Plate boundary deformation at the Azores triple junction determined from continuous GPS geodetic measurements, 2002-2017

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Abstract

Ground deformation in the Azores, at the triple junction between the Eurasian, Nubian, and North American plates, has been mapped with continuous GPS (Global Positioning System) geodetic measurements to improve tectonic motion estimates and for understanding volcanic unrest. We compute daily GPS positions, spanning almost 17 years (2000-2017), from 18 continuous GPS stations. The GPS time-series are analyzed by searching for discontinuities and periodic functions. Results show that Flores and Graciosa islands have displacements close to predicted North American and Eurasian plate motions, respectively, while São Miguel, Terceira, São Jorge, Faial and Pico islands have displacements in between predicted Eurasian and Nubian plate motions. The Eurasian-Nubian plate boundary in the Azores behaves as a diffuse ultra-slow oblique spreading center with focused deformation found in the Central Group and Sao Miguel Island. The velocity field is modeled by approximating segments of the Eurasian-Nubian plate boundary with vertical dislocations with right-lateral motion and opening below a locking depth. Best fitting models have deep motion in the range of 2.4-2.7 mm yr^{-1} on segments directed N(76.5-78.8º)E. Such displacement accounts for more than half predicted Eurasian-Nubian relative plate motion. The modeling results suggest that the locking depth in the Central Group is about 17 km while in São Miguel is about 2 km. We found transient deformation at Fogo volcano, S\~{a}o Miguel Island, due to unrest activity mainly during 2003–2006 and 2011–2012, and local continuous subsidence in Terceira Island, attributed to a deflation source centered on the island.

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Key Points:

- The EU-NU plate boundary in the Azores show ultra-slow oblique spreading with focused deformation found in the Central Group and São Miguel
- The velocity field of the EU-NU plate boundary is modeled with vertical sliding dislocations with deep motion of ∼2.6 mm/yr directed ENE
- Transient deformation occurs at São Miguel due to episodic unrest at Fogo volcano and local continuous subsidence occurs in Terceira

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Abstract

Ground deformation in the Azores, at the triple junction between the Eurasian, Nubian, and North American plates, has been mapped with continuous GPS (Global Positioning System) geodetic measurements to improve tectonic motion estimates and for understanding volcanic unrest. We compute daily GPS positions, spanning almost 17 years (2000-2017), from 18 continuous GPS stations. The GPS time-series are analyzed by searching for discontinuities and periodic functions. Results show that Flores and Graciosa islands have displacements close to predicted North American and Eurasian plate motions, respectively, while São Miguel, Terceira, São Jorge, Faial and Pico islands have displacements in between predicted Eurasian and Nubian plate motions. The Eurasian-Nubian plate boundary in the Azores behaves as a diffuse ultra-slow oblique spreading center with focused deformation found in the Central Group and São Miguel Island. The velocity field is modeled by approximating segments of the Eurasian-Nubian plate boundary with vertical dislocations with right-lateral motion and opening below a locking depth. Best fitting models have deep motion in the range of 2.4-2.7 mm yr^{-1} directed N(76.5-78.8)°E. Such displacement accounts for more than half predicted Eurasian-Nubian relative plate motion. The modeling results suggest that the locking depth in the Central Group is about 17 km while in São Miguel is about 2 km. We found transient deformation at Fogo volcano, São Miguel Island, due to unrest activity mainly during 2003-2006 and 2011-2012, and local continuous subsidence in Terceira Island, attributed to a deflation source centered on the island.

Plain Language Summary

The Azores is located at the junction of three tectonic plates, the North American, Eurasian and Nubian plates. The boundary between the North American and the other two plates is well defined by the Mid-Atlantic Ridge, but the boundary between the Eurasian and Nubian plates is unclear. Ground deformation in the Azores has been mapped with GPS (Global Positioning System) measurements between 2000 and 2017 to estimate tectonic motion and understand volcanic unrest. We calculate the velocity of 18 continuous GPS stations and compare it with predicted velocities from plate motion models. Results show that Flores and Graciosa islands are close to stable North American and Eurasian plate motions, respectively. In contrast, São Miguel, Terceira, São Jorge, Faial and Pico islands are subject to inter-plate motion between the Eurasian and Nubian plates, with focused spreading in the Central Group and São Miguel Island. The velocity field can be explained by the motion of vertical rectangular dislocations in the Central Group and São Miguel Island buried at 17 and 2 km, respectively. The focused spreading in the central part of São Miguel Island helps explain the episodic intrusions at Fogo volcano during unrests.

1 Introduction

The Azores archipelago is located at the triple junction between the Eurasian, Nubian, and North American plates (Figure 1). The islands rise from the so-called Azores Plateau, an area of thickened crust, roughly defined by the 2000 m isobath. Estimates of the crustal thickness in the Azores are in the range of 14-17 km (Escartin et al., 2001; Spieker et al., 2018).

The boundary between the North American and the other two plates is well defined by the Mid-Atlantic Ridge (Figure 1), but this is not the case for the boundary between the Eurasian and Nubian plates. The Corvo and Flores islands form the Western Group and are located west of the Mid-Atlantic Ridge, on the North American plate. The other seven islands lie to the east of the Mid-Atlantic Ridge. The Graciosa, Terceira, São Jorge, Faial and Pico islands form the Central Group, while São Miguel and Santa Maria form the Eastern Group.

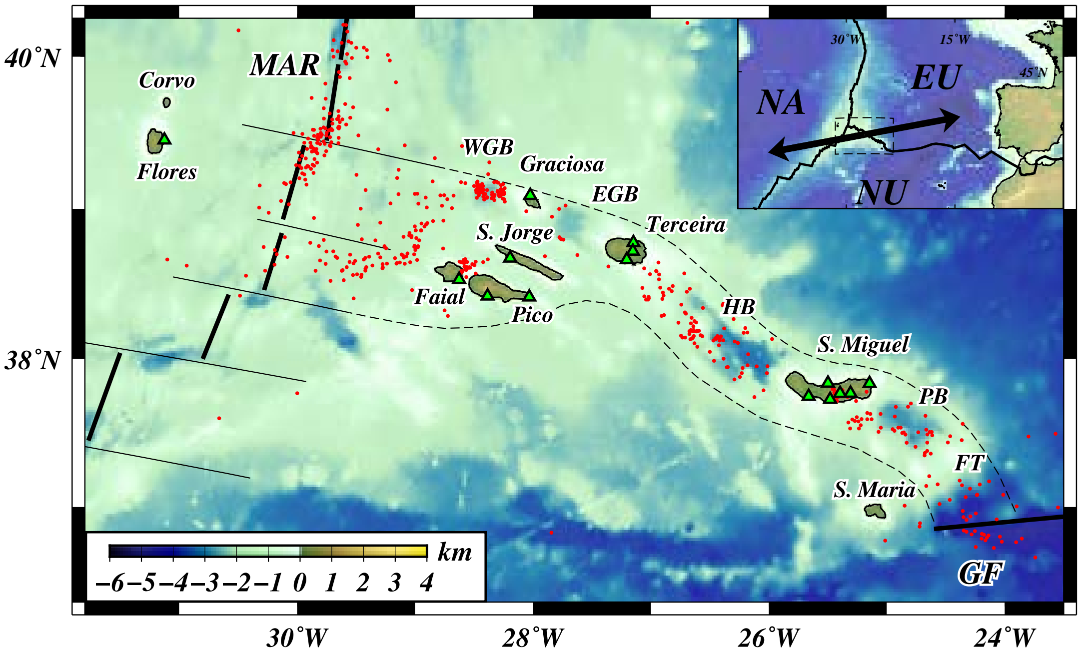

Figure 1. Overview of the tectonic setting of the Azores Plateau roughly defined by the 2000 m isobath. Mid-Atlantic Ridge (MAR) segments are represented by heavy black lines and the intersecting fracture zones by black narrow lines (Luis et al., 1994). The Terceira Rift comprises, from west to east, the West Graciosa Basin (WGB), Graciosa Island, East Graciosa Basin (EGB), Terceira Island, Hirondelle Basin (HB), São Miguel Island, Povoação Basin (PB) and Formigas Through (FT). The Gloria Fault (GF) is located to the east of Santa Maria Island. The GF and plate boundaries (inset) (DeMets et al., 2010) are represented by black heavy lines. The dashed line represent a proposed area of the Eurasian-Nubian inter-plate deformation zone. Green triangles are continuous GPS stations located in Flores (FLRS), Graciosa (AZGR), São Miguel (PDEL, RIB1, RCHA, PCNG, FRNS, and QBN1, from west to east), Terceira (NOV1, TERC, and SRPC, from north to south), São Jorge (QEMD), Faial (HORT) and Pico (PTRP and PIED, from west to east). Red circles are recorded earthquakes ($M_L \geq 3$) between April 2000 and January 2017 (CIVISA database). The bathymetric and topographic data have been derived from 30 arc seconds resolution SRTM (Becker et al., 2009). The arrows in the inset show the opening rate of 4.3 ± 0.1 mm yr^{-1} in direction N(80.5 ± 2.5)°E between EU and NU plates according to ITRF2008 plate motion model (Altamimi et al., 2012), calculated at the average location of all GPS sites to the east of MAR.

