

Recent Macaronesian kinematics from GNSS ground displacement analysis

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ABSTRACT

Macaronesia is a complex oceanic region spanning three tectonic plates in the north-east Atlantic ocean. It is composed of four archipelagos, widely distributed and limited to the east by the Iberian Peninsula and north-western coast of Africa. This study aims to clarify recent Macaronesian kinematics from 19 GNSS stations located on the four archipelagos and the Iberian and African coastlines. The analysis is based on nearly 15 years of common data acquisition and aimed to detect new effects of intraplate tectonics or similar local/regional events consistent with calculated ground displacements. Evaluating the GNSS stations residual velocities relative to those expected from the NNR-MORVEL56 model, higher residuals were found at continental coastal stations (Africa) than at oceanic ones (Canaries and Madeira). From the computed strain rate map, the possible existence of a shear zone connecting the Gloria and Transmoroccan fault systems, already mentioned by other authors, was depicted. Cluster statistical analysis of the horizontal residual velocities helped to identify tectonic boundaries in Macaronesia and four groups of analogous intraplate residual velocities within this region. Three of four groups were identified in the Azores, highlighting the African-Nubian-Eurasian diffuse plate boundary in this region. Furthermore, in the Canary Islands, two distinct kinematic behaviours were detected, possibly due to the activity along a previously detected tectonic fault between Tenerife and Gran Canaria, where some stations have similar intraplate residuals to those at Madeira and Cape Verde stations, while others have similar intraplate residuals to those of continental stations. Finally, all stations on

1 oceanic crust, except Cape Verde, present recent ground subsidence which may be
 2 attributed to isostatic adjustment.

3
 4 Keywords: continuous GNSS time series, Canary Islands, cluster analysis, strain
 5 rate analysis, isostatic adjustment

6 1. INTRODUCTION

7 Macaronesia is the collective name given to the group of islands that lie in the north-
 8 east Atlantic ocean between 10°N and 40°N latitude (Fig. 1). These islands form four
 9 archipelagos, which are, from north to south: the Azores, Madeira, the Canary Islands and
 10 Cape Verde. The Mid-Atlantic Ridge (MAR) marks its western boundary and the Gloria
 11 transform fault its northern boundary (Scheidegger, 2002). However, the Azores lie on
 12 a triple junction, where the North American, Eurasian and Nubian Plates interact.
 13 Although these archipelagos are widely distributed, these islands and the coastlines of
 14 north-west Africa and the Iberian Peninsula are the available emerged land where Global
 15 Navigation Satellite System (GNSS) observations can be made.

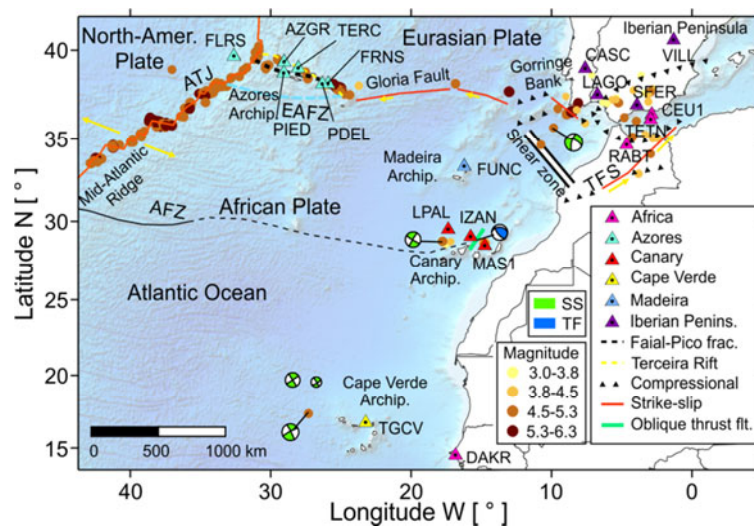


Fig. 1. Macaronesian GNSS stations and African-Nubian plate boundary elements. Focal mechanisms from the ISC catalogue, within each event from the ISC Bulletin for focal mechanism solutions from the *International Seismological Centre (2019)*; between 40°W–0°W and 15°N–40°N and weighted by the earthquake magnitude. A seismic hypocentre depth limit < 70 km and a magnitude $M_w > 3.0$ were established between 2000/01/01 and 2016/12/31. Standard regime of normal faulting (NF), thrust faulting (TF), strike-slip (SS) and unknown (U) is shown; ETOPO1 basemap is obtained from NOAA National Centres for Environmental Information (NCEI). Map is represented in Mercator projection over WGS84 Earth reference system. AFZ: Atlantis Fracture Zone, EAFZ: East Azores Fracture Zone, ATJ: Azores Triple Junction, TFS: Transmoroccan Fault System. See Table 1 for GNSS station codes.²

Table 1. Continuous GNSS stations used with public access data and managed by public institutions: International GNSS Service (IGS, <http://www.igs.org>), EUREF Permanent GNSS Network (EPN, <http://www.epncb.oma.be>), Rede Nacional de Estações Permanentes GNSS (ReNEP, <https://renep.dgterritorio.gov.pt/estacoes>).

GNSS	Location	Region	Owner	Start [year, day#]	End [year, day#] ³
FLRS	Flores	Azores	IGS	2008,159	2015,090
PDEL	São Miguel	Azores	IGS	2000,241	2015,090
TERC	Terceira	Azores	EPN	2008,016	2015,090
PIED	Pico	Azores	ReNEP	2008,016	2012,177
FRNS	São Miguel	Azores	ReNEP	2008,016	2014,005
AZGR	Graciosa	Azores	ReNEP	2009,347	2012,177
FUNC	Madeira	Madeira	IGS	2005,314	2015,090
MAS1	Gran Canaria	Canary Islands	IGS	2000,211	2015,090
IZAN	Tenerife	Canary Islands	EPN	2008,110	2015,090
LPAL	La Palma	Canary Islands	EPN	2001,179	2015,090
TGCV	Sal	Cape Verde	IGS	2000,004	2014,155
CASC	Portugal	Iberian Peninsula	EPN	2000,241	2015,090
LAGO	Portugal	Iberian Peninsula	EPN	2000,229	2015,090
SFER	Spain	Iberian Peninsula	EPN	2000,242	2015,090
VILL	Spain	Iberian Peninsula	IGS	2000,116	2015,090
CEU1	Spain	Africa	EPN	2008,314	2015,090
TETN	Morocco	Africa	EPN	2002,083	2015,090
RABT	Morocco	Africa	EPN	2000,166	2015,090
DAKR	Morocco	Africa	IGS	2012,209	2015,090

1 Only a few studies have focused on Macaronesian kinematics, since rigidity,
2 continuity and insignificant seismicity seem to be fundamental aspects of the main plate,
3 the African-Nubian, regardless of the activity of both the MAR and Nubian-Eurasian plate
4 boundaries (Fig. 2). Additionally, its low speed relative to its neighbouring plates of
5 nearly 1 mm yr⁻¹ (Burke and Wilson, 1972; Kogan et al., 2000; Malservisi et al., 2013)
6 and its minimum internal strain, with no significant deformation with values <1 mm yr⁻¹
7 (Calais et al., 2003; McClusky et al., 2003; Serpelloni et al., 2007), are other suitable
8 descriptions for this plate. The global stress map database (Heidbach et al., 2018) and
9 some physical models of Macaronesia (Geyer et al., 2016; Jiménez-Munt and Negredo,
10 2003) are other sources where low values of internal stress are shown.

