ma, Cande & Kent, 1995). They showed that Iberia was attached to Africa from the late Cretaceous to middle Eocene. Between the middle Eocene to late Oligocene it behaved almost as an independent plate with slight motion relative to Africa, while most of the deformation was concentrated along the northern border. Since the late Oligocene Iberia is considered as a part of the Eurasia plate (Srivastava *et al*., 1990). Luis and Miranda (2008) refined the magnetic compilation of the North Atlantic, and concluded that the establishment of the EU-AF-NA triple junction south of the Azores occurred between chrons C11- C12 (ca. 30 Ma) and C6c (ca. 24 Ma) and following the addition of Iberia to Eurasia.

The location and northward motion of the Azores triple point was analyzed by Luis *et al.* (1994) at a segment scale. The study was based on a detailed aeromagnetic data set covering mostly the area close to the MAR, up to chron c5 (~10 Ma). They concluded that the Eurasia-Nubia-North America triple junction was located north of the East Azores Fracture Zone between anomaly 4 and anomaly c3a times, approximately at 38º20’N, 30º15’W (Eurasia fixed co-ordinates) and proposed a present-day location close to 38º55´N, 30º00’W (Eurasia fixed co-ordinates), after anomaly Chron c2a, approximately 2.45 Ma ago. Being so, the evolution of the Azores plateau was determined first by the joining of Iberia to Eurasia and then by the progressive attachment of Eurasia to Nubia (Lourenço *et al.*, 1998), associated with the northward migration of the triple junction, and rifting and eventually the spreading associated with Terceira rift. The reanalysis of regional marine magnetic data for the North-Atlantic also showed that the width of the lithospheric sliver, that can be attributed to Azores rifting and incipient spreading, is much smaller than the plateau itself, corresponding to a total extension close to 75 km. Stretching of the Azores plateau took place essentially in the last ~20-25 Ma (Luis and Miranda, 2008).

The precise location and the nature of the geological processes associated with Azores extension are more difficult to establish: the identification of young magnetic anomalies with a trend similar to the Terceira rift was made by Miranda *et al.* (1991) and Luis *et al.* (1994); however, no stable magnetic striping was found and apparently only Brunhes and Matuyama chrons can be identified, and in some cases not strictly confined to the Terceira Rift: S. Jorge or the Pico-Faial Islands also show large positive magnetic anomalies and there is evidence for the Brunhes-Matuyama transition in the island of Faial, with clear continuation offshore. The fact that only young chrons are represented in the new Azores domain was checked independently in the Islands of Faial (Miranda *et al.*, 1991), S. Miguel (Johnson *et al.*, 1998) and S. Jorge (Silva *et al.*, 2012) and this shows that spreading related with the Azores axis is young, ~2 Ma, and driven by discontinuous stages of volcanism and tectonic movements, both in space and in time. Gravity modeling (Luis *et al.,* 1998, Luis and Neves, 2006) confirmed that the secondary Azores spreading ridge is not sufficiently mature to generate a significant thermal effect. Vogt and Jung (2003) compared the Terceira Rift with other ultra-slow spreading ridges (e.g. Southwest Indian and Gakkel) suggesting the existence of a hyper-slow regime characterized by a wider rift valley and a thicker axial lithosphere, that would characterize the Azores.

The existence of a hotspot as a driving mechanism for the formation and evolution of the Azores is supported by several authors. The Azores plateau and nearby topographic anomalies were first attributed to a mantle hotspot (Schilling, 1975) and its interaction with the Mid-Atlantic Ridge. Gente *et al.* (2003) proposed the Great Meteor Seamounts as the original location of the hotspot, 85 Ma ago, before migrating northward, and showed that the development of the plateau occurred 20 Ma to 7 Ma BP, before being tectonically rifted. Body wave tomography by Yang *et al.* (2006) mapped a low-velocity anomaly beneath the Azores Plateau at approximately 38.5°N, 28.5°W, extending northeastward and downward to connect to a plume-like column from ~250 km to at least 400 km depth, centered northeast of Terceira Island. Cannat *et al.* (1999) emphasized the influence of the Azores hotspot on the buildup of the morphology of the MAR close to the Azores, and interpreted the Faial Ridge and a number of other volcanic ridges as the result of a northward mantle flux along the MAR. Vogt and Jung (2003) and Beier (2006) interpreted the existence of volcanic ridges south of Terceira Rift as volcanic growth along a fossil rift and attributed the northward progression of the active rifting area as a consequence of differential motion of the hotspot with respect to the overlying lithosphere.

Space domain studies of the geoid to topography ratio in the Azores, found that the Plateau may be supported solely by thickened crust (Grevemeyer, 1999). The same conclusion was achieved by the work of Luis and Neves (2006) that investigated the gravity and geoid to bathymetry relationship in the spectral domain. They found that the anomalously shallow depths of the Azores Plateau were not due to dynamic forces sustained by mantle upwelling. The alternative explanation was that the plateau is supported by thickened crust, which mainly results from large volumes of accreted extrusives.

Morpho-structure of the Azores Plateau

The first regional bathymetric compilation of the Azores region was made by Krause and Watkins (1970) and this supports their plate tectonic interpretation of the Azores. Searle (1980) added new vertical soundings to the surveys made by Laughton *et al.* (1975) in the area and a large amount of GLORIA side-scan sonar data along the plateau. The first systematic swath bathymetry survey of the Mid-Atlantic ridge, close to the Azores, was made by Needham *et al.* (1991) up to a distance that corresponds roughly to MAR magnetic chron c3 (~5 Ma). Lourenço *et al.* (1998) extended Needham *et al.* (1991) compilation to the Azores, combining vertical soundings with swath bathymetry data. Surveys over the MAR southern section were extended to a wider off-axis region (Cannat *et al.*, 1999*)* and to the Azores triple junction, northwards off the Azores plateau (Goslin *et al.*, 1999). Gente *et al.* (2003) collated the data originally prepared by Thibaud *et al.* (1998), into a 1 km grid, covering the area 32-49N and 22-43W. While not homogeneous, and not as detailed close to the islands as the compilation by Lourenço *et al.* (1998), it gave the first regional overview covering the entire Azores Plateau and the MAR. Nevertheless two key areas were not well described in these compilations: the complex tectonic area close to the triple junction and the succession of basins that characterizes the Terceira rift.

