The Contribution of Space-Geodetic Techniques to the Understanding of the Present-Day Geodynamics of the Azores Triple Junction

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Abstract

Since the last few decades, Space-Geodetic techniques have provided new observations and understanding of many geodynamics processes. They offer an accuracy in position and spatial coverage that was not available using classical methodologies. Even in regions like the Azores Triple Junction, where the tectonic plates of North America, Eurasia and Nubia meet and that is mostly covered by the ocean, the use of Global Navigation Satellite Systems (GNSS) and Interferometry Synthetic Aperture Radar (InSAR) has undoubtfully contributed to a better understanding of the tectonic and volcanic processes. This chapter focuses on the major contributions obtained with Space-Geodesy in the Azores through a review of results published by different authors that have been

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actively working in this region since the late eighties. In fact, the first efforts to accurately measure relative crustal deformations between the different islands of the Azores Archipelago date back to 1988, when a network of nine markers (one per island) was observed using the Global Positioning System (GPS). Since then, several networks of GNSS points have been installed and regularly reoccupied in the islands by different research groups, in particular in the Central Group (Graciosa, Terceira, São Jorge, Pico, and Faial) and São Miguel, where the geodynamic processes of this triple junction manifest themselves through recurrent episodes of seismic and volcanic activity. Additionally, and starting in 1999 (Ponta Delgada), continuously operating GNSS (cGNSS) stations have been installed in almost all islands which permits today permanent monitoring even if the existing coverage is still not optimal. The initial results provided by GNSS studies focused on the understanding of the large-scale processes taking place in Azores by modelling inter-island displacements constrained by estimated angular velocities of the three tectonic plates. More recently, using the denser networks installed, several works have been concentrated on intra-island deformations due to tectonic but also volcanic activity. We also discuss recent results published using InSAR data. This technique has been

successful applied worldwide for volcanic studies and Azores is no exception. Several works have been published providing relevant information for the understanding of the tectonic dynamics that are taking place at the different islands of the Archipelago.

1 Introduction

GNSS is the most commonly used space-geodetic technique to study geodynamic processes since the early 1990s but it was not the first one. Very Long Baseline Interferometry (VLBI) was the first space-geodetic technique that could estimate distances between stations with sub-centimetre accuracy (e.g., Ryan and Ma 1998). Another space-geodetic technique that has been available since the 1970s is Satellite Laser Ranging (SLR), based on measuring the travel time of a light pulse reflected by a satellite (Degnan 1993).

SLR and VLBI were the first spatial-geodetic techniques contributing to quantify the kinematics of the tectonic plates on a global scale. Dedicated campaigns using mobile VLBI and SLR systems were made during the 1980's decade in some regions of the world with more significant tectonic activity (e.g., Vermaat et al. 1998). In addition, these techniques are also fundamental to materialize the International Terrestrial Reference System (ITRS) since VLBI is able to provide accurate scale and SLR has an important role in the determination of the Earth's geocenter. However, both techniques lack portability, have high costs, and they require complex operational procedures. Consequently, the global distribution of both techniques, VLBI (International VLBI Service for Geodesy and Astrometry—http://ivscc.gsfc.nasa.gov) and SLR (International Laser Ranging Service—http://ilrs.gsfc.nasa.gov) suffer from a bias towards the northern hemisphere (e.g., Bastos et al. 2010).

VLBI and SLR observations were carried out in Azores in the early 1990's. However, the short data-span of the observations did not permit to obtain robust velocities for these stations and they never have been published. The situation might change in the near future with the installation of two VLBI 2010 stations in Santa Maria and Flores in the framework of RAEGE project (RAEGE 2013).

The dissemination of space-geodetic techniques for geodynamic studies occurred in the early eighties with the advent of the GNSS, in particular GPS. The scientific community promptly started to develop and use GPS observations in geodynamic applications since it was able to provide similar, or even better accuracies, as the previously mentioned techniques with a fraction of the (financial and logistics) costs.

Actually, although other GNSS systems are being implemented (e.g., GLONASS), GPS is still the most commonly used space-geodetic technique for geodynamic studies. The interested reader has available immense literature of the principles of the GPS technique (e.g., Hoffman-Wellenhof et al. 1997). Specific reviews on the application of GPS for geodynamics, in particular requirements, technical issues, and developments, can also be consulted in Bastos et al. (2010) and references listed therein.

The other technique discussed in this chapter is the SAR interferometry. It is currently the only geodetic system capable of mapping the deformation (associated with earthquakes, volcanoes, mass movements, or the movement of large ice masses or glaciers.) of vast areas of the Earth's surface with spatial continuity and high accuracy.

The first significant result of the application of differential SAR interferometry was the surface deformation map associated with the 1992 Landers Earthquake presented by Massonnet et al. (1993). It was shown for the first time that the displacement of the surface with centimetre accuracy could be quantified over a wide area using pairs of SAR images and a reference terrain model. Since then, this technique has been applied in many regions to map the deformation caused by major earthquakes: Landers in 1992 (Zebker et al. 1994; Price and Sandwell 1998); Izmit in 1999 (Delouis et al. 2000; Sarti et al. 2000);

Hector Mine in 1999 (Fialko et al. 2001; Zeng 2001) or more recently, Tohoku-Oki in 2011 (Kobayashi et al. 2011; Feng et al. 2012).

The monitoring of volcanic surface deformations using SAR interferometry also dates back to the early stages of this technique with studies focused on active volcanoes like Etna (Massonnet et al. 1995) and Kilauea, Hawaii (Rosen et al. 1996). The use of SAR interferometry for volcanic observing has been also continuously developed with the introduction of the new approaches (e.g., Persistent Scatterers—Hooper et al. 2004).

This chapter presents the current status of the geodetic results in Azores concerning the determination of the present-day plate boundary both at archipelago and island scales (Sect. 2). Afterwards, we discuss in detail the published results focused on São Miguel where dedicated GNSS networks to monitor volcanic deformation has been installed (Sect. 3). Finally, we present the efforts to use SAR interferometry in Azores to detect surface displacements due to earthquake and volcanic activities (Sect. 4).

2 Present-Day Geodynamics of Azores Using GNSS Data

The use of precise space-geodetic techniques to study the present-day displacement field associated with the Azores Triple Junction started in 1988 with the Trans-Atlantic Network for Geodynamics and Oceanography (TANGO) project (Bastos et al. 1998). The initial network consisted of one station per island (cf. Fig. 1) that were re-occupied with an approximate triennial periodicity until 1997.