11 Observations from continuous GNSS stations in Macaronesia started in 2000 with
12 a limited number of permanent stations. Most previous studies were carried out by mixing
13 observations from periodic or episodic GNSS campaigns in their calculations (Barbero et
14 al., 2018; Garcia et al., 2014; Marques et al., 2013a, 2015; Mendes et al., 2013; Pérez-
15 Peña et al., 2010; Prates et al., 2013; Vernant et al., 2010). Overall, these locally or
16 regionally determined velocities are similar to the velocities of geologic plate motion
17 computed from global models such as NNR-MORVEL56 (DeMets et al., 2010) and NNR-
18 NUVEL1A (DeMets et al., 1994), and azimuths only disagreeing slightly by a few
19 degrees.

1 In 2004, the unusual increase in seismic events in Tenerife, with some earthquakes felt
 2 by the population, and the underwater eruption off the coast of El Hierro augmented
 3 volcanic studies in the Canary Islands (*Domínguez-Cerdeña et al., 2011; García et al.,*
 4 *2014; Prates et al., 2013*). One of these recent studies focused on Tenerife showed distinct
 5 kinematics between this island and the neighbouring island of Gran Canaria, with
 6 different horizontal velocities computed over 10 years (*Barbero et al., 2018*). The increase
 7 of permanent GNSS stations in Macaronesia and their data accessibility since 2000 offer
 8 the possibility of carrying out a precise ground displacement analysis of the whole Canary
 9 archipelago and the opportunity of finding similarities and differences to the kinematics of
 10 other archipelagos. Therefore, the purpose of this study is to evaluate the regional
 11 geodynamics of the Canary Islands and provide an overall interpretation of the recent
 12 intraplate kinematics of the African-Nubian Plate. For this, velocities between May 2000
 13 and March 2015 were calculated for 19 stations, aiming at accuracy of less than
 14 1 mm yr^{-1} over such long periods (*Blewitt and Lavallée, 2002; Bos et al., 2010*).
 15 Furthermore, a statistical cluster analysis was performed to identify and group residuals
 16 with similar velocity and, finally, strain maps were generated to define intraplate
 17 kinematics in Macaronesia and, particularly, in the Canary Islands.

2. REGIONAL SETTING

19 Although all archipelagos in Macaronesia have a minimum of five islands and
 20 volcanic origin, the nature of this volcanism is not always clear (*Geldmacher et al., 2006;*

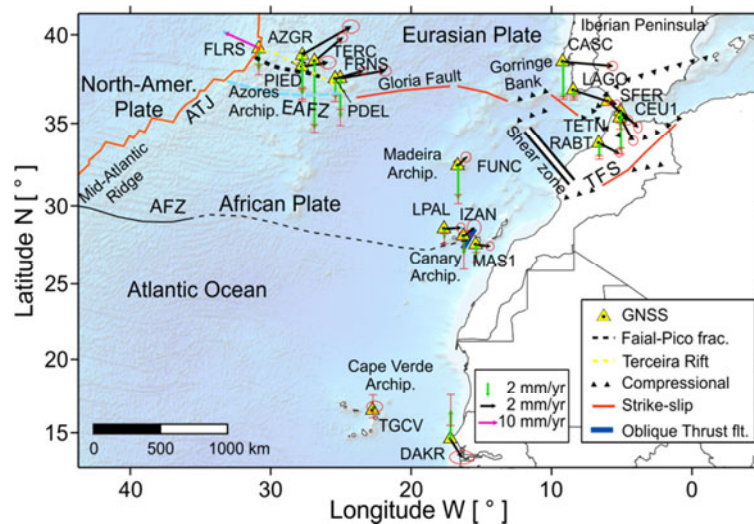


Fig. 2. Macaronesia residual kinematic map for 2000–2015. The arrows represent residual horizontal and vertical velocities at GNSS stations after removing NNR-MORVEL56. Biases with a 95% confidence level are shown as ellipses for the horizontal and intervals for the vertical velocities. AFZ: Atlantis Fracture Zone, EAFZ: East Azores Fracture Zone, GB: , TFS: Transmoroccan Fault System.⁴ See Table 1 for station codes.⁵

1 *Métrich et al., 2014; Pacheco et al., 2013; Ramalho, 2011*). The ages of their old
2 seamounts date from 142 Myr to 200000 years (*von den Bogaard, 2013*). From the north-
3 west, near the MAR, the first of the four archipelagos is the Azores which includes nine
4 islands aligned NW-SW (see Fig. 1). The two most westerly islands, Flores and Corvo,
5 are located on the North American plate. The other seven islands lie to the east of the
6 MAR, arranged in two groups: the central group includes Graciosa, Terceira, São Jorge,
7 Faial and Pico, while the eastern group includes São Miguel and Santa Maria. Both groups
8 are in the vicinity of the Eurasian-African-Nubian plate boundary. This region shows an
9 anomalously thick crust (*Silveira et al., 2010*) with modern volcanism (1957 Capelinhos
10 volcano in Faial and 1999–2000 underwater eruption near Terceira) (*Pacheco et al., 2013*)
11 and recent moderate to high magnitude seismicity (1980 - *M7.2*, 1997 - *M5.1* and 1998 -
12 *M6.2* earthquakes) (*Borges et al., 2007*). The most important geological structures are the
13 Terceira Rift, aligned by Graciosa, Terceira and São Miguel islands, and the East Azores
14 Fracture Zone (EAFZ).