Luis *et al.* (2006) made a high quality swath bathymetry survey of the Azores Triple Junction area, using the French vessel Le Suroît and a Kongsberg EM300 multibeam echosounder. This system images a variable swath width with 135 beams and a 32-kHz pulse, reaching a maximum swath of 140°. For the average depth of the surveyed area (less than 2000 m below sea level), this configuration enabled a typical 4-km across-track swath to be covered and a 50x50m grid to be produced. Two areas were surveyed in 2006 and 2007 (see Fig. 2 for locations) covering essentially an area between the plateau and the MAR. The area is bounded to the north by the North Azores Fracture Zone (~39º30'N) previously identified by Searle (1980) as the probable structure connecting Terceira Rift with the MAR. The southerly limit is bounded by latitude 38º30'N, which was identified by Luis *et al.* (1994), based on magnetic data, as the probable location of the Azores triple junction.

Terceira rift was surveyed in the course of the United Nations Convention on the Law of the Sea (UNCLOS) Surveys, by the Portuguese NRP Gago Coutinho, equipped with Kongsberg EM120 and EM170 systems for deep and intermediate to shallow water depths respectively (Madureira *et al.*, 2011). A 50x50m grid was produced covering an area of approximately 15400 km^2. Dedicated surveys were processed following IHO order 3 standard for hydrographic surveys (IHO, 1987). Transits of opportunity were corrected using climatological profiles and added to the systematic surveys as additional coverage to fill in the data gaps.

In Fig. 2 we present a 250 m bathymetric grid collating all new data. Most of the large scale characteristics known from previous studies (Needham *et al.*, 1990; Lourenço *et al.*, 1998; Gente *et al.*, 2003) are here expressed: the topographic anomaly which affects the MAR between 35ºN and 44ºN generates a triangular plateau approximately bounded by the 2000 m isobaths, and split by the MAR between a small western plateau and a large eastern plateau. Its southern limit is marked by a major fracture zone (East Azores Fracture Zone) and the sequence of steep basins that reach 2500-3000 m deep and volcanic highs which form the Terceira rift developed close to its northeastern flank. Southwest of the Terceira rift one can observe the volcanic highs of S. Jorge, Pico and Faial islands, and the Princess Alice Basin and bank, all sub-parallel to Terceira rift. A number of small elongated volcanic ridges punctuate the plateau with a similar strike.

The bathymetric data presented in Fig. 2 provides an accurate description of abyssal hill topography associated with rifting at the MAR and with rifting at Terceira axis. It is the result of high-angle faulting in slow spreading ridges and accounts for 10-20% of plate separation (cf. Searle and Escartin (2004) and references herein). The geometry of abyssal hills and their distribution can be used to identify the different tectonic patterns present in the Azores Plateau, and in some situations they can be interpreted as chrons similar to what is done with marine magnetic anomalies.

The small thickness of the sediment cover (Gente *et al.*, 2003) and the near absence of volcanic features, allows for a clear bathymetric expression of the Azores related tectonic pattern. The area between the MAR and 28º40’W, which corresponds to the northwestern tip of the Western Graciosa Basin, is dominated by MAR-related abyssal hill topography, with a strike similar to the MAR: ~N12E. At this stage there is no evidence of a single structure relaying Terceira Rift to the MAR.

East of 28º40’W, the Terceira Rift becomes the main structural entity that disrupts the Azores Plateau. MAR-related abyssal hill topography is dissected by ~N140º high angle faults associated with the extension of the Western Graciosa Basin. The fault strike rotates continuously up to N110º-120º which corresponds to the direction of the flanks of the eastern and western Graciosa basins, and of the islands located south of the Terceira Rift. Basin flanks are uplifted as a consequence of the equilibrium between isostasy and rifting extension (Lin and Parmentier, 1990). The North Hirondelle basin flanks strike ~N130º while the South Hirondelle basin flanks strike ~N140º. The Povoação basin, the easternmost basin of Terceira rift strikes ~N160º, almost orthogonal to the small circle of the Eurasia-Nubia present-day infinitesimal rotation pole, as given by MORVEL model (DeMets *et al.* 2010). Between rift basins, three large volcanic structures form the islands of Graciosa, Terceira, and S. Miguel, and shallow banks such as D. João de Castro (between North and South Hirondelle basins) and the Formigas islets (east of the Povoação Basin). S. Miguel is differently located: the western part of the island is aligned with the South Hirondelle Basin, while the eastern part of the island is aligned with Povoação Basin. Taken together this succession of deep basin and topographical highs defines the crude segmentation pattern of the Terceira rift which presents a typical wavelength of 60 to 100 km between major volcanoes or main basin depocenters along strike.

Close to the southwest corner of the eastern Azores Plateau, there is another steep basin that shares strong similarities with the Terceira Rift: the Princess Alice Basin. It offsets the Faial Ridge, approximately 20 km, at its eastern end. It is bounded by steep N130º flanks and approximately 1200m deep, when compared to the neighboring plateau.

Magnetic Analysis

Magnetic surveys and magnetic chronology

The first magnetic compilation of the Azores was prepared by Krause and Watkins (1970) and used to support the existence of a secondary spreading centre. In the late eighties, a large aeromagnetic survey covered the entire plateau. First results were presented by Miranda *et al.* (1991) and the whole survey was processed and interpreted by Luis (1996) and Luis *et al.* (1994). The survey was dense and homogeneous but suffered from the limitations of the inertial positioning system used for the aeromagnetic survey. Luis and Miranda (2008) presented a new grid 2' magnetic compilation of the North Atlantic between 35ºN and 47ºN, where the most accurate (post-GPS) marine data were collated. These magnetic data were merged with complementary magnetic profiled acquired in the course of the UNCLOS Surveys. The final grid was continuously reduced to the pole following the technique described by Luis and Miranda (2008). In Fig. 3 we present the magnetic anomaly grid reduced to the pole, with a resolution of 30'' covering the area 36N-41N and 32W-24W. Magnetic chrons were picked from the correlation between measurements and synthetic profiles along small circles of the presumed relative finite rotation poles. The following chrons were identified: C2, C2a, C3, C3a, C4, C4a, C4, C5, C6, C6c, C13, C18, C20, C21, C22, C23, C24, C25, C26 and C28.

