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Distributed deformation close to the Azores Triple "Point"

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ABSTRACT

Terceira Rift and the northern and southern branches of the Mid-Atlantic Ridge (MAR) form a triple junction close to 39°N known as the Azores Triple Junction. New swath bathymetric data are used to investigate the surface expression of faulting close to the triple junction, by the systematic mapping of MAR-generated abyssal hills. It is shown that close to the geometrical intersection between the three spreading axes there exists no single transform fault connecting Terceira Rift to the MAR but a distributed tectonic deformation area characterized by mesoscale brittle deformation close to the surface, covering approximately 90 km by 100 km, and almost no volcanism, which links Terceira Rift to the MAR, accommodating the relative displacement of the three plates close to the geometrically triple point. Magnetic chrons are used to compute the spatial variation of spreading velocity at the Mid-Atlantic Ridge and confirm the above interpretation: they show a progressive increase of spreading velocity along a single MAR segment, between pure "Nubian" at 38°30′N and pure "Eurasian" at 39°25′N, without the development of a transform fault that would integrate the Eurasia–Nubia plate boundary. The comparison of similar triple junctions where a slower axis joins two faster ridges, shows that the slower arm does not reach the "triple point" and that there is always a finite triple junction area, highly tectonized, in which size is dependent on the angle between the two faster arms and, consequently, on the relative spreading velocity of the slower arm.

1. Introduction

The Azores triple junction is formed by a northern branch of the Mid-Atlantic Ridge (MAR), with a full spreading rate of 23 mm/year, a southern MAR branch with a full spreading rate of 19 mm/year and a much slower WNW-ESE branch along Terceira Rift, with a spreading rate of ~5 mm/year. The three branches do not meet at a single point: the western Graciosa basin (see Fig. 1) which is the westernmost unit of the Terceira Rift is located ~100 km away from the MAR axial valley. Searle (1980) hypothesized that the fracture zone located close to 39°30′N could be interpreted as a dextral strike slip fault connecting Terceira Rift with the MAR, representing the northern boundary of the Nubian plate. Luis et al. (1994) challenged the conclusion, claiming that the spreading velocity north of 38°N given by the younger (C2a, C2) chrons was close to "Eurasian" and proposed that the northern limit of the Nubian plate is located close to 38°N at the latitude of Faial Island (Fig. 1).

The tectonic studies of the Azores triple junction have always been limited by the quality of bathymetric data. The first swath survey of the MAR (Needham and Sigma Scientific Team, 1991) did not include the Azores plateau. Subsequent compilations (Lourenço et al., 1998; Gente et al., 2003) still showed large limitations close to the Azores. Only in 2006 and 2007, in the framework of MARCHE missions, that high resolution bathymetric surveys were made to search for the morphological signature of the triple junction. The surveys were performed with the French vessel Le Suroît, using the EM300 swath bathymetry system that performs optimally around 1500 m water depths. Given that the water depths range between 1000 and 2000 m it was possible to compute a high resolution gridded dataset with a horizontal spacing of 50 m. It was merged afterwards into a regional digital bathymetric with 250 m resolution covering the Azores plateau. The merged dataset is used through this study (Luis et al., 2007, see Fig. 1) but the identification and quantification of fault parameters are made using the 50 m grid.

While bathymetric data are fundamental to map the surface expression of the tectonic and volcanic processes, magnetic data provide an objective way to study their spatial and temporal variations. The Azores plateau was covered by a high resolution aeromagnetic survey in the late eighties, but still suffering from the low accuracy of pre-GPS positioning systems (Miranda et al., 1991). The large number of research cruises made afterwards, particularly those in the scope of the United Nations Convention on the Law of the Sea, provided a set of very well located marine magnetic data. The combination of high quality bathymetric and magnetic data provides the opportunity to revisit the tectonics of the triple junction, at the sub-kilometer scale, to investigate the area

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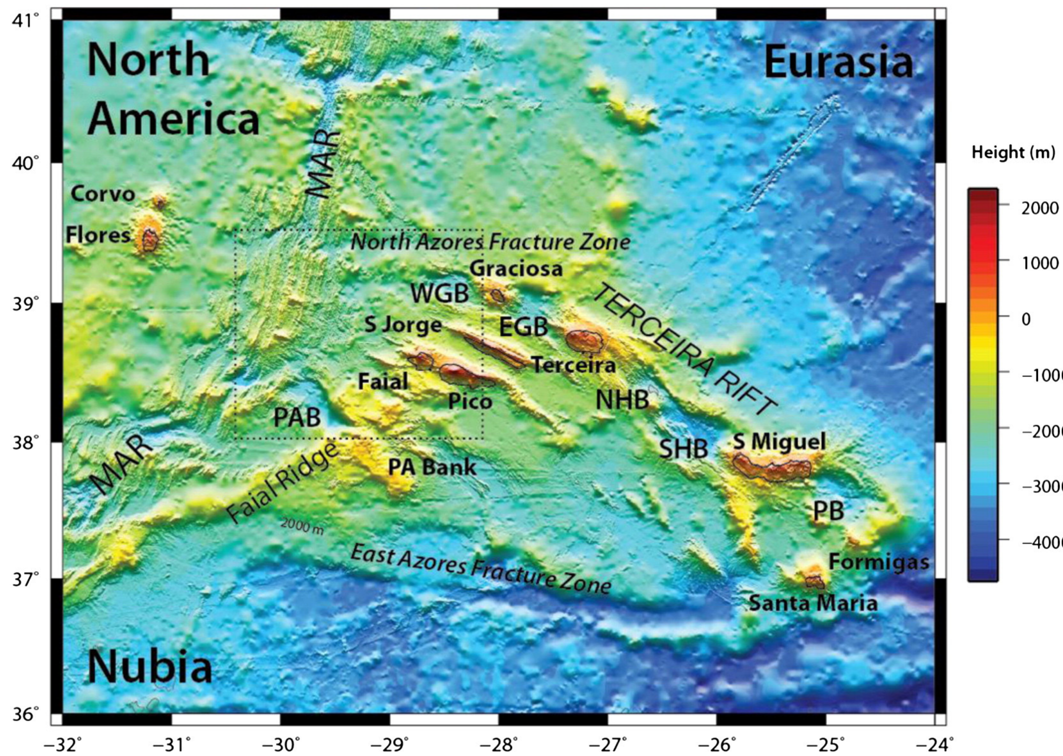