15 The archipelagos of Madeira, the Canary Islands and Cape Verde are concentrated in
16 the east Atlantic Ocean away from plate boundaries. The Madeira archipelago comprises
17 Madeira, Porto Santo, Deserta Grande and Selvagem Grande islands. The most recent
18 volcanic eruptions occurred 6500 years ago. The Canary Islands archipelago is formed by
19 seven major islands: La Palma, El Hierro, La Gomera, Tenerife, Gran Canaria,
20 Fuerteventura and Lanzarote, located less than 100 km off the north-west coast of Africa.
21 In the past 500 years, volcanic eruptions have been recorded and documented at El Hierro,
22 Lanzarote, Tenerife and La Palma. The Cape Verde archipelago lies 450–600 km off the
23 western coast of Africa and is composed of ten islands: Santo Antão, São Vicente, Santa
24 Luzia, São Nicolau, Sal, Boa Vista, Maio, Santiago, Fogo and Brava, arrayed in a west-
25 facing horseshoe shape. The volcanic activity probably started in the Oligocene/Miocene
26 and extended well into the Holocene. Historical eruptions are unknown except on Fogo,
27 a highly active volcano whose last eruptions occurred in 1995 and 2014 (*Ramalho, 2011*).

28

3. RECENT NUBIAN KINEMATICS

29 The African plate consists of two subplates separated by the East African rift system:
30 the Nubian to the west and Somalian to the east. Most of Macaronesia is part of the
31 African-Nubian Plate. The main Atlantic fractures present in this area are related to
32 different velocities of the MAR opening revealed by two main transform faults: the Gloria
33 Fault, linked to the MAR by the EAFZ and the Terceira Rift (*Fernandes et al., 2006*), and
34 the Atlantis Fracture Zone (AFZ), extending from the MAR to the Transmoroccan Fault
35 System (TFS) and limiting the Morocco subplate (*Mantovani et al., 2007*) (Fig. 1). The
36 Gloria transform fault, which is part of the Nubian-Eurasian plate boundary, involves
37 predominantly right-lateral compression along the eastern segment, strike-slip along the
38 central segment and oblique extension on the westernmost segment in the Azores.
39 *Mantovani et al. (2007)* proposed another shear zone connecting the Gloria Fault and the
40 EAFZ propagation towards the TFS, marking the Atlantic-Mediterranean transition,
41 where the Nubian-Eurasian plate boundary changes to a diffuse transpressive region,
42 comprising a wide range of active deformation. Other authors have suggested that
43 a subduction zone is forming at the south-west of the Iberian Peninsula, as a result of both

1 propagations of the Gibraltar Arc compressive stresses and pressures related to the large-
2 scale Nubian-Eurasian convergence (Duarte et al., 2013).

3 Mostly, GNSS calculations in the African-Nubian Plate offer values with slight
4 velocity differences relative to global models, around ± 1 mm yr⁻¹, but nevertheless show
5 greater differences in azimuth. Specifically, from campaign and continuous GNSS data
6 from 2001 until 2013, the African-Nubian Plate was inferred to move 4.6 ± 0.3 mm yr⁻¹
7 toward S87.9°W (167.9°) $\pm 3.3^\circ$ (95% uncertainty) relative to Eurasia in the Azores
8 (Marques et al., 2013a), similar to the NNR-MORVEL56 model value of
9 4.5 ± 0.4 mm yr⁻¹ toward S68.1°W (148.1°) $\pm 2.8^\circ$ (DeMets et al., 2010), mainly
10 depicting an azimuth difference of nearly 20°. Another relevant aspect is that the NNR-
11 NUVEL1A model (DeMets et al., 1994) considers Terceira (station TERC, see Fig. 1),
12 Graciosa (station AZGR) and eastern São Miguel (station FRNS) as part of the Eurasian
13 Plate, and western São Miguel (station PDEL) and Pico (station PIED) as part of the
14 African-Nubian Plate. The horizontal velocity of the African-Nubian Plate computed by
15 the UNAVCO plate motion calculator (<https://www.unavco.org/software/geodetic-utilities/plate-motion-calculator/plate-motion-calculator.html>),
16 with Eurasia as the
17 reference plate, was 4.0–4.2 mm yr⁻¹ with an azimuth of S65°–75°W (245°–255°) for
18 both stations (PDEL and PIED). Within the central group, the Pico/Faial volcanic ridge
19 was shown to move mostly with the African-Nubian Plate, Terceira island moves mostly
20 with the Eurasia Plate, and São Jorge island has an intermediate position between African-
21 Nubian and Eurasian Plates (Marques et al., 2013a; Mendes et al., 2013). Similar values
22 were calculated by Borges et al. (2007) who found an average seismic strain rate of about
23 4.4 mm yr⁻¹ with a NW direction for the period 1980–1998. Subsidence was detected on
24 Terceira island between 1999 and 2006 based on GPS (Miranda et al., 2012) and also
25 between 2001 and 2013 by combining InSAR and GPS techniques (Marques et al., 2015).

26 Near Gibraltar, velocities in stations TENT, SFER and CEU1 present values between
27 4.4 and 4.7 mm yr⁻¹ and azimuths of N40°–50°W (310°–320°) from NUVEL1A, with
28 Eurasia as the reference plate, using the UNAVCO Plate Motion Calculator, while
29 southwards horizontal velocity magnitude decreases to 3.9 mm yr⁻¹ and an azimuth of
30 N41°W (319°) in station RABT. Koulali et al. (2011) inferred a south-westward motion of
31 the Rif Mountains in northern Morocco⁶, with velocities between 3.5 and 4 mm yr⁻¹.
32 McClusky et al. (2003) determined an NW-SE convergence within the Mediterranean,
33 with a larger westerly component of motion than NUVEL1A, with Eurasia as the
34 reference plate, ranging from 5.4 ± 1 mm yr⁻¹ in the Eastern Mediterranean to
35 4.5 ± 1 mm yr⁻¹ near Gibraltar. The study of Pérez-Peña et al. (2010) found slight
36 differences in azimuth between their calculations and NUVEL1A between 1995 and 2005
37 in Southern Spain. Finally, Vernant et al. (2010) showed that the deformation associated
38 with the Nubian-Eurasian plate boundary that occurs in the Betic-Rif-Alboran domain has
39 velocities of around 4 mm yr⁻¹, and showed azimuths in clockwise rotation between
40 CASC and RABT stations between 1997 and 2009.

41 In the region defined by Madeira, the Canary Islands and Cape Verde archipelagos,
42 horizontal velocities follow the MAR transform fault direction of SW-NE. A recent GPS
43 study from 1998–2005 showed similar velocities between MAS1 and the continental
44 TETN station and slight differences in azimuth between both and the TGCV station

1 (Serpelloni *et al.*, 2007). Martín *et al.* (2014) showed similar horizontal velocities in all
2 Canary Islands, between 2002 and 2009, so no strain within the archipelago was detected
3 with **root mean square (RMS)** values of 2 mm. However, the Canary Islands have
4 experienced an increase in seismic activity since 2003, which is considered a precursor of
5 the recent volcanic unrest and eruption on El Hierro island (López *et al.*, 2017) and an
6 overall uplift until 2011 and subsidence from then on has also been detected (López *et al.*,
7 2017). Finally, in Cape Verde, overall subsidence has been detected with data from
8 Sentinel-1 between 2017 and 2018 (Dias *et al.*, 2018).