The interpretation of the magnetic anomaly map is straightforward: between the Mid-Atlanic Ridge and chrons C4a-C5 magnetic striping is normally developed. Magnetic anomalies are continuous between the North Azores Fracture Zone and Princess Alice Basin and spreading is mostly regular since chron c4a. South of 38º30'N there is evidence of a jump to the west of the ridge axis in the segment 38ºN-38º30'N at chron C3, associated with the northward progression of the triple junction (Luis *et al.*, 1994).

Between chrons C5 and C22 MAR magnetic chrons are disrupted by a sequence of linear magnetic anomalies sub-parallel to Terceira rift, but with no systematic magnetic stripping.

These anomalies have high amplitudes (~1000 nT) and so probably correspond to the youngest magnetic ages of Brunhes and Matuayama. The strike of magnetic anomalies changes continuously from east to west, between Gloria Fault and the western Graciosa Basin: South Hirondelle Basin ~N125º, North Hirondelle Basin ~N135º, East Graciosa Basin ~N125º, West Graciosa Basin ~N140º. The only place where magnetic stripping seems better developed corresponds to the East Graciosa Basin close to Terceira Island, where a succession of reduced-to-the-pole positive and negative anomalies can be found. The two positive anomalies that follow the southern and northern flanks of the rift basin and can be interpreted as magnetic chrons (C2?). This is the oldest magnetic signature associated with the development of the Terceira Rift.

South of the Terceira Rift linear magnetic anomalies match the volcanic highs of S. Jorge, Pico and Faial islands with strikes ~N110º-N120º. They are not a topographic effect as shown by inversion (Luis, 1996). In several places these anomalies continue on-shore where their ages have been determined by radiometric methods. This is the case in the islands of Pico, Faial and S. Jorge, where K/Ar ages given by Féraud *et al.* (1980) are compatible with the Brunhes-Matuyama transition interpreted on magnetic anomalies (Miranda *et al.*, 1991). Radiometric ages determined for Faial (Hildenbrand *et al.*, 2011), S. Miguel (Johnson *et al.*, 1998) and S. Jorge (Silva *et al.*, 2012) reinforce the interpretation that the Matuyama-Brunhes transition is found almost everywhere in the Azores islands and that Azorean magnetic anomalies are younger than ~2 Ma. The exception is Santa Maria Island, believed to have formed between 5.2 Ma and 4.6 Ma (Féraud *et al.*, 1981), and the only island of the Azores archipelago where fossiliferous sediments of Zanclean age (5.3Ma-3.6Ma) were found (Abdel-Monem *et al*. 1974; Janssen *et al.*, 2008).

Princess Alice basin also disrupts the MAR-related magnetic pattern and its western limit follows chron c2a (~3 Ma) at 38º30'N. It is very difficult to identify magnetic lineations on the basin floor.

Islands Aeromagnetic Surveys

In 1985 two aeromagnetic surveys were made in the Azores islands covering Faial and S. Miguel, respectively. The results of the first were published by Miranda *et al.* (1991) and showed the existence in SW Faial of the Bruhnes-Matuyama onshore. A recent work (Hildenbrand *et al.*, submitted) that included extensive analysis of radiometric ages of volcanic outcrops in the main units of Faial, and complementary paleomagnetic research, confirmed the existence of at least two main phases in the construction of Faial Island. The older phase is associated with widespread volcanism older than 800 ka, and consequently magnetically reversed. The younger phase is directly magnetized, and extends up to the present-day.

The aeromagnetic survey of S. Miguel was made in 1985 at an average altitude of 1200 m (western panel) and 1500 m (eastern panel). The magnetic anomalies, after analytical continuation to a common level of 1500 m, and subtraction of the International Geomagnetic Reference Field for the corresponding epoch, are plotted in Fig. 4A. There is a general agreement between the plateau survey and the more accurate island aeromagnetic survey, and one can observe that most of the island displays high amplitude positive magnetic anomalies, coherent with the existence of highly magnetized and young eruptive rocks covering the flanks of most of the volcanic systems. Two of the calderas (Sete Cidades and Furnas) match relative magnetic lows and Fogo Volcano flank corresponds to a negative magnetic anomaly. A similar situation can be found in the Nordeste area, with a WNW-ESE magnetic negative trend.

Using the total magnetic anomaly field and the bathymetry of S. Miguel, an equivalent horizontal distribution of the magnetization is computed using some assumptions on the thickness and vertical homogeneity of the magnetic layer. This inversion procedure, developed by Parker and Huestis (1974), eliminates the dependence of the magnetic anomaly field from the effect of the topography and the declination and inclination of the main field and the magnetization. We considered a constant thickness source layer of 0.5 km, whose upper surface follows the bathymetry, and a geocentric dipole magnetization with inclination 54º and declination -13º. The equivalent magnetization draped upon the topography is shown in Fig. 4B. It emphasizes the magnetization decrease associated with the calderas of Sete Cidades and Furnas, the large negative magnetization associated with Fogo Volcano and linear negative magnetization associated with the Nordeste Volcanic Complex.

We interpret the magnetization decrease as the result of hydrothermal alteration. A similar interpretation was given by Blanco *et al.* (1997) for the decrease in the magnetic field anomaly of Furnas, detected by a land magnetic survey. The intense fumarolic and soil degassing activity observed at Furnas caldera (Ferreira *et al.*, 2013-this issue; Viveiros *et al*. 2013-this issue) suggests the presence of a mature hydrothermal system beneath this central volcano and supports such interpretation. On Sete Cidades Volcano present-day degassing processes are not so evident due to the presence of a large superficial aquifer system but the intracaldera volcanic activity in the last 5000 years shows the largest eruptive frequency in the Azores suggesting a very active plumbing system (Queiroz *et al*., 2008; Queiroz *et al*., 2013-this issue). The negative magnetization of Fogo Volcano and Nordeste Volcanic Complex are probably the result of reversed magnetization, acquired before the Brunhes-Matuyama transition, as is found elsewhere in the Azores. In the case of Fogo Volcano, it can be the consequence of a thick layer of reversely magnetized rocks, partially overlain by more recent volcanic products (Wallenstein *et al,* 2013-this issue), which (vertically integrated) effect can be seen in Fig. 4B. In the case of

Nordeste Volcanic Complex this interpretation matches the radiometric ages determined by Johnson *et al.* (1998) in surface outcrops.

Present-day surface displacement field

Inter-island displacement field

The first GPS network campaign was made in the Azores in 1988 that included only one station per island. Observations have been carried regularly since then (see Fernandes *et al.* 2006 and references herein).