The TANGO network was densified with new 27 stations in 1999 and 30 stations in 2001, distributed over the islands of the so-called Central group (Terceira, Graciosa, São Jorge, Pico and Faial) in the framework of three projects: Extended-TANGO (Fernandes 2004), STAMINA (Navarro et al. 2003, 2009) and SARAZORES (Catita et al. 2005). This network continued to be re-observed in the framework of several follow-up projects, in particular KARMA (Catalão et al. 2010) and KINEMA (Fernandes et al. 2011).

Fig. 1 Episodic GPS sites installed in the framework of several projects: TANGO (black circles), Extended-TANGO (white triangles), STAMINA and SARAZORES (black squares)
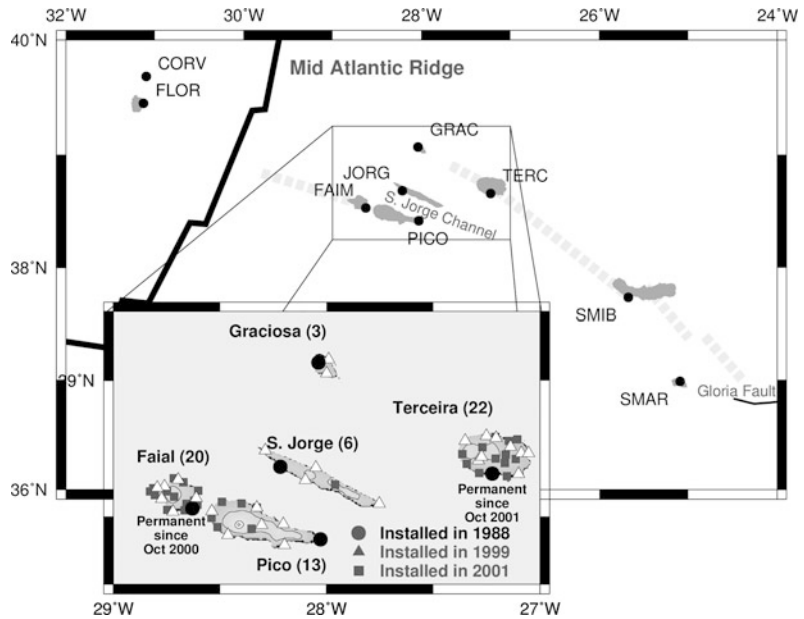
Fig. 2 Horizontal Displacement field—opening rates (represented by the contour lines and background colors; in mm/yr) with respect to the location of the fault segments (red lines) used for elastic modelling presented at Fernandes et al. (2006)
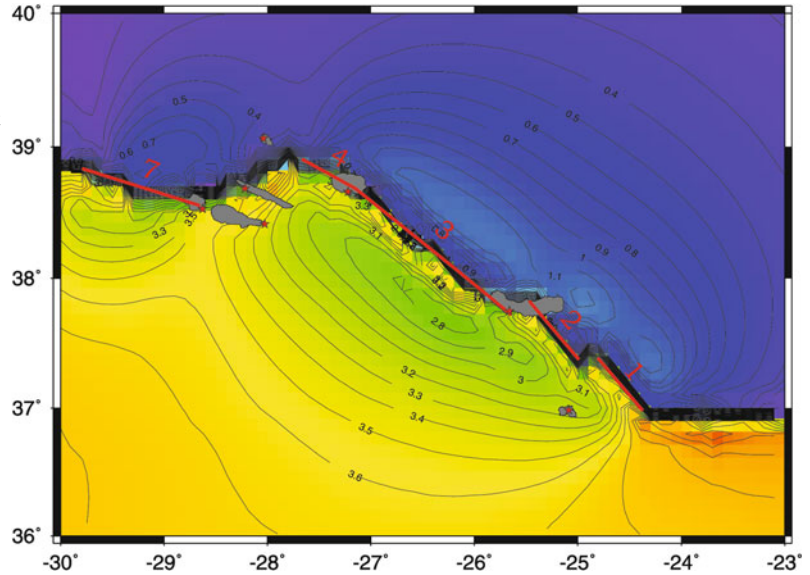
Figure 1 does not depict all episodic stations installed in Azores in the last 15 years. Mendes et al. (2013) refer a network of 59 episodic stations installed in the islands of Faial, Pico, and São Jorge in the framework of the DISPLAZOR project in 2001 that were re-observed three times until 2011.

Furthermore, the geodetic group of Instituto de Investigação em Vulcanologia e Avaliação de Riscos (IVAR), called CVARG before 2017, also installed other GNSS episodic networks during the last decade. Whenever possible, new markers were installed on rocky stable substratum, such as lava flows. However, due to the difficulty to find proper locations, some of the IVAR networks made also use of local geodetic public markers (Trota 2009).

Most of these stations (some were lost over the years) have now a data-span of more than a decade with up to 8 occupations. Fernandes et al. (2004, 2006) analyzed the 9 initial stations (forming the original TANGO network, cf. Fig. 1), corresponding to the period 1993–2000 and 1993–2001, respectively. They conclude that the islands in the Eastern and Central groups present velocities between pure Eurasian (Graciosa) and pure Nubian (Santa Maria) behaviour. The major result of these works was to favor a model (cf. Fig. 2) where two major spreading axes, an eastern one running from western edge of Gloria fault to northwestern of Terceira, indicated by numbers 1–4, and a western one from Faial to the Mid-Atlantic Ridge, number 7 in Fig. 2, were defining the active Nubia-Eurasia plate boundary. Such model was based on an elastic half-space approach with a locking depth of 8 km (Fernandes et al. 2006).

Concerning the present-day intra-island deformations, despite the number of existing stations, robust conclusions are still difficult to draw due to the uncertainties of the used data sets and the small amount of differential displacements expected at each island. This is evident on the velocity solutions (estimated and predicted) shown in Fig. 3. It presents the horizontal motions (w.r.t. ITRF2008) for the episodic stations with more than 6 years of observations (cf. all markers shown in Fig. 1) for a transect from Faial/Pico through São Jorge until Terceira. The solutions presented in Fig. 3, computed using GIPSY-OASIS software package, differ from the solutions presented in Fernandes et al. (2006) by using upgraded models and procedures (e.g., Fernandes et al. 2013) and by including additional observations for some few points carried out in 2010.