9 4. GNSS DATA

10 In order to study the kinematics of Macaronesia, a total of 19 continuous GNSS
11 stations were selected, managed by public institutions and with public data access; six
12 GNSS stations were selected in the Azores (AZGR, PIED, TERC, PDEL, FRNS and
13 FLRS), one in Madeira (FUNC), one in Cape Verde (TGCV), three in the Canary Islands
14 (IZAN, LPAL and MAS1), four on the Iberian Peninsula (VILL, SFER, LAGO and
15 CASC) and four on the African western coastline (TENT, CEU1, RABT and DAKR)
16 (Table 1 and Fig. 1). The observation window span was nearly 15 years, from May 2000
17 to March 2015. The most representative continuous GNSS stations were selected based on
18 their long and stable time series.

19 5. METHODOLOGY AND RESULTS

20 5.1. GNSS data processing

21 The GNSS data were processed using Bernese software v.5.0, particularly the Bernese
22 Processing Engine module (Dach *et al.*, 2011), with satellite antenna bias corrections and
23 REPRO2 files (daily orbits, satellite clocks and Earth rotation parameters) (Rebischung *et al.*,
24 2016). A sampling rate of 30 s and a 10° elevation mask were applied. Hourly
25 tropospheric refraction corrections to the combined Saastamoinen (2013) and Niell (2004)
26 models were computed. The average distance between stations was 1562 km, the shortest
27 distance being 483 km and the longest 3105 km, so the Quasi Ionosphere-Free algorithm,
28 recommended for long baselines, was applied to resolve ambiguity (Mervart, 1995). Also,
29 the Ocean Tide Load bias was corrected by the GOT00.2 model (Ray, 1999; Scherneck
30 and Bos, 2002).

31 The VILL station, located on the Iberian Peninsula on the Eurasia Plate, was selected
32 as the reference in the differential positioning ionosphere-free mode, due to its very stable
33 time series in this time span (<http://www.igs.org/network>). The known reference station
34 position and velocity and precise satellite ephemeris data allow the daily coordinates to be
35 computed for each station in the ITRF2008 reference frame. From daily topocentric
36 positions (east, north and up), time series velocities were computed. The model fitted to
37 these time series was:

$$38 \quad x(t) = x_0 + v_x(t - t_0) + \sum_{i=1}^2 \left(a_i \sin(\omega_i(t - t_0)) + b_i \cos(\omega_i(t - t_0)) + \varepsilon(t) \right), \quad (1)$$

1 where $x(t)$ is the value of the topocentric coordinate at time t , t_0 is the reference epoch,
 2 x_0 is the initial position, v_x is the velocity, ω_i is the angular frequency for harmonic
 3 components, and a_i and b_i are the amplitudes of the sine and cosine, respectively. Finally,
 4 $\varepsilon(t)$ represents the noise.

5 HECTOR software was applied to estimate velocities, as well as other parameters and
 6 the noise model (Bos et al., 2013). This software uses maximum likelihood estimation
 7 (MLE) to estimate these parameters and related uncertainties. White noise and power-law
 8 noise close to flicker noise with a spectral index of -1 were considered as the optimum
 9 noise models to describe the stochastic part of the time series (He et al., 2017; Klos et al.,
 10 2018, 2019; Williams et al., 2004).

11 The horizontal velocities contain the tectonic plate motion normally defined by
 12 rotation around a Euler pole. NNR-MORVEL56 (Argus et al., 2011) defines the African-
 13 Nubian Plate Euler pole at 47.68°N and 68.44°W with an angular velocity of
 14 $0.292^\circ\text{Ma}^{-1}$. The horizontal velocities calculated by this model were subtracted from the
 15 ITRF2008 horizontal velocities of each GNSS station using EPC software (Goudarzi et
 16 al., 2014). Therefore, the eastward and westward⁸ horizontal residual velocities of the
 17 African-Nubian Plate motion (dV_{E_Eul} and dV_{N_Eul} respectively) and module (dV_{Eul})⁹ for
 18 each GNSS station were computed (see Fig. 2 and Table 2).

19 Analysing the horizontal residual velocities, without taking into account station FLRS
 20 located on the North American Plate, some aspects can be highlighted:

- 21 • All GNSS stations in the Azores archipelago have similar magnitudes and
 22 azimuths with directions between E and NE.
- 23 • There is continuous azimuth rotation of stations on the Iberian Peninsula and
 24 Gibraltar, depicted by the horizontal residual velocities in CASC, LAGO, SFER,
 25 CEU1 and TETN. These stations show similar magnitudes to those from Azores
 26 stations, although those not on the African-Nubian Plate present, as expected,
 27 higher-velocity residuals.
- 28 • All stations on the Canary Islands have small horizontal velocity residuals with E
 29 to NE azimuths, as does FUNC in the Madeira archipelago.
- 30 • DAKR and RABT, on the African western coastline, have SE azimuths and higher
 31 magnitudes than the Canary Islands.
- 32 • TGCV in Cape Verde presents no horizontal velocity residual above the GNSS
 33 accuracy, hence agreeing with NNR-MORVEL56 model velocity for the African-
 34 Nubian Plate there.
- 35 • Finally, overall subsidence was detected in all Macaronesian stations, except for
 36 DAKR and TGCV, with higher values north of São Jorge Island in the Azores
 37 (TERC nearly -9 mm yr^{-1} and AZGR with -5 mm yr^{-1}).