Fig. 1. Regional bathymetric compilation of the Azores. MAR: Mid-Atlantic Ridge; WGB: West Graciosa Basin, EGB: East Graciosa Basin; NHB: North Hirondelle Basin; SHB: South Hirondelle Basin; PB: Povoação Basin; PAB: Princess Alice Basin; PA Bank: Princess Alice Bank; GF: Gloria Fault. The dashed rectangle corresponds to the area of Fig. 2.

where the two arms of the MAR and Terceira Rift are supposed to meet and to test the different proposals that have been put forward to interpret the triple junction.

2. Morpho-structural interpretation

Fig. 2 shows the 250 m bathymetric compilation of the area. We systematically identified the main morpho-structural trends, associated with MAR-generated ridges, abyssal hill relief or extensional processes related with the Azores. In slow spreading ridges normal faulting associated with abyssal hills accounts for 10–20% of plate separation (Searle and Escartin, 2004) and their identification outside the ridge active tectonic area can be used in a way similar to isochrons, in particular they inform about the directions of the strain field associated with their development, and the existence of crustal rotations. Abyssal hill faults were identified from the original 50 m grids, considering that the steepest flank corresponded to the ridge ward direction.

Morpho-structural trends are classified into three main categories. The first one (N1) comprises MAR abyssal hill fabric. It has developed orthogonally to the spreading direction, with a trend of N10°E–N20°E, spaced 1–3 km and with hill lengths of tenths of kilometers along the axial direction. N1 is the dominant fabric west of 29°W but it can be found elsewhere in the plateau, even if dissected by N2 or N3 faulting, fault interplay between N2 and N3 sometimes defines v-shaped limits, pointing eastwards, of tectonically depressed blocks (cf. for examples in Fig. 3B, C and D). Away from the Mid-Atlantic Ridge (MAR) N1 topography keeps the same strike as the MAR valley south of 38°55′N (N11°E), but rotates up to N18°E north of this latitude. This change in strike is not present on the American plate and one must conclude that it is the result of the Azores related deformation. In all cases, it can be concluded that the underlying lithosphere was generated at the MAR and no important re-surfacing processes took place in the meantime, with the exception of those associated with the evolution of the Terceira Rift.

N2 structures with N110°E–N120°E fault direction can be found on the southern and northern flanks of the Western Graciosa Basin (WGB), and correspond to the strike of the islands located south of Terceira Rift (São Jorge, Pico and Faial). A similar strike is also found on the grabens that have developed WNW of São Jorge (see Fig. 3A) and the grabens (and volcanic ridges) that cut N1 abyssal hills close to the MAR at 38°50′N to the east of the axis. The N2 trend matches the strike of the elongated volcanic ridges that develop of the larger Azorean volcanoes (such as western Faial ridge and the eastern ridge of Pico island). Volcanic ridges are mostly associated with Pico-Faial, the largest volcanic system, and show a curvilinear shape, sub-radial to the volcanic systems in its vicinity, and are progressively aligned with the N2 direction closer to the MAR.

N3 trends can be found away from the volcanic highs associated with the small extensional basins (~N140°E) that develop NW of the West Graciosa Basin and the long faults that develop between the islands and the MAR (~N160°E). They border the younger basins that developed in the northern limb of the plateau, or the eastern and western flanks of the West Graciosa Basin. N3 trends also match the strike of the NNW-SSE mesoscale faults (see Fig. 3C and 3D) with characteristic lengths close to 30 km, and vertical offsets of hundreds of meters. There is a conjugate set of N80° faults that define with the precedent N3 faults a number of southeastward tilted lithospheric blocks, devoid of volcanic activity, except at its boundaries, with some dextral strike slip (~1 km in the case shown in Fig. 3C). These blocks are the site of the rotated N1 abyssal hills described above.

The new EM300 data provide adequate spatial and vertical resolutions to allow a quantitative analysis of the brittle strain represented by the fault scarps associated with the extension of Terceira Rift and neighboring triple junction area. We followed the approach by Escartin et al. (1999) developed for the estimation of brittle strain from fault heaves on a segment of the Mid-Atlantic Ridge, as it can also be used to study distributed tectonic strain. Apparent fault heaves were compiled from eight profiles crossing Terceira Rift along the Eurasian–Nubian spreading direction, nearly perpendicular to N3 faults