Several plate angular velocity models are used here in order to present the variation of predicted
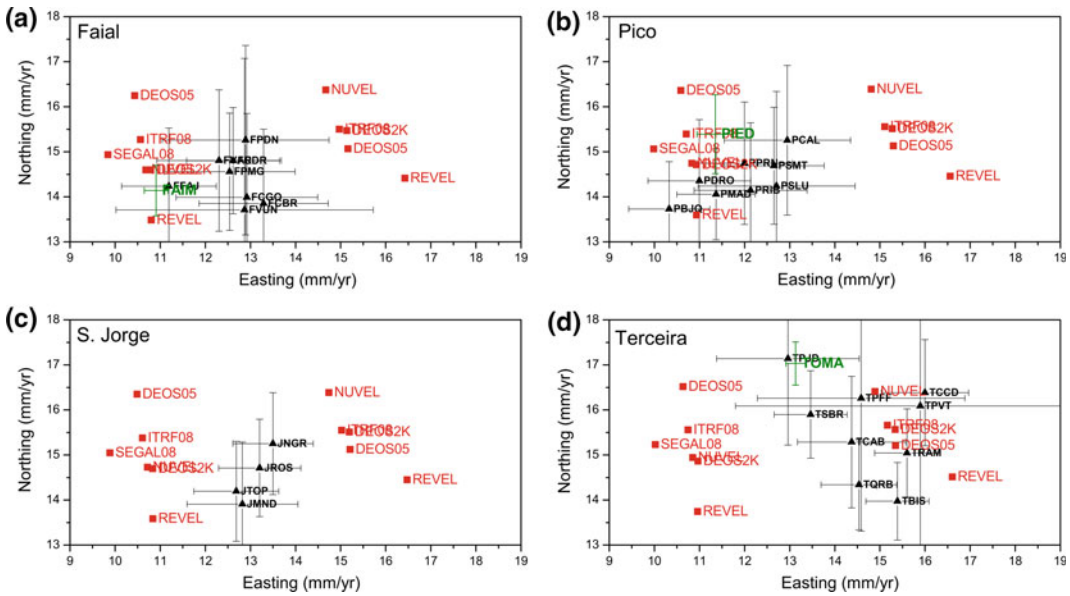
Fig. 3 Observed (black—campaign; green—permanent) and predicted (red) motions for Faial, Pico, São Jorge and Terceira with 95% uncertainty error bars. The predicted motions by different models for Nubia (left) and Eurasia (right) are relative to a point in the middle of each island

velocities for Nubia and Eurasia based on different models: NUVEL-1A (DeMets et al. 1994), REVEL (Sella et al. 2002), DEOS2k (Fernandes et al. 2003), DEOS05 (re-computation with respect to ITRF2005 of the data used in Fernandes et al. 2006), ITRF2008 (Altamimi et al. 2011), and SEGAL08 (Fernandes et al. 2013). In this respect, it is possible to conclude that the uncertainty of these models is nowadays of few mm/yr for both plates in the Azores region since the estimates given by the most recent angular velocity plate models tends to be similar.

The analysis of Figs. 2 and 3 permits to conclude that Graciosa appears to be situated on the Eurasia plate while Santa Maria is on the Nubia plate. All other stations in the Central and East groups appear to be in the deformation region with Faial/Pico closer to Nubia and Terceira closer to Eurasia (cf. Fig. 3).

As observed, the uncertainties of the estimated velocities are still too large to compute robust deformation models at intra-island level. Nevertheless, several intra-island studies have been published in recent years. The research

focused in São Miguel, mainly evaluating local volcanic processes, are discussed in the next section. In the Central Group, the majority of the studies focused on kinematic models and derived strain partition. Miranda et al. (2012) analysed 17 stations in Terceira to corroborate the initial results presented by Navarro et al. (2003) that point for lateral compression due to the Terceira Rift. However, the authors were cautious since the rate of strain field obtained after the removal of the rigid-body motion was of the same magnitude as the 95% confidence ellipses concerning the horizontal components. More interestingly, the estimated average rates were close to 10 mm/yr of subsidence for most of the island, which was attributed to the volcanic processes that shaped the Serreta Ridge, NW of Terceira. In this respect, the results presented by Catalão et al. (2010) based on the network installed in Faial and Pico indicate that that some stations were subsiding by 9 mm/yr in those islands. Trota (2009) and Trota et al. (2010) obtained subsidence rates in the order of 10 mm/yr for the period 2000–2007 in Terceira Island and for

western part of São Miguel Island, which were independently confirmed in São Miguel by tide-gauge data.

Finally, Mendes et al. (2013) presented results for São Jorge Island based on the analysis of the 2001, 2004, and 2010 GNSS campaigns, which recorded data on 17 stations. Surface velocities estimated at 15 inland locations were interpreted as deformation related to local sub-surficial magmatic/volcanic processes occurring near the island. The authors point out that the intra-island deformation may also be related to the stress field and seafloor spreading occurring in an area situated on the western sector of the Azores Plateau.

cGNSS stations have several advantages when compared with episodic networks: they are much less prone to suffer errors related to installation procedures (normally, only faulty equipment is replaced) and they can sense other signals, in particular seasonal signals, that are not detected or modelled in episodic time-series. In fact, the only limitation of cGNSS when compared with episodic stations is the costs associated with installation and maintenance. Such constraint prevented the fast development of cGNSS network in Azores. Nevertheless, the situation has been continuously improving since the installation of the first cGNSS in Ponta Delgada in 1999. At the time of writing this chapter, only Santa Maria and Corvo still do not have any cGNSS station providing public data to the community (a new station in Santa Maria is planned). The public network of cGNSS stations in Azores is managed by the Regional Government (REPRAA 2013). Although the major goal of this network is to serve technical geo-referencing activities, the highest requirements applied to the monuments permit their use also for geodynamic studies in the region. Currently two stations (PDEL and FLRS, on São Miguel and Flores islands, respectively) are part of the global IGS (International GNSS Service) permanent network (RAEGE 2013). Additionally, and with the specific purpose of geo-hazards monitoring, in particular volcano monitoring, several stations were installed by CVARG. This network

presently has 10 cGNSS stations distributed at São Miguel (5), Terceira (2), and Pico (3), respectively.

Most of the cGNSS stations in Azores are relatively recent (2010 onwards). Consequently, their time-series are still too short to derive robust velocity estimates. Until the present, few results have been published based on these stations with the exception of Ponta Delgada station and of two stations installed in previous TANGO markers (FAIM and TOMA) that were operational during the last decade.

Figure 4 shows recent results published by Miranda et al. (2015) using only cGNSS stations. Residual velocities are plotted with respect to stable Nubia (according to SEGAL08, Fernandes et al. 2013). For comparison, Fig. 4 also shows the predicted relative motions for points in the stable Eurasia using SEGAL08 (published in Miranda et al. 2015), GEODVEL (Argus et al. 2010) and MORVEL (DeMets et al. 2010) models. The authors conclude, based on magnetic and this geodetic data, that most of the extension takes place today within the Terceira Rift (cf. Fig. 1) and that São Miguel Island shows significant intra-island extension.