Table 2. Geographical coordinates, first and final date of data¹⁰, easting (V_E), northing (V_N) and vertical (V_U) velocities, all with respect to the ITRF2008 reference frame with uncertainties and the corresponding residuals after correction from the NNR-MORVEL56 Nubian Euler pole (dV_{E_Eul} , dV_{N_Eul} and module dV_{Eul}) for each GNSS station. Except for coordinates, all the values in mm yr^{-1} .¹¹

GNSS	Lat. N [°]	Lon. E [°]	V_E	V_N	V_U	σ_E	σ_N	σ_U^{12}	dV_{N_Eul}	dV_{E_Eul}	dV_{Eul}
AZGR	39.08786	-28.02295	14.52	17.87	-5.20	1.21	0.74	1.85	3.68	6.42	7.40
CASC	38.69342	-9.41852	18.25	18.14	-4.74	0.37	0.38	0.39	-0.56	6.55	6.57
CEU1	35.89197	-5.30639	15.96	17.41	-5.32	0.29	0.53	0.81	-2.09	2.27	3.09
DAKR	14.72090	-17.43950	21.15	14.68	3.87	2.56	0.76	4.07	-2.32	1.45	2.74
FLRS	39.45383	-31.12639	-10.59	21.43	-2.84	0.64	0.45	1.32	8.13	-18.10	19.84
FRNS	37.76933	-25.30821	15.11	16.02	-5.12	0.63	0.49	2.15	1.02	5.92	6.01
FUNC	32.64795	-16.90762	13.93	18.23	-4.41	0.43	0.46	1.18	1.13	1.04	1.54
IZAN	28.30806	-16.49968	18.16	17.06	-2.40	0.30	0.31	0.39	1.12	1.36	1.76
LAGO	37.09894	-8.66838	16.58	17.06	-1.05	0.32	0.40	1.36	-1.83	5.67	5.96
LPAL	28.76387	-17.89383	16.94	17.21	-1.25	0.26	0.34	1.32	0.16	2.19	2.20
MAS1	27.76374	-15.63328	12.87	15.95	-1.68	0.33	0.27	0.81	-0.18	1.85	1.86
PDEL	37.74775	-25.66277	11.89	14.77	-2.59	1.13	0.67	1.36	1.06	3.68	3.83
PIED	38.41382	-28.03246	16.73	17.85	-3.54	0.19	0.26	0.46	0.57	3.40	3.45
RABT	33.99810	-6.85429	15.93	16.94	-1.87	0.33	0.37	0.52	-1.35	2.64	2.97
SFER	36.46435	-6.20564	12.21	17.50	-0.24	0.41	0.39	1.04	-2.45	2.63	3.59
TERC	38.71899	-27.15299	15.53	16.31	-8.81	0.36	0.39	0.80	3.11	3.72	4.85
TETN	35.56160	-5.36300	18.82	16.00	-1.18	1.10	0.53	3.00	-3.18	1.73	3.62
TGCV	16.75477	-22.98276	19.23	16.32	0.47	0.21	0.23	0.05	0.40	0.23	0.46
VILL	40.44359	-3.95198	14.52	17.87	-1.75	1.21	0.74	1.85	-3.38	7.04	7.81
Average (without FLRS)			16.22	16.87							

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5.2. Cluster analysis

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Statistical cluster analysis (*Kaufman and Rousseeuw, 1990*) was performed to evaluate similarities in the horizontal residual velocities and thus to group stations based on their kinematics. This method has been previously applied to GNSS data in California to classify stations within the San Andres fault system (*Savage and Simpson, 2013; Simpson et al., 2012*) and is widespread in GNSS studies (*Özdemir and Karshoğlu, 2019*).

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The k -means clustering method (*Larose and Larose, 2014*) was applied to the horizontal residual velocity space. This approach groups the data set into a defined number of clusters, k . The algorithm consists of randomly assigned k records (residual velocities) as the initial cluster centre locations. For each record, the nearest cluster centre using the Euclidean distance was found. A subset of the records was assigned to each centroid, representing partition of the data set or cluster. For each of the k clusters, the mean value of the records was found, named the centroid, and the location of each cluster centre updated to the new value of the centroid. This process was repeated until the centroids no longer changed or there was no significant shrinkage in the mean squared

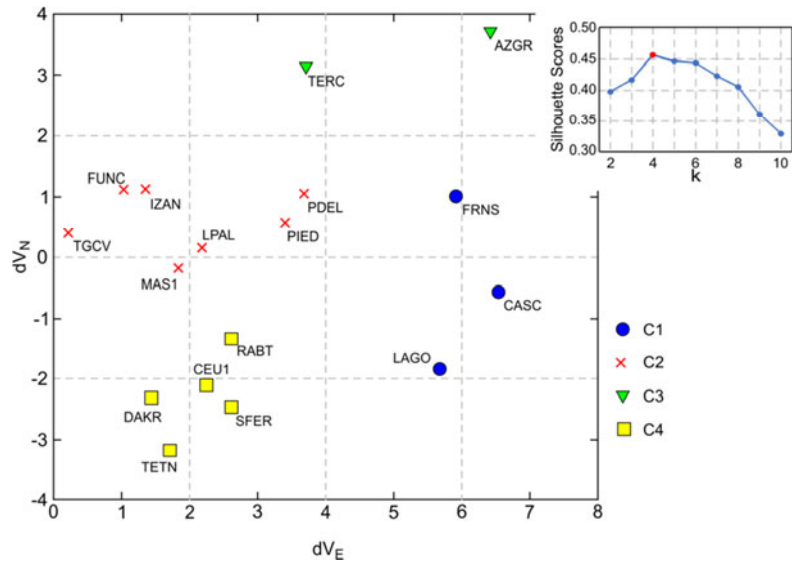


Fig. 3. Four clusters obtained from the cluster analysis using residual north and east velocity components (dV_N and dV_E) in the studied period. Inset shows the mean silhouette values of data grouped from two to ten clusters; mean value is maximum for number of clusters $k = 4$. See Table 1 for GNSS station codes.¹³

1 error. To determine the optimal number of clusters k , the silhouette criterion (*Rousseeuw,*
 2 *1987*) was chosen; see the top inset of Fig. 3. The stations VILL and FLRS were excluded
 3 from this process because VILL was chosen as a reference station and FLRS is a cluster
 4 itself due to its very different velocity compared to the other stations, as it is the only one
 5 on the North American Plate. The silhouette criterion suggested that the optimal number
 6 of clusters k was 4 (Fig. 3). Other clustering criteria such as hierarchical complete and
 7 ward or agglomerative nesting determined the same number. The clustering detected
 8 Eurasian (C1: LAGO, CASC and FRNS), Nubian-Macaronesian Islands (C2: PIED,
 9 PDEL, FUNC, LPAL, IZAN, MAS1 and TGCV), Terceira Rift (C3: AZGR and TERC)
 10 and Gibraltar-African (C4: SFER, CEU1, TETN, RABT and DAKR) behaviours.
 11 Grouping of the Azores stations in three different clusters (C1, C2 and C3) highlights the
 12 tectonic complexity within this archipelago and, further, subdivision into five and six
 13 clusters affected only the Azores stations (AZGR, TERC, PDEL and PIED). Table 3
 14 shows the mean horizontal residual velocities and the mean azimuths for each group.

