Reevaluation of magnetic chrons in the North Atlantic between 35°N and 47°N: Implications for the formation of the Azores Triple Junction and associated plateau

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[1] In this paper we present a new magnetic compilation for an area of the North Atlantic located between 35°N and 47°N and up to anomaly 33r. We also present a strategy to pick magnetic isochrones and compute finite rotation poles. This technique is based on a continuous reduction to the pole technique and some basic assumptions regarding the direction of the remanent magnetization vector. A cost function that measures the misfit between interpreted and rotated isochrones and the systematic exploitation of the parameter space is used to compute the best set of finite Eulerian rotations for the chrons 5, 6, 6C, 11–12, 13, 18, 20, 21, 22, 23, 24, 25, 26, 28, 29, 30, 32, 33, and 33r. This set of chrons and poles is used to discuss the evolution of the North Atlantic close to Iberia and, in particular, the onset and early development of the Azores Triple Junction area. We show that the relative motion between the Eurasian and the African plates can be coherently described in terms of rigid plate kinematics, respecting both the anomalies shapes and the precise location of the main structural elements of the area: the Pico Fracture Zone, the East Azores Fracture Zone, and the Gloria Fault. We distinguish from the magnetic point of view two different areas of the Azores plateau: the South Azores domain where almost undisturbed NNW magnetic lineations can be found and the Azores domain close to the topographic highs and with no systematic magnetic stripping with the exception of a few recent lineations, probably Matuyama and Brunhes. We present an approximate reconstruction of the plate configuration after chron 18 to conclude that the attachment of Iberia to Eurasia was younger than previously thought (lower Miocene), triggering the formation of the Azores domain, in which stretching took place essentially in the last 20 Ma at an average rate of ∼3.8 mm/a, and progressively attaching the South Azores domain to the African plate by a northward progression of the triple junction.

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1. Introduction

[2] Magnetic anomalies are the most important source of information to compute past plate motions. The standard procedure for their identification is the comparison between real magnetic profiles, measured at the sea surface, with synthetic profiles obtained from a model that takes into account reversals, profile orientation and basic magnetic parameters.

[3] Our study area, north Atlantic between 35°N and 47°N (see Figure 1 for locations), has been the subject of a number of kinematic analyses focused on the evolution of the North Atlantic and the Arctic, from the early works of *Pitman and Talwani* [1972], *Le Pichon et al.* [1977], and *Olivet* [1978] up to the synthesis made by *Srivastava and Tapscott* [1986] and *Srivastava et al.* [1990a] on the basis of much denser magnetic and morphological data. To further constrain the onset and evolution of the Azores, we lack enough good quality magnetic profiles and most of the existing ones have a large obliquity regarding the spreading direction, making anomaly shape recognition very difficult for the poorly mapped anomalies. This created large unknowns in the identification of magnetic chrons close to the Azores Triple Junction, where the magnitude of the tectonic and volcanic processes disrupts the continuity of the magnetic lineations.

[4] A valid alternative to the use of sparse profiles is the direct digitization of chrons from a good quality magnetic grid, where spatial continuity can be better judged. Such approach has not been openly applied in the past not only because this kind of magnetic data are seldom available, but also because of the difficulty in defining a clear criterion for a magnetic chron, which, when working along profiles is

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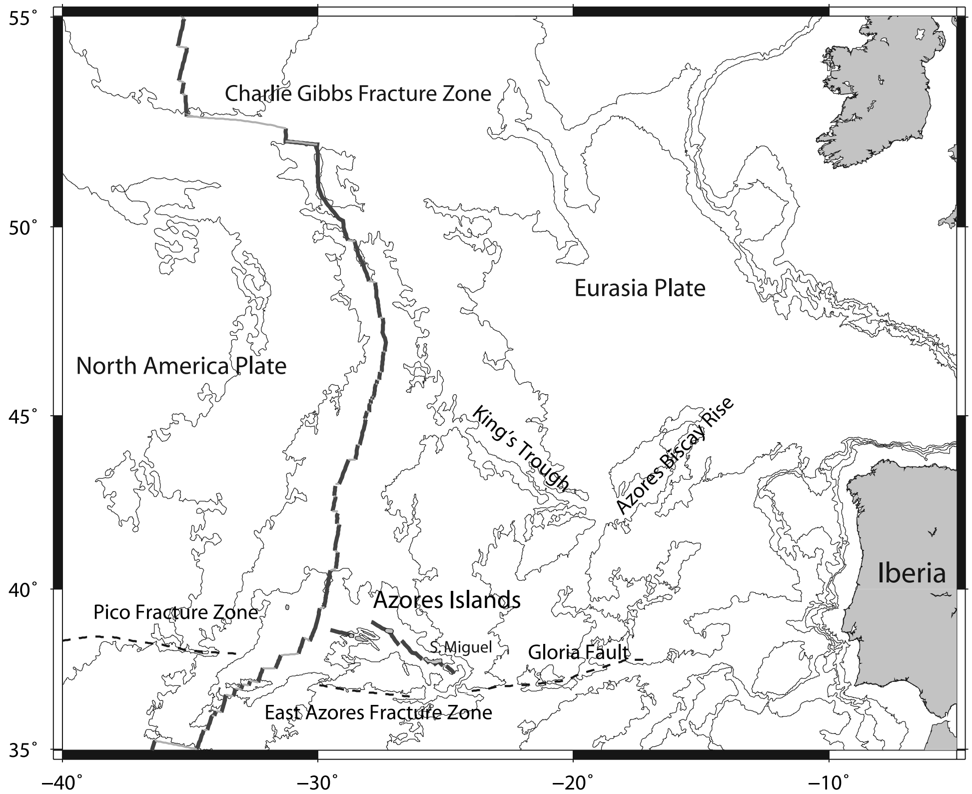