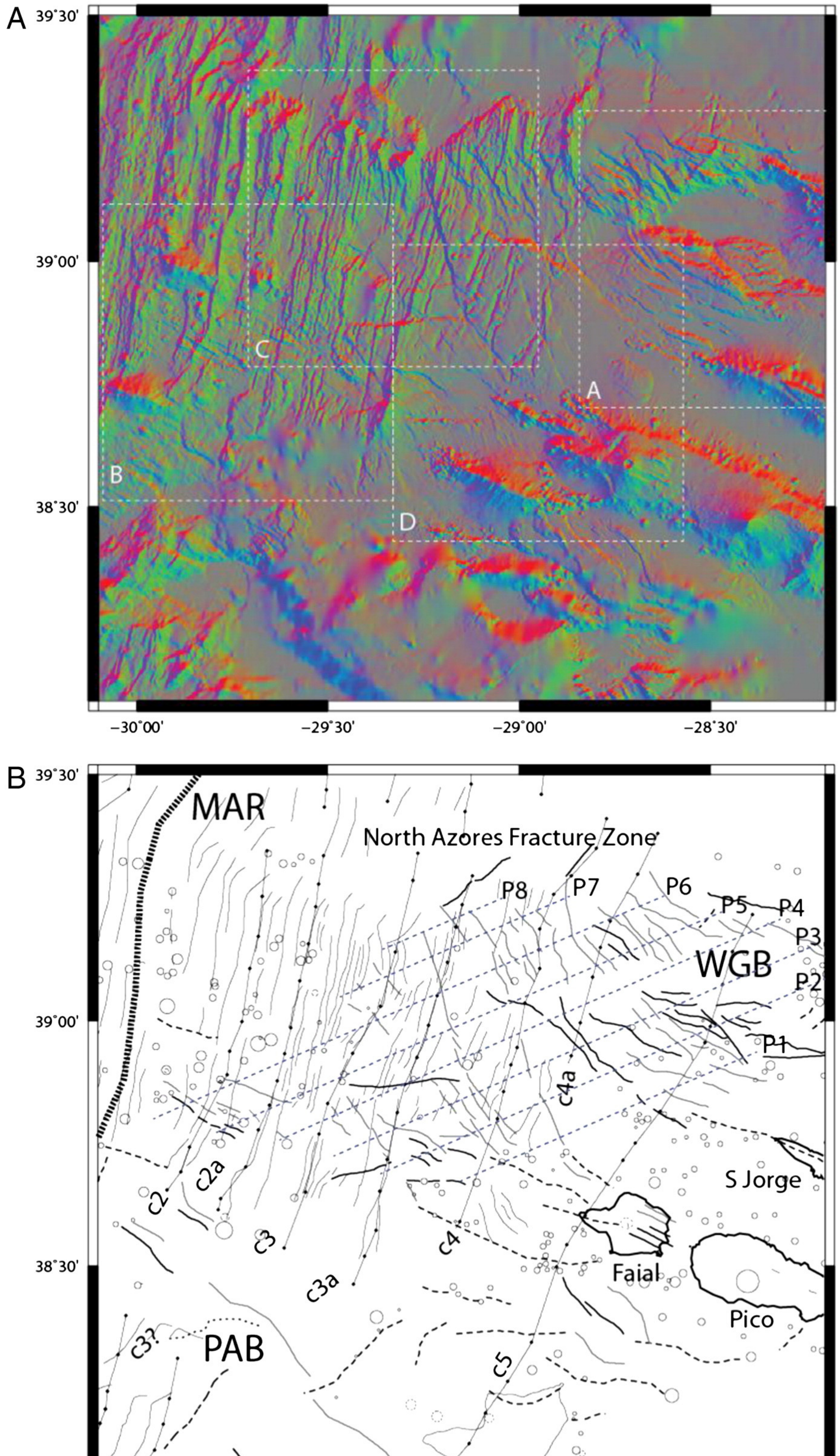

Fig. 2. A: High resolution bathymetric compilation for the Azores triple junction area. A composite RGB image is produced from the illumination of the digital elevation model from three directions (N0°, N120°E, N240°E), to emphasize slope changes. The rectangles labeled A to D correspond to the four areas depicted at Fig. 3. B: Interpretation of the abyssal hill morphology; magnetic chron identifications are overlapped. WGB: West Graciosa Basin; PAB: Princess Alice Bank; MAR: Mid-Atlantic Ridge. The profiles P1 to P8 are analyzed in Fig. 4.

and oblique to N2. Fault scarps were digitized and compared with fault interpretations in map view, using composite shaded relief images (see Fig. 2 for location). Cumulative apparent heave profiles were computed and are presented in Fig. 4.

Cumulative apparent heave profiles depict a flat-ramp configuration. Flats represent areas where scarps are absent or covered by sediment; ramps present constant slopes which provide a measure of tectonic strain imposed on the ATJ region. Varying slopes across adjacent profiles