15 5.3. Strain rate computation

16 A first approximation to the velocity field description may be given by the t parameter
 17 as defined by *Teza et al. (2012)*. This parameter highlights differences in sign and
 18 magnitude between the easting (V_E) and northing (V_N) components of the horizontal
 19 velocity residuals and, hence, identifies regions with similar kinematic behaviours and
 20 their corresponding boundaries. The t parameter is given as:

Table 3. Kinematic clusters with mean horizontal residual velocity (V), mean azimuth (Az) and corresponding root mean square errors (σ) in ITRF2008 reference frame.¹⁴

	V [mm yr ⁻¹]	σ_V [mm yr ⁻¹]	Az [°]	σ_{Az} [°]
Eurasian	6.2	0.3	101.4	9.2
Nubian-Macaronesian Islands	2.2	1.2	65.5	24.6
Terceira Rift	6.1	1.8	55.1	7.1
Gibraltar–African	3.2	0.4	316.4	13.8

$$t = \frac{V_E - V_N}{V_E + V_N}. \quad (2)$$

As defined, if velocity components present the same sign, they have values in the interval $[0, 1]$ for $|V_E| > |V_N|$ and in the interval $[-1, 0]$ for $|V_E| < |V_N|$, whereas if velocity components present opposite signs, they have values in the intervals $[1, \infty]$ and $[-\infty, 1]$ for $|V_E| > |V_N|$ and $|V_E| < |V_N|$, respectively. The t values were also computed in the nodes of a regular grid of 300×300 km, without nodes inside a buffer of 300 km from each station. In these regular grid nodes, horizontal velocities were computed in ITRF2008 with the UNAVCO Plate Motion Calculator, with values of 16.3 mm yr^{-1} for easting and 17.1 mm yr^{-1} for northing (23.6 mm yr^{-1} in magnitude), which are similar to the mean horizontal velocity for all GNSS stations in this study, with values of $16.2 \pm 0.5 \text{ mm yr}^{-1}$ for easting and $16.8 \pm 0.6 \text{ mm yr}^{-1}$ for northing ($23.4 \pm 0.8 \text{ mm yr}^{-1}$ in magnitude). Finally, the ordinary kriging technique was applied to interpolate the t parameter from this regular grid and GNSS station horizontal velocity. The t prediction standard error rates were calculated to show the interpolation quality rates (Fig. 4a).

Following Fig. 4a, the t parameter distinguishes four regions in Macaronesia and allows a deeper analysis:

- The Azores central and eastern islands region which, from east to west, presents positive to negative t values where two major structures are identified: the Terceira Rift and Pico-Faial volcanic ridge (Marques *et al.*, 2013b; Silva *et al.*, 2018).
- The Gibraltar arc region with low positive t -values to the east and near zero to the west.
- The Madeira and Canary Islands regions have similar negative t values, though these values are lower in the islands of Madeira, Tenerife, Gomera, La Palma and El Hierro compared to Gran Canaria, Lanzarote and Fuerteventura, possibly due to an alignment of high seismic activity between the islands of Tenerife and Gran Canaria (Fig. 2).
- Finally, the Cape Verde and Dakar regions with positive t values, near zero in Cape Verde, agreeing with no significant horizontal velocity residuals relative to African-Nubian Plate motion in Cape Verde, becoming slightly higher towards the African coastline.

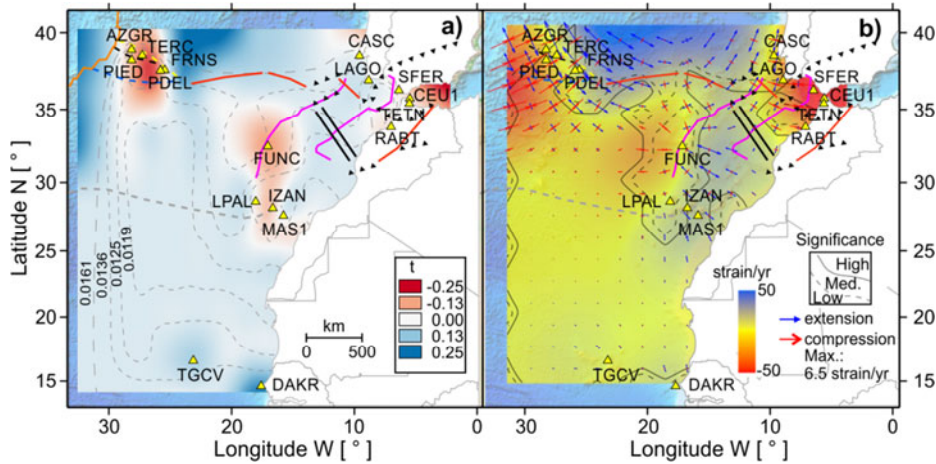


Fig. 4.¹⁵ Macaronesia t parameter (Eq. (2)) and strain rate field maps for 2000–2015. **a)** Kinematic field based on t parameter rates; t prediction standard error rates shown with dotted and dashed isolines. **b)** Strain rate field represented by extension and compression. **Inside two solid thin white lines**¹⁶, the map shows a branch of low Curie point depth values that extends continuously from the Canary Archipelago to the Gulf of Cadiz, as in *Catalán et al. (2019)*. Black continuous, dashed and dotted curves delimit high, medium and low significance, respectively. See Fig. 1 for the meaning of individual features and Table 1 for GNSS station codes.¹⁷

1 Additionally, the strain was computed for the same grid. SSPX Software (*Cardozo and*
 2 *Allmendinger, 2009*) and the grid strain package (*Teza et al., 2008*) were used to compute
 3 the strain rate at the nodes of the grid. A total of 98 points with 17 real values in GNSS
 4 stations (except FLRS and VILL) were included. For every grid node, the principal strain
 5 rates (eigenvalues of the strain rate tensor) and the corresponding directions
 6 (eigenvectors) were found. The grid resolution was set at 200 km and the grid distance
 7 weighted routine was applied with a 300 km weighting factor to infer global patterns of
 8 strain rates, where negative values indicate compression and positive values extension
 9 (Fig. 4b). The strain rate allows distinction between regions with distinct tectonic
 10 deformation patterns and boundaries between them as follows (Fig. 5):

- 11 • The Canary Islands archipelago presents horizontal residual velocities and a strain rate similar to those of Madeira.
- 12 • North-eastward from the Canary Islands to southern Spain, on the Morocco subplate, the strain rate has positive values (20 to 40 strain yr⁻¹) with an azimuth of 115° (see also Fig. 4b), due to different velocity values between islands (lower) and continents (higher).
- 13 • From westernmost Macaronesia towards the east, lower kinematic rates induced a decrease in the extension rate, where the strain field changes from compression of about 0 to -50 strain yr⁻¹ with an azimuth of 60° on the main axes to extension of about 20 to 0 strain yr⁻¹ with an azimuth of 115° near to the shear zone.