Figure 1. Regional setting of the Azores Plateau showing the location of the major tectonic provinces and features. The heavy line represents the Mid-Atlantic Ridge (MAR).

taken as the beginning, the end or particular midpoints of the target anomalies. This problem can be minimized if the magnetic anomaly is "reduced to the pole" [*Baranov*, 1957] so that the maximum of each chron can be considered a natural tie point, since it corresponds to the axis of the homogeneous magnetized block. The exception occurs only in chrons produced during long periods of constant polarity where edge effects are important.

[5] Both strategies have their advantages and disadvantages. The profile procedure is more precise for favorably oriented profiles (i.e., profiles normal to the spreading direction), but is rather difficult to use in highly oblique profiles. Furthermore, the synthetic profile used as reference does not normally take into account the fact that the magnetization and ambient field vectors may not be collinear and that their direction changes along the profile. The grid procedure suffers from the fact that grids are coarser than conventional profiles, and so the small wiggles, which help the positive identification of the shape of some chrons, risk smoothing during the interpolation process. However, the location of the anomalies axes is not greatly affected by that processes and the spatial continuity is an important tool for the identification. Poorly developed anomalies gain understanding when the spatial continuity can be used even when they are very hard or impossible to find if inspected on individual profiles.

[6] In this work we present a new magnetic compilation that assures better resolution and accuracy particularly close to the Azores Triple Junction, we compute the reduction to the pole anomaly and we identify the chrons 5, 6, 6C, 11–12, 13, 18, 20, 22, 22, 23, 24, 25, 26, 28, 29, 30, 32, 33, and 33r on the Iberian as well as on the American plate, between 35°N and 47°N. We choose not to identify chron 34 because it corresponds to a very long period of constant polarity. The procedure of picking the anomaly maximum over this zone, also known by the "superchron" or the Cretaceous Quiet Zone, is clearly not possible to apply because it only displays sensible variations on its edges. Also the chron

Table 1. Eulerian Best Fit Poles for the Iberian/North American Plate Pair[a]

		This Work			*Srivastava et al.* [1990a]		
Chron	Age (Ma)	λ	φ	Δ	λ	φ	Δ
5	10.3	140.52	53.03	2.26	-	-	-
6	19.6	140.12	56.64	4.48	138.20	68.00	4.75
13	33.3	124.99	71.27	7.51	117.33	76.34	7.98
18	39.1	117.22	77.19	9.43	-	-	-
20	43.1	113.70	76.01	10.23	-	-	-
21	47.1	112.09	78.68	11.57	126.96	74.70	11.05
22	49.4	126.60	72.01	11.51	-	-	-
23	51.3	124.59	72.60	12.15	-	-	-
24	52.8	124.68	73.23	12.93	133.28	72.98	12.94
25	56.1	133.40	68.48	13.79	133.88	73.29	14.25
26	57.7	133.74	70.17	14.44	-	-	-
28	63.1	137.30	66.82	15.24	-	-	-
29	64.3	135.28	70.90	16.09	-	-	-
30	67.0	135.65	69.70	16.51	135.34	74.96	17.19
32	72.3	132.63	77.31	18.48	-	-	-
33	78.0	118.50	85.33	22.05	110.28	85.49	22.41
33r	81.0	119.98	85.92	23.22	-	-	-

[a]Ages of the different chrons are taken from *Cande and Kent* [1995].

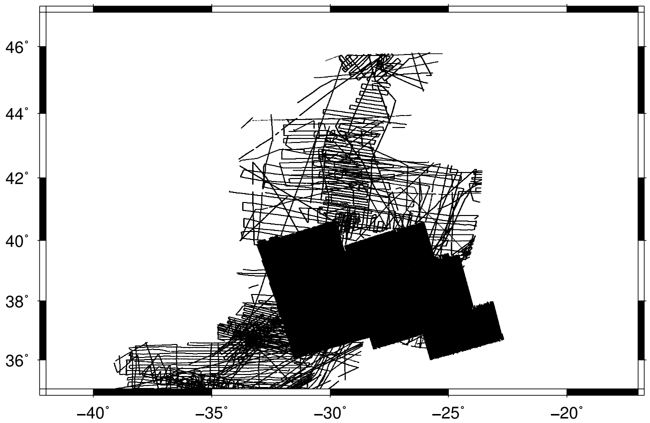

Figure 2. Spatial coverage of the new data that were merged within the *Verhoef et al.* [1996] compilation. Very dense distribution corresponds to the Portuguese aeromagnetic survey. Other data are originated from the Woods Hole aeromagnetic surveys [*Phillips et al.*, 1975] and several magnetic surveys done during MAR missions as well as new magnetic data compiled from the National Geophysical Data Center database.

33 corresponds to a period reasonably large (5.5 Ma) so the identification obtained corresponds more to its end than to its "middle" age. We have tentatively attributed it an age of 78 Ma (see Table 1).