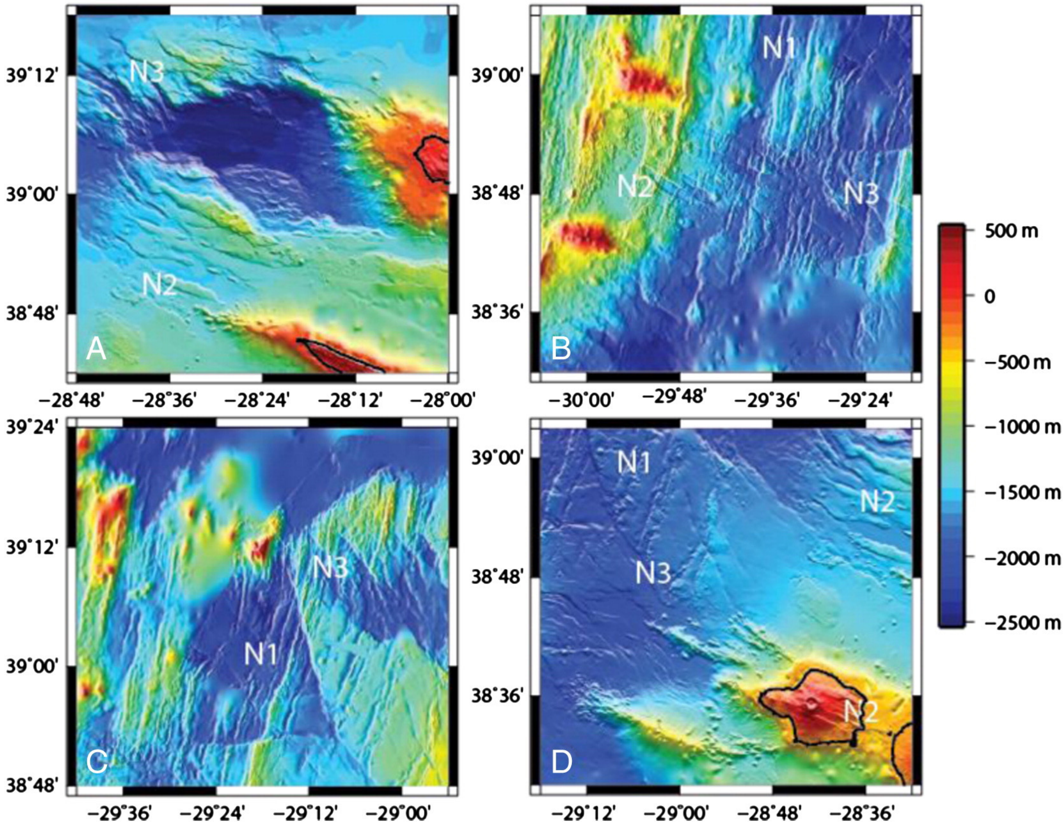

Fig. 3. Details of the morphology of the Azores triple junction area plotted from a 50 m bathymetric grid. The limits of the four panels are plotted in Fig. 2. N1, N2 and N3 refer to the three morpho-structural trends described in the text.

reflect that tectonic strain is not distributed evenly across the region. Total brittle extension varies consistently across the ATJ between a maximum of h = 14.5 km (11.5% extension on the southeasternmost profile) and h = 4.3 km (5.5% extension on the northwesternmost profile). Such a reduction is consistent with a progression towards younger MAR generated seafloor. These values can be considered as estimates for the tectonic extension across the ATJ, the remaining extension being accommodated by dyke intrusions associated with volcanic ridge development. They represent minimum estimates, as fault scarps are generally under-represented due to partial sedimentation and cover by talus deposits and because fault population will not represent faults bellow the footprint of the swath bathymetry used, remaining undetected.

3. Magnetic chronology

Luis and Miranda (2010) presented a new analysis of magnetic data for the North Atlantic area, where they picked the location of the main

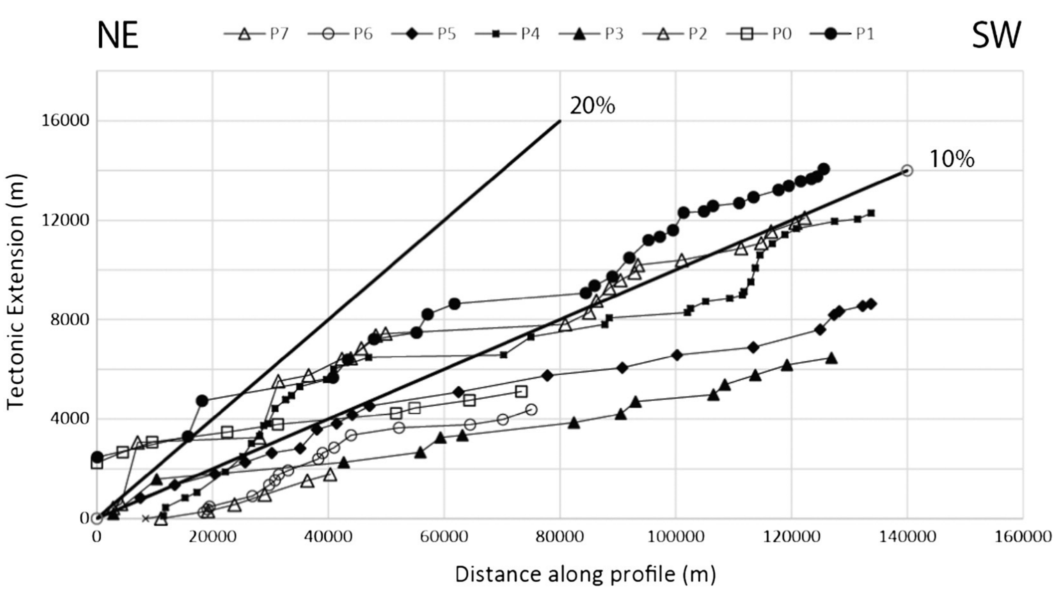

Fig. 4. Cumulative apparent heave profiles across Terceira Rift. The location of the profiles is shown in Fig. 2.

magnetic chrons between C2 and C6 from 20ºN up to Iceland; magnetic chrons in the Azores domain, between C2 and C5, are depicted in Fig. 5. They also computed a set of new rotation parameters for the relative motion between the three megaplates which is reproduced in Table 1, which fits rather well with the Nubia–North America plate pair south of the East Azores Fracture Zone and the Eurasia–North America plate pair north of the North Azores Fracture Zone. Using this set of rotation poles and angles we rotated the magnetic picks located east of the MAR, on the Azores plateau, onto their North American conjugates (Fig. 5) using both the "Eurasian" and the "Nubian" parameters. It can be seen that (i) when using "Eurasian" rotation poles and angles the fit is good close to the North-Azores Fracture Zone while the misfit increases progressively to the south; (ii) when using the "Nubian" rotation poles and angles, the fit is good close to the latitude of the Princess Alice basin up to chron C3a, while the misfit increases progressively to the north. Chrons older than C4 behave differently as they are cut by Terceira Rift and displaced with respect to their north-American homologous, by the combination of the Azores and the Mid-Atlantic Ridge related extension, closer to a "rigid plate behavior" than chrons younger than C3a, mainly sheared by the differential motion between Eurasia and Nubia.