The so-called Terceira Rift (Machado, 1959; Searle, 1980) is an important geological structure located to the east of the Mid-Atlantic Ridge and comprises a series of basins alternating with volcanic highs aligned NW-SE to WNW-ESE direction, from the West Graciosa Basin to Formigas Through (Figure 1). To the south of Terceira Rift, the São Jorge and Faial-Pico alignments have a general WNW-ESE direction defined by the islands volcanic systems and adjacent submarine volcanic ridges.

Previous GPS (Global Positioning System) geodetic measurements in the Azores show that to the east of the Mid-Atlantic Ridge, Graciosa and Santa Maria islands have displacements closer to predicted Eurasian and Nubian motion, respectively, while the other islands display an intermediate motion (Fernandes et al., 2006). According to plate motion models based on geologic and geodetic data (Argus et al., 2010; DeMets et al., 2010; Altamimi et al., 2012), the predicted plate spreading between the Eurasian and Nubian plates in the Azores is slow compared with most active plate spreading regions, with full velocity in the range of 4.2-4.8 mm yr^{-1} and direction of N(73-82)°E. The plate boundary is highly oblique to this direction with a strike ranging N(45-75)°W. This obliquity leads to a complex deformation zone accommodating right-lateral shear and extension.

Since the fifteenth century, many destructive earthquakes and volcanic eruptions have been registered in the Azores (Gaspar et al., 2015). Most seismic activity is located on the Mid-Atlantic Ridge, the Terceira Rift, and on the Faial-Pico alignment towards the Mid-Atlantic Ridge (Figure 1). Some areas are more affected by seismic activity than others. For example, the central area of São Miguel Island, has experienced periods of increased seismic activity (Silva et al., 2012). Ground deformation including inflation and deflation of Fogo volcano was observed in the unrest episodes of 2003-2006 (Trota, 2008) and 2011-2012 (J. Okada et al., 2015).

This study reports results from 18 continuous GPS stations (CGPS) in the Azores from April 2000 to January 2017. The time-series show long-term displacements due to plate motion in the Azores and temporal variations of the deformation, particularly in the central area of São Miguel Island during periods of unrest.

2 CGPS and Data Analysis

2.1 The CGPS network

CGPS (Continuous GPS) station measurements in the Azores began in 2000 with the installation of the PDEL station in Ponta Delgada, São Miguel Island (Figure 1). In 2002 RIB1 station was installed on São Miguel Island and in 2003 three stations were installed: QBN1 in São Miguel Island and NOV1 and SRPC on Terceira Island. In 2005, HTN1, PCNG, and RCHA stations were installed on São Miguel Island. On the same island, BVF1 was installed in 2007. A regional CGPS network (REPRAA, 2021) was created to support users interested in precise GPS data from the region. Three stations were installed in 2008: AZGR on Graciosa Island, FRNS on São Miguel Island, and TERC on Terceira Island. Other three stations started operating in 2009: FLRS on Flores Island, PIED on Pico Island, and VFDC on São Miguel Island. More recently, PTRP station was installed on Pico Island in 2010, QEMD station on São Jorge Island in 2012, and HORT station on Faial Island in 2013.

Most of the CGPS monuments of CIVISA (Centro de Informação e Vigilância Sismovulcânica dos Açores) consist of a ∼1-meter high stainless steel rod screwed in a stainless steel benchmark cemented directly into a solid bedrock or a concrete platform with a deep foundation in soil. The benchmarks are leveled during the installation, and the GPS antennas are fastened to the top of the rod. Choke ring antennas are used with radomes covering most of them. Some stations are located in public buildings, with the antennas fixed at the top, while other stations are remote. Presently, most of the remote stations contain solar panels, batteries, and data transmission devices. However, some stations have been operated without data transmission devices for several years, and data were collected intermittently. This resulted in data gaps in some stations, especially during the first years of observation. The data files from CGPS stations with data transmission are downloaded automatically daily via ADSL or digital radio to the CIVISA database.

Presently, CIVISA together with IVAR (Instituto de Vulcanologia e Avaliação de Riscos), operates a CGPS network comprising around 30 stations, aiming to monitor ground deformation in near real-time and to contribute to a better understanding of processes causing deformation in the Azores.

2.2 Data Processing

Dual-frequency phase and pseudo-range data at 30-second intervals are recorded at all CGPS stations in 24 hour-long RINEX files, with antenna elevation angle limit set in the range of 5°-15°, depending on the local terrain and open-sky visibility.

The daily positions of the CGPS stations are calculated using the RINEX files and reprocessed precise orbits from the Center for Orbit Determination in Europe (CODE) aligned to the ITRF2008 reference frame (Susnik et al., 2016). Data from about 50 stations from the International GNSS Service (IGS) are also used. The data is analyzed using Bernese 5.2 software (Dach & Walser, 2015) using the following strategy: (1) preprocessing, including receiver clock synchronization and cycle slip correction; (2) initial ionosphere-free analysis with computation, analysis, and removal of residuals; (3) ambiguity resolution scheme using multiple strategies depending on the length of the baseline: Code-Based Widelane (WL), Phase-Based Widelane (L5), Quasi-Ionosphere-Free (QIF) and Direct L1/L2; (4) computation and analysis of station coordinate solutions and uncertainties. All the daily coordinate solutions are transformed into the ITRF2008 reference frame with a 3-parameter Helmert solution imposed on the coordinates of 20 fiducial stations from the IGS (ALGO, BOR1, BREW, DRAO, DUBO, GODE, GODZ, JOZE, MAR6, MATE, NYAL, ONSA, STJO, THU3, WILL, WSRT, WTZR, YEBE, YELL, and ZIMM). We selected the fiducial stations after checking the data quality from the GPS time-series analysis performed by JPL. The processing utilizes absolute antenna phase center offset models from the IGS (Schmid et al., 2016), ocean tidal loading effects from FES2004 model (Lyard et al., 2006), troposphere refraction effects from Vienna Mapping Function data (Böhm et al., 2006), and zenith path delay corrections from the European Centre for Medium-Range Weather Forecasts.

2.3 Time-series and Velocity Estimation

2.3.1 Time-series Analysis

The coordinate time-series resulting from data processing, in the ITRF2008 reference frame, are evaluated using the FODITS program included in the Bernese 5.2 software. FODITS allows computing functions that fit times-series. The functions include four elements: outliers, discontinuities, linear velocities, and periodic functions. A statistical test, based on the defined user level of significance, terminates the analysis when the model adequately represents the time-series (Dach & Walser, 2015).

The discontinuities in GPS time-series are the result of equipment changes or ground deformation processes. Known equipment changes at the CGPS stations (see Table S1) are detected as discontinuities in the time-series using FODITS (see Table S2).

In addition to discontinuities from known equipment changes, there are others of unknown origin (see Table S2). These discontinuities may relate to unreported equipment changes or ground deformation processes. It was not possible to check equipment changes in some cases, especially from older data-sets and from the REPRAA agency stations. We find unknown discontinuities in the time-series of AZGR, PDEL, and SRPC stations located in relatively stable areas where no significant seismic activity was recorded. These discontinuities are very sudden and classified as unreported equipment changes. Additional unknown discontinuities are found in the time-series of stations located around the Fogo volcano. These discontinuities happen more gradually during the 2003-2006 and 2011-2012 unrest periods of Fogo, and are classified as ground deformation events.