[7] The set of poles and chrons is used to compute the previous locations of the plate boundaries as a function of time and, most importantly, it supports the positive identification of magnetic isochrones within the complex Azores domain, enabling the use of standard plate reconstruction techniques to quantify the time evolution of the three megaplates and, indirectly, the space that was "made available" and where the Azores plateau developed.

2. Magnetic Data Collation

[8] The amount of magnetic data collected in the north Atlantic is large but heterogeneous. For the whole area the *Verhoef et al.* [1996] compilation is available but its quality is dependent on the resolution and accuracy of the surveys upon which it was prepared, being rather good in areas where it relies on dense and accurate surveys, usually close to the shelf, and not so good in deep oceanic areas where data are scarce. Close to the Azores Triple Junction there are additional sources of magnetic data: the aeromagnetic survey made between 1984 and 1993 by the Portuguese Meteorological Institute [*Luis*, 1996]; three aeromagnetic surveys carried out by Woods Hole Oceanographic Institute [*Phillips et al.*, 1975] north and south of the triple junction; small magnetic surveys done during Mid-Atlantic Ridge (MAR) missions [e.g., *Goslin et al.*, 1999]. These additional surveys provide a large amount of good quality magnetic data, which can largely enhance our ability to identify magnetic isochrones, particular along the Azores plateau.

[9] We collated the above surveys and, in order to obtain the greatest rectangular grid that includes all our data, while containing a minimum of loosely constrained grid nodes, we complemented our basic data set with recent magnetic data compiled from the National Geophysical Data Center database. Figure 2 shows the spatial coverage of the new data that were merged within the *Verhoef et al.* [1996] compilation. Data were gridded using a minimum curvature algorithm with a final spacing of 2 min.

[10] In order to keep as best as possible the original magnetic information, no analytical continuation to a single reference height was applied. This means that data from the Azores aeromagnetic survey are referred to an altitude of 700 m [*Luis*, 1996], *Phillips et al.* [1975] surveys to 1000 m, and the surface ship magnetic data to the geoid.

3. Continuous Reduction to the Pole

[11] Away from topographic effects, marine magnetic anomalies are a consequence of lateral changes in remanent magnetization and mainly a result of magnetic reversals. In a simplified description where the magnetic layer has a constant thickness and magnetization, and the borders between contiguous polarity blocks are vertical, the magnetic anomaly field shows strong edge effects, resolvable as individual anomalies. As the present geomagnetic field and the preserved remanent magnetization are generally not collinear and non vertical, there is an additional effect often called "magnetic skewness" that can displace significantly the midpoints of magnetic stripes and skew the above described edge anomalies. It is often desirable to derive the magnetic anomalies that would have been produce if the bodies were magnetized vertically and the anomalies were observed at the geomagnetic pole. The advantage of this operation is that the shapes of the magnetic anomalies are simplified and are recentered directly above the causative body. Such procedure is known as reduction to the pole (RTP) [*Baranov*, 1957]. RTP procedure is usually carried out in the Fourier domain for an assumed flat earth, where it can be computed as a convolution of the Fourier transform of the magnetic field with a filter given by

$$G(u,v) = -\frac{((\alpha u + \beta v)(\lambda u + \mu v) + \gamma\rho\upsilon\rho)\rho^2}{\left((\alpha u + \beta v)^2 + (\gamma\rho)^2\right)\left((\lambda u + \mu v)^2 + (\upsilon\rho)^2\right)} + i\frac{((\alpha u + \beta v)\upsilon + (\lambda u + \mu v)\gamma)\rho^3}{\left((\alpha u + \beta v)^2 + (\gamma\rho)^2\right)\left((\lambda u + \mu v)^2 + (\upsilon\rho)^2\right)} \quad (1)$$

where (λ, μ, ν) and (α, β, γ) are the direction cosines of the magnetization vector and the main field, respectively, (u, v) are the coordinates in the Fourier domain, and ρ is $\sqrt{u^2 + v^2}$.

[12] Standard RTP procedure assumes the direction of magnetization to be uniform throughout the causative body, and the geomagnetic field to be uniform in direction throughout the study region. Although these assumptions are reasonable for small areas, they do not hold for large areas. Modified versions of the RTP procedure have been designed to take into account geomagnetic field variations along the study area; they are known as continuous or differential reduction to the pole techniques.

[13] Several methods have been designed to compute continuous RTP. These include the equivalent layer method of *von Frese et al.* [1981] and an iterative technique to solve