4. Discussion

4.1. ATJ present day configuration

Tectonic processes in the Azores are the combined result of (i) the large scale plate driving force of ridge push and to a higher extent slab pull, both active now and present during the development of the pre-existing Azores lithosphere, (ii) the extensional process associated with Nubia–Eurasia relative motion that became active after chron C6c (Luis and Miranda, 2008), (iii) the stress field induced at the base

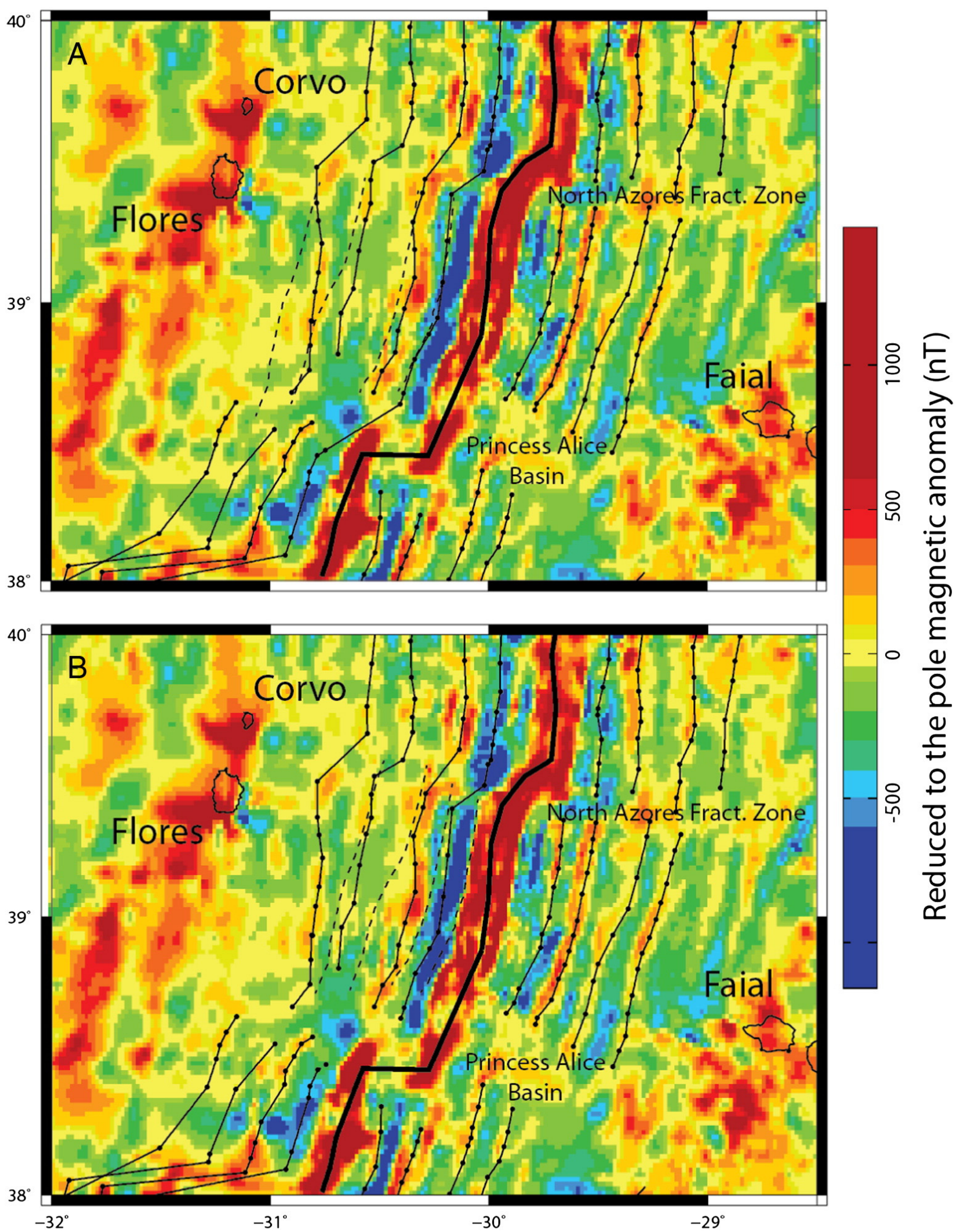

Fig. 5. Fit between Azorean magnetic chrons not intersected by Terceira Rift (C2, C2a, C3 and C3a), using the Eurasian–North American finite rotation poles (A — top) and the Nubian–North America rotation poles (B — bottom) given in Table 1. Solid lines correspond to actual isochrones while dashed lines correspond to rotated isochrons from the Eurasia, or Nubia, plate. The North-American plate is kept fixed.

Table 1
Eulerian finite rotation parameters for the Eurasia/North America and Nubia–North America plate pairs used in this study (Miranda and Luis, submitted). Angles are positive for anticlockwise rotations. Residuals are the average misfit between each isochron and its (rotated) conjugate, in km. Ages of chrons are from Cande and Kent (1995).

Chron	Age (Ma)	Nubia–North America				Eurasia–North America				Eurasia–Nubia		
		East Long	North Lat	Angle (°)	Res (km)	East Long	North Lat	Angle (°)	Res (km)	East Long	North Lat	Angle (°)
C2	1.82	41.1	79.2	−0.42	2.03	143.9	44.9	−0.39	1.15	−21.25	24.30	0.3331
C2a	3.06	41.8	78.0	−0.71	1.65	140.9	49.8	−0.63	1.86	−20.81	25.20	0.4998
C3	4.72	34.7	78.6	−1.12	2.05	138.0	61.0	−1.03	2.36	−20.10	18.35	0.6229
C3a	6.20	41.0	79.0	−1.46	1.82	139.4	55.6	−1.29	1.97	−20.21	24.17	0.8967
C4	7.74	50.4	79.4	−1.79	1.73	140.4	56.5	−1.62	1.74	−18.53	23.05	1.0367
C4a	8.88	49.3	79.3	−2.14	1.54	139.2	59.7	−1.94	1.77	−17.67	21.87	1.1390
C5	10.30	55.0	79.6	−2.56	2.67	139.0	60.3	−2.32	2.45	−17.12	22.62	1.2947
C6	19.60	43.1	80.5	−5.35	4.30	139.5	62.0	−4.58	3.94	−16.65	26.66	2.7096

of the lithosphere by thermal and density contrasts, affected by the relative motion between the lithosphere and the mantle and (iv) the volcanic dynamics at the island scale, including the local effects of fluid pressure, topography and mass wasting. The interaction between those mechanisms creates the complex tectonic pattern depicted in Fig. 2.