The amplitudes of the seasonal signals found in the time-series (see Table S3) are small when compared with values found, for example, at CGPS stations in Iceland where water and snow loading effects are large (Geirsson et al., 2006; Drouin et al., 2016). Amplitudes of seasonal signals estimated in this study are in the range of 0.8-2.5 mm in the

Table 1. Velocities of the more stable CGPS stations in the ITRF2008 reference frame, with 1σ Uncertainties, in East, North, and Up components, and correlation factor between horizontal components

				Velocity (mm yr^{-1})			
Station	Latitude	Longitude	Date Interval	E	N	U	Corr
AZGR	39.088	-28.023	2008/07 - 2016/07	15.1 ± 0.3	16.7 ± 0.3	-2.7 ± 0.6	-0.1
FLRS	39.454	-31.126	2009/01 - 2017/01	-9.9 ± 0.6	20.1 ± 0.3	-1.3 ± 1.1	-0.2
FRNS	37.769	-25.308	2008/07 - 2016/07	14.9 ± 0.4	15.9 ± 0.5	-1.2 ± 1.0	-0.1
HORT	38.531	-28.626	2013/03 - 2016/03	12.1 ± 0.9	15.4 ± 0.9	-4.1 ± 2.1	-0.2
*HTN*1	37.773	-25.315	2005/05 - 2012/05	15.0 ± 0.4	15.7 ± 0.6	-1.1 ± 1.3	-0.1
*NOV*1	38.776	-27.149	2003/02 - 2016/02	13.3 ± 0.2	15.1 ± 0.2	-2.8 ± 0.5	-0.1
PDEL	37.748	-25.663	2000/05 - 2016/05	12.6 ± 0.2	16.1 ± 0.2	-1.6 ± 0.4	-0.1
PIED	38.414	-28.032	2009/01 - 2017/01	11.8 ± 0.3	14.9 ± 0.4	-2.3 ± 0.7	0.0
PTRP	38.420	-28.386	2010/05 - 2016/05	11.8 ± 0.5	15.6 ± 0.6	-3.0 ± 1.4	-0.1
*QBN*1	37.835	-25.146	2003/07 - 2016/07	14.8 ± 0.2	16.9 ± 0.2	-1.0 ± 0.5	0.1
QEMD	38.672	-28.194	2012/11 - 2016/11	12.7 ± 0.5	15.6 ± 0.6	-1.9 ± 1.4	0.0
SRPC	38.663	-27.205	2003/02 - 2016/02	13.9 ± 0.2	16.8 ± 0.2	-3.5 ± 0.5	0.0
TERC	38.719	-27.153	2008/09 - 2016/09	12.8 ± 0.3	16.3 ± 0.4	-3.8 ± 0.7	-0.1

horizontal components and 0.4-3.7 in the vertical component. The seasonal signals are more clear in the north component than in the east and up components, ranging in the direction from 151° to 173° at most stations. It was not possible to estimate seasonal signals for the time-series of HORT and QEMD stations because of the short period of observations.

Using the results of FODITS, we remove outliers, discontinuities from equipment changes, and annual seasonal signals from the time-series in the ITRF2008 reference frame (Figure S1). Other discontinuities are not removed from the time-series.

2.3.2 Velocity Estimation

We estimate the time-series velocities in the ITRF2008 reference frame using linear fitting of the data (Table 1). Similarly to Geirsson et al. (2006), we estimate the velocity uncertainty from the variance of the residuals of the regression and the length of the time-series, using the formula $\sigma_v = \sigma/T$, where σ is the standard deviation of the residuals and T is the length of the time series in years. A correlation factor between the horizontal velocity error components is computed from the covariance of the residuals. The velocities of stations at Fogo volcano are not estimated because of the transient disturbances in the time-series.

We finally remove the ITRF2008 predicted motion (Altamimi et al., 2012) from the estimated time-series velocities (Figures 2C, 3C and S2). The time-series of FLRS station is relative to predicted North American plate motion, while all other time-series are relative to predicted Eurasian plate motion. There are differences in the time-span of the time-series of the CGPS stations. The station with the longest time-series is PDEL spanning almost 17 years, whereas the station with shortest time-series is HORT with almost 4 years. There are some gaps in the time-series, mostly at remote stations operating without data transmission devices. The time-series from PDEL, HTN1, FRNS, and QBN1 stations at São Miguel Island and the stations at the other islands show stable displacements. In contrast, the time-series of RIB1, RCHA, BVF1, VFDC, and PCNG stations located at Fogo volcano, in São Miguel Island, show significant variations in the rate of the displacement, as a result of unrest episodes at the volcano during the study period.

3 Eurasian-Nubian Plate Spreading

3.1 Velocity Field and Predicted Motion

We analyze the regional deformation field in more detail from the estimated velocities of the more stable CGPS stations. We exclude the data from the stations located around Fogo volcano affected by transient deformation. Most previous ground deformation studies have relied on sparse GPS data, mostly from annual campaign surveys (Fernandes et al., 2006; Trota et al., 2006; Miranda et al., 2012; Marques et al., 2013; Mendes et al., 2013). Besides lower temporal resolution, the data from campaign observations have several limitations, such as high susceptibility to severe atmospheric conditions, multipath error, and bad satellite geometry, resulting in lower precision of the estimated velocities. The number of stations used in this study is small compared with some previous GPS campaign surveys, but the higher temporal resolution of the CGPS data allows estimating velocities with higher precision. Therefore, CGPS data analyses allow us to better discriminate between long-term displacements such as plate motion and local short-term displacements such as volcano deformation.

The velocities show differential motion between the CGPS stations (Table 1). In the ITFR2008 reference frame, the FLRS station on the North American plate is moving at a rate of 22.4 mm yr^{-1} in direction N26°W. In contrast, all other stations located east of the Mid-Atlantic Ridge are moving at a rate of $20.5^{+1.9}_{-1.6}$ mm yr^{-1} to $N(39^{+4}_{-2})°E$ in the same reference frame.

Various plate motion models provide estimates of plate spreading direction and full plate velocity across the Azores. We use the ITRF2008 plate motion model (Altamimi et al., 2012), which has an intermediate Eurasian-Nubian full plate velocity compared with MORVEL2010 (DeMets et al., 2010) and GEODVEL2010 (Argus et al., 2010) (see Table S4). We compare the horizontal velocity of FLRS station with predicted stable North American displacement and the velocities of the stations located in the Central Group and São Miguel Island with both the predicted stable Eurasian and Nubian velocities.

The station on Flores Island (FLRS) (Figure 4A) moves with a velocity close to predicted North American velocity and the lack of significant recorded seismic activity in the area is an indication that the island is located on a relatively stable area. However, the deviation of ∼3 mm yr^{-1} between estimated and predicted motion suggests that the island could be subject to local deformation. Using the GEODVEL2010 and MORVEL2010 plate motion models we get a slightly better correlation between estimated and predicted velocities. The deviation may also relate to the lack of data from this area in the eastern edge of the North American plate used to compute plate motion models.

The station located on Graciosa Island (AZGR) (Figure 4B) moves close to predicted Eurasian motion. The maximum estimated Eurasian-Nubian motion is found between this station and PIED station located on the eastern part of Pico Island. The AZGR station is moving at a rate of 3.7 ± 0.2 mm yr^{-1} to N(62 ± 4)°E relative to PIED station, which is ∼85% of predicted spreading in the area, indicating that the inter-plate deformation zone is broader than the area between the two stations. Despite the displacement close to Eurasian predicted motion, the recurrent seismicity west of Graciosa is an indication that the island is located in an active deformation area.

The stations located in the eastern part of São Miguel Island (HTN1, FRNS, and QBN1) (Figure 4C) and Terceira Island (NOV1, TERC, and SRPC) (Figure 4D) are also moving close to predicted Eurasian motion, but at a lower rate. The small deviation of the QBN1 velocity is an indication that the eastern part of São Miguel Island is not fully within the predicted stable Eurasian plate and is subject to some inter-plate deformation.

On the other hand, PDEL station on the western part of São Miguel Island and the stations located on São Jorge (Figure 4E), Faial (Figure 4F) and Pico (Figure 4G) islands have higher displacements away from the Eurasian predicted motion and displacements closer to the Nubian motion. Spreading between the western and eastern parts of São Miguel Island is revealed from the differential motion between PDEL station and stations HTN1, FRNS and QBN1, with a maximum displacement of 2.4 ± 0.2 mm yr^{-1} in direction N(72 ± 2)°E and 0.17 μstrain. The station QEMD on São Jorge Island is moving closer to the Eurasian motion than the stations on Faial and Pico islands. The station PIED in the eastern part of Pico Island has the fastest displacement away from Eurasian motion and closer to Nubian motion. The other stations, HORT on Faial and PTRP on Pico, are moving with intermediate displacements relative to QEMD and PIED stations. The similar velocities displayed from HORT and PTRP stations located on Faial and Pico islands, respectively, suggest that the eastern part of Faial Island and the western part of Pico Island are moving as a block as indicated from previous campaign GPS surveys (Marques et al., 2013). Both HORT and PTRP stations move about 1 mm yr^{-1} away from QEMD station located on São Jorge Island. The small differential motion observed between the stations of São Jorge and Faial/Pico islands constitute evidence that spreading occurs between the islands.

Comparing with previous GPS studies in the Azores, the values of the vertical velocities in this study are well constrained, with uncertainties ranging from sub-millimeter level to a few millimeters. The results from the more stable CGPS stations show that the Azores Islands are subsiding at an average rate of 2.3 ± 0.4 mm yr^{-1} during the study period (see Table 1).