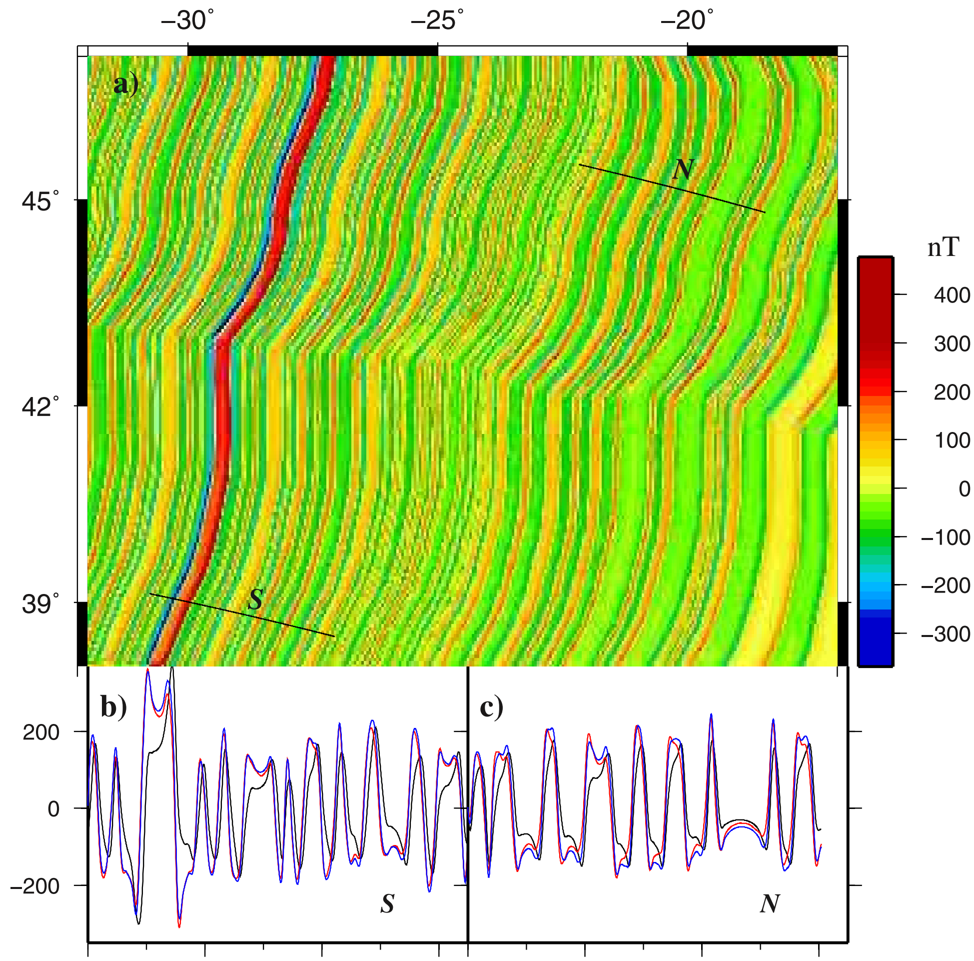

Figure 3. (a) Comparison between analytical reduction to the pole (RTP) magnetic anomalies and results from the continuous reduction to the pole technique described in the text. The comparison is made for a large range of latitude and longitude values assuming that the magnetization vector corresponds to natural remanent magnetization acquired at the ridge, following the geocentric dipole approximation. (b) Profiles taken along the black line depicted in Figure 3a as line S of the magnetic anomaly (black line), the continuous reduction to the pole solution (red line), and a synthetic RTP anomaly that is one computed with declination = 0 and dip = 90° (blue line). (c) Similar to Figure 3b but the profiles are now taken on the northeast corner of Figure 3a (black line named N). Magnetic anomalies are expressed in nanotesla.

for the variations in the directions as finite perturbations about the mean values of the region [*Arkani-Hamed*, 1988]. More recently *Lu et al.* [2003] used a "brute-force" approach in which the reduction at each grid node is obtained by performing a RTP over the entire area but retaining only the value corresponding to current grid node. While this allows the variation of both the ambient and magnetization vectors, the method was implemented on a parallel computer and requires a computer power not easily available. A simpler algorithm was proposed by *Cooper and Cowan* [2005] that employs a Taylor series expansion in the space domain about RTP_{mean}. Where RTP_{mean} represents the data set reduced to the pole using the ambient field area average inclination and declination.

[14] The method used here, though comparable to the approach used by *Cooper and Cowan* [2005], follows previous work by *Galdeano* [1980] and *Miranda and Pais* [1997]. The computations are carried out in both the frequency and the space domains. The idea is that a large area may be decomposed in small size windows where both the ambient field and the magnetization vector change by a very small amount. Inside each of those windows, or bins, we calculate the set of filter coefficients as in equation (1) and the α, β, γ, λ, μ and ν derivatives for its central point, and reconstruct for each individual point the component filter using a first-order Taylor series expansion (equation (2)). In the more general case where both the ambient field and the magnetization are let to have different directions, there are six independent derivative filters:

$$G(u,v) = G(0,0) + \frac{\partial G}{\partial \alpha} d\alpha + \frac{\partial G}{\partial \beta} d\beta + \cdots \frac{\partial G}{\partial \upsilon} d\upsilon. \qquad (2)$$

