The Tectonic Evolution of the Azores Based on Magnetic Data

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Abstract

The Azores attracted the interest of geoscientists since the beginning of the XX century. In the late 60s, when plate tectonics was established as the basic geodynamic paradigm, the peculiar morphology of the Azores Islands and the surrounding plateau, located close to the Mid-Atlantic ridge, were early interpreted as the result of the separation between the Eurasian and the North-America plates. Nevertheless, a number of particular geological features were targeted for explanation: (i) the long active fault going from Gibraltar to the Azores (now called Gloria Fault), (ii) the existence of a large but inactive fracture on the North-American plate, offset tenths of kilometres to the north with respect to Gloria Fault, (iii) the curvilinear succession of islands marked by pervasive volcanic and seismic activity, (iv) the development of a plateau, partially split by the Mid-Atlantic Ridge. These questions remained elusive for a long time, despite the large amount of geological and geophysical data available, as most of the conventional approaches were not as fruitful as expected, and new identified features raise new unknowns or revealed uncommon geological environments. Here, we present a review of the progress made in the understanding of the tectonic evolution of the Azores, mainly based on the interpretation of magnetic and morphological data and we present an updated interpretative scheme for the genesis and evolution of the Azores triple junction.

1 Triggering of the Azores Triple Junction

The early identification of the Azores morphological plateau can be traced up to 1855 (Vogt and Jung, Chapter "The "Azores Geosyndrome" and Plate Tectonics: Research History, Synthesis, and Unsolved Puzzles"). Early works by Azores researchers include the pioneering studies made by Agostinho (1927) and Machado (1959).

The use of magnetic data to derive the first kinematic interpretation of the Azores was attempted by Krause and Watkins (1970), based on the pioneering works of Heirtzler et al. (1968) on marine magnetic anomalies, and the first sea-floor spreading models (Le Pichon 1968). They were particularly puzzled by a number of "unique" features: (i) the seismically active East Azores Fracture Zone (EAFZ) extending from Gibraltar to the Mid-Atlantic Ridge; (ii) the

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seismically inactive West Azores Fracture Zone (WAFZ, often misleadingly called “Pico Fracture Zone”) offset northwards from the trend of EAFZ; (iii) the transverse island chain of the Azores, almost linear, but oblique to the EAFZ; (iv) the change in direction of the Mid-Atlantic Ridge (MAR) from northeast-southwest to north-south across the Azores; and (v) the broadening of the Mid-Atlantic Ridge (Krause and Watkins 1970; Vogt and Jung, Chapter “The “Azores Geosyndrome” and Plate Tectonics: Research History, Synthesis, and Unsolved Puzzles”).

Some of these questions were early explained by Krause and Watkins (1970) as consequences of differences between plate spreading directions and velocities, north and south of the East Azores Fracture Zone after the establishment of a new plate boundary new plate boundary. Using simple geometric considerations, Krause and Watkins (1970) concluded that the onset of velocity contrast is older than 45 Ma. This would have triggered the development of a secondary spreading axis, within a “leaky transform” environment, and creating a triple junction between the Eurasian, African and North America plates. The change in spreading directions was also interpreted as the responsible for the latitudinal offset between the EAFZ and the WAFZ. Krause and Watkins (1970) considered EAFZ as an active feature, in contrast to WAFZ, considered a fossil structure within the single North-American plate. Using 13.3 mm/year as the half-spreading rate between the Eurasian and North American plates immediately north of the Azores, and 11.0 mm/year for the African and North American plate pair, south of the Azores, they predicted a 2.5 mm/year of half-spreading rate for Terceira Rift and partially checked this computation with the direct modelling of three magnetic profiles across almost perpendicular to the new rift. Additional geophysical surveys (Schilling and Krause 1970; Krause and Schilling 1970) were made in the following years to test their interpretation, but new interpretations were never presented afterwards.

The rough estimation made by Krause and Watkins (1970) for the triggering of the Azores triple junction was refined by Srivastava et al. (1990) based on the analysis of a large compilation of magnetic data for the North Atlantic and on a hypothesis put forward by Schouten et al. (1984) that the Iberian plate has either been attached to Africa or to Eurasia at various times. They show that (i) Iberia was attached to Africa from the late Cretaceous to middle Eocene; (ii) between the middle Eocene to late Oligocene it behaved as an independent plate with slight motion relative to Africa, while most of the deformation was concentrated along its northern border, which corresponds now to the King’s Trough and Azores-Biscay Rise; (iii) Iberia became part of the Eurasia plate since the late Oligocene (Srivastava et al. 1990), ultimately leading to the development of a plate boundary south of the Iberian plate along the Azores-Gibraltar Fracture Zone (see Fig. 1 for locations).