3.2 Plate Boundary Modeling

Previous studies of geodetic measurements across oblique spreading plate boundary such as the Reykjanes Peninsula, southwest Iceland (Árnadóttir et al., 2006; Keiding et al., 2008) have used analytical models of opening and shearing dislocation sources to fit observed horizontal velocity fields. We follow this approach and approximate segments of the Eurasian-Nubian plate boundary with infinitely long-buried vertical rectangular dislocations, embedded within uniform elastic half-space (Y. Okada, 1985). We perform the modeling for the Central Group (Figure 5A) and São Miguel Island (Figure 5B) in separate runs using different dislocations. We assume that the dislocations have opening and right-lateral slip displacements. The dislocations have a locking depth, which represents the depth of the brittle-ductile boundary in the crust. The brittle crust is locked while the ductile part below opens and slips freely.

We perform an inversion of the data to estimate the best fit values of the locking depth, opening and right-lateral slip by determining the minimum value of the chi-square statistic between observed velocities of the CGPS sites and model predictions (Table 2), using the Dmodels software (Battaglia et al., 2013).

Before the inversion, we corrected the velocity field from a local subsidence in Terceira Island by estimating the deformation generated by a spherical source of pressure decrease within uniform elastic half-space (Mogi, 1958) located between Guilherme Moniz caldera and Pico Alto volcano summit at 5 km depth, with a volume change of -2.5×10^5 m^3 yr^{-1}. During the inversion, we search for a locking depth in the range of 1-20 km, following estimates of crustal thickness in the Azores. The opening and slip motion variables are constrained between zero (no displacement) and the maximum predicted Eurasian-Nubian relative plate motion of 4.8 mm yr^{-1} (see Table S4).

Table 2. Elastic Half-space Dislocation Model Parameter Estimates for São Miguel Island (SM) and Central Group (CG)

			Velocity (mm yr-1)				
Model	Stations	Depth (km)	Open	Slip	Deep Motion[a]	Azimuth[b] (N°E)	$\chi_\nu{}^2$
SM1	4	1.8	1.6	2.2	2.7	76.5	1.1
CG1	8	17.4	1.3	2.0	2.4	78.8	2.9
CG2	8	20.0	1.8	2.4	3.0	76.7	2.6

[a]Magnitude of the vector sum of the right-lateral slip and opening.
[b]Direction of the deep motion.

We use geologic, geodetic and seismic data to constrain the location and direction of the dislocations. Neotectonic studies show that the dominant morpho-tectonic structures at São Miguel Island are NW-SE to WNW-ESE trending faults (Carmo et al., 2014; Madeira et al., 2015). The location of the boundary in the central part of São Miguel Island, between Fogo and Furnas volcanoes, is constrained from previous geodetic and seismic studies (Jónsson et al., 1999; Trota et al., 2006; Silva et al., 2012; J. Okada et al., 2015). We test a dislocation model with the N112.5°E direction (WNW-ESE) and assume it crosses the seismically active Achada das Furnas fissure zone between Fogo and Furnas volcanoes, where the main morpho-tectonic structures have a WNW-ESE direction (see Figure 3A). There is more uncertainty about the location of the spreading axis in the Central Group. There we test the dislocation model with two different locations (see Figure 2A): between Faial-Pico islands and São Jorge Island (CG1), and between Graciosa-Terceira islands and São Jorge Island (CG2). We also define the dislocation orientation in the Central Group as N112.5°E following the main orientation of the shape of the islands and surrounding bathymetric structures (Lourenço et al., 1998).

The model results (Table 2) for São Miguel Island (SM1) predicts a deep motion of 2.7 mm yr^{-1} in N76.5°E direction, with 1.6 mm yr^{-1} opening motion, and 2.2 mm yr^{-1} right-lateral slip motion. The locking depth is about 2 km, much shallower than the crustal thickness in the Azores. It may be an underestimate because of the relatively low number of CGPS stations from São Miguel Island used in the modeling. For the Central Group, we favor the model CG1 over CG2, despite the slightly higher chi-square value. The quality of fit in the stations located on Terceira Island is similar in the CG1 and CG2 models. On the other hand, the quality of fit in the stations located on São Jorge, Faial and Pico islands is better in the CG1 model, while the quality of fit in the AZGR station located on Graciosa Island is better in the CG2 model. The CG1 model predicts a deep motion of 2.4 mm yr^{-1} at N78.8°E direction, with 1.3 mm yr^{-1} opening motion, and 2.0 mm yr^{-1} right-lateral slip motion. The locking depth is about 17 km, agreeing well with estimates of crustal thickness.

4 Seismic Activity and Volcano Deformation

Some areas in the Central Group are more affected by seismic activity than others, including the northeast area of Faial Island (see Figure 2). Many earthquakes northeast of Faial Island are clustered at deep levels, between 10 and 20 km (see Figure 2B). Most seismic activity in this area occurred before 2007 and is possibly related in part to crustal relaxation processes after the 1998 major earthquake (M_L 5.8) that occurred in the area (Matias et al., 2007). The station HORT located about 10 km south of the area most affected by seismicity in Faial Island was installed in 2013. The time-series of this station show no transient disturbances.

The central part of Terceira island is also affected by higher seismic activity. We find relatively high subsidence levels in the stations located on Terceira island, with a maximum estimated subsidence rate of 3.8 ± 1.0 mm yr^{-1} at TERC station located close to the center of the island. Also, the horizontal velocities of Terceira stations show convergence towards the center of the island.

The central part of São Miguel Island has been the stage of recurrent unrest activity in the last 20 years. The seismic activity is mainly concentrated in the central area of São Miguel Island, between Fogo and Furnas volcanoes, and is characterized by a large number of small magnitude events along the main fault system. Most seismic events in the area have hypocenters above the 5 km depth level (see Figure 3B). There were several episodes of unrest activity in the central part of São Miguel Island during the study period, including a major episode in 2005 with a maximum of more than 150 events ($M_C \geq 2$) recorded per month. Evidence of volcano deformation at Fogo, with both inflation and deflation, is inferred from the time-series of stations RIB1, RCHA, BVF1, VFDC, and PCNG located around the volcano (see Figure 3C).

5 Discussion

Our results show that Flores Island has a very distinct motion compared with the other islands consistent with its location in the North American plate. Graciosa Island shows a displacement close to predicted Eurasian motion, while São Miguel, Terceira, São Jorge, Faial and Pico islands have displacements in between predicted Eurasian and Nubian motions. The modeling results predict a deep motion of 2.7 mm yr^{-1} at N76.5°E direction for São Miguel Island, and 2.4 mm yr^{-1} at N78.8°E direction for the Central Group. This motion account for 50-64% of predicted Eurasian-Nubian relative plate motion.

Observations from morpho-tectonic analysis (Lourenço et al., 1998) and previous campaign GPS surveys in the Central Group (Fernandes et al., 2006; Marques et al., 2013) show evidence that the Eurasian-Nubian boundary in the Azores is diffuse. Our observations from CGPS data are in line with this assessment. The Eurasian-Nubian motion in the Azores appears not to change gradually across the inter-plate deformation zone but instead is more focused in some areas, namely in the central area of São Miguel Island and between Faial-Pico ridge and Terceira Island. In particular, a narrow area in the central part of São Miguel Island accommodates at least half of predicted regional spreading. The existence of active plate spreading in São Miguel Island is suggested from other studies using both campaign (Trota et al., 2006) and CGPS data (J. Okada et al., 2015).

Our results show spatial variations of the differential motion along the Eurasian-Nubian plate boundary in the Azores Plateau. The broader deformation zone in the Central Group is consistent with volcanism distributed over a wider area, while in São Miguel Island, the deformation is more focused. Seismic activity is also focused in some areas of the Eurasian-Nubian boundary (see Figure 1), with stronger earthquakes more concentrated in rift basins between the islands and in the central area of São Miguel Island. From 2002 to 2010, the central area of São Miguel Island has experienced a higher seismic activity than in the previous decades, mainly as swarms with events of small magnitude (Silva et al., 2012).

There is evidence of low degrees of partial melting beneath the thick lithosphere caused by a mantle anomaly centered under the Central Group (Moreira et al., 1999; Gente et al., 2003; Yang et al., 2006). The existence of deep processes in the Central Group is also suggested from the large locking depth of our prefered model dislocation in the area (see Table 2) and the deep earthquake activity (see Figure 2B).

Analysis of geochemical data indicates that focused magmatism occurs along the Terceira Rift below volcanic systems (Haase & Beier, 2003; Beier et al., 2008; Storch et al., 2020). The existence of shallow processes in São Miguel Island is inferred from the shallow locking depth of our modeled dislocation for the island (see Table 2) and the shallow earthquake activity (see Figure 3B). The shallow processes may weaken the crust and cause strain localization. Strain focusing in the central area of the island may relate to the episodic intrusions at Fogo during volcano unrests.