3 Volcanic Studies in Azores Using Geodetic Data

During the last decades, several geodetic and surveying techniques were used to study, monitor and supervise volcanoes around the world. Volcanologists use several observation techniques from inexpensive simple tape measurements on fracture openings to high precision extensometer continuous measurements. However, due to several factors (e.g. harsh landscape, soil use, access, political reasons, price, logistics, precision of technique and deformation rate of the area under study) only some of them can be applied successfully. In Azores, studies aiming at ground deformation due to volcanic activity commonly use the GNSS technique.

The first application of the GNSS technique devoted to volcanic deformation studies was
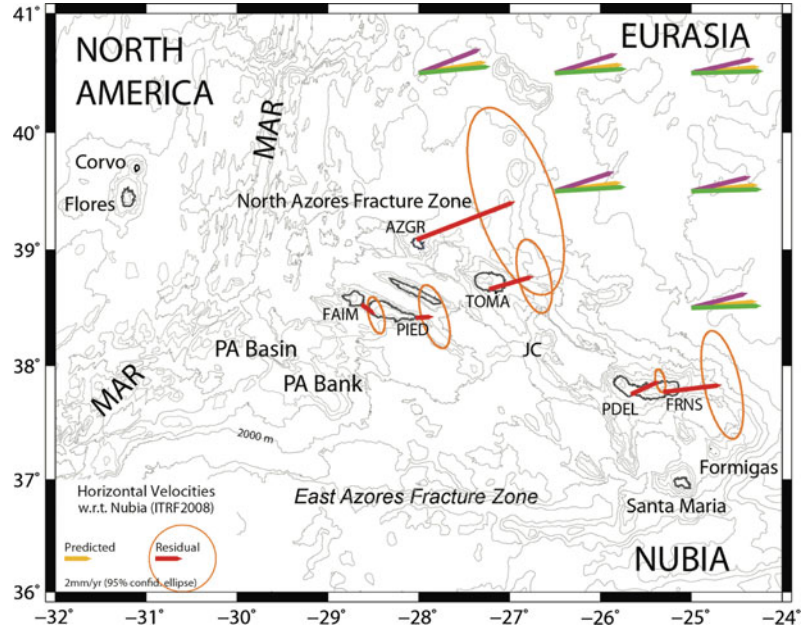
used at Furnas volcano (in the scope of the European Laboratory Volcanoes, International Decade for Natural Disaster Reduction) on São Miguel. During this experiment, other geodetic techniques were also applied as precise optical levelling (lake, dry tilt, and profile levelling; Sigmundsson et al. 1995; Jónsson et al. 1999). Based on a network of 16 sites, distributed mainly at Furnas volcano and some at Fogo volcano, and three additional surveys carried out in 1993, 1994, and 1997, Jónsson et al. (1999) were able to measure slowly progressing ground deformation of Furnas volcano. Despite the small time interval for the data set and the low deformation rate the authors hypothesized that a source of inflation was located northwest of Furnas caldera or, alternatively, that a combination of two processes is responsible for the observed deformation pattern; i.e. plate divergence between the Eurasian and African plates together with a deflation of the Furnas caldera. Most of the markers used in this study were later on used in other GNSS surveys (e.g., Trota et al. 2006).

From 1999 on, the network installed in the framework of the Furnas Project were augmented to cover all São Miguel Island, and densified in

some zones, e.g., in the Fogo Congro area in central São Miguel Island (Trota 2003). Most markers were installed as episodic stations although some are capable (in terms of ancillary systems and security) to be converted into cGNSS stations.

Based on a GNSS data set obtained from 1999 to 2007 an important and complex deformation period was determined in the Fogo Congro area (Trota 2009). The observed deformation (cf. Fig. 5) is now being interpreted as consequence of a basaltic magma intrusion episode, updating the results presented by Trota (2009), who considered them a possible consequence of trachytic magma injection or siliceous magma body intrusion. This new conclusion is based on an updated inversion of the GNSS data for spherical-like and prolate spheroid pressure sources along with reinterpretation of geological, seismic and geochemical results (Trota et al. 2015). The volcanic unrest that took place between 2000 and 2007 in the northeast flank of Fogo stratovolcano was characterized by three different main deformation phases of inflation and deflation process. The maximum surface ground deformation, which was recorded in September 2005, was concomitant with the
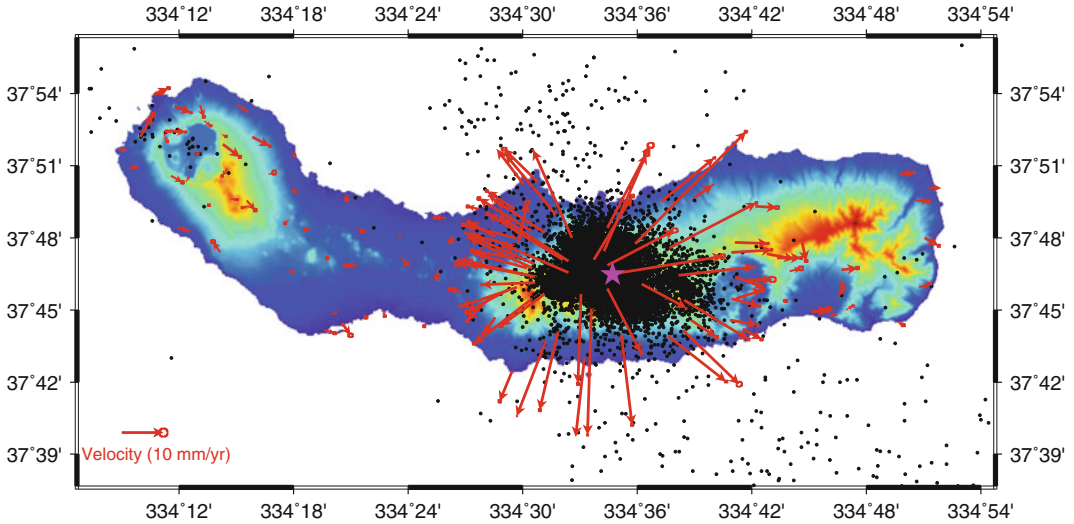
Fig. 5 Representation of the horizontal velocity field (red arrows) for the period 1999–2007 for the Fogo/São Brás/Congro area, São Miguel Island, interpreted as probable basaltic magma intrusion (Trota et al. 2015). The map also shows all the seismic events for the analyzed period, along with plot of location of the modelled deformation centre. The map shows a strong concentration of events plots enclosing the deformation centre (extracted from Trota 2009)

maximum seismic energy released. The new inversion of GNSS data is showing a north-eastward moving source from Fogo lake to São Brás lagune. The pressure source migrated from an initial depth around 3.9 to 2.3 km and then inward moving to 6.1 km, provides indication of a moving pressure source along a probable fault zone trending SW–NE. This trend coincides with local old volcanic vent alignments (craters and cones). The pressure source model volume change was estimated as 0.018 km^3. This volume, estimated for the Phase III of the event (Trota 2009) is one order of magnitude lower than the products emitted by the AD 1563 eruption in Fogo volcano, explaining why the basaltic mass flow intrusion did not turn into an eruption (Trota et al. 2015).