Magnetic chrons provide a simple method to analyze the timing of the different processes, even if the identification of magnetic chrons has always a degree of subjectivity when the attributed ages cannot be verified by independent methods. In the case of the MAR segment 38°30′N–39°30′N this is not a limitation because it is a robust segment since chron C5, where the magnetic anomalies are well reproduced by the magnetic grid and shape a continuous transition between "Nubian" velocities in the south and "Eurasian" velocities in the north, after chron C3. This implies an apparent northward gradient of spreading velocity in a single segment. It is also the reason why it was so difficult up to now to establish the location of the plate boundary west of western Graciosa basin.

Both morphological and magnetic data show that Terceira Rift is not linked to the MAR by a right lateral strike slip fault along the North Azores Fracture Zone as hypothesized by Searle (1980) or by Vogt and Jung (2003). There is no discrete triple junction but otherwise a complex tectonic area characterized by mesoscale brittle deformation close to the surface, which accommodates the oblique extension imposed by the lithospheric boundary conditions.

MAR related abyssal hills are well preserved up to chron C4 in the south and chron C4a in the north; after chron C5 we can no longer identify similar features. This can be interpreted as a transition, at the time of chron C4a between a "mantle-dominated" period, associated with the uplift of the plateau and a "lithospheric-dominated" period where rifting by the MAR splits the previous unique plateau into western and eastern plateaus, in the same line as described by Gente et al. (2003). However we must not underestimate the role of post-C4a volcanic activity south of Terceira Rift, in the re-surfacing of the previous MAR lithosphere.

It has been understood for a long time (Lourenço et al., 1998; Borges et al., 2007) that there are two main surface tectonic regimes: one is predominant west of Terceira Island, with large obliquity between local extension and Eurasia–Nubia relative motion and is characterized by extension in the direction ~N20°E. The other is predominant east of Terceira Island, up to Gloria Fault, with much smaller obliquity, characterized by extension in the direction ~N40°E. Nevertheless, even in the same area we can get a combination of both regimes as is the case of the West Graciosa Basin, whose quadrangular form reflects its superposition (see Fig. 3A). It is worth to mention that the "lithospheric" regime results in eastern and western steeper rift flanks, while the northern and southern flanks are less steep while dominant in the bottom of the basin (Fig. 3A), emphasizing the importance of vertical variations of the stress field. This difference calls for the prevalence of two stress regimes with different driving mechanisms. Adam et al. (2013) modeled the influence of mantle dynamics on the surface tectonics, showing that ~N20°E extension can be mostly attributed to upwelling from a buoyant mantle.

Close to the islands of São Jorge, Pico and Faial, normal faulting (N2) develops in the plateau seafloor with the same direction as the islands, not only close to the flanks of Terceira Rift but also close to the flanks of the islands themselves. This was directly confirmed by the analysis of 60 years of geodetic data (Catalão et al., 2006), which showed that historical extension was normal to the direction of the Faial graben and, in the case of the rift basins, by the strike of rift flanks. This stress pattern cannot be the effect of elastic deformation at the Eurasi–Nubia plate boundary, because the obliquity between the two is large. It cannot be the result of ridge push associated with the Azores spreading arm, because it happens not only close to Terceira Rift but also close to the linear volcanic ridges, located south of the rift, or even close to the MAR (Fig. 3B), and so must be the result of buoyancy driven plate motion (Adam et al., 2013). The area where mantle dynamic effects are the most important corresponds to the box 27.0°W–28.5°W–38.5°N–39°N, which is also the area where the seismic velocity anomalies are highest. West of 28.5°W the anomalies in the teleseismic body waves become smaller or deeper, and surface processes are mainly driven by the Mid-Atlantic Ridge push.

Closer to the islands, where local processes dominate, curvilinear volcanic ridges form almost radial to the volcanic edifices, becoming progressively linear moving away from the islands, under the influence of the regional stress field. The growth processes of these ridges create the conditions for deflation of magmatic systems, graben development and subsidence (see Fig. 3D), with an orientation similar to the local stress field. These curvilinear ridges give us an additional marker for the regional stress field: on the study area it corresponds to the N2 direction, and we must conclude that south of Terceira Rift mantle flow driven by thermal and density heterogeneity is the main driving mechanism for lithospheric extension.

4.2. The evolution of ATJ

Luis and Miranda (2008) showed that the development of the Azores triple junction has developed after the welding of Iberia to Eurasia during the lower Miocene. According to Luis et al. (1994), the triple junction was located approximately at 38°20′N, 30°15′W (in Eurasia fixed co-ordinates) between C4 and C3a times, and close to 38°55′N, 30°00′W (Eurasia fixed co-ordinates), after C2a. Fig. 2A and B shows that rifting in Princess Alice basin does not affect lithosphere younger than C2a. This can be interpreted as an indication that, after the jump of the triple junction to 38°20′N, and before C2a, extension between the Eurasian and Nubian plates was mostly accommodated as rifting across Princess Alice Basin. We hypothesize that a RRR triple junction, with Princess Alice Rift as its eastern arm, existed during a period of ~6 Ma (chrons C3–C4a). This corresponds to the first configuration of the Azores triple junction (Luis and Miranda, 2008). After chrons C2a–C3 the triple junction moved northward. The misfit shown in Fig. 5, and the lack of major discontinuities between Princess Alice and North