The high temporal resolution of the CGPS data allows calculating velocities with high precision and performing an inversion of the data using simple analytical models. On the other hand, the low spatial resolution and poor distribution of CGPS stations are limitations to the modeling. There is no geodetic data from large submarine areas, and some islands have no CGPS stations or only a single station. In particular, our preference for CG1 model for the Central Group is constrained by the higher number of CGPS stations located in Terceira, São Jorge, Faial and Pico islands, comparing with the Graciosa Island area.

The spatial variation of the crustal deformation and the seismicity distribution suggest partitioning of strain release, in rift basins with tectonic earthquakes and on the islands with volcano unrests. The spreading in the Eurasian-Nubian plate boundary in the Azores follows patterns similar to other ultraslow mid-ocean ridges (Sibrant et al., 2015; Storch et al., 2020). The ultra-slow spreading axes of the Gakkel Ridge and the South Indian Ridge comprise segments showing amagmatic extension and segments with magmatic extension (Cochran, 2008; Cannat et al., 2019).

We infer that some submarine areas of the Eurasian-Nubian plate boundary in the Azores are presently subject to rifting, contributing to the remaining predicted plate spreading not detected with our observations, such as the Povoação basin to the east of São Miguel Island and the Hirondelle basin between São Miguel and Terceira islands.

Previous campaign GPS surveys show evidence of continuous subsidence of Terceira Island (Miranda et al., 2012; Marques et al., 2015). The previous surveys show horizontal residual velocities compatible with a deflation in the center of the island, but no confirmation from the vertical component was possible. The horizontal velocities of Terceira stations from this study show a deviation towards the center of the island, which agrees with a deflation source located in that area. The higher subsidence rate found in TERC station in the central part of Terceira confirms the existence of deflation in the area. The extended period of deformation and modeling results suggests that the deflation could be due to crystallization and degassing of a underlying magma body or decompression of an hydrothermal system in the center of the island. The deflation could contribute to concentrated seismicity occuring in the center of the island.

The time-series of the stations located around Fogo volcano (BVF1, RCHA, RIB1, PCNG, and VFDC), on São Miguel Island, show disturbances related to unrest activity, signaling the likely accumulation of volcanic fluids below the volcano.

6 Conclusions

The current analysis of CGPS data from the Azores shows the importance of estimating high precision velocities. The analysis of long time-series with removed estimated noise is critical to measure accurately the ultra-slow spreading rate in the region. The results show that Flores and Graciosa islands have displacements close to predicted North American and Eurasian motions, respectively, while São Miguel, Terceira, São Jorge, Faial and Pico islands have displacements in between predicted Eurasian and Nubian motions. The spreading in the Eurasian-Nubian plate boundary in the Azores occurs in a wide area between the Mid-Atlantic Ridge and southeast of São Miguel Island. The interplate motion does not change gradually across the boundary but is instead focused in some areas, including the central area of São Miguel Island and between Faial-Pico ridge and Terceira Island. Modeling, using a freely sliding dislocation below a locking depth, in a uniform elastic half-space, predict a deep motion in the range of 2.4-2.7 mm yr^{-1} directed N(76.5-78.8)°E located in the Central Group and São Miguel Island. This motion account for more than half predicted Eurasian-Nubian relative plate motion. The results suggest that spreading in the Central Group is dominated by deep processes while in São Miguel is dominated by shallow processes. Transient deformation occurs at Fogo volcano, São Miguel Island, due to unrest activity, and local subsidence occurs in Terceira Island explained by a continuous deflation source centered in the island.

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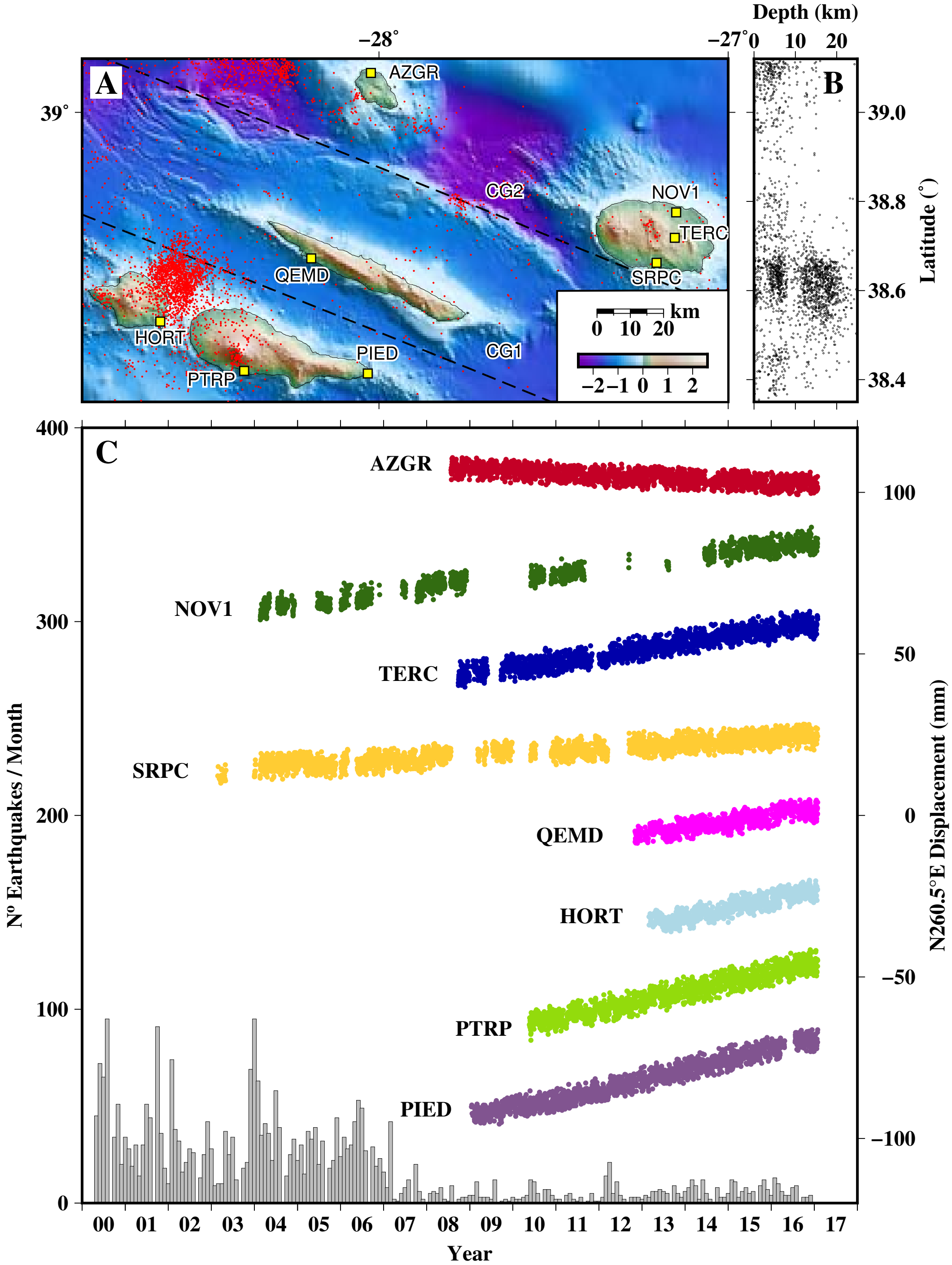

Figure 2. A - Location of the CGPS stations AZGR, NOV1, TERC, SRPC, QEMD, HORT, PTRP and PIED located in the Central Group. Red circles are recorded earthquakes ($M_C \geq 2$). Dashed lines are the profiles CG1 and CG2 modeled in this study for the area. B - Time-series of the CGPS stations movement relative to predicted ITRF2008 Eurasian motion (Altamimi et al., 2012), transformed onto the direction away from predicted Eurasian motion (N260.5°E). The times-series are shifted from top to bottom to display the CGPS stations movement from the north (AZGR) to the south (PIED). The vertical gray bars are the monthly number of earthquakes in the area ($M_C \geq 2$).