A number of studies have been based in campaign GPS observations. Fernandes *et al.* (2004, 2006) analyzed a set of 9 stations, corresponding to the period 1993-2000 and 1993-2001. They concluded that the absolute motion for all stations was intermediate between pure Eurasia and pure NubiaNubia behavior where the end members appeared to be Graciosa and Santa Maria islands, respectively. All other sites were located along the presently active inter-plate deformation zone. This was also supported by the averaged motion per island using the solutions from the dense networks (Fernandes *et al.*, 2006; Miranda *et al.*, 2012).

More recently, the number of permanent GNSS stations in Azores has also improved significantly. This work, we focuses only in such type of stations, which although still with a distribution less dense than the existing networks of episodic stations (particularly on the islands of Terceira, S. Jorge and Faial), are already able to provide reliable estimates concerning the dynamics of the region. In fact, such stations do not suffer from reoccupation errors (for most of the Azorean permanent stations, the antenna and receiver have been the same since the initial installation) and most of the effects due to seasonal signals have been already mitigated after 2.5yr (Blewitt & Lavallé, 2002). Table I details the most significant properties of the network of permanent stations in Azores available to this research group. In addition to the stations with data-span smaller than 2.5yr (VFDC and PTRP), TERC has also been excluded from the analysis. This station has many data gaps and a significant number of outliers in a relative short time-series (2.9yr).

Fig. 5 shows the estimated velocity field with respect to stable Nubia using as reference the SEGAL08 plate tectonic model (Fernandes *et al.*, 2011). This model includes estimations of the angular velocity of Nubia and Eurasia derived from GPS velocities computed with respect to ITRF08, the latest realization of the International Terrestrial Reference System. For comparison, we also plot the predicted relative motion for points in the stable Eurasia using SEGAL08, GEODVEL (Argus *et al.*, 2010) and MORVEL (DeMets *et al.*, 2010). GEODVEL is also a space-geodetic based angular velocity model whereas MORVEL is the most recent geophysical/geological angular velocity model averaging the motions of the plate tectonics in the last 3Ma. As it is observed, the predicted motions given by all these models are similar with SEGAL08 and GEODVEL (N82º-85ºE) predicting a more oblique opening of the Terceira Rift – almost West-East, whereas MORVEL (N69º-77ºE) shows a more pure opening regime of the Nubia-Eurasia plate boundary between S. Miguel and Graciosa islands.

The Graciosa station (AZGR) presents an abnormal residual suggesting this island is presently locked to Eurasia. Even if the large uncertainty of the derived solution does not allow a robust conclusion to be reached, this estimation is coherent with other solutions computed in the past based on episodic data (Fernandes *et al.*, 2004, 2006), which also showed Eurasia motion for this island.

The results for the other stations in Faial, Terceira and Pico (FAIM, TOMA and PIED, respectively) also confirms the previous computed velocity fields of these islands presented by Fernandes *et al.* (2006) and Miranda *et al.* (2012) based on the combination of permanent and episodic data (for Faial and Terceira) or episodic data only (Pico). Clearly, Faial and Pico present a motion that is practically Nubia whereas the motion for Terceira is intermediate between Nubia and Eurasia.

The vertical component of the surface displacement field is less constrained than the horizontal components. There is evidence for subsidence of Terceira Island close to 0.8 mm/yr . PDEL station in S. Miguel Island shows also subsidence rate of -0.66 +/- 0.21 mm/yr in the last 10 years of continuous observations (Miranda *et al.*, 2012). The station showing the largest subsidence is also located in S. Miguel – FRNS (-3.21 +/- 1.51 mm/yr). In fact, the only station showing uplift is AZGR (1.46 +/- 2.73 mm/yr) but the associated uncertainty is too large to derive any sound conclusion.

Intra-island deformation field

Intra-island deformation was studied in S. Miguel Island (Sigmundsson *et al.*, 1995; Jónsson *et al.*, 1999; Trota *et al.*, 2006; Trota, 2008), Terceira (Navarro *et al.*, 2003, Trota, 2008, Miranda *et al.*, 2012), Faial (Catalão *et al.*, 2006), and Pico (Catalão *et al.*, 2010).

Jónsson *et al.* (1997) analysed GPS campaign data from S. Miguel Island and found significant extension within the island. They hypothesize that a 10-15 km wide zone, in the Furnas region was accommodating about 75% of the divergence between Eurasia and Nubia plates. Trota *et al.* (2006) extended this study, analysing data from five GPS campaigns between 1993 and 2002 in S. Miguel. They concluded that a somewhat larger zone of the island, ~15-25 km wide, accommodates most of the deformation WNW–ESE extension at a rate close to 5 mm/yr , which has the same order of magnitude as the Eurasia-Nubia relative motion according to all geodetic models.

Our results based on the two analysed permanent GPS stations in S. Miguel (PDEL and FRNS) also confirm an extension of the island almost in the WNW-ESE direction (N100ºE). However, the estimated opening rate using the derived secular motions (2.2 mm/yr) is only about half of the predicted opening rate given by the considered tectonic angular velocity models (cf. Figure 5). This opening rate is even reduced if only the common period of observations for both stations is considered (September 2007 – November 2011) and only the rate of the change of the baseline between both stations is computed (which is independent of any errors associated with the reference frame). In this case, the averaged opening rate is reduced to 1.64 +/- 0.20 mm/yr. This is only about 35% of the expected deformation.

Different results were obtained for Terceira Island, where no significant intra-island deformation patterns were identified and the magnitudes of local deformation processes measured by the GPS network are low when compared with the accuracy of the velocities. According to Miranda *et al.* (2012) Terceira moved most closely with Eurasia during the period 1996-2010 and the two studies (Navarro *et al.*, 2003 and Miranda *et al.* 2012) point to small lateral compression, with no evidence of extensional processes.

Intra-island deformation of Faial was studied by Catalão *et al.* (2006) using conventional geodetic measurements made between 1937 and 1997 and GPS campaign data. They showed that Faial intra-island deformation during most of the 20th century could be attributed to a single event (Capelinhos eruption and subsequent earthquake), and not to tele-tectonic processes. A similar conclusion was obtained for Pico, where surface displacements are related with mass waste processes (Catalão *et al.*, 2010).