The structure and geometry of this plate boundary was studied in the early seventies by Laughton and Whitmarsh (1974) and Laughton et al. (1975). They made bathymetric and side-scan sonar surveys between Gibraltar and the Mid-Atlantic Ridge, mapping a major scarp now called Gloria Fault, where several large magnitude strike-slip earthquakes were known to occur. The Gloria Fault was interpreted as a segment of the plate boundary separating Eurasia from Núbia and it was confirmed that close to the Azores, west of 25°W, there is no continuity between Gloria Fault and a marked topographic linear depression that corresponds to the now called East Azores Fracture Zone (EAFZ), earlier interpreted also as part of the plate boundary (see Krause and Watkins 1970). East of the Gloria fault, the geometry of the plate boundary up to the Mediterranean Sea is still controversial.

Luis and Miranda (2008) improved the magnetic compilation of the North Atlantic and re-interpreted the magnetic chrons of the Eurasia-North America plate pair. They confirmed most of the interpretation made by previous studies (e.g. Srivastava et al. 1990) and concluded that the establishment of the Azores triple junction occurred between chrons C6c (ca. 24 Ma) and C11-C12 (ca. 30 Ma) following the

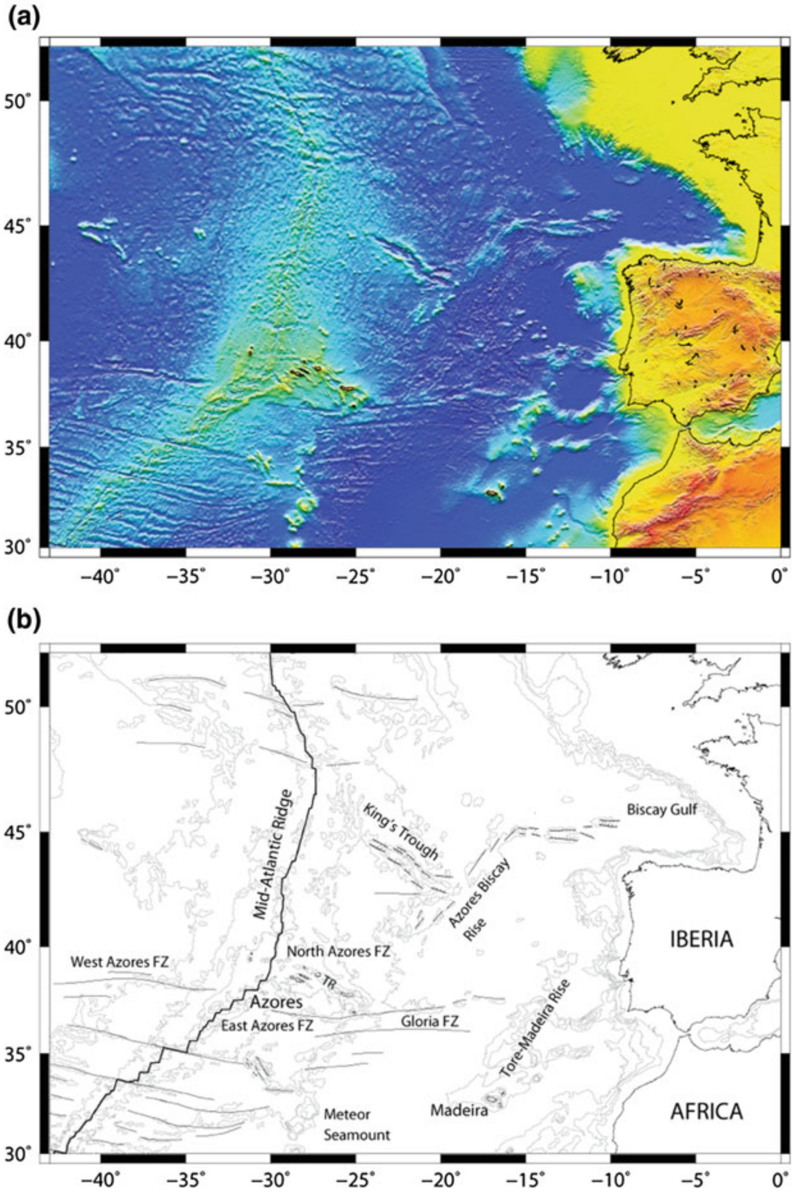

Fig. 1 General framework of the Azores triple junction. Main morphological structures are sketched below: FZ: Fracture Zone. The plate boundary between Eurasia and Nubia is supposed to presently follow Terceira Rift (TR in the figure), Gloria Fault up to Tore-Madeira Rise. Close to Iberia the plate boundary becomes more complex and its geometry within the Southwest Iberian transpressive area is controversial

welding of Iberia to Eurasia, at ~27 Ma ago. Main stages can be simply summarised as:

(i) The initial opening of the North Atlantic at the latitude of Iberia took place after chron M0 (~120 Ma); Spreading continued during Cretaceous times, leading to the opening of Biscay Gulf and the development of a plate boundary along the Azores-Biscay Rise and King's Trough;
(ii) At ~27 Ma Iberia became welded to Eurasia and its northern plate boundary became

inactive. Extension developed south of the Iberian plate leading to the onset of a new triple junction, presently known as the Azores Triple Junction (ATJ).