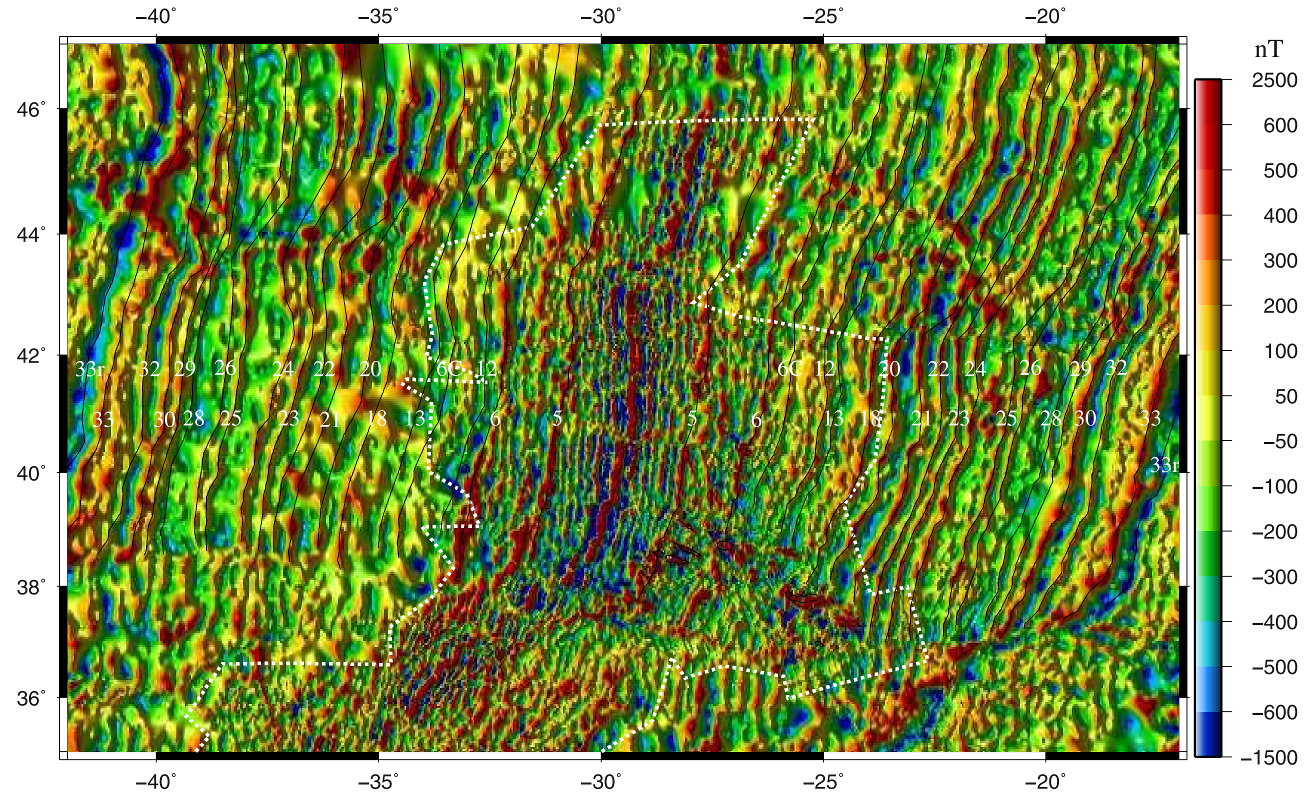

Figure 4. Magnetic anomalies continuously reduced to the pole. The polylines with vertex corresponding to the anomaly picks along the magnetic isochrones are overlain. White dashed line encompasses the area where new magnetic data have been added to the existing compilation.

Using the same notation as above, the derivative filter in order to α has the following form in the Fourier domain:

$$
\begin{aligned}
\frac{\partial G}{\partial \alpha} = & -\frac{u(\lambda u+\mu v)\rho^2}{\left((\alpha u+\beta v)^2+\gamma^2\rho^2\right)\left((\lambda u+\mu v)^2+\upsilon^2\rho^2\right)} \\
& -2\frac{u(\lambda u+\mu v)\rho^2+2((-\alpha u-\beta v)(\lambda u+\mu v)+\gamma\rho^2\upsilon)\rho^2(\alpha u+\beta v)u}{\left((\alpha u+\beta v)^2+\gamma^2\rho^2\right)\left((\lambda u+\mu v)^2+\upsilon^2\rho^2\right)(\alpha u+\beta v)^2\gamma\rho^2} \\
& +i\frac{u\upsilon\rho^3}{\left((\alpha u+\beta v)^2+\gamma^2\rho^2\right)\left((\lambda u+\mu v)^2+\upsilon^2\rho^2\right)} \\
& -2i\frac{((\alpha u+\beta v)\upsilon+(\lambda u+\mu v)\gamma)\rho^3(\alpha u+\beta v)u}{\left((\alpha u+\beta v)^2+\gamma^2\rho^2\right)\left((\lambda u+\mu v)^2+\upsilon^2\rho^2\right)(\alpha u+\beta v)^2\gamma\rho^2}
\end{aligned}
\qquad (3)
$$

The set of coefficients is then FFT inverted and the RTP is carried out on the current bin, by convolution in the space domain. To ensure a smooth transition between the filter coefficients on neighboring bins, the number of filter terms is made large enough and the bin width sufficiently small. Tests for a grid node spacing of 2 min, showed that $2° \times 2°$ bins and 45 filter terms assure a smooth transition along the entire domain. The strong point of this method is that we may let the ambient field and magnetization directions vary continuously.

[15] How to get the information about the magnetization direction and its spatial variation? On continents, because of the predominance of induced magnetization, one can reasonably assume that it is collinear with the ambient field, but on ocean crust this assumption does not hold, particularly in regions far from the ridge axis, where remanent magnetization is the most important contribution to the magnetic anomaly. To handle this unknown, one can assume a geocentric dipole approach for the main field regarding the original acquisition of the natural remanent magnetization (NRM) and its time stability and plate motion parameters to compute the present direction of the magnetization vector. That is, we can use the isochrones and reconstruction Euler poles presented in this work to assess the age and initial location of each element of the study area, keeping the North America plate fixed, the apparent polar wander path (APWP) for the North American plate [*Besse and Courtillot*, 2002] to assess its original remanent inclination and decli-

nation, measured in the present-day geocentric coordinate system, and once again the kinematic poles to compute the present direction of these remanent magnetization vectors for each element of the Iberian plate.