All existing studies (Catalão et al., 2006, 2010) point to the importance of local volcanic dynamics on the intra-island deformation field. Inflation leads to the development of elongated volcanic ridges associated with all large volcanic units and deflation leads to contraction and graben development (Miranda *et al.*, 2012).

Discussion and Conclusions

Vogt and Jung (2004) considered that while the distance between magmatic centers in the Azores is similar to what is found in ultra-slow ridges, the rift valley is wider than the nearby MAR, as a consequence of the smaller spreading rate (4 mm/yr compared with 23 mm/yr at a latitude of 40ºN), corresponding to a thicker axial lithosphere, geometrically similar to what is found in extinct rifts (e.g. Guadalupe and Aegir). A similar situation is supposed to occur on the amplitude of the topographic segmentation (2000-4000 m) which greatly exceeds that of “normal” slow MAR segments and registers the more abundant magma supply that has created the Azores Plateau. The data presented here do not contradict this view: ultra-slow spreading along the Azores arm creates morphological highs and deep basins along the Terceira Rift, with episodic volcanic events south of the main rifting area, focusing under large volcanoes instead of occurring widespread along the Terceira rift zone.

The northward migration of the Azores triple junction, with the progressive attachment of Eurasia lithosphere to Africa has been identified as an important process that shaped the Azores plateau (Lourenço *et al.*, 1998). However, only two major rift features can be found in the plateau. The first one is the Terceira Rift, which corresponds to the present-day location of rifting processes in the Azores, as demonstrated by historical and instrumental seismic and volcanic activity (Gaspar *et al.* 2013-this issue), magnetic, tectonic (Madeira *et al*., 2013-this issue) and space geodetic data. The second one is the Princess Alice basin and bank, which is now located south of the triple junction area, and most probably corresponds to the previous location of the rift. The shift between the two must have occurred previous to chron C2a.

Vogt and Jung (2003) and Yang *et al.* (2006) proposed the existence of a succession of NE jumps of the oblique spreading axis between an initial location close to the Princess Alice Basin and a final one close to the so-called North Azores Fracture Zone. These jumps are seen as consistent with the existence of a relative stationary Azores mantle "hotspot" across which the Gripp and Gordon (2002) model predicts a N247 direction velocity varying between 22 and 33 km/Ma (Vogt and Jung, 2003). As the distance between Princess Alice Basin and the Western Graciosa Basin, along the direction N247 is close to 150 km, this will imply a time span of 4.5-6.8 Ma. This is inconsistent with the data and interpretation presented here. So, the construction of the volcanic ridges between the two rifts must be considered as having occurred almost concomitantly with the Terceira rift formation as an expression of off-rift volcanism and cannot be interpreted as an intermediate stage materializing progressive migration of the Azores Triple Junction.

The relative motion between Eurasia and Nubia along the Azores is mostly concentrated on Terceira Rift as demonstrated by magnetic and geodetic data. While Graciosa and Terceira are progressively attached to Eurasia, and subsiding as they move away from the rift axis, S. Miguel is being strained by rifting with a significant amount of the inter-plate displacement field being accommodated within the island. In S. Miguel subsidence is a more complex process and seems to be particularly high in the central part of the island as it was first discussed by Muecke et al. (1974) based on rock samples from a borehole drilled in the north flank of Fogo, where subaerial rocks were found at about 800 m depth.

The identification of magnetic chrons between C2 and C5 shows that south of 38N Nubia rotations apply, north of 39.5N Eurasia rotations apply, and between the two limits there is an almost continuous change between the two (Miranda *et al.*, 2011). In this sense, there is no right lateral strike slip fault along the North Azores Fracture Zone as hypothesized by Searle (1980) or by Vogt and Jung (2003), but instead, the differential motion between Eurasia and Nubia, west of Western Graciosa Basin is accommodated within a ~100 km wide subject to right lateral transtension generating the complex tectonic pattern described above.

The angle between the Terceira basins flanks (or the strike of magnetic anomalies), and the direction of the relative motion between Eurasia and Nubia as given by both geodetic and “geological” kinematic plate models, was interpreted by Lourenço *et al.*, 1998 as “oblique spreading”. However, both the morphological expression of the rift flanks and the trend of magnetic anomalies point to the conclusion that rifting is approximately orthogonal, close to the rift. We hypothesize that mantle processes associated with the velocity anomalies mapped by seismic tomography (Yang et al., 2006) are constraining the rift direction close to the actively deforming zone. At the island scale, volcanic dynamics, in particularly inflation and deflation control intra-island deformation and normal faulting.

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FIGURE CAPTIONS

Figure 1: The Azores plateau defined by the 2000 m isobath. MAR: Mid-Atlantic Ridge; WGB: Western Graciosa Basin; EGB: Eastern Graciosa Basin; NHB: North Hirondelle Basin; SHB: South Hirondelle Basin; PB: Povoação Basin; PAB: Princess Alice Basin. Vectors at the flanks of Terceira Rift basins indicate the relative motion between Eurasia and Nubia from geodetic models

Figure 2: 250 m bathymetric grid. New swath bathymetry surveys are indicated by thin white polygons.

Figure 3: Magnetic compilation and isochron identification. Chrons identified close to the Mid-Atlantic Ridge are c2, c2a, c3, c3a, c4 and c4a. Other chrons are labeled. Black dots indicate positive identification and thin solid black lines indicate the probable geometry of the isochron.

Figure 4: Velocities relative to Nubia, as given by the permanent GNSS stations. In spite of the still large error associated with the determination of Graciosa velocity, most of the extension takes place within Terceira rift and São Miguel Island shows significant intra-island extension. Within the Eurasia plate, away from the boundary we plot the velocities given by models MORVEL (violet), yellow (GEODVEL) and SEGAL (green). See text for details.

Figure 5: A: aeromagnetic Survey of São Miguel Island; total field anomalies are plotted every 100 nT. B: drape of magnetization on a detailed topographic map of S. Miguel Island. Magnetization values plotted every 1 Am-1. The main calderas are labeled: Sete Cidades; AP: Agua de Pau or Fogo; FU: Furnas; PV: Povoação.

Fig. 1. The Azores plateau defined by the 2000 m isobath. MAR: Mid-Atlantic Ridge; WGB: Western Graciosa Basin; EGB: Eastern Graciosa Basin; NHB: North Hirondelle Basin; SHB: South Hirondelle Basin; PB: Povoação Basin; PA: Princess Alice; JC: João de Castro Bank. Vectors at the flanks of Terceira Rift basins indicate the relative motion between Eurasia and Nubia from geodetic models.