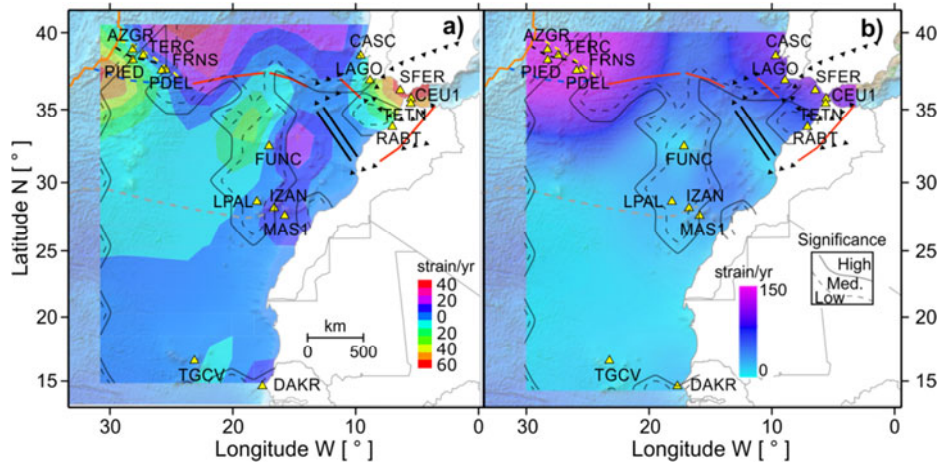


Fig. 5.^{18,19} a) Macaronesia strain-rate changes for 2000–2015; b) rates of engineering shear normalised to strain-rate changes.²⁰

- 1 • Extension rates close to 0 strain yr^{-1} appear to the east of the shear zone. Area
- 2 strain change and shear strain analysis showed a region from the Canary Islands
- 3 towards the Iberian Peninsula of $20 \text{ to } 40 \text{ strain yr}^{-1}$ (Fig. 5).
- 4 • The shear strain rate field further highlights the subdivision of Macaronesia into
- 5 four regions again: a) values of $\sim 150 \text{ strain yr}^{-1}$ can be found in the north-west of
- 6 Macaronesia (Azores) with an extensional mechanism where the east of the Gloria
- 7 Fault is characterised by a dominant right-lateral strike-slip; b) the Strait of
- 8 Gibraltar is more diffuse with strain values of $\sim 100 \text{ strain yr}^{-1}$, a) and b) both
- 9 having high seismic activity and being located at plate boundaries (Fig. 1);
- 10 c) values of $\sim 75 \text{ strain yr}^{-1}$ were obtained in the Canary Islands and Madeira
- 11 archipelago as intraplate strain; and d) values near zero were obtained for the Cape
- 12 Verde and Dakar regions (Fig. 5b).

13 6. DISCUSSION

14 Three different approaches were used to analyse kinematics in the Macaronesia region,

15 from nearly 15-year-long time series, between 2000 and 2015, of 19 GNSS public

16 permanent stations. These GNSS time series are long enough to allow for horizontal

17 velocities with uncertainty of less than 1 mm yr^{-1} (Blewitt and Lavallée, 2002). The

18 horizontal velocities computed for the African-Nubian Plate show an average magnitude

19 of $16.1 \pm 2.5 \text{ mm yr}^{-1}$ east and $16.8 \pm 1.1 \text{ mm yr}^{-1}$ north with a mean module velocity of

20 $23.3 \pm 1.8 \text{ mm yr}^{-1}$ and direction of $46.4^\circ \pm 5^\circ$. The direction is comparable to that

21 obtained by NNR-MORVEL56 of 44°N in this zone (Argus et al., 2011) and similar to

22 those from previous GNSS studies (Marques et al., 2013a; Miranda et al., 2012). This

1 mean module velocity is analogous to the value in ITRF2008 using the UNAVCO Plate
2 Motion Calculator that was applied as a standard value in the strain computation.

3 Rigidity seems to be a fundamental aspect of the African-Nubian Plate (*Burke and*
4 *Wilson, 1972; Malservisi et al., 2013*) and recent kinematics from GNSS studies by
5 *McClusky et al. (2003), Serpelloni et al. (2007) and Martín et al. (2014)* agree that there is
6 no significant internal deformation ($> 1 \text{ mm yr}^{-1}$). This new analysis shows values
7 $> 1 \text{ mm yr}^{-1}$ using more stations, without episodic data and a longer observation interval
8 than those previous studies. Only the horizontal velocity residual for Cape Verde (TGCV
9 station), relative to NNR-MORVEL56, is under the GNSS precision ($< 1 \text{ mm yr}^{-1}$), in
10 agreement with global plate motion models, being the area where some authors locate the
11 Euler pole for the African-Nubian Plate, therefore offering almost zero drift motion
12 (*McClusky et al., 2003*). In all other areas, residuals are higher; for example, in Madeira
13 and the Canary Islands, the horizontal residual velocities relative to the NNR-
14 MORVEL56 model present values between 1 and 2 mm yr^{-1} , and on the continental
15 margin of Africa the values reach 2–3 mm yr^{-1} (DAKR and RABT stations). As expected,
16 stations in the Azores and Gibraltar arc regions present horizontal velocity residuals
17 greater than 3 mm yr^{-1} , influenced by their high seismicity, their proximity to plate
18 boundaries and/or their location outside the African-Nubian Plate.

19 Different kinematic behaviours have been marked by the three different approaches
20 applied. Firstly, the t parameter highlights anomalous kinematics in the oceanic intraplate
21 (Canaries and Madeira archipelagos) and Azores archipelago as the main nonconforming
22 velocity residuals (Fig. 4a).

23 Secondly, from cluster analysis, stations in the Azores archipelago were classified into
24 three different groups. Although PDEL and FRNS stations are both on São Miguel Island,
25 they were assigned to African-Nubian and Eurasian groups, respectively. Furthermore,
26 FRNS not only has different horizontal ground displacement compared to PDEL but also
27 has twice the subsidence of PDEL. This separation within São Miguel has already been
28 identified previously (*DeMets et al., 1994; Marques et al., 2013a; Weiss et al., 2015*), here
29 with an inferred extension strain rate of near 13 strain/yr and azimuth of 260° . AZGR and
30 TERC, with a strain rate of near 6 strain yr^{-1} and azimuth of 253° , were not assigned to
31 either the Eurasian or Nubian–Macaronesian Islands groups. This is due to the influence
32 of the Terceira Rift extension and is in agreement with previous studies (*Marques et al.,*
33 *2015; Mendes et al., 2013; Miranda et al., 2012*). PIED on Pico island and PDEL were
34 grouped with Madeira, Canary Islands and Cape Verde stations, therefore with Nubian-
35 Macaronesian behaviour, however revealing ground displacement slightly induced by the
36 Terceira Rift (*Hipólito et al., 2014; Madeira et al., 2015*). Although cluster analysis
37 detected differences on São Miguel, it did not detect significant differences on the Canary
38 Islands, despite the clear azimuth difference of the velocity residuals of IZAN station in
39 Tenerife. Nevertheless, within the Canary Islands, compression was inferred west and
40 extension was inferred east, following previous studies. In the numerical stress model
41 from *Geyer et al. (2016)*, areas of deformation were deduced from local structural
42 discontinuities which depend on pressure values applied to the EAFZ. The strain rate in
43 the Canary Islands was calculated as positive (extension) in the NW-SE direction. This
44 direction is perpendicular to the NE-SW line that coincides with a seismically active
45 oblique reverse fault that separates the Tenerife (NE orientation) and Gran Canaria (SE

1 orientation) insular blocks (Ruiz *et al.*, 2000), with a transpression regime area with
2 a strain rate of 17 strain yr⁻¹.