2 Northward Migration of the Azores Triple Junction

Searle (1980) improved the bathymetric and the magnetic compilations and acquired a large set of side-scan sonar data between the Azores islands and the Mid-Atlantic Ridge (MAR) to understand the geometry of the triple junction. He confirmed several of the Krause and Watkins (1970) interpretations, and proposed a final configuration change corresponding to a northward jump of the Eurasia-Africa plate boundary. This jump took place from the latitude of the East Azores Fracture Zones, to the vicinity of the North Azores Fracture Zone, which would connect the western tip of Terceira Rift to the MAR (Searle 1980) and would correspond to its present-day location. This interpretation was challenged by Luis et al. (1994) based on a detailed Azores Aeromagnetic Survey covering mostly the area close to the MAR, up to chron C5 (~10 Ma) on both plates. They concluded that the Eurasia-Nubia-North America triple junction was located north of the East Azores Fracture Zone between chron C4 and chron C3a, approximately at 38°20′N, 30°15′W (Eurasia fixed co-ordinates) and proposed a present-day location close to 38°55′N, 30°00′W (Eurasia fixed co-ordinates), after chron C2a, approximately 2.45 Ma ago, and not to the North-Azores Fracture Zone as predicted by Searle (1980).

The Azores plateau is interpreted by Schilling (1975) as a hotspot derived feature (see also O'Neill and Sigloch, Chapter "Crust and Mantle Structure Beneath the Azores Hotspot—Evidence from Geophysics"). Geochemical studies (e.g. Dosso et al. 1999) detect a long wavelength geochemical anomaly from 33°N to 41°N and seismic tomography (Yang et al. 2006) confirms the existence of an anomaly on body wave seismic velocity matching the plateau (O'Neill and Sigloch, Chapter "Crust and Mantle Structure Beneath the Azores Hotspot—Evidence from Geophysics"). Gente et al. (2003) studied the role of mantle processes in the time evolution of the Azores triple junction. They hypothesize that a plume was formed at ~85 Ma ago, SW of the Azores and that it is responsible for the early formation of the Azores plateau between 20 and 7 Ma. Gente et al. (2003) invoke a "magmatic phase" followed by a "tectonic phase", splitting the western from the eastern plateaus.

Numerical modelling shows that the topographic excess associated with the plateau can be partially attributed to the geometry of the triple junction (Georgen and Sankar 2010) but most of it is of dynamic origin (Adam et al. 2013). The shift between the magmatic and the tectonic phases corresponds to chron C4a, and matches a sudden global ~25% decrease in spreading velocity occurring between ~8.2 and ~6.2 Ma simultaneously in both plate pairs (Merkouriev and DeMets 2008, 2014a, b). Despite the relevance of the mantle processes in the buildup of the Azores domain, abyssal hill morphology is not destroyed (see Miranda et al. 2014) thus implying that most of the plateau construction is sub-crustal.

Recent data acquired in the framework of the project for the extension of the Portuguese continental shelf allow a better description of magnetic anomalies over the entire plateau and provide reliable magnetic chrons (see Miranda et al. 2014), which confirm some of the abovementioned hypotheses (see Fig. 2):

(i) Between the Mid-Atlantic Ridge and chrons C4a-C5 ocean floor magnetic anomalies are well developed and spreading is mostly regular since chron C4a, coherent with the split of the pre-existing plateau into an "eastern" and a "western" units.