[16] To test the efficiency of this method, we computed a realistic synthetic anomaly map that reproduces the conditions prevailing at the center of our working zone. The assumptions of the model are (1) a magnetization of 15 A/m for the central anomaly and 5 A/m elsewhere; (2) on each point of the domain the inclination and declination of the ambient field is that provided by the IGRF model; (3) the remanent magnetization vector is computed as described above; and (4) the thickness of the magnetic layer was fixed to 500 m. Note that the model is not sensitive to the minimalist changes that would occur if a different set of finite poles had been utilized.

[17] With the conditions stated above, the magnetic anomaly (Figure 3a) was computed using the Okabe's method, as described by *Miranda et al.* [2005]. An advantage of this method is that it provides a different vector for the field and the magnetization at each point of the domain. As a further step one can also use *Okabe's* [1979] method to compute the magnetic anomaly already reduced to the pole. That is, the anomaly produced by bodies magnetized with a declination of zero and an inclination of 90°. Figure 3b display profiles taken along the black line depicted in Figure 3a of the magnetic anomaly (black line), the continuous reduction to the pole solution (red line), and a synthetic RTP anomaly, i.e., one computed with declination = 0 and dip = 90° (blue line). The goodness of the fit between the red and blue lines represents how well the continuous RTP transform is able to recover the "true" RTP as computed directly. In terms of standard deviation and taken over the all area, there is a mean difference of 29.6 nT for the case of fixed RTP and 22.9 nT for continuous one. One can conclude than that the method described above compensates better the skewness effect over a large area than a fixed RTP approach.

[18] The final result is displayed in Figure 4, which has overlain the anomaly picks of the isochrones described in the next section.

4. Isochrons and Poles

[19] Anomaly picking was performed graphically with the RTP grid following the anomalies axes. To help further with the crests identification, the grid was shade illuminated along a direction perpendicular to the main direction of the isochrones development. These isochrons identifications can be used to compute the Euler poles that "best fit" the match between the North American anomalies and the corresponding Iberian ones, assuming that a single finite rotation is sufficient to ensure a good match. In this work, though we identified isochrones up to the Charlie-Gibbs Fracture Zone, we focused on the computation of Euler poles for the Iberian/North America plate pair, when this motion could clearly be distinguished, and for the Eurasia/North America pair for the more recent epochs.

[20] The fit between each magnetic isochron at the fixed plate and rotated corresponding isochron was evaluated by means of the following procedure. Let a_i and b_j designate the vertices of two polylines A and B, where $i = 1{:}N$ and $j = 1{:}M$ with N and M representing the number of vertices of polylines A and B, respectively. To find the Euler pole that best fits polylines A and B upon rotation about that pole, we minimized the following cost function:

$$\varepsilon = \left(\sum_{i}^{N} d_i + \sum_{j}^{M} d_j \right) \tag{4}$$

where d_i stands for the distance between each a_i element and polyline B. Note that d_i does not represent the distance between a_i and the closest b_j point but is, instead, the minimum distance between a point and the closest segment of the conjugated isochron, measured in the direction perpendicular to the segment. The d_j stands for the converse distances; that is, the distance between each b_j vertex and polyline A. The use of minimum length cost function instead of conventional least squares presumably ensures a more robust behavior toward the existence of outliers in the data.

[21] For each computation a systematic swath of the parameter space (longitude, latitude, and angle) was performed, with increments on the order of tenths of degrees. The minimum of the cost function was computed directly using (4). To estimate the standard deviation of the poles estimations, we used a jackknife approach where the starting sample of measurements corresponds to the set of distances described above and we built a set of "resampled" values throwing out a measurement at a time [*Quenouille*, 1949]. The pole parameters and their standard deviations are displayed graphically on Figure 5. This brute force approach is effective because of the small amount of computations needed to evaluate (4) and is available with a graphical interface within the Mirone suite [*Luis*, 2007].

[22] As previously noticed by *Srivastava et al.* [1990b] it is not possible to obtain a satisfactory match by single rotations for all chrons within our study area. The reason lies in the fact that it encloses a jumping plate boundary and a component of independent movement of the Iberian plate. The northern limits of the Iberian plate have been proposed to follow the Azores Biscay Rise and the King's Trough structure up to the period between chron 13 and chron 6 [*Srivastava et al.*, 1990a] before jumping to the Gloria Fault. According to these authors, there is also a transition zone between a southern domain (Iberian/North America plate pair) and a northern one (Eurasia/North America plate pair). This is an important issue because the exercise of computing a coherent set of Euler poles relies on the assumption that all magnetic identifications belong to the same pair of plates under analysis and that those plates moved rigidly.