The data obtained in campaign style markers networks installed in one of the most active volcanic systems in Azores along with the cGNSS stations are allowing for a comprehensive investigation of the active volcanoes in Azores and are contributing to a better understanding of the interplay between tectonics and volcanic activity. The large region to monitor, the type of intrusions and eruption styles, and the observed low deformation rates creates additional challenges to the geodetic observations in Azores but will contribute to a better understanding of volcanic processes in this region and finally worldwide.

4 InSAR in Azores

Differential SAR interferometry (DInSAR) was used in 1998 Faial (Azores) earthquake to validate the GPS estimated co-seismic fault rupture model parameters (Fernandes et al. 2002; Catita et al. 2005) and used to discriminate between the sinistral NNW–SSE and the dextral ENE–WSW fault rupture, along with other complementary data (Marques et al. 2013). The displacement associated with a seismic event provides the limits of the co-seismic fault rupture model and can reveal the relations in the adjacent fault system imposing constraints on its model parameters. Examples are the 1992 Landers and 1999 Hector Mine earthquakes in the south of California and 1999 Izmit, Turkey in which

DInSAR has revealed the interaction between the fault rupture and adjacent fault systems.

In the case of the 1998 Faial (Azores) earthquake (Senos et al. 1998), the epicentre was offshore, preventing the imaging of the fault rupture with INSAR or GPS measurements. However, the seismic waves were strongly felt in the northeast Faial causing 8 casualties. Catita et al. (2005) applied the differential InSAR technique to ERS data, acquired between 1992 and 2000, to analyse surface deformation produced by the 9 July 1998 earthquake. Twelve co-seismic interferograms were produced from a small set of 17 ERS images in descending mode, evenly distributed in time (only four SAR images after the earthquake). Even under such limited conditions (temporal and geometric decorrelation) the authors managed to achieve fringe patterns with approximately 3 cm of range change between 1992 and 1998. Although correlation decreases in most areas, the fringe pattern is legible on the NW part of Pico Island.

The fringe pattern detected on the NW of Pico is closely related to the synthetic model computed from the fault parameters of Fernandes et al. (2002), and the authors concluded that the observed interferometric fringes generally agree with the synthetic models and, therefore, are coherent with the available seismological and GPS data. However, it was not possible to decide which fault was responsible for the earthquake mainly due to unfavourable geometric relation between the line of sight and the displacement directions (perpendicular). Besides, Faial is covered with dense vegetation and forest which cause decorrelation with ERS SAR wavelength (5.2 cm).

The study by Catita et al. (2005) was the first attempt to apply differential InSAR to the evaluation of ground displacement in the Azores archipelago. Results obtained are limited if compared with similar studies developed for most of the well-known volcanic systems. For active volcanoes, InSAR has revealed unexpected phenomena such as the magma movement in Isabela and Fernandina Islands in Galápagos (Amelung et al. 2000; Hooper et al. 2007) or the deflation movements in the Etna, Italy (Massonnet et al. 1995). Early detection based on the InSAR technique of the deformation caused by volcanoes can provide a warning indicator of imminent eruptions reducing the loss of lives and mitigating impacts on properties/assets.

The applications of differential interferometry are limited due to geometrical and temporal decorrelation. The first is due to the different acquisition geometries in repeated track interferometry and the second due to variation in the backscattering in the time interval between acquisitions. In the case of Azores, where most of the islands are highly vegetated and with very variable weather conditions, InSAR is limited by several sources of decorrelation (water vapour variability or changes of backscatter characteristics with time, etc.). To overcome these limitations, Ferretti et al. (2001) propose a new technique, the *Permanent Scatterers technique, PS,* (registered trademark). The technique allows the analysis of time series of interferograms of a set of points (pixels) with phase stability in time. The technique was applied in the Azores by Catalão et al. (2010) and Cong et al. (2010) to measure the internal deformation of Faial and Pico Islands and São Miguel Islands, respectively. In the case of São Miguel, the authors have complemented the set of PS with two corner reflectors (CR) installed on Lagoa do Fogo, the summit lake of Fogo volcano. The CRs ensure stability of the signal over a long period of time. A set of SAR stripmap images from TerraSAR-X satellite was used in this study. The authors pointed out the difficulties in the use of CR in Azores, mostly due to extreme weather conditions causing damage or orientation change on the CR.

The episodic stations installed in the framework of several projects in Faial and Pico (cf. Fig. 1), in particular the markers installed by the SARAZORES project (Catita et al. 2005), were used to study the vertical deformation on these islands. Most of the geodetic marks were surveyed 4 times since 2001 until 2013 (Marques et al. 2014). The results point to a time consistent and spatial coherent deformation rate between most of the points. Nonetheless, the GPS network is only the expression of a spatial sampling

of the surface deformation and better spatial coverage is required. For that, a set of ASAR (Advanced SAR, on board of the ENVISAT satellite) images (ascending and descending passes), acquired between 2006 and 2009, were interferometrically processed and the line-of-sight deformation was derived using the Persistent Scatterers approach (Hooper et al. 2004). Because of different geometry acquisitions, ascending and descending passes produce different sets of Persistent Scatterers, with complementary spatial coverage, and different line-of-sight velocities. Besides, the estimated velocities are relative to the master image (different from ascending and descending) and must be referred to an absolute velocity (in the sense of referred to a geodetic reference frame). The strategy proposed by the authors to overcome aforementioned problems was based on the combination of sparse GPS 3D-velocities with two sets of Persistent Scatterers determined from ascending and descending passes.