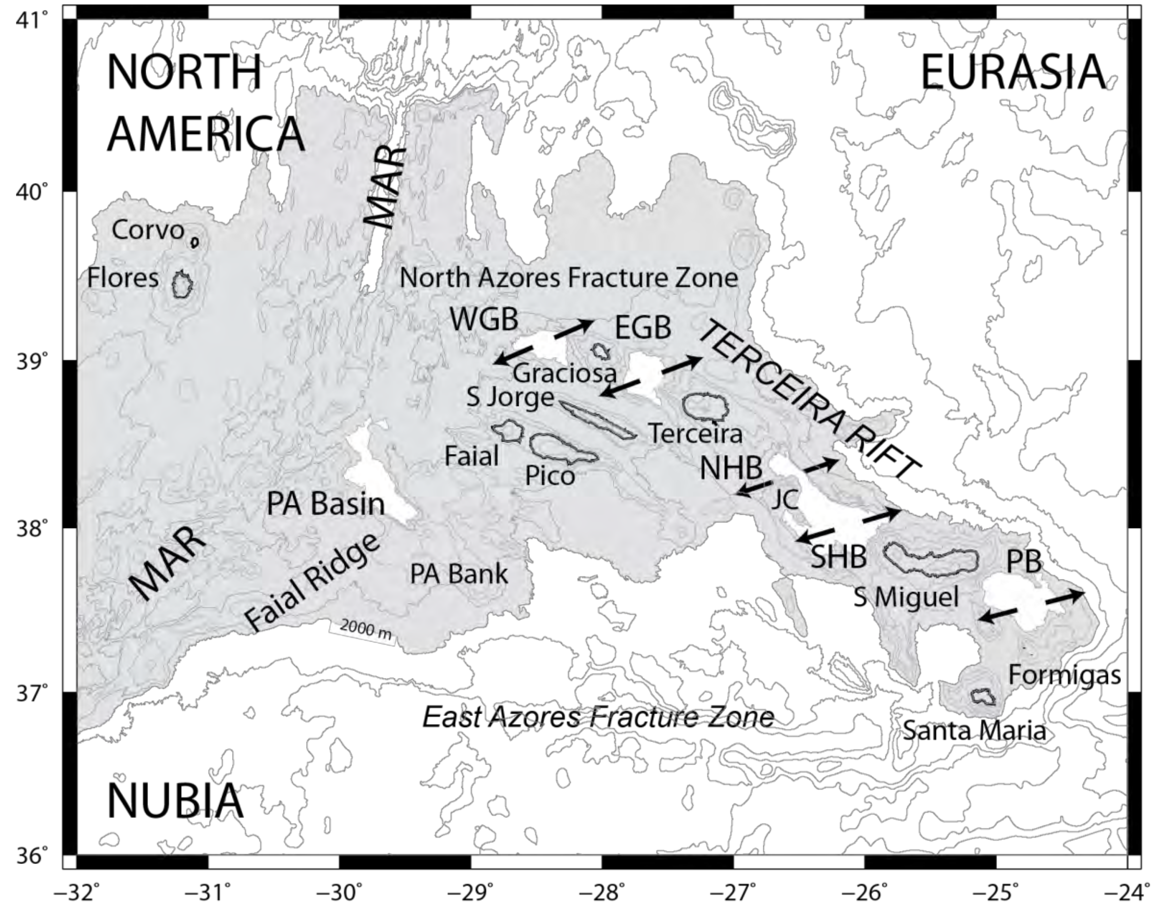
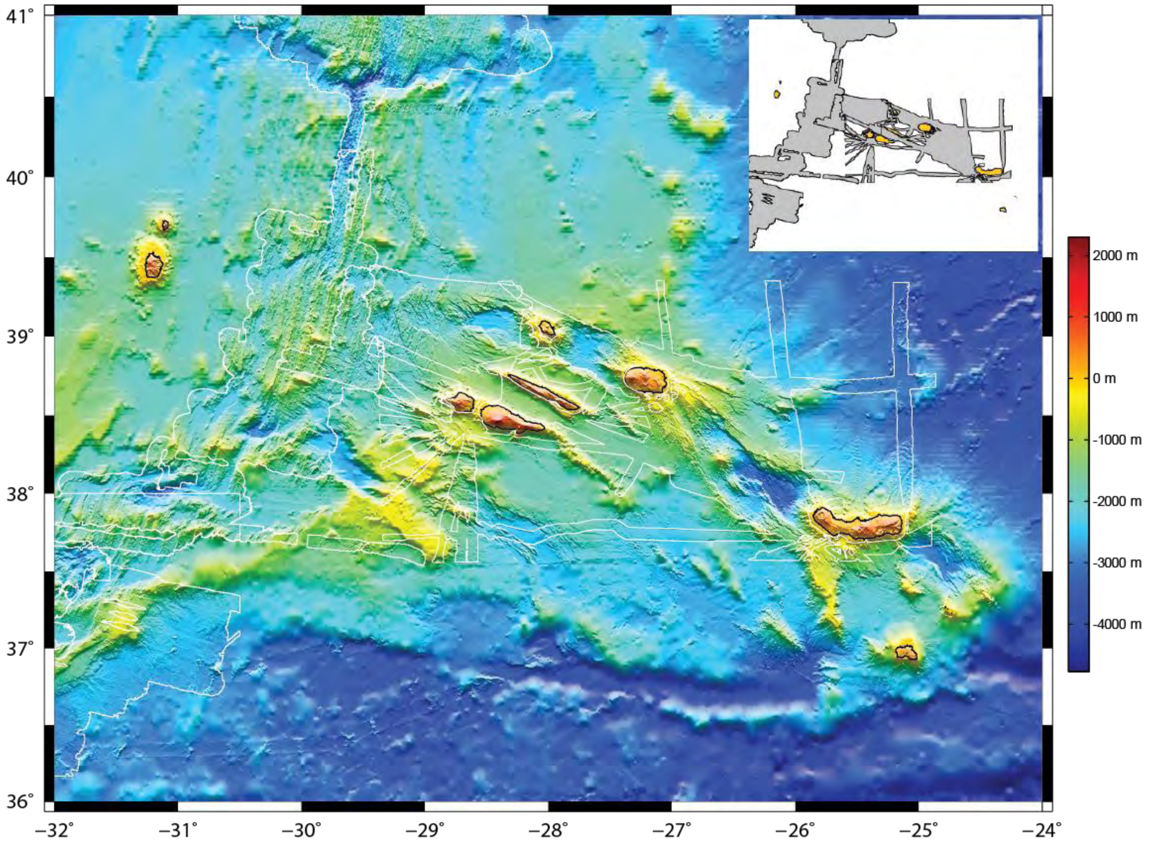


Fig.2. 250 m bathymetric grid. New swath bathymetry surveys are indicated by thin white polygons.