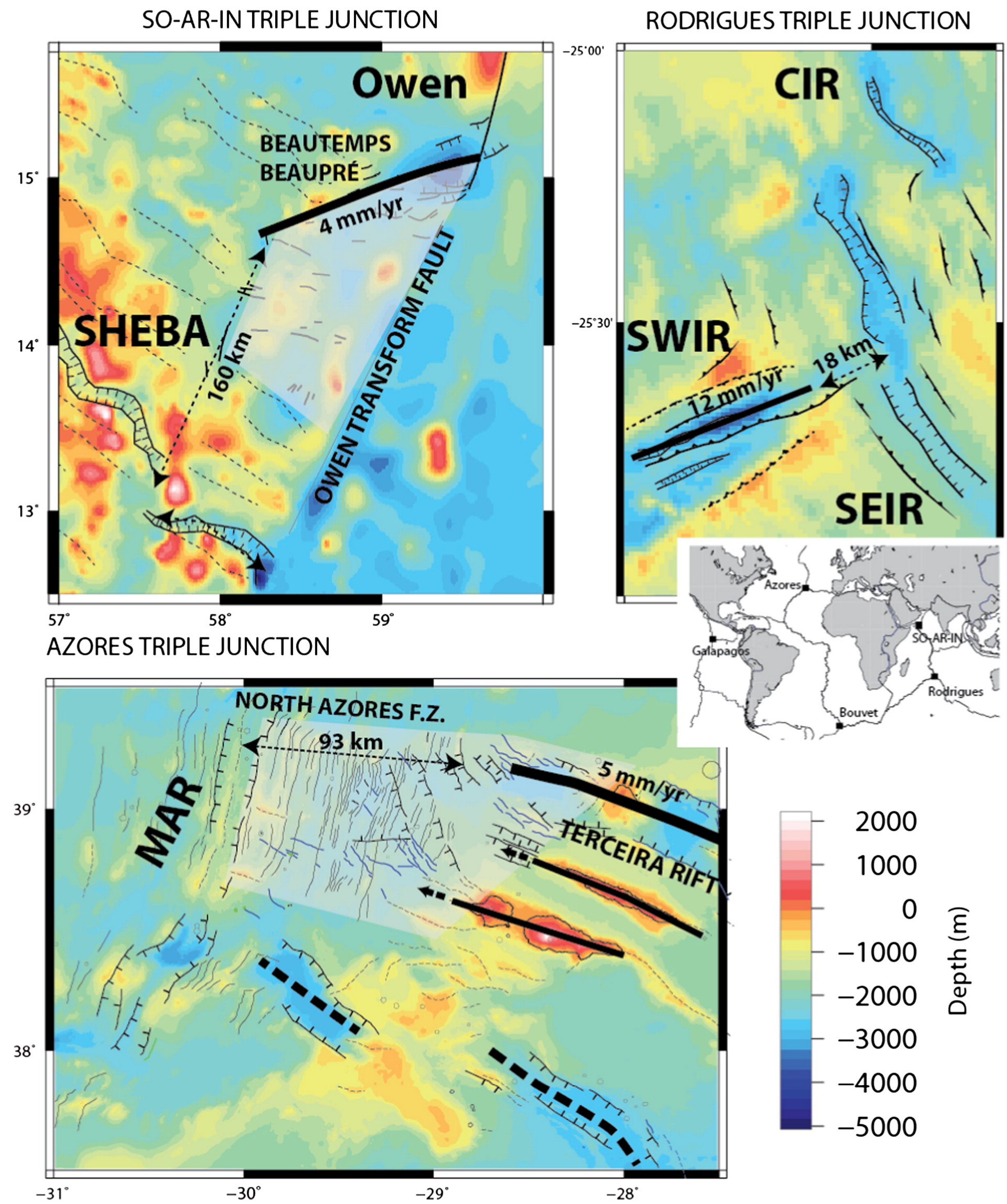

Fig. 6. Comparison between the three triple junctions where a slow arm joins a faster ridge. Azores: The Somalia–Arabia–India, the Rodrigues and the Azores triple junctions. The distances between the tip of the slow arm and the triple point are 160 km, 18 km and 93 km, respectively. CIR: Central Indian Ridge; SWIR: Southwest Indian Ridge; SEIR: Southeast Indian Ridge; MAR: Mid-Atlantic Ridge.

Azores fracture zones, indicate that the second configuration of the triple junction is the present one.

4.3. The onset of Terceira rifting

When did rifting start in Terceira? The only information we can extract from magnetic anomalies comes from the chrons identified on the plateau associated with Terceira Rift incipient spreading. Between chrons C5 and C22 MAR magnetic chrons are disrupted by a sequence of magnetic anomalies sub-parallel to Terceira Rift, with no systematic magnetic stripes. These anomalies have high amplitudes (~1000 nT) and so probably correspond to the youngest magnetic ages of Brunhes and Matuyama. The strike of magnetic anomalies changes continuously from east to west, between Gloria Fault and the West Graciosa Basin: South Hirondelle Basin ~N125°E, North-Hirondelle Basin ~N135°E, East Graciosa Basin ~N125°E, West Graciosa Basin ~N140°E. The only place where magnetic stripping seems better developed corresponds to the East Graciosa Basin close to Terceira Island, where a succession of normal and reversed anomalies can be found. The two anomalies with normal magnetic polarity follow the southern and northern flanks of the rift basin. If we consider them as chrons they correspond to C2, the normal period just before Matuyama reversal. However they can be the magnetic signature of rifting or scattered neovolcanic ridges developed in the context of off-rift extensional regime (Neves et al., 2013).

If we consider that brittle extension accounts for ~14.5 km of the extension and that it has been active since C3 times (~4.7 Ma), then the magmatic extension is incipient (~8 km) and took place after C2 (~1.8 Ma), which must match the development of the Azores islands.

4.4. How does the Azores compare with other RRR triple junctions?

High resolution studies of triple junctions, which on a broad scale are interpreted as RRR type, show that three axes often fail to connect in a small size domain (Georgen and Lin, 2002). This is only observed in a few cases like Galapagos and Bouvet triple junctions (see Fig. 5 for locations). In the case of the Galapagos triple junction, which joins the northern and southern branches of the East-Pacific Rise (EPR), and Cocos–Nazca ridges, half-spreading rates are approximately 12.3, 12.3 and 10.8 cm/year respectively; the slower Cocos–Nazca ridge has its tip ~30 km away from the East Pacific Rise, but secondary active rifts developed, north and south of the triple junction, connecting to the EPR, and defining a small microplate (Smith et al., 2011). This is also the case of Bouvet triple junction, which joins the American-Antartica, the Mid-Atlantic and the Southwest Indian ridges, with half-spreading rates of 0.9, 1.60, and 0.8 cm/year respectively (Ligi et al., 1999). There is morphological evidence for the connection of three axes in a single "point", active 1 Ma ago, with the shifts between RFF and RRR configurations in the recent past (Ligi et al., 1999).