The result of the integration of both ascending and descending persistent scatterers with GPS velocity data, is shown in Fig. 6 (Catalão et al. 2011). A large subsiding area on the west of Pico in the Madalena area can be identified, corresponding mostly to creep movement and the subsidence of the summit crater of Pico Island. On the west of Faial, on the flank of Capelinhos eruption, a large continuous area of subsidence is

observed. The integrated geodetic approach, by merging GPS and PS-InSAR velocities, allowed the authors to draw several conclusions: (a) Faial, as a whole, behaves like a rigid body whose absolute motion is similar to Nubia motion (Marques et al. 2013); (b) intra-island deformation, given by the estimated strain rates, reveals north-south areal contraction at the western part of the island (Catita 2005); (c) the north-western flank of western Faial is subsiding, with a maximum subsidence rate of 89 mm/yr (Catalão et al. 2010); (d) The subsidence of the north west Faial or related with Capelinhos eruption, due to magma cooling and migration at depth and may be precursor of large-scale mass wasting events (Catalão et al. 2006).

Large scale mass wasting has been reported by Hildenbrand et al. (2012) for Pico Island. Due to its steep topography, Pico is particularly sensitive to flank instability. The southern flank of the ridge close to Lajes village shows several curved structures concave toward the ocean, previously interpreted as reflecting early caldera development, faulting or ancient lateral collapse(s). Hildenbrand et al. (2012) show from high-resolution digital elevation model (DEM), fieldwork, GPS and InSAR data that part of the flank in the analysed period (2001–2006) displacing toward the ocean, accommodated by the motion of large blocks that may eventually detach and have catastrophic consequences.
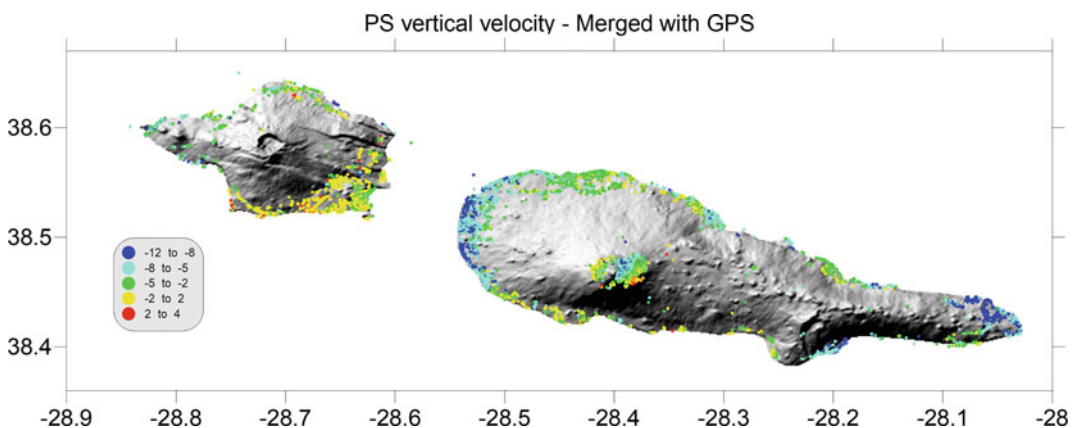
Fig. 6 Vertical velocity map resulting from the integration of ascending and descending PS and GPS data. The velocity is shown in mm/yr (Catalão et al. 2010)

SAR interferometry has shown great potential in measuring surface deformation with ability to map natural (tectonic, volcanic) and anthropogenic processes with particular focus on uplift/subsidence, due to its acquisition geometry. As already mentioned, this technique is strongly limited in the Azores by the density of vegetation with severe effects on the coherence of interferograms and the consequent reduction of the precision of the measurement phase. Nevertheless, the evolution of SAR sensors with higher spatial resolution, continuous SAR imaging of the earth surface by the new ESA Sentinel-1, JAXA ALOS2 and NASA DESDynI missions, as well as the ongoing evolution of algorithms for image processing are foreseen to improve the reliability and accuracy of the InSAR results even in such in such highly vegetated place as the Azores.

References

Altamimi, Z., Collilieux, X., & Métivier, L. (2011). ITRF2008: An improved solution of the international terrestrial reference frame. *Journal of Geodesy, 85*(8), 457–473. https://doi.org/10.1007/s00190-011-0444-4.

Amelung, F., Jónsson, S., Zebker, H., & Segall, P. (2000). Widespread uplift and trap door faulting on Galapagos volcanoes. *Nature, 407*(993–996), 2000.

Argus, D. F., Gordon, R. G., Heflin, M. B., Ma, C., Eanes, R. J., Willis, P., et al. (2010). The angular velocities of the plates and the velocity of Earth's center from space geodesy. *Geophysical Journal International, 180,* 913–960. https://doi.org/10.1111/j.1365-246X.2009.04463.x.

Bastos, L., Bos, M. S., & Fernandes, R. M. S. (2010). Deformation and tectonics: Contribution of GPS measurements to plate tectonics—Overview and recent developments. In G. Xu (Ed.), *Sciences of geodesy—I, advances and future directions* (pp. 155–184). Heidelberg: Springer.

Bastos, L., Osório, J., Barbeito, A., & Hein, G. (1998). Results from geodetic measurements in the western part of the African-Eurasian plate boundary. *Tectonophysics, 294,* 261–269.

Catalão, J., Miranda, J. M., & Lourenço, N. (2006). Deformation associated with the Faial (Capelinhos) 1957–1958 eruption: Inferences from 1937–1997 geodetic measurements. *Journal of Volcanology and Geothermal Research, 155,* 151–163.

Catalão, J., Nico, G., Hanssen, R., & Catita, C. (2010). Integration of InSAR and GPS for vertical deformation monitoring: A case study in Faial and Pico

Islands. FRINGE 2009—Advances in the science and applications of SAR interferometry. ESA ESRIN, 30th November–4th December 2009, Frascati, Italy. ESA as Special Publication SP-677.

Catalão, J., Nico, G., Hanssen, R., & Catita, C. (2011). Merging GPS and atmospherically corrected InSAR data to map 3D terrain displacement velocity. *IEEE Transactions on Geoscience and Remote Sensing, 49* (6), Part: 2, https://doi.org/10.1109/tgrs.2010.2091963.

Catita, C., Feigl, K. L., Catalão, J., Miranda, J. M., & Victor, L. M. (2005, July 10). Time series analysis of SAR data applied to the study of the co-seismic deformation of the 9th July 1998 Pico-Faial (Azores) earthquake. *International Journal of Remote Sensing, 26*(13), 2715–2729.