3 Strain rate computation also showed, between Madeira and the continental margin of
4 Africa, an inferred WNW-ESE to NE-SW change in orientation of the main extensional
5 strain that may be explained by a high seismicity transform fault proposed by Mantovani
6 *et al.* (2007) (delimited by two thick black solid curves). There is an NE-SW extensional
7 strain rate and higher change area rates which progress from the north-western part of the
8 Canary Archipelago to the Gulf of Cadiz, which coincide with the shallowest Curie point
9 depths. These values were obtained in oceanic domains, being constant along this track,
10 supporting the presence of an aospheric connection between both locations (Catalán *et al.*,
11 2019) or an active mantle upwelling from a remnant plume (Miller *et al.*, 2015; Saki
12 *et al.*, 2015). The higher horizontal velocity for the stations on the continental margin of
13 Africa compared to those of Madeira, the Canary Islands and Cape Verde, although nearly
14 perpendicular, promotes a slight compression north of the Canary Islands and extension
15 south, near the continental margin. In the Gibraltar arc, the SFER velocity residual has
16 greater similarity to those of the North-African GNSS stations (CEU1 or TETN),
17 compared to CASC and LAGO also on the Iberian Peninsula. The azimuths in this region
18 indicate a rotation to accommodate a Gibraltar arc slow subduction rate and possible slab
19 roll-back, which may be responsible for the arc propagation towards Atlantic domains
20 (Duarte *et al.* 2013; Vernant *et al.*, 2010). Furthermore, the inferred NW-SE compression
21 south-west of the Iberian Peninsula and W-E west of Gibraltar are both compatible with
22 corresponding geological structures - the Gorringe ridge and the Gibraltar arc,
23 respectively (Duarte *et al.*, 2013; Zitellini *et al.*, 2009). The Gibraltar arc region presents
24 high seismic activity, overlapping faults (Geyer *et al.*, 2016; Jiménez-Munt and Negredo,
25 2003; Negredo *et al.*, 2002) and a widespread transition between plates already shown by
26 several GNSS studies (de Lis Mancilla *et al.*, 2013; Koulali *et al.*, 2011; López *et al.*,
27 2017; Zitellini *et al.*, 2009). Our results are consistent with these structures defined by all
28 these previous studies.

29 Regarding the height component, there is an overall subsidence, except for at the
30 DAKR and TGCV stations. All oceanic stations show this trend over 15 years. This
31 negative trend is similar to those from other recent GNSS studies (López *et al.*, 2017;
32 Miranda *et al.*, 2012) and DInSAR results. Top values are located in the Terceira Rift
33 group in the Azores (TERC nearly -9 mm yr⁻¹ and AZGR -5 mm yr⁻¹) and, without
34 ruling out possible local effects, this behaviour could be related to down-bending of the
35 crust by the weight of material added to the crust by active volcanoes, similar to the
36 isostatic adjustment of Miocene islands (Moore, 1970). The subsidence in Madeira and
37 the Canary Islands could be also explained by a partial magma withdrawal at different
38 depths in the mantle (Klügel *et al.*, 2015).

39 7. CONCLUSIONS

40 This study approximates present day relative motion in Macaronesia, a geographical
41 area in the north-east Atlantic ocean, based on GNSS data from 19 permanent stations
42 with a long observation period of nearly 15 years (from May 2000 to March 2015).
43 Although previous GNSS studies found no intraplate deformation, this analysis found

1 velocity residuals in regions with low to non-existent seismic activity, specifically: greater
2 than 1 mm yr⁻¹ in Madeira, between 1 and 2 mm yr⁻¹ in the Canary Islands and between
3 2 and 3 mm yr⁻¹ on the continental margin of Africa (DAKR and RABT stations). In
4 addition, stations in the Azores and Gibraltar arc regions present horizontal velocity
5 residuals greater than 3 mm yr⁻¹, influenced mainly by their proximity to plate boundaries
6 and with directions according to previous studies.

7 The similar kinematic behaviour between islands is not followed by stations on the
8 continental margin of Africa. The difference in magnitude, but particularly in azimuth,
9 causes the inferred strain rate extension NW-SE in the Canary Islands to shift to W-E
10 to the east of Madeira and NE-SW at the Gloria Fault. From seismicity, kinematic and strain
11 data analysis, a shear zone was located in harmony with other studies (*Mantovani et al.,*
12 *2007*). Seismic activity and strain rates suggest some dextral strike-slip deformation
13 occurring within the Morocco subplate along a NNW-SSE direction from the Goringe
14 Bank to Agadir, and/or a remnant mantle plume upwelling (*Saki et al., 2015*).

15 In the Canary archipelago, horizontal residual velocities show a slight azimuth shift
16 that affects the strain rate between Tenerife and Gran Canaria. The strain rate in the
17 Canary Islands, inferred as positive (extension) in the NW-SE direction, is perpendicular
18 to the NE-SW seismically active oblique reverse fault identified in previous studies
19 (*Barbero et al., 2018*). It could be also due to a temporary magma accumulation zone that
20 contributes to deep endogenous growth and uplift of the volcanoes.

21 All GNSS stations in the Macaronesian islands show subsidence, possibly linked to
22 isostatic adjustment of volcanic islands (*Moore, 1970*). Finally, although this study
23 presents large areas without GNSS stations, limiting conclusions there, in regions covered
24 by several GNSS stations our GNSS data analysis presents consistency with and support
25 to previous local studies, providing an overall interpretation of the recent intraplate
26 kinematics of the African-Nubian Plate, particularly between emerged land.

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- ¹ Please, specify also the city.
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 - ¹⁹ The same as in the bw case of Fig. 4a. Moreover, in bw Fig. 5b the scale does not correspond to the plot, there are darker greys in the plot.
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