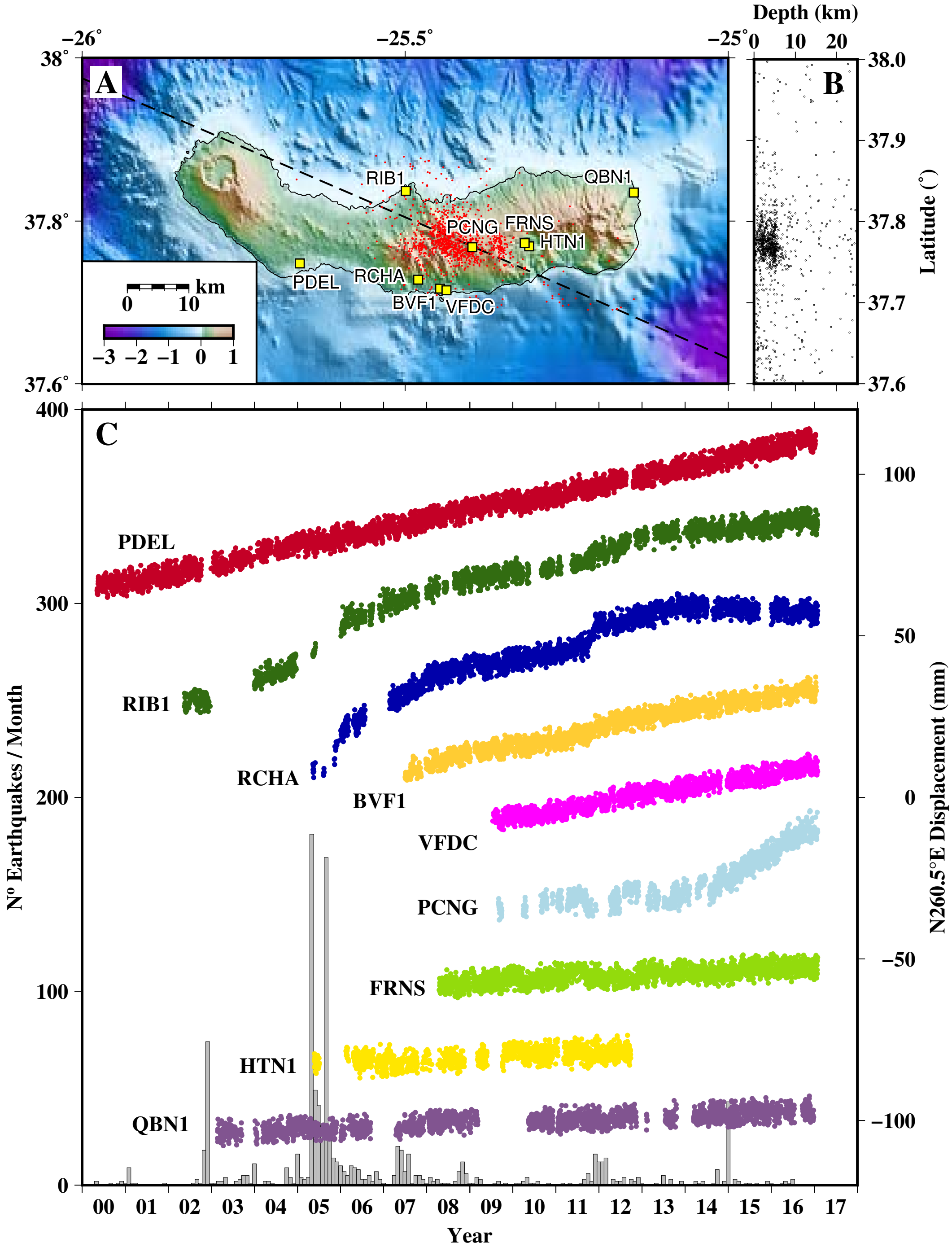

Figure 3. A - Location of the CGPS stations PDEL, RIB1, RCHA, BVF1, VFDC, PCNG, FRNS, HTN1 and QBN1 located in São Miguel Island. Red circles are recorded earthquakes ($M_C \geq 2$), concentrated between Fogo and Furnas volcanoes. Dashed line is the profile SM1 modeled in this study for the area. B - Time-series of the CGPS stations movement relative to predicted ITRF2008 Eurasian motion (Altamimi et al., 2012), transformed onto the direction away from predicted Eurasian motion (N260.5°E). The times-series are shifted from top to bottom to display the CGPS stations movement from the west (PDEL) to the east (QBN1). The vertical gray bars are the monthly number of earthquakes in the area ($M_C \geq 2$).

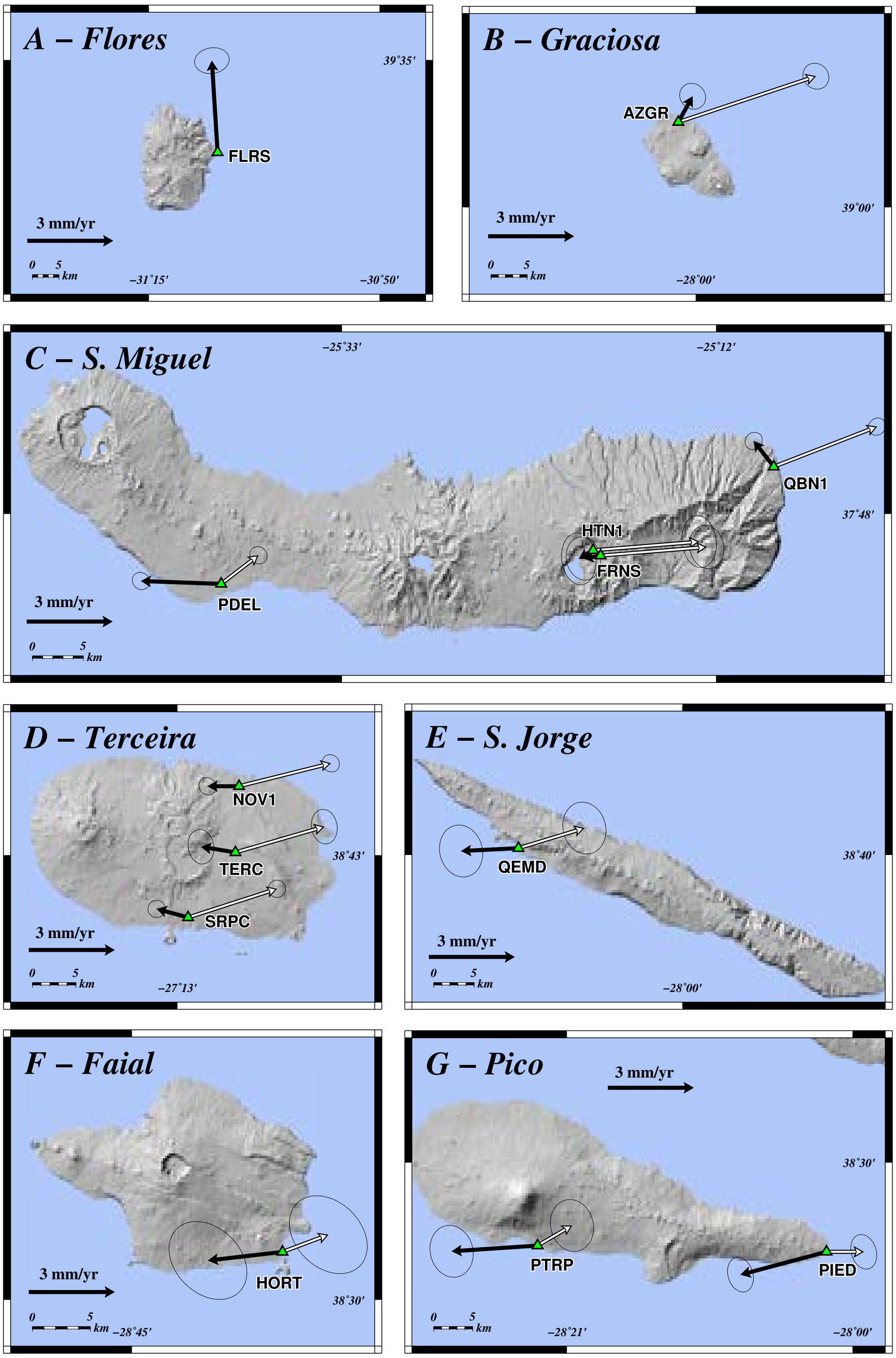

Figure 4. Horizontal velocities of CGPS stations located on Flores (A), Graciosa (B), São Miguel (C), Terceira (D), São Jorge (E), Faial (F) and Pico (G). In figure A, the black arrow represent the velocity from Table 1 relative to predicted ITRF2008 North American motion. In figures from B to G, the black and white arrows represent the velocities from Table 1 relative to predicted ITRF2008 Eurasian and Nubian motions, respectively (Altamimi et al., 2012). The ellipses represent the 1σ confidence level and the green triangles are the CGPS stations.