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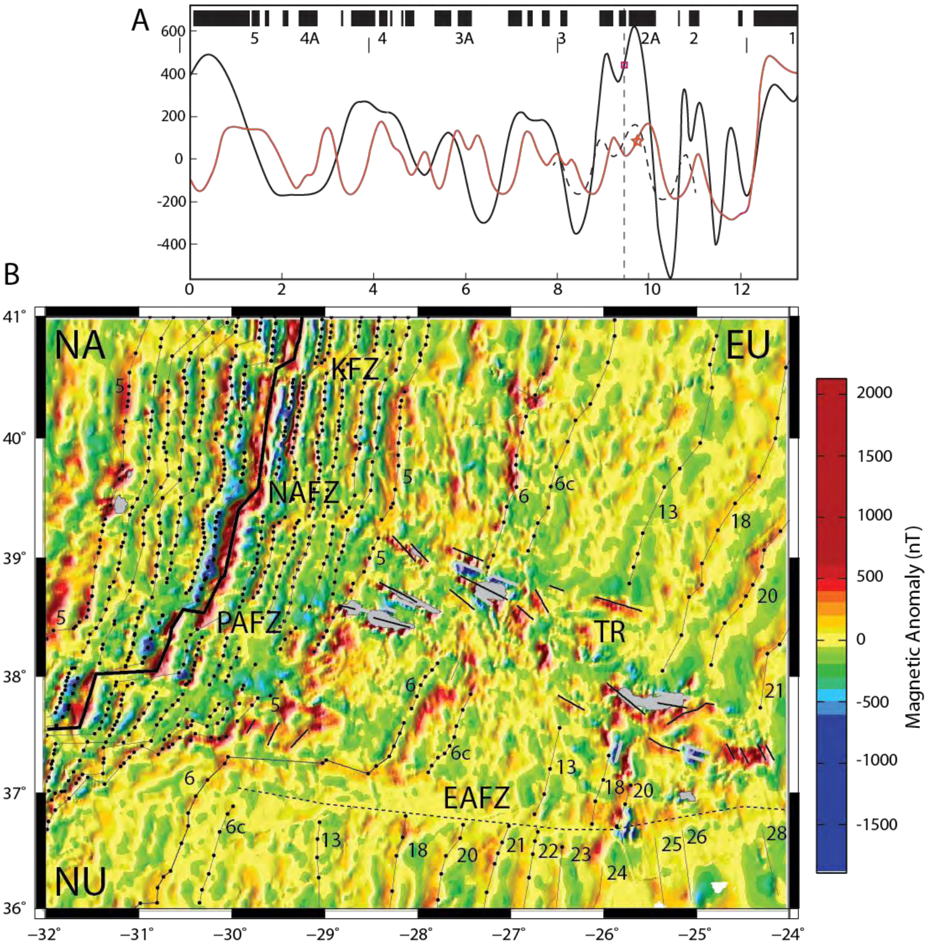

Fig.4. Top: aeromagnetic Survey of São Miguel Island; total field anomalies are plotted every 100 nT. Middle: drape of magnetization on a detailed topographic map of S. Miguel Island. Magnetization values plotted every 1 Am^{-1}. Bottom: topographic map of S. Miguel Island. The main calderas are labeled: SC - Sete Cidades;FG – Fogo Volcano; ; FU - Furnas; PV - Povoação.