[23] The influence of an eventual intraplate deformation area was dealt in the following way: (1) rotation of a western anomaly using an approximate pole derived from the literature; (2) visual inspection to detect the zone northward of which a good fit could not be achieved, usually close to 45°N; (3) clip of the chrons retaining only points south of that zone; (4) computation of the rotation pole using only the clipped data; (5) if needed iterate the whole procedure using the rotation pole previously computed. We were unable to find a morphological (and

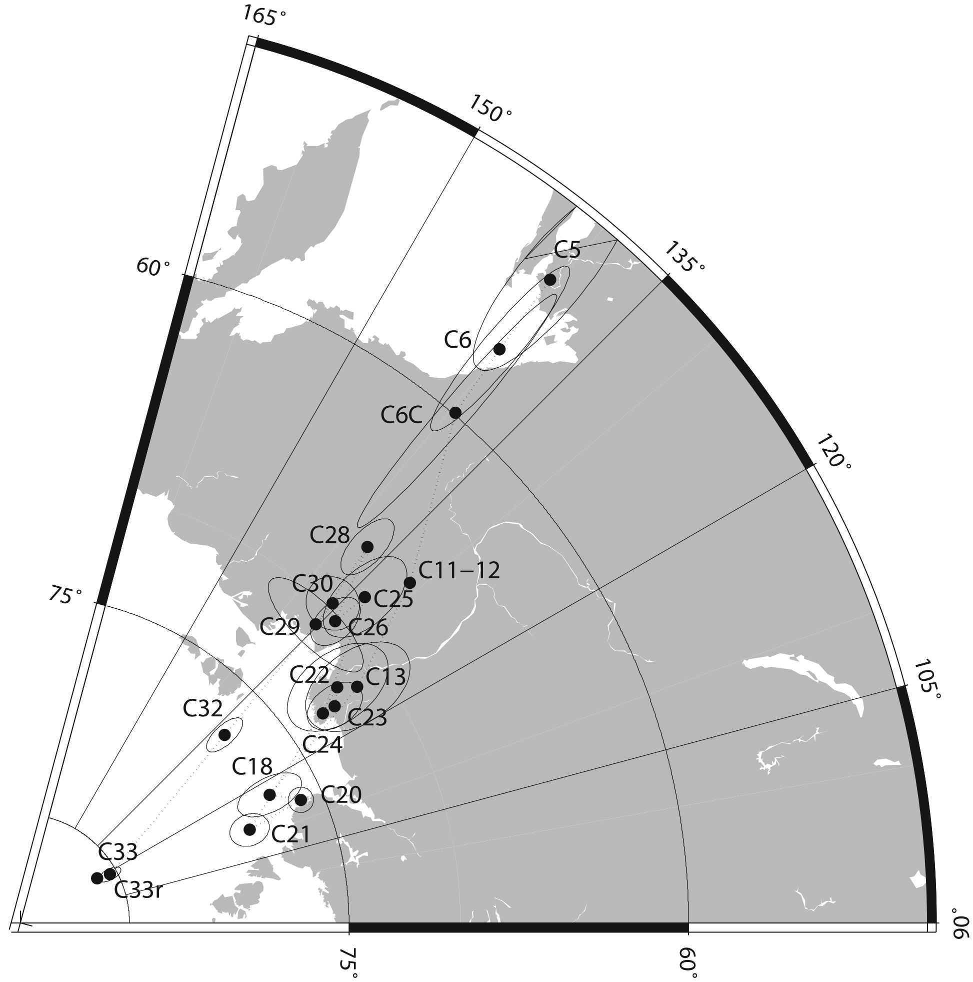

Figure 5. Location of the Eurasia-Iberia Euler rotation poles with respect to the North American plate as listed in Table 1. Error ellipses were obtained using a jackknife standard deviation computation.

magnetic) discontinuity that can be interpreted as the northern limit of a Iberian plate and thus the northern limit of the magnetic anomaly picking; in all cases the above-mentioned limit lies north of King's Trough Azores-Biscay Rise as pointed out by *Srivastava et al.* [1990a].

[24] Figure 6 shows the fit between the western and eastern (rotated) magnetic chrons using the poles of Table 1.

[25] This result differs from *Srivastava et al.* [1990b], which also investigated the same area. Although the poles coordinates do not differ significantly (see Table 1), the set obtained here predicts a better fit along the Gloria Fault, an important result because this constraint was not included in any step of our determination. In Figure 6 we present a comparison between a "magnetic block model" [*Miranda et al.*, 2005] and the anomaly picks within the Iberian plate. It can be verified that the agreement is rather good and there are no relevant artifacts, in spite of the large number of independent poles used to describe the Iberian–North America relative motion.

[26] Figure 7 displays the fit of all chrons identified in this work for the whole region between the Azores and the Charlie-Gibbs Fracture Zone. Previous works proposed that Iberia moved relatively to Eurasia to as late as the time of anomaly 6 [*Klitgord and Schouten*, 1986; *Srivastava et al.*, 1990a] or 6C [*Roest and Srivastava*, 1991]. Following Figure 6 the Iberia plate becomes attached to the Eurasia plate between chrons 13 and 6. At the time of chron 6 the pole is equally valid from the Azores to Charlie-Gibbs Fracture Zone. To refine this determination, we picked two chrons between chron 6 and chron 13. Using the geomagnetic time scale of *Cande and Kent* [1995] we consider that they represent chron 6C and chron 11–12 and, from the inspection of Figure 6, it can be checked that the major change took place between chron 6C and chron 11–12.

5. Magnetic Reconstructions

[27] A number of key questions regarding the onset of the Azores plateau are known for a long time: How was the plateau formed? Was it formed along the Mid-Atlantic Ridge and later on shaped by tectonic and volcanic processes related with the development of the Islands or the trace of a hot spot? Was it formed along the Terceira Axis, as predicted by *Krause and Watkins* [1970] or *McKenzie's* [1972] spreading schemes? When did the plateau started to form? How did its shape changed with time?