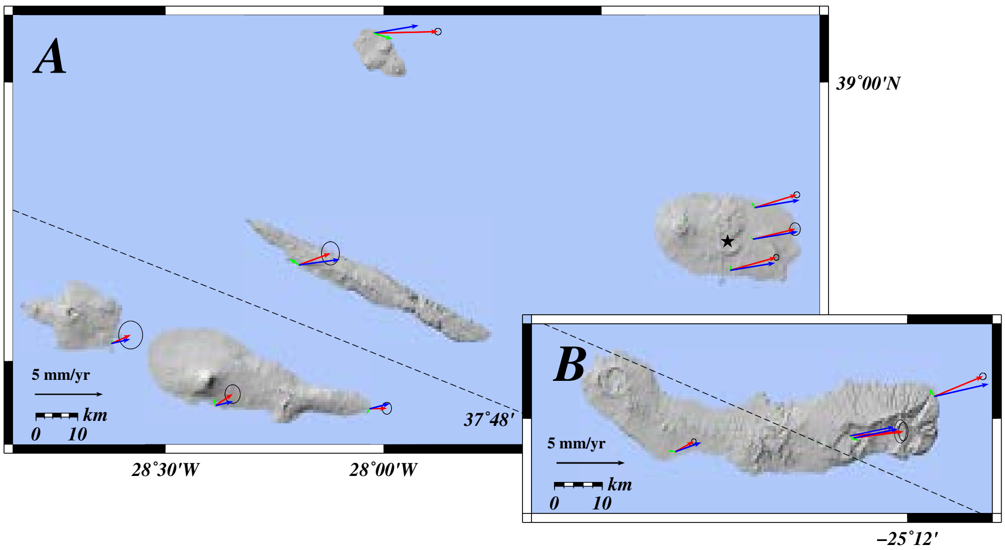

Figure 5. Results of kinematic plate boundary modeling of the horizontal velocities for Central Group (A) and São Miguel Island (B). The velocity arrows show observed corrected from Mogi source (blue, 2σ confidence ellipses), predicted from data inversion using Okada dislocations (red), and residuals (green). The dislocations CG1 (A) and SM1 (B) are shown with dashed black lines. Mogi source is shown with black star (A).

Supporting Information for "Current Plate boundary deformation at the Azores triple junction determined from continuous GPS geodetic measurements (2002-2017)"

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Contents

Introduction

This supporting information provides:

a) Tables with known equipment changes in the CGPS stations, results including discontinuities, annual amplitudes and phases found in the CGPS time-series, and predicted Eurasian-Nubian plate velocities for the CGPS stations;
b) Figures showing a time-series analysis example using FODITS program and all time-series of the CGPS stations in east, north and up components.

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Table 1. Equipment Changes in CGPS Stations

Station	Date	Receiver Type	Antenna Type	Antenna Height (m)
AZGR	2008/07/26	TRIMBLE NETR5	TRM55971.00 NONE	0.000
	2012/04/31	TRIMBLE NETR9	TRM55971.00 NONE	0.000
BVF1	2007/07/18	TRIMBLE NETRS	TRM29659.00 NONE	0.498
FLRS	2009/01/01	LEICA GRX1200GGPRO	LEIAT504GG NONE	0.498
FRNS	2008/04/16	LEICA GX1230GG	LEIAX1202GG NONE	0.498
HORT	2013/01/01	LEICA GX1230GG	LEIAR25 NONE	0.000
HTN1	2005/05/23	LEICA RS500	LEIAT504 NONE	0.861
	2006/02/15	TRIMBLE NETRS	TRM29659.00 NONE	0.571
	2007/07/18	LEICA GRX1200	LEIAT504 NONE	0.571
NOV1	2003/02/23	LEICA RS500	LEIAT504 LEIS	0.483
PCNG	2012/08/01	LEICA GRX1200	LEIAT504 NONE	0.485
	2013/02/15	LEICA RS500	LEIAT504 NONE	0.485
	2014/07/23	LEICA GR25	LEIAT504 NONE	0.485
PDEL	2001/11/06	LEICA CRS1000	LEIAT504 NONE	0.000
	2002/12/19	LEICA RS500	LEIAT504 NONE	0.000
	2008/04/06	LEICA GRX1200GGPRO	LEIAT504GG NONE	0.000
PTRP	2010/05/19	LEICA GRX1200GGPRO	LEIAT504GG LEIS	0.000
QBN1	2003/02/21	TRIMBLE 5700	TRM29659.00 TCWD	0.485
QEMD	2012 11 01	LEICA GRX1200GGPRO	LEIAT504 LEIS	0.000
RCHA	2005/02/01	ASHTECH Z-X	ASH701975.01A NONE	0.932
	2005/12/14	TRIMBLE NETRS	TRM29659.00 NONE	0.932
RIB1	2002/05/07	LEICA RS500	LEIAT504 LEIS	0.485
	2015/06/12	LEICA GR25	LEIAT504 LEIS	0.485
SRPC	2003/02/25	LEICA RS500	LEIAT504 LEIS	0.485
TERC	2008/09/18	LEICA GRX1200GGPRO	LEIAT504GG LEIS	0.000
VFDC	2009/07/14	LEICA GRX1200+GNSS	LEIAX1203+GNSS NONE	0.000

Table 2. Discontinuities of the CGPS Time-Series in East, North, and Up Components

Station	Date	Event	N(mm)	E(mm)	U(mm)	SD[c](mm)
AZGR	2009/06/27	*Equipment*[a]	2.0	3.1	7.8	0.3
AZGR	2013/11/17	*Equipment*[a]	1.1	-1.2	4.4	0.3
AZGR	2015/06/25	*Equipment*[a]	-0.0	-1.0	13.2	0.2
BVF1	2011/11/20	*Deformation*	-6.1	-0.8	2.5	0.4
PDEL	2006/12/12	*Equipment*[a]	6.7	2.9	1.7	0.3
PDEL	2008/04/06	*Equipment*	2.3	-0.4	11.5	0.3
PDEL	2012/10/17	*Equipment*[a]	-4.6	-4.4	-2.1	0.2
PCNG	2014/07/23	*Equipment*[b]	2.1	-7.2	-9.9	0.4
RCHA	2005/12/14	*Equipment*[b]	-21.7	-2.4	1.3	0.7
RCHA	2011/10/20	*Deformation*	-7.1	-4.4	5.1	0.4
RIB1	2005/06/05	*Deformation*	11.4	-9.4	-7.7	0.6
SRPC	2013/01/20	*Equipment*[a]	-0.7	-5.6	-0.9	0.3
HTN1	2006/02/15	*Equipment*	1.8	1.1	7.4	0.6
HTN1	2007/07/18	*Equipment*	6.7	-4.3	-0.6	0.5

[a] Unreported equipment change.
[b] Possible influence from volcano deformation.
[c] Global Standard Deviation.

Table 3. Annual Amplitudes and Phases of the CGPS Time-Series in East, North, and Up Components

Station	Amplitude (mm)			Phase (°)		
	N	E	U	N	E	U
AZGR	1.8	1.0	1.4	165.3	23.3	-156.0
BVF1	1.8	1.0	1.1	172.4	16.4	178.8
FLRS	1.7	2.2	1.9	163.7	-17.5	-65.5
FRNS	2.1	1.1	1.8	171.6	1.9	173.3
HTN1	2.2	0.8	3.7	-165.1	17.6	142.9
NOV1	1.5	1.4	0.7	170.9	3.2	164.9
PBOI	2.7	1.2	2.8	164.7	81.8	130.8
PDEL	2.0	1.0	2.1	163.2	-2.6	174.4
PIED	2.2	1.3	0.5	159.5	2.7	-92.0
PCND	2.5	0.9	1.6	173.2	20.1	94.1
PCNG	2.1	1.5	0.7	145.2	24.4	-161.0
PTRP	2.2	1.3	2.2	143.0	42.1	141.9
QBN1	1.9	1.4	1.2	157.5	20.9	-178.3
RCHA	2.4	1.2	1.1	162.3	46.7	136.9
RIB1	1.8	1.4	1.3	164.5	17.8	152.8
SRPC	2.1	1.0	2.1	151.1	52.9	158.9
TERC	2.3	1.2	1.4	145.1	-5.9	-102.3
VFDC	2.2	1.3	0.4	158.7	35.4	-172.5

Table 4. Eurasian-Nubian Plate Motion for Plate Motion Models ITRF2008, GEODVEL2010 and MORVEL2010

Model	Full Plate Velocities (mm yr^{-1}) East	North	Speed	Azimuth (°)
$ITRF2008$	$4.2^{+0.1}_{-0.0}$	$0.6^{+0.3}_{-0.1}$	$4.3^{+0.1}_{-0.0}$	$81.9^{+0.7}_{-3.9}$
$GEODVEL$	$4.8^{+0.1}_{-0.0}$	$0.5^{+0.3}_{-0.1}$	$4.8^{+0.1}_{-0.0}$	$83.5^{+0.7}_{-3.9}$
$MORVEL$	$4.0^{+0.3}_{-0.0}$	$1.2^{+0.7}_{-0.1}$	$4.2^{+0.4}_{-0.0}$	$72.7^{+1.7}_{-8.0}$

Plate motion is calculated at the average location of all CGPS stations located to east of MAR (-26.556°E 38.187°N).