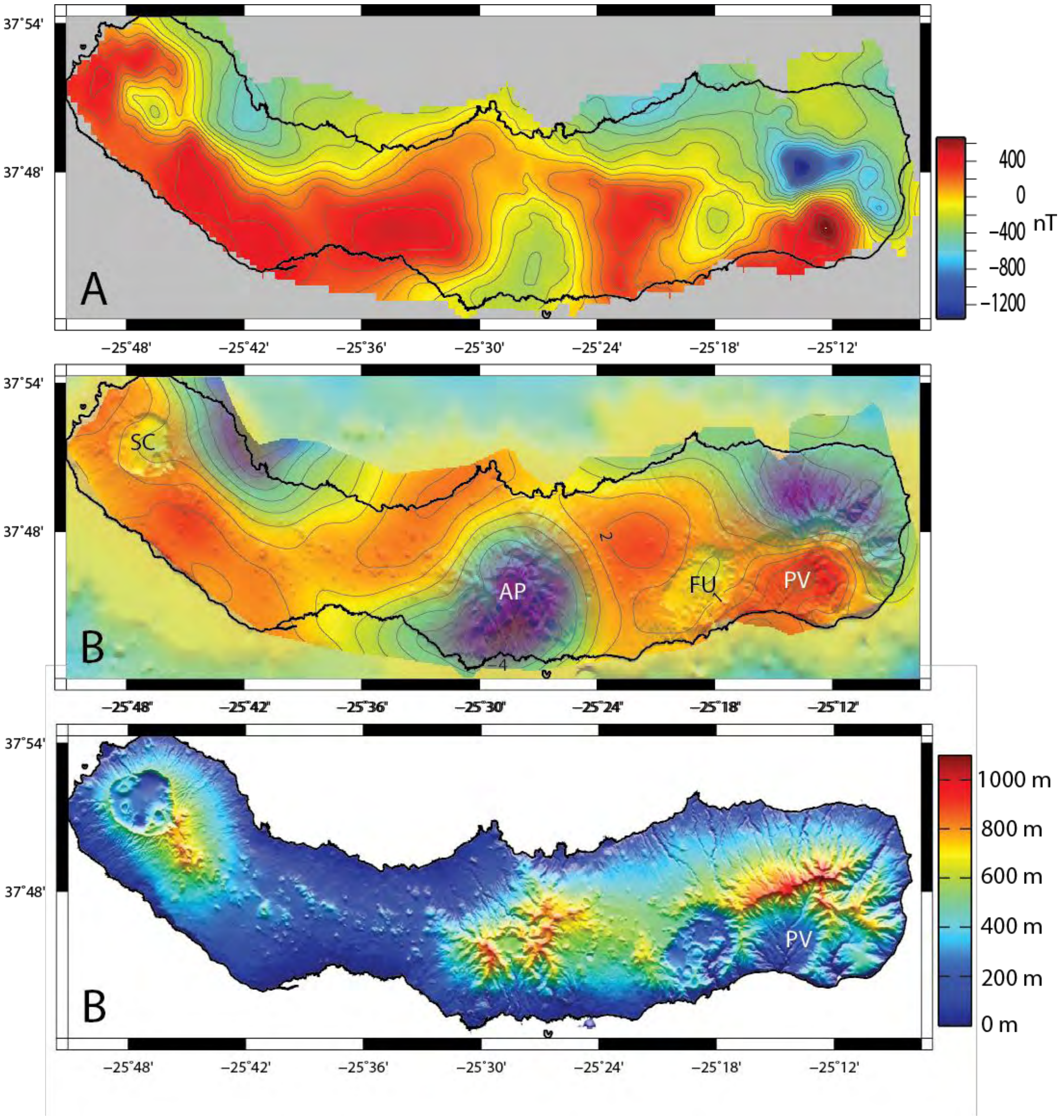

Fig.5. Velocities relative to Nubia, as given by the permanent GNSS stations. In spite of the still large error associated with the determination of Graciosa velocity, most of the extension takes place within Terceira Rift and S. Miguel island shows significant intra-island extension. Within the Eurasia plate, away from the boundary we plot the velocities given by models MORVEL (violet), yellow (GEODVEL) and SEGAL (green) (see text for details). PA: Princess Alice; JC: João de Castro bank.

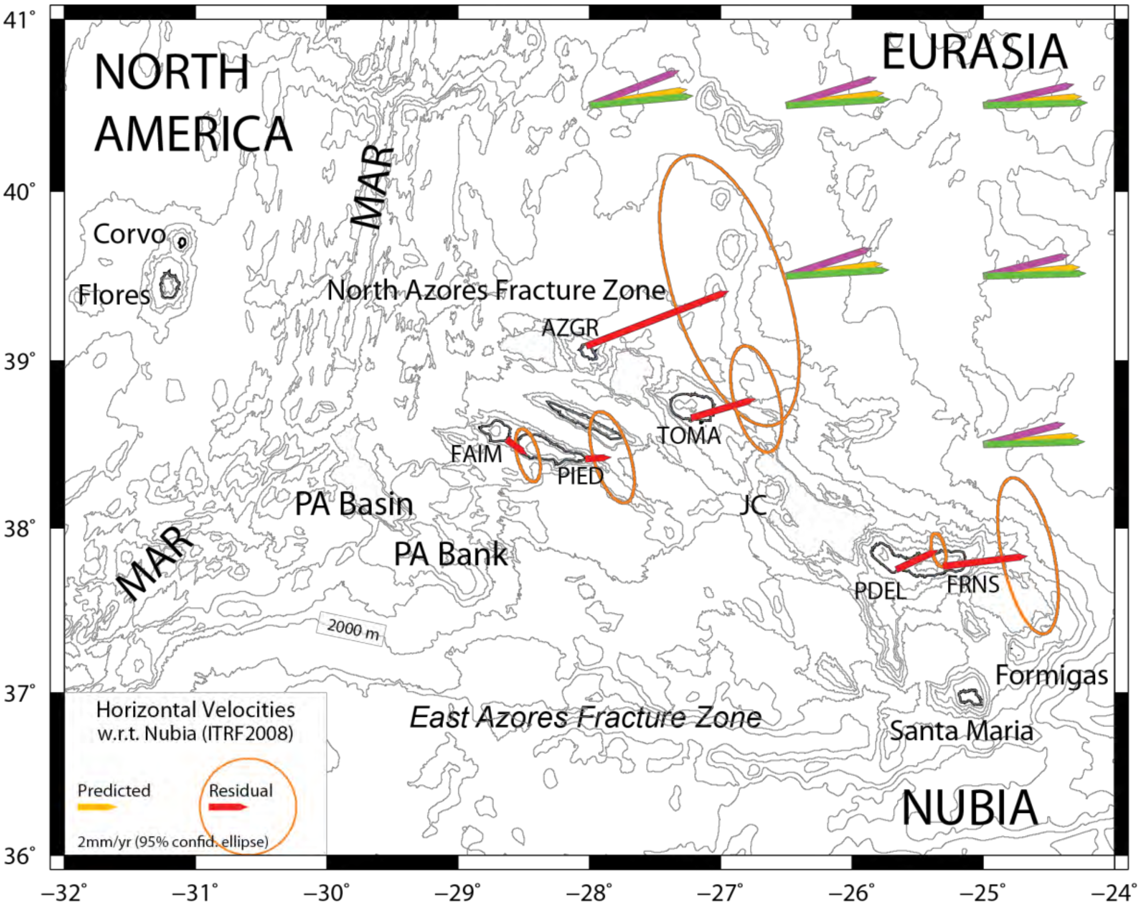

Table 1. Permanent GNSS stations in Azores (see Figure 5 for locations). The only present inactive station is FAIM.

SITE	Starting Date	Final Date	Years	Total Days	Island	Network
PDEL	01-02-2000	23-11-2011	11.8	4067	S. Miguel	IGS
FAIM	05-10-2000	19-07-2010	9.8	2259	Faial	IDL
TOMA	02-10-2001	26-04-2010	8.6	1479	Terceira	IDL
PIED	27-07-2006	23-11-2011	5.3	957	Pico	REPRAA
FRNS	15-07-2007	23-11-2011	4.2	855	S. Miguel	REPRAA
FLRS	14-07-2008	23-11-2011	3.4	852	Flores	IGS
TERC	14-12-2008	21-11-2011	2.9	689	Terceira	REPRAA
AZGR	14-01-2009	22-11-2011	2.9	859	Graciosa	REPRAA
VFDC	26-03-2010	22-11-2011	1.7	511	S. Miguel	REPRAA
PTRP	19-05-2010	22-11-2011	1.5	247	Pico	REPRAA