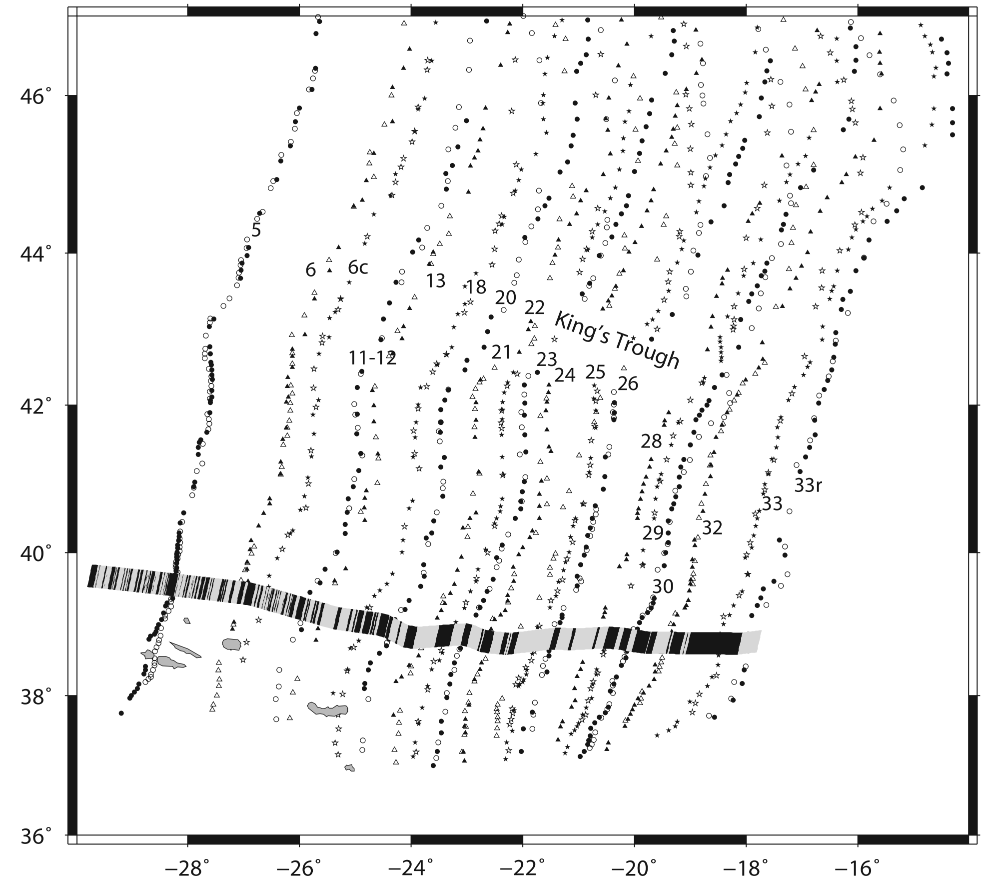

Figure 6. Comparison between Iberian magnetic anomaly picks (solid symbols) and the rotated ones (from the North American plate) using the set of Eulerian rotation parameters presented in Table 1. Overlaid is a magnetic block model produced by the set of poles presented in this work.

[28] The first step toward magnetic reconstructions of the past plate configurations close to the Azores Triple Junction must deal with the possibility of magnetic chron identification over the plateau. Considering in detail the plateau's magnetic anomalies (see Figures 4 and 8) we can distinguish between two different domains: the first one, that we will call here South Azores domain lies close to the East Azores Fracture Zone, and displays magnetic stripping almost parallel to the Mid-Atlantic Ridge. The second one, here called Azores domain is the place where most of the Islands lie along, where no systematic magnetic pattern can be found, with the exception of a few high-amplitude anomalies that are close to the morphological highs. Those anomalies must correspond to younger magnetic epochs, probably Brunhes and Matuyama chrons and interpreted in a previous work [*Miranda et al.*, 1991].

[29] Between chron 5 and the present-day Eurasia magnetic chrons show continuity parallel to the MAR with change in spreading velocity between pure African behavior and pure Eurasia behavior, as previously discussed by *Freire Luis et al.* [1994]. The youngest chron that is displayed continuously up to the East Azores Fracture Zone without being disturbed by the plateau is chron 22 (Figure 8). All others, up to anomaly 5, are disrupted by the Azores plateau. The positive identification of magnetic chrons in the South Azores domain is limited by its size; however, accepting that the South Azores domain is approximately west limited by chron 5 (almost continuous across the Eurasia plate) and by anomaly 22 at east, and that there are no major changes in velocity or ridge location, which seems to be a fair assumption, we can get a good guess of their identification by comparing the Eurasian "normal" spreading as seen north of the Azores with the magnetic stripes along the South Azores domain.

[30] Are the magnetic anomalies within the South Azores domain the "missing parts" of the magnetic anomalies that are identified north of the Azores? This hypothesis will be evaluated in the magnetic reconstitutions presented in the next section. To understand the limits of this assumption, we compute the successive configurations of the three plates, selecting the areas that we considered weakly affected by Azores onset and evolution: (1) the whole North American plate; (2) the African plate south of East Azores Fracture Zone and Gloria Fault, (3) the Eurasia plate north of the Azores between 22 and 5, and (4) the magnetic chrons within the South Azores domain as discussed above. We keep the North American plate fixed, rotate regions 2 and 4 using the *Klitgord and Schouten* [1986] poles, and rotate region 3 using the new set of poles shown in Table 1. It was assumed that the southern border of the South Azores domain follows the consecutive reconstitutions of the East