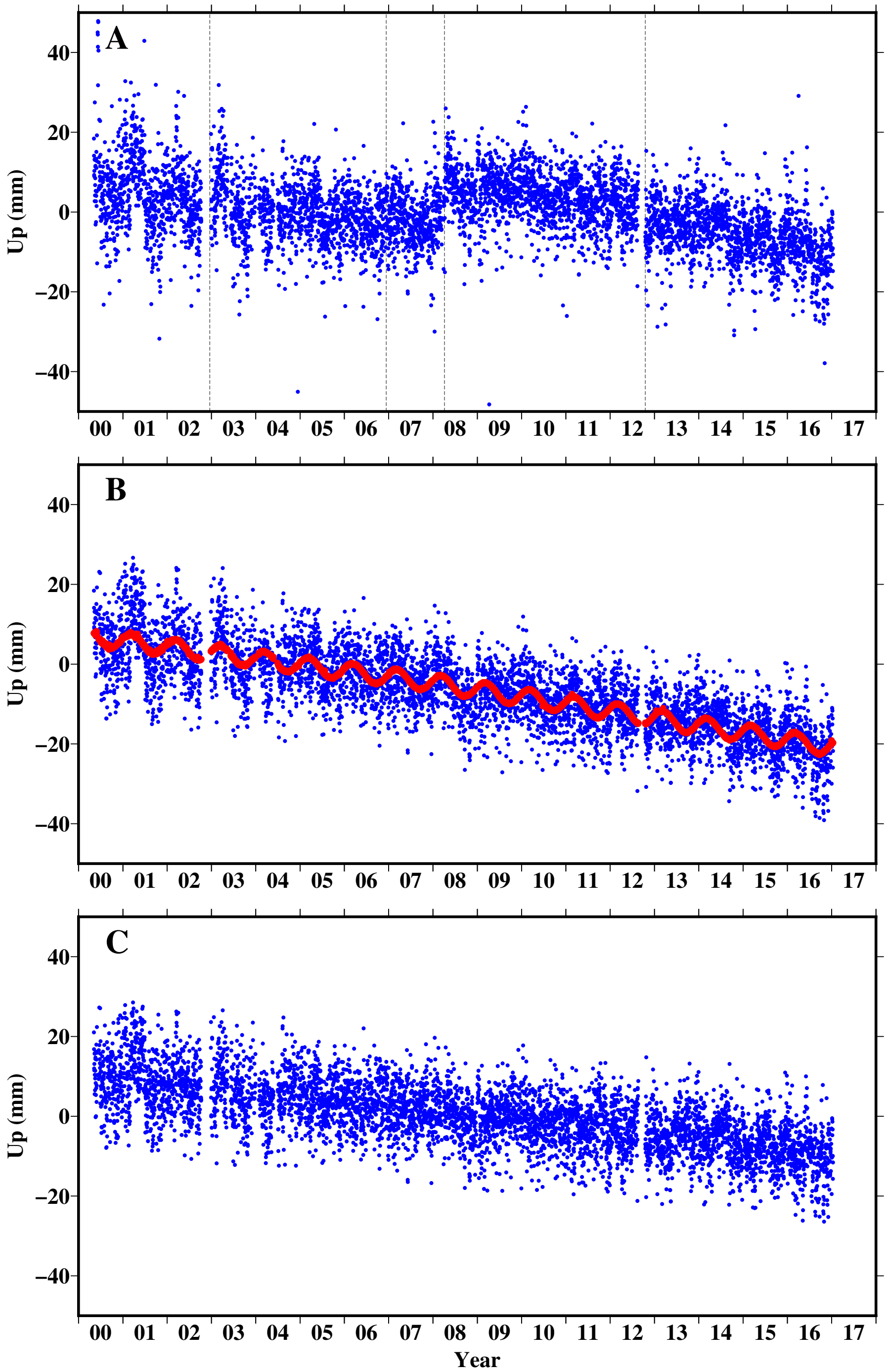

Figure 1. Time-series of the vertical component of PDEL station for the period between May 2000 and January 2017, relative to ITRF2008 reference frame with A) all solutions from Bernese 5.2 processing before the time-series analysis using FODITS program, B) solutions with filtered out discontinuities and outliers found from FODITS program analysis, and C) filtered solutions from discontinuities, outliers and seasonal signals found from FODITS program analysis.

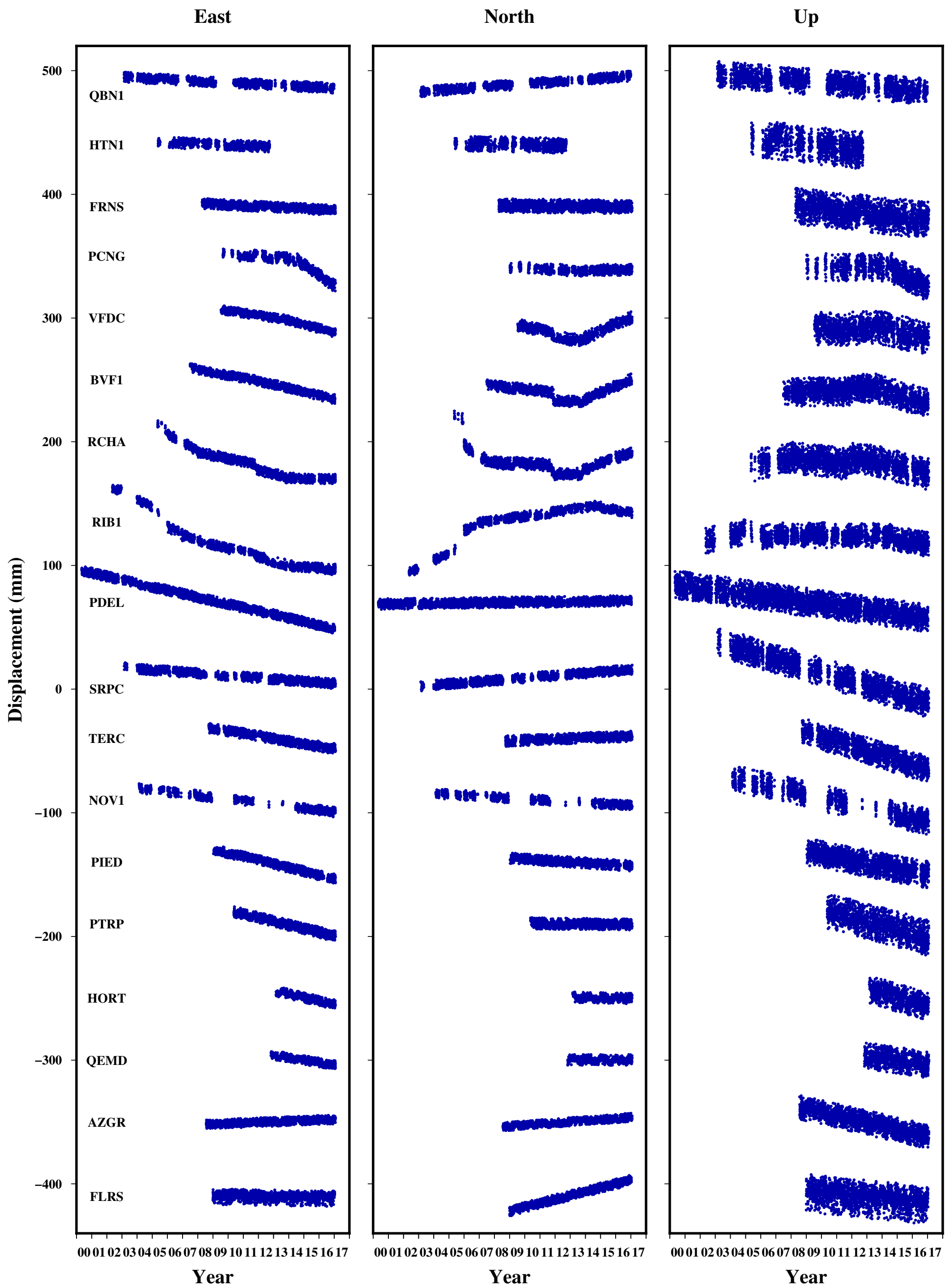

Figure 2. Time-series of the CGPS stations in east, north, and up components for the period between May 2000 and January 2017, relative to ITRF2008 plate motion model. The time-series of FLRS site are relative to predicted North American plate motion, while all others are relative to predicted Eurasian plate motion.