Cong, X., Minet, C., & Eineder, M. (2010). Deformation monitoring using Sar interferometry on the Azores within Exupéry Project, Proceedings of 'Fringe 2009 Workshop', Frascati, Italy, 30 November–4 December 2009 (Esa Sp-677, March 2010).

Degnan, J. J. (1993). Millimeter accuracy satellite laser ranging: A review. In D. E. Smith & D. L. Turcotte (Eds.), *Contributions of Space Geodesy to Geodynamics: Technology*, Washington, D. C.: American Geophysical Union. https://doi.org/10.1029/gd025p0133.

Delouis, B., Lundgren, P., Salichon, J., et al. (2000). Joint inversion of InSAR and teleseismic data for the slip history of the 1999 Izmit (Turkey) earthquake. *Geophysical Research Letters, 27*(20), 3389–3392. https://doi.org/10.1029/2000gl011511.

DeMets, D. C., Gordon, R. G., & Argus, D. F. (2010). Geologically recent plate motions. *Geophysical Journal International, 181,* 1–80. https://doi.org/10.1111/j.1365-246X.2010.04491.x.

DeMets, C., Gordon, R. G., Argus, D. F., & Stein, S. (1994). Effect of recent revisions to the geomagnetic reversal timescale on estimates of current plate motions. *Geophysical Research Letters, 21*(20), 2191.

Feng, G., Ding, X., Li, Z., et al. (2012). Calibration of an InSAR-derived coseimic deformation map associated with the 2011 Mw-9.0 Tohoku-Oki earthquake. *IEEE Geoscience and Remote Sensing Letters, 9*(2), 302–306. https://doi.org/10.1109/lgrs.2011.2168191.

Fernandes, R. M. S. (2004). *Present-day kinematics at the Azores-Gibraltar plate boundary as derived from GPS observations*. Delft: DUP. ISBN 90-407-2557-8.

Fernandes, R. M. S., Ambrosius, B. A. C., Noomen, R., Bastos, L., Wortel, M. J. R., Spakman, W., et al. (2003). The relative motion between Africa and Eurasia as derived from ITRF2000 and GPS data. *Geophysical Reseach Letters, 30*(16), 1828. https://doi.org/10.1029/2003GL017089.

Fernandes, R. M. S., Bastos, L., Ambrosius, B. A. C., Noomen, R., Matheussen, S., & Baptista, P. (2004). Recent geodetic results in the Azores Triple Junction region. *Pure and Applied Geophysics, 161*(3), 683–699. https://doi.org/10.1007/s00024-003-2469-y.

Fernandes, R. M. S., Bastos, L., Miranda, J. M., Lourenço, N., Ambrosius, B. A. C., Noomen, R.,

et al. (2006). Defining the Plate Boundaries in the Azores Region. *Journal of Volcanology and Geothermal Research, 156,* 1–9. https://doi.org/10.1016/j.jvolgeores.2006.03.0192006.

Fernandes, R. M. S., Miranda, J. M., Catalão, J., Luis, J. F., Bastos, L., & Ambrosius, B. A. C. (2002). Coseismic displacements of the M_w = 6.1, July 9, 1998, Faial earthquake (Azores, North Atlantic). *Geophysical Research Letters, 29*(16), 21-1, 21-4. https://doi.org/10.1029/2001gl014415.

Fernandes, R. M. S., Miranda, J. M., Delvaux, D., Stamps, D. S., & Saria, E. (2013). Re-evaluation of the kinematics of Victoria Block using continuous GNSS data. *Geophysical Journal International, 193,* 1–10. https://doi.org/10.1093/gji/ggs071.

Fernandes, R. M., Miranda, J. M., & Luis, J. M. (2011). Strain Distribution across the Terceira (Azores) Rift from 13 years of GPS data. *AGU Fall Meeting Abstracts, 1,* 0839.

Ferretti, A., Prati, C., & Rocca, F. (2001). Permanent scatterers in SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing, 39*(1).

Fialko, Y., Simons, M., & Agnew, D. (2001). The complete (3-D) surface displacement field in the epicentral area of the 1999 M(w)7.1 Hector Mine earthquake, California, from space geodetic observations. *Geophysical Research Letters, 28*(16), 3063–3066. https://doi.org/10.1029/2001gl013174.

Hildenbrand, A., Ornelas, F., Catalão, J., Catita, C., & Costa, C. (2012, October). Large-scale active slump of the southeastern flank of Pico Island, Azores. *Geology, 40,* 939–942 (First published on August 9, 2012). https://doi.org/10.1130/g33303.1.

Hoffman-Wellenhof, B., Lichteneger, H., & Collins, J. (1997). *Global positioning system: Theory and practice* (4th ed.). Berlin: Springer.

Hooper, A., Segall, P., & Zebker, H. (2007). Persistent scatterer InSAR for crustal deformation analysis, with application to Volcán Alcedo, Galápagos. *Journal of Geophysical Research, 112,* B07407. https://doi.org/10.1029/2006JB004763.

Hooper, A., Zebker, H., Segall, P., & Kampes, B. (2004). A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers. *Geophysical Reseach Letters, 31,* L23611. https://doi.org/10.1029/2004GL021737.

Jónsson, S., Alves, M. M., & Sigmundsson, F. (1999). Low rates of deformation of the Furnas Volcanoes, São Miguel, Azores, observed with the Global Positioning System, 1993–1997. *Journal of Volcanology and Geothermal Research, 92,* 83–94.

Kobayashi, T., Tobita, M., Nishimura, T., et al. (2011). Crustal deformation map for the 2011 off the Pacific coast of Tohoku Earthquake, detected by InSAR analysis combined with GEONET data. *Earth Planets and Space, 63*(7), 621–625 https://doi.org/10.5047/eps.2011.06.043.

Marques, F. O., Catalão, J., DeMets, C., Costa, A. C. G., & Hildenbrand, A. (2013). GPS and tectonic evidence for a diffuse plate boundary at the Azores triple

Junction. *Earth and Planetary Science Letters, 381,* 177–187.

Marques, F. O., Catalão, J., Hildenbrand, A., Costa, A. C. G., & Dias, N. A. (2014). The 1998 Faial earthquake, Azores: Evidence for a transform fault associated with the Nubia-Eurasia plate boundary? *Tectonophysics, 633*(2014), 115–125. https://doi.org/10.1016/j.tecto.2014.06.024.

Marques, F. O., Catalão, J., Hildenbrand, A., & Madureira, P. (2015). Groundmotion and tectonics in the Terceira Island: Tectonomagmatic interactions in an oceanic rift (Terceira Rift, Azores Triple Junction). *Tectonophysics, 651–652*(2015), 19–34. https://doi.org/10.1016/j.tecto.2015.02.026.