In three well studied cases where there is a large difference in spreading rate between one of the arms and the other two (Rodrigues, Somalia–Arabia–India and Azores, see Fig. 5), spreading in the slowest axis must compete with the more efficient spreading process in the faster ridges. This leads to the development of a deformation zone, magmatically starved, where the relative interplate motion is tectonically accommodated. In the case of the Rodrigues Triple Junction, joining the Southeast Indian (SEIR), the Central Indian (CIR), and the Southwest Indian (SWIR) ridges, half spreading rates are approximately 2.99, 2.73, and 0.65 cm/year, respectively (Munschy and Schlich, 1989). Close to the triple point area, the morphology of the slowest ridge (SWIR) is a succession of deep valleys 4300–5000 m deep, with no magnetic stripes and no neo-volcanic zone (Munschy and Schlich, 1989). The tip of SWIR ridge has no evidence for the formation of a new crust and stops 19 km away from the triple point; close to the triple point there is progressive tectonic extension (Mitchell, 1991). In the case of the So-Ar-In triple junction joining the Sheba Ridge and the Beautemps-Beaupré Rift, spreading rates are 2.4 cm/year, 2.2 cm/year and ~0.2 cm/year (Fournier et al., 2010). Fournier's et al. (2010) interpretation of this triple junction is similar to Searle's (1980) for the Azores: the Owen fracture zone is the equivalent of Gloria fault, also a long slow moving strike slip fault with scarce seismicity, the Beautemps-Beaupré rift basin is the equivalent of Terceira rift and Fournier et al. (2010) hypothesize the existence as a discrete transform fault similar to the North Azores fracture zone, joining the Somalia–Arabia (Sheba) ridge at 57.7°E and extending to the north of the Carlsberg ridge. The morphological expression of rifting at the Beautemps-Beaupré basin stops at ~160 km from the triple junction, and there are no magnetic stripes sub-parallel to the rift basin. Comparing the published picks of chron C2 north and south of this limit and the fabric of the bathymetry published by Fournier et al. (2010), there is no evidence of a discrete fracture similar to that of the Owen ridge, where the interplate differential motion is supposed to be the same, and so Somalia–India relative motion is most probably accommodated by the deformation of a lithospheric band 25 km wide. Azores depicts a very similar geometry but with a wider band as described earlier in this paper.

Most of the above interpretative models characterize unstable triple junction and in particular the size of the deformation zone changes with time (Bird et al., 1999; Fournier et al., 2010) or even the configuration of the triple junction changes (Ligi et al., 1999). If we understand the surface expression of the axial segmentation pattern as a competition between three spreading systems, small changes in mechanical boundary conditions, produced by small rearrangements of plate velocities or mantle dynamics, can lead to significant changes in the segmentation pattern of the slower ridge, involving segment rotation, rift-along axis propagation and formation of distributed deformation zones closer to the Triple Junction. In this sense, some of the differences described above can be attributed to the relationships between the three vector spreading rates and directions, and others to different time "snapshots" of a dynamic process. One specific characteristic of the Azores is the size of the deformation zone, which is much wider than what is found in the case of the similar Rodrigues and the Somalia–Arabia–India triple junctions.

We hypothesize that such deformation zone is a consequence of the "lagging behind" of the ultra-slow Terceira rift arm in its progressive migration westwards. The rate of rift progression is slower than spreading rate on the MAR, resulting in the accommodation of plate differential movement in a non-structurally confined rift. The prominent tectonic character of that distributed deformation zone, coincides with the main rifting stage of the Azores plateau (Gente et al., 2003). Eastwards of the distributed deformation zone, more magmatically robust volcanic ridges have formed, SW of Terceira rift and are still active, as a consequence of the shallow mantle anomalies identified by Adam et al. (2013).

5. Conclusions

1. Three morpho-structural trends coexist within the ATJ Area. N1 corresponds to MAR generated abyssal hills, and can be interpreted as a proxy to chrons. N1 abyssal hills are slightly rotated in the Eurasian plate, and we interpret this as a consequence of the development of Terceira Rift. N2, with N110°E–N120°E trend, related with graben formation is probably associated with shallow mantle processes, including the deflation of large volcanic units. N3 corresponds to N140°E–N160°E normal faults with left-lateral components and its conjugate N80ºE faults with right lateral displacement, as observed from offsets on N1 fabric.
2. The Azores Triple Junction is not defined by any discrete feature marking the intersection of the Eurasia–Nubia plate boundary with the MAR. This area is marked by an apparent northward increase of the spreading velocity as measured by magnetic chrons, between "Nubian" and "Eurasian" velocities, within a single MAR segment, and the "triple area" of 90 km by 100 km is deformed by brittle faulting, where volcanism is barren or absent. The abovementioned meso-scale tectonic blocks accommodate a large fraction of the Eurasian–Nubian relative motion and link Terceira Rift with the Mid-Atlantic Ridge. Magnetic chrons are also affected by this deformation process and so the computation of rigid rotations to describe the motion of the Azores domain has severe limitations.
3. The comparison of three triple junctions (Rodrigues, Azores and Somalia–Arabia–India) where a slower axis joins two faster ridges, shows that the slower arm does not reach the "triple point" and that there is always a finite triple junction area, highly tectonized, in which size is dependent on the angle between the two faster arms and, consequently, on the relative spreading velocity of the slower arm. When the angle becomes very small, there is no RRR triple junction (e.g. the first phase of the development of the Azores); when it increases, and the velocities of the three arms become comparable, then a true triple point can develop (e.g. early phase of Bouvet triple junction, Ligi et al., 1999).

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