(ii) Magnetic anomalies are continuous between the North Azores Fracture Zone

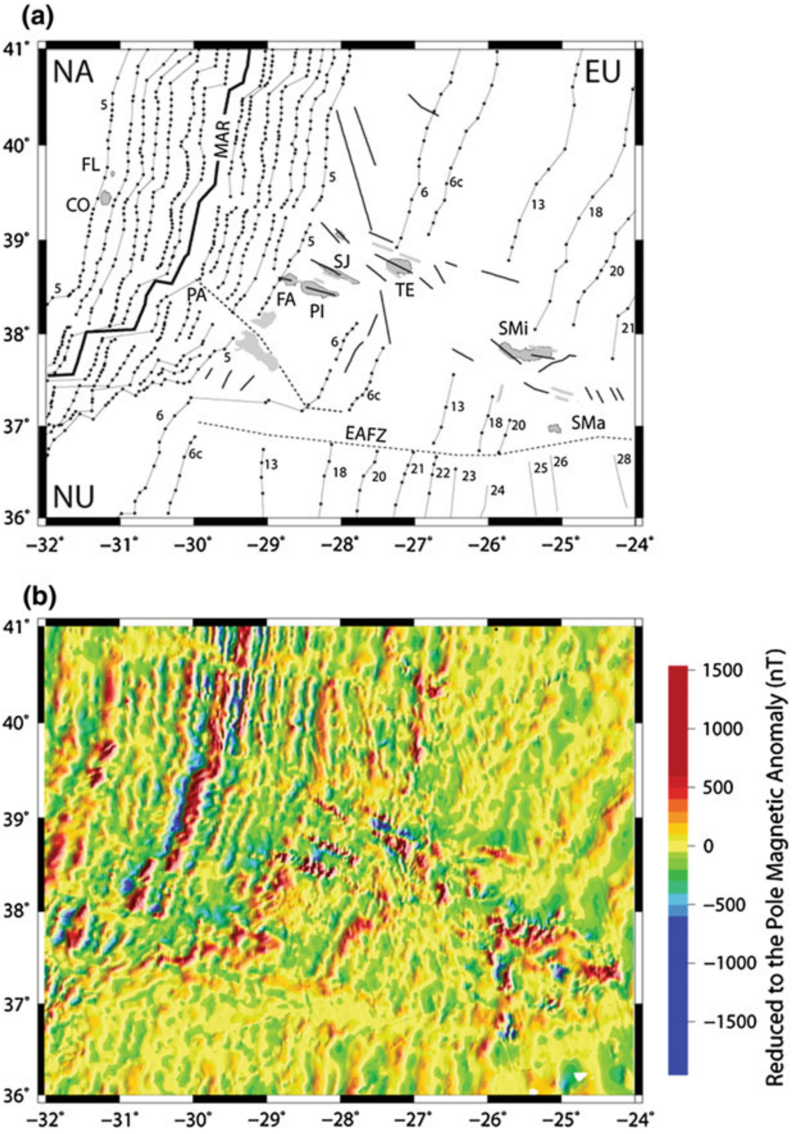

Fig. 2 **a** Morphotectonic sketch and main magnetic chrons. Magnetic chrons 5, 6, 13, 18, 20 and 21 are interpreted according to Luis and Miranda (2008). Younger chrons 2, 2A, 3, 3A, 4 and 4A are also interpreted close to the Mid-Atlantic Ridge. Along Terceira spreading axis magnetic lineations corresponding to the Brunhes epoch (black) and Matuyama (gray) are also plotted. NA: North America; EU: Eurasia; NU: Nubia; EAFZ: East Azores Fracture Zone; MAR: Mid-Atlantic Ridge; FL: Flores Island; CO: Corvo Island; FA: Faial Island; PI: Pico Island; SJ: São Jorge Island; TE: Terceira Island; SMi: São Miguel Island; SMa: Santa Maria Island. Below **b** Reduced to the Pole Magnetic anomaly map, with an horizontal resolution of 30”

and Princess Alice Basin South of 38°30′ N, with no sign of a discrete plate boundary.

(iii) There is evidence of a jump of the ridge axis to the west in the segment 38°N–38° 30′N at chron C3.

3 Rifting of the Azores Domain

The extension in the Azores domain can be quantified using the poles determined for the whole plates (Miranda et al. 2014; Merkouriev

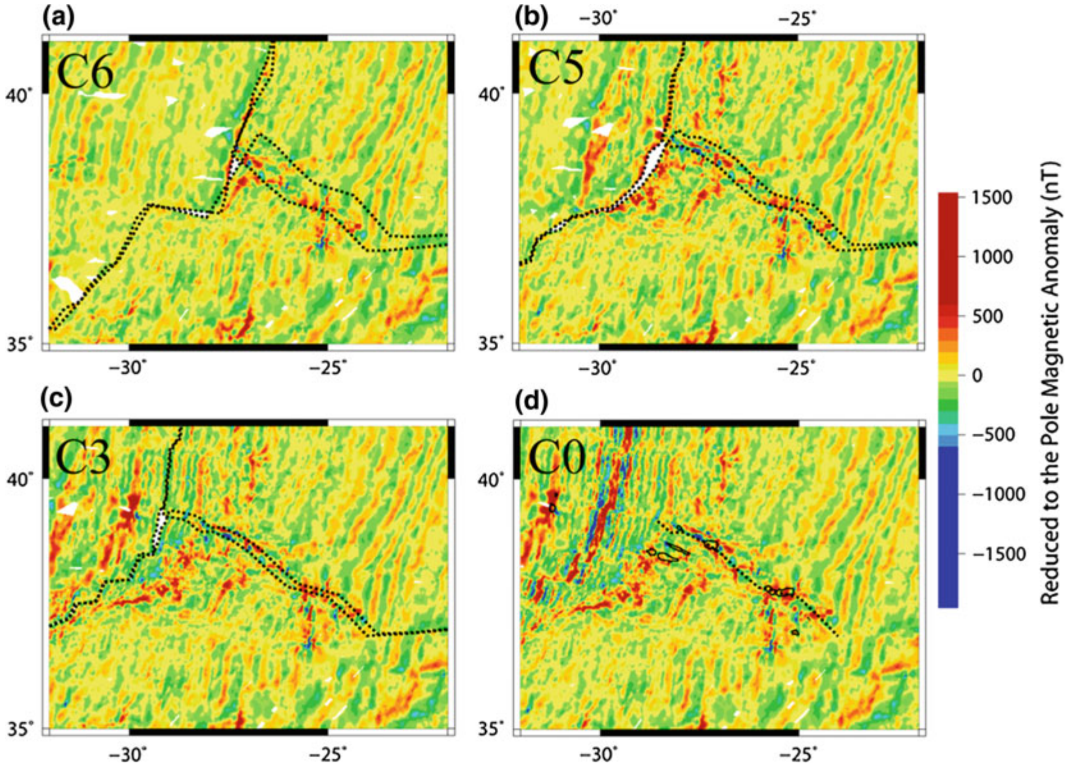

Fig. 3 Magnetic reconstruction of Eurasia, Iberia and Nubia at the time of chrons C6 (**a**), C5 (**b**), C3 (**c**) and C0 (**d**). Euler rotation parameters are taken from Miranda et al. (2014). Dashed lines delimit the lithospheric blocks based on the interpretation of magnetic anomalies. In the case of Terceira Rift they follow the shoulders of the basins as depicted in the swath bathymetry data. The Azores domain was rotated as Nubia and so, the reconstitution at C6 times shows an overlap of Nubia and Eurasia that quantifies the integrated extension that took place south of Terceira rift; the angular mismatch in the MAR segment that corresponds to the Azores plateau quantifies the integrated shear deformation that is applied to the Azores domain by the difference in velocity north and south of that segment

and DeMets 2014a, b) and reconstructing the previous locations of the "lithospheric blocks". In this case, significant overlaps or gaps between the rotated lithospheric blocks correspond to extensional or compressional processes respectively. In Fig. 3 we present the reconstructions for chrons C6 (early phase of the development of the ATJ), C5, C3 and the present configuration using Eurasian-fixed coordinates. The delimitation of the lithospheric blocks (dashed lines in Fig. 3) is based on the interpretation of magnetic anomalies and transform faults. In the case of Terceira Rift the lithospheric blocks follow the axis of the basin deduced from the location of the rift shoulders, as depicted by the swath bathymetry data. For the reconstructions corresponding to C6 when the Azores domain is rotated using Nubian poles with respect to the North American plate, there is an overlap in the north of the domain and an angular mismatch in the west. This results from the internal deformation in the Azores domain during the last ~20 Ma.

While the amount of total extension can be estimated from the magnetic reconstructions, the location of the extensional features can be inferred from morphological data. From the morpho-structural point of view two major rift features can be found in the plateau which can correspond to stable configurations of the triple junction: Terceira Rift that corresponds to the present-day configuration (see Vogt and Jung, Chapter "The "Azores Geosyndrome" and Plate

Tectonics: Research History, Synthesis, and Unsolved Puzzles"), and Princess Alice basin and bank, now located in the Nubian plate (Luis et al. 1994). The Princess Alice Basin disrupts the magnetic pattern generated by the Mid-Atlantic Ridge spreading. Its western limit follows approximately the chron 2A (~3 Ma), close to the Mid-Atlantic Ridge transform zone of 38°30′N. We interpret it as a previous location of the rift (see Fig. 2).

It is now relatively straightforward to infer the amount and probable evolution of rifting within the Azores domain (see Fig. 3):

(i) There is an overlap between Nubia and Eurasia in the magnetic reconstructions for C6 times, when the Azores domain south of Terceira Rift is rotated as Nubia. This quantifies the extension in the Azores domain that took place in the last ~20 Ma (~60 km in ENE direction).
(ii) The comparison between the total extension and the width of Terceira Rift allows to conclude that Terceira Rift accommodated most, but not all, of this extension (compare Fig. 3a, d).
(iii) The first phase of extension in the Azores triple junction was probably focused on the formerly continuous WAFZ-EAFZ transform fault, within a "leaky transform" environment. The morphology of the western segment of the EAFZ reflects this extensional phase, as well as the gap that is found between the magnetic anomalies north and south of EAFZ (see Fig. 2).
(iv) Terceira Rift is the main structure presently active, and Princess Alice basin and bank are likely remnants of a previous triple junction configuration which predated the development of Terceira Rift.

4 Spreading at Terceira Rift

The magnetic map used by Krause and Watkins (1970) to locate oceanic spreading related to Terceira rift (see also Vogt and Jung, Chapter "The "Azores Geosyndrome" and Plate Tectonics: Research History, Synthesis, and Unsolved Puzzles") was based on a few profiles where chron picking could not be robustly accomplished. Miranda et al. (1991) and Luis et al. (1994) analyses of the Azores Aeromagnetic Survey show no stable magnetic anomaly pattern parallel to Terceira rift (see Fig. 3), in disagreement with the original interpretation of Krause and Watkins (1970). They also conclude that a few high-amplitude magnetic lineaments, which could be interpreted to reflect more recent chrons, are not strictly confined to the Terceira Rift: São Jorge and the Pico-Faial Islands also show large positive magnetic anomalies with the same trend and linear prolongation on the plateau. The linear magnetic anomalies that match the volcanic highs of São Jorge, Pico and Faial islands with strikes ~N110°–N120° do not reflect topographic effects as shown by inversion (Luis 1996). Miranda et al. (1991) also show that the abovementioned young chrons could be interpreted as Brunhes and Matuyama, because their on-shore prolongation into the Faial island was confirmed by both a refined aeromagnetic survey (Miranda et al. 1991) and by radiometric dating (Féraud et al. 1980, 1981). This was interpreted as a demonstration that the Azores islands are mostly young and do not show any age progression either as a function of the distance to the MAR or a function of the distance to Terceira Rift (Miranda et al. 1991).

Hildenbrand et al. (2008) confirmed this assumption with a new set of radiometric ages of volcanic outcrops in the main units of Faial, arguing for widespread volcanism older than 800 ka, but within the Matuyama chron. The interpretation of a recent aeromagnetic survey covering the island of São Miguel (Miranda et al. 2015) shows magnetization lows associated with hydrothermal alteration above the main volcanic systems, and evidence of the Bruhnes-Matuyama transition on-shore, matching the radiometric ages determined by Johnson et al. (1998) in surface outcrops. A similar situation was found on the island of São Jorge (Silva et al. 2012) supporting the interpretation that the Matuyama-Brunhes transition is found almost everywhere in the Azores islands and that Azorean magnetic anomalies associated with the islands are younger than ~2 Ma. The exception is Santa Maria Island, believed to have formed between 5.2 and 4.6 Ma (Féraud et al. 1981), and the only island of the Azores archipelago where fossiliferous sediments of Zanclean age (5.3–3.6 Ma) were found (Abdel-Monem et al. 1975; Janssen et al. 2008).

The only place where magnetic lineations seem better developed is the East Graciosa Basin close to Terceira Island, where a succession of normal and reversed anomalies can be identified. The two anomalies with normal magnetic polarity that follow the southern and northern flanks of the rift basin are the oldest magnetic signature associated with the development of the Terceira Rift. Princess Alice basin also disrupts the MAR-related magnetic pattern and its western limit follows chron C2a (~3 Ma) at 38°30′N.

The thermal regime of Terceira rift, deduced from the analysis of gravity data also favors the interpretation that it is a young feature, with a small thermal signature which could be associated with a stable spreading regime (Luis et al. 1998).

The main conclusions can be summarised as:

(i) The Terceira rift is a relatively young feature, and the same occurs with the main volcanic islands that separate the individual basins: Graciosa, Terceira and São Miguel (see Fig. 3 for locations). Available magnetic and radiometric data point to ~3 Ma as an upper limit;

(ii) Spreading is discontinuous, with several linear magnetic anomalies that can be interpreted as the signature of linear neovolcanic ridges, sub-parallel to the rift direction;

(iii) Lithospheric rifting is focused on Terceira Rift at least after C3. So, the whole EAFZ and Princess Alice basin are now fossil. The western Eurasia-Nubia plate boundary follows now Terceira Rift and Gloria Fault. The northward migration of the plate boundary to Terceira Rift led to the subsidence of Princess Alice island, now a submerged bank (Fig. 4).

5 The Development of Linear Volcanic Ridges

The relative motion between Eurasia and Nubia after the establishment of the Azores Triple Junction was mostly accommodated by Terceira Rift, Princess Alice Rift and, in the early phases, close to the EAFZ. However, there is a significant amount of deformation along a series of Linear Volcanic Ridges (LVR) located on the Azores plateau. Islands like São Jorge, Pico and Faial are extreme cases of LVR development. Lourenço et al. (1998) mapped fault scarps, and elongated seamounts, to conclude that the two most frequent strikes are N110E-N120E, at west, and N140E-N150E, at east, in agreement with the arcuate form of the Terceira axis itself. Lourenço et al. (1998) interpreted this pattern as the result of the prevalence of co-axial oblique extension, focalised within the Terceira axis, and a stress field with minimum compressive axis sub-parallel to the opening directions predicted by geological and geodetic kinematic models.

The mechanism beyond the development of LVR in the Azores plateau was also discussed by Vogt and Jung (2003 and Chapter "The "Azores Geosyndrome" and Plate Tectonics: Research History, Synthesis, and Unsolved Puzzles"), interpreting them as traces of failed rifts either spreading obliquely (west of Terceira island) or normal (east of Terceira island) to the relative motion between the Eurasian and the Nubian plates. They also suggested that the arcuate shape of the Terceira Ridge may result from the relocation of active spreading in response to the emplacement of massive volcanic loads or tectonic piles. Such a mechanism seems valid at a broad scale and coherent with the northward migration of the Triple Junction. However, the age progression it implies for the LVR, progressively younger towards NE, is not supported by magnetic or geochronology data.

Neves et al. (2013) suggest an alternative explanation for the development of LVRs. They assumed that the crustal deformation is driven by plate boundary forces applied at the edges, as describe by global plate kinematic models.

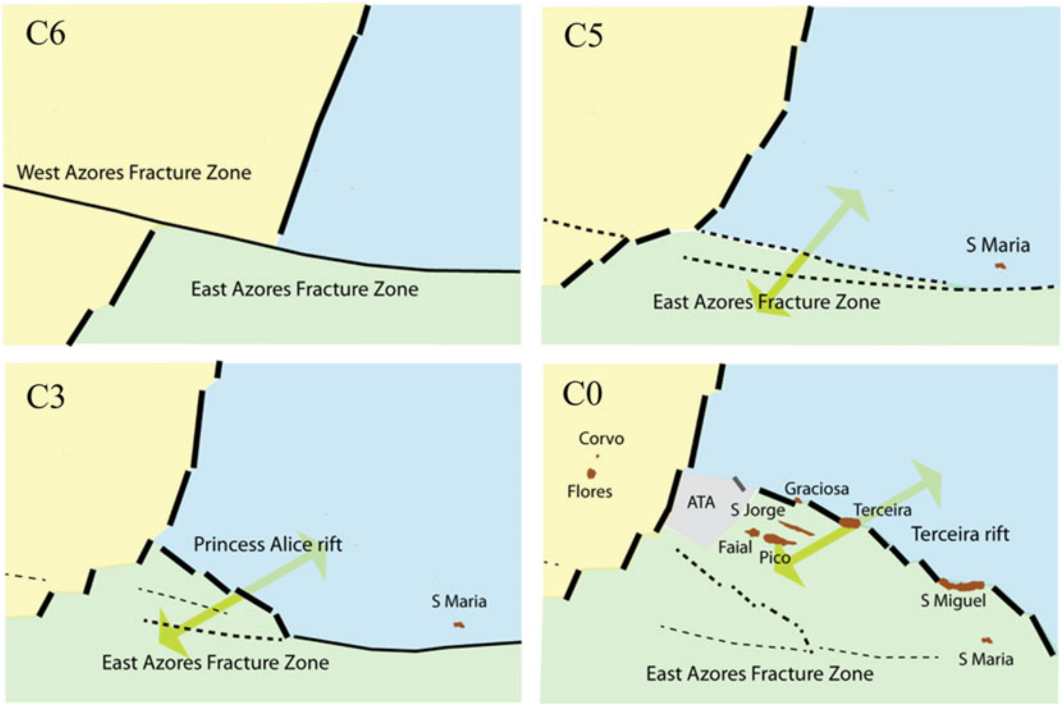

Fig. 4 Sketch of the main phases of the evolution of the Azores domain. At the time of chron C6 the western and the eastern Azores fracture zones form a single transform boundary; at the time of chron C5 the extensional component of the motion between Eurasia and Nubia is mainly accommodates as transtension close to the East Azores Fracture Zone; at the time of chron C3 there is a new RRR triple junction with an active rift incorporating the Princess Alice basin; after chron C3, the rift moves to the NE, leading to the development of Terceira rift, ~100 km away from the Mid-Atlantic Ridge. The area between Terceira rift and the MAR (ATA, Azores triple area) is marked by significant internal deformation

Using a 3D numerical model where the brittle layer is described by an elasto-plastic rheology and the mantle underneath is modeled as a viscoelastic layer. Assuming also that fractures are analogous to localised shear bands, they show that lithospheric processes alone can justify the spatial distribution of most of the linear volcanic ridges.

6 Distributed Deformation at the Azores Domain

The spatial distribution of the extensional processes associated with the Nubian-Eurasian plate boundary along the Azores was systematically addressed by Vogt and Jung (2003) in what concerns the problem of distributed versus non-distributed deformation. Miranda et al. (2014) tried to understand the tectonic mechanism associated with the internal deformation of the Azores domain combining very high resolution bathymetric data with detailed magnetic chron identification. They conclude that there is no discrete plate boundary between the Mid-Atlantic Ridge and Terceira rift as thought by early interpretations (e.g. Searle 1980 or Luis et al. 1994). The triple junction area is marked by an apparent northward increase in the spreading velocity as measured by magnetic chrons, between a “pure” Nubian velocity at the latitude of Faial Island and a “pure” Eurasian velocity at the latitude of Graciosa Island. This defining a “triple junction area” with approximately 90 km × 100 km characterised by brittle faulting where volcanism is barren or absent.

The complex fault system within this area accommodates the differential motion between the three plates. Similar configurations can be found in oceanic triple junctions where a slower axis joins two faster ridges as is the case of Rodrigues and Somalia-Arabia-India triple junctions (Miranda et al. 2014).

The main conclusions can be summarised as:

(i) There is no discrete plate boundary between Nubia and Eurasia west of the western Graciosa Basin and the deformation is distributed among a complex tectonic environmental where volcanism is mostly absent. This tectonic pattern can be roughly quantified by the angular mismatch (~12°) shown by the Mid-Atlantic Ridge segments in the magnetic reconstructions corresponding to C3, C5 and C6 times.

(ii) The Azores domain shows that it cannot be treated like a single rigid block, particularly west of Terceira Rift.

7 Main Steps of ATJ Evolution

After more than four decades of research, a few questions have been clarified concerning the different phases of development of the Azores triple junction and allowing the design of the following interpretation sketch:

- ~27 Ma ago there was a major rearrangement of tectonic plates and microplates in the Atlantic amalgamating Iberia to Eurasia and developing a new plate boundary along the Azores-Gibraltar Fracture Zone, here comprising the Gloria Fault and the East Azores Fracture Zone. This was early realised by Krause and Watkins (1970), and confirmed by later kinematic studies covering the evolution of the North Atlantic since the Cretaceous (e.g. Srivastava et al. 1990; Luis and Miranda 2008).
- 20 Ma ago the East Azores Fracture Zone ceased to act either as a plate boundary or a transform fault. This corresponded to a northward jump of the ATJ and to onset of rifting in the Azores. This is predicted by the McKenzie triple junction stability model.
- 20–8 Ma: Extension across the Azores is maintained at the rate of 3.7 mm/year in the N220E direction. The plateau is in the "magmatic phase": the topographic anomaly develops slightly east of the MAR but close to it. Significant surface reshape takes place but the MAR abyssal hill morphology is not destroyed thus implying that most of the plateau build-up is sub-crustal. The northern limit of Nubia is displaced to the north of the EAFZ: the previous single 200 km segment immediately north of EAFZ is split into several smaller en-echelon segments at the time of chron 5 (~10 Ma), when spreading had a significant obliquity like what can be observed now in the Reykjanes ridge. This matches the period of maximum magmatic productivity. The topographic signature of this period can be found both east and west of the MAR and even south of EAFZ.
- 8 Ma: Major rearrangement in the Atlantic corresponding to a sudden decrease of spreading velocity in the MAR and acceleration of the stretching rate across the Azores (Merkouriev and DeMets 2008, 2014a, b; Miranda et al. 2014), with a change of azimuth of the stretching direction; this corresponds also to the end of the magmatic phase of the plateau, and its split by the MAR (Gente et al. 2003) into the "eastern" and the "western" plateaus.
- 8–3 Ma: Extension at the rate 4.5 mm/year in the N240E direction (Miranda et al. 2014), corresponding to the rifting phase of the plateau. In this phase Santa Maria Island developed. Rifting started probably at Princess Alice Rift into a RRR configuration.
- 3 Ma: Abandon of Princess Alice Rift and rifting starting at Terceira Rift close to the northern limb of the plateau. Rifting is controlled by boundary kinematic conditions (McKenzie 1972) and mantle heterogeneities (Vogt and Jung 2003; Yang et al. 2006; Adam et al. 2013), associated with the two well know families of surface faults (Miranda

et al. 1998): N120E associated with magmatic processes and N150E associated with brittle tectonics.

- 3–0 Ma: Extension at the rate 4.5 mm/year in the N240E direction. Opening of all TR basins, and accommodation of distributed extension into the ATA (Azores triple area), with the development of mesoscale blocks, almost deprived of volcanism. Development of most of the Azores islands in both pre-existing Azores plateaus, by a combination of buoyancy and tectonics; island volcanos drifted away of the TR to the Eurasia or the Nubia plates, except for São Miguel Island internally stretched by TR (Miranda et al. 2015), and Flores and Corvo trapped in the North-America plate (see Fig. 3 for locations and Fernandes et al., Chapter "The Contribution of Space-Geodetic Techniques to the Understanding of the Present-Day Geodynamics of the Azores Triple Junction "); development of off-ridge extension controlled by mantle dynamics.

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