Massonnet, D., Briole, P., & Arnaud, A. (1995). Deflation of Mount Etna monitored by spaceborne radar interferometry. *Nature, 375*(6532), 567–570. https://doi.org/10.1038/375567a0.

Massonnet, D., Rossi, M., Carmona, C., Adragna, F., Peltzer, G., Feigl, K., et al. (1993). The displacement field of the Landers earthquake mapped by radar interferometry. *Nature, 364,* 138–142.

Mendes, V., Madeira, J., Brum da Silveira, A., Trota, A., Elosegui, P., & Pagarete, J. (2013). Present-day deformation in São Jorge Island, Azores, from episodic GPS measurements (2001–2011). *Advances in Space Research, 51*(8), 1581–1592.

Miranda, J. M., Luis, J. F., Fernandes, R. M. S., & Lourenço, N. (2015). The structure of the Azores triple junction: Implications for S. Miguel Island. In *Volcanic Geology of S. Miguel Island (Azores Archipelago)* (Vol. 44), Geological Society, London, Memoirs series.

Miranda, J. M., Navarro, A., Catalão, J., & Fernandes, R. M. S. (2012). Surface displacement field at Terceira Island deduced from repeated GPS measurements. *Journal of Volcanology and Geothermal Research.* https://doi.org/10.1016/j.jvolgeores.2011.10.009.

Navarro, A., Catalão, J., Miranda, J. M., & Fernandes, R. M. S. (2003). Estimation of the Terceira Island (Azores) main strain rates from GPS data. *Earths, Planets and Space, 55,* 637642.

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*(1–4), 98–113.

Price, E. J., & Sandwell, D. T. (1998). Small-scale deformations associated with the 1992 Landers, California, earthquake mapped by synthetic aperture radar interferometry phase gradients. *Journal of Geophysical Research, 103*(B11), 27001–27016. https://doi.org/10.1029/98JB01821.

RAEGE. (2013). http://www.raege.net, viewed September 16, 2013.

REPRAA. (2013). http://www.repraa.azores.gov.pt, viewed September 16, 2013.

Rosen, P. A., Hensley, S., Zebker, H. A., Webb, F. H., & Fielding, E. J. (1996). Surface deformation and

coherence measurements of Kilauea Volcano, Hawaii, from SIR C radar interferometry. *Journal Geophysical Research, 101*(E10), 23109–23126. https://doi.org/10.1029/96JE01459.

Ryan, J. W., & Ma, C. (1998). NASA-GSFC's geodetic VLBI program: a twenty-year retrospective. *Physics and Chemistry of the Earth, 23*(9–10), 1041–1052. https://doi.org/10.1016/S0079-1946(98)00144-X.

Sarti, F., Adragna, F., Pourthie, N. et al. (2000). InSAR analysis of the effects of the Izmit earthquake with ERS data. In R. A. Harris & L. Ouwehand (Eds.), *CEOS SAR* (Vol. 450, pp. 663–669), Toulouse, France, October 26–29, 1999. European Space Agcy; CNES; Comm Earth Observat Satellites. CEOS SAR Workshop, ESA Special Publications.

Sella, G. F., Dixon, T. H., & Mao, A. (2002). REVEL: A model for recent plate velocities from space geodesy. *Journal Geophysical Research, 107*(B4), 2081. https://doi.org/10.1029/2000JB000033.

Senos, M. L., Gaspar, J. L., Cruz, J., Ferreira, T., Nunes, J. C., Pacheco, J. M., et al. (1998). O terramoto do Faial de 9 de Julho de 1998. 1º Simpósio de Materorologia e Geofisica da APMG, Lagos, pp. 61–67.

Sigmundsson, F., Tryggvason, E., Alves, M. M., Alves, J. L., Pálsson, K., & Olafsson, H. (1995). Slow inflation of the Furnas volcano, São Miguel, Azores, suggested from initial levelling and Global Positioning System measurements. *Geophysical Reseach Letters, 22,* 1681–1684.

Trota, A. (2003). "Aplicação da técnica de GPS à monitorização de vulcões activos na ilha de S. Miguel (Açores)." Tese de Mestrado em Vulcanologia e Avaliação de Riscos Geológicos, Departamento de Geociências, Universidade dos Açores, Ponta Delgada, 152p (in Portuguese).

Trota, A. (2009). "Estudos de deformação crustal nas ilhas de S. Miguel e Terceira (Açores). Avaliação da actividade vulcânica na área do Fogo/Confro (S. Miguel)". Tese de doutoramento no ramo de Geologia, especialidade de Geodesia. Universidade dos Açores. 281p (in Portuguese).

Trota, A., Houlié, N., Briole, P., Gaspar, J. L., Sigmundsson, F., & Feigl, K. L. (2006). Deformation studies at Furnas and Sete Cidades Volcanoes (São Miguel Island, Azores). Velocities and further investigations. *Geophysical Journal International, 166*(2), 952–956. https://doi.org/10.1111/j.1365-246X.2006.03039.x.

Trota, A. N., Mendes, V., & Amaral, P. (2010). Subsidência generalizada nas ilhas de São Miguel e Terceira (Açores) detetada por GPS. In Actas da VI conferência nacional de cartografia e geodesia (pp. 330–335), 7 a 8 de maio 2009. Ed. Lidel, Lisboa, Portugal.

Trota, A., Mendes, V. B., Amaral., P., Rodrigues, R., Gaspar, J. L., Houlié, N., et al. (2015). Crustal deformation modelling of the Fogo/S. Brás/Congro volcanic unrest, São Miguel, Azores (in preparation).

Vermaat, E., Degnan, J. J., Dunn, P., Noomen, R., & Sinclair, A. (1998). Satellite laser ranging, status and impact for Wegener. *Journal of Geodynamics, 25,* 195–212. Deformation and Tectonics: Contribution of GPS Measurements to Plate Tectonics—Overview and Recent Developments.

Zebker, H. A., Rosen, P. A., Goldstein, R. M., Gabriel, A., & Werner, C. L. (1994). On the derivation of coseismic displacement fields using differential radar interferometry: The Landers earthquake. *Journal of Geophysical Research, 99,* 19617–19634.

Zeng, Y. H. (2001). Viscoelastic stress-triggering of the 1999 Hector Mine earthquake by the 1992 Landers earthquake. *Geophysical Research Letters, 28*(15), 3007–3010. https://doi.org/10.1029/2000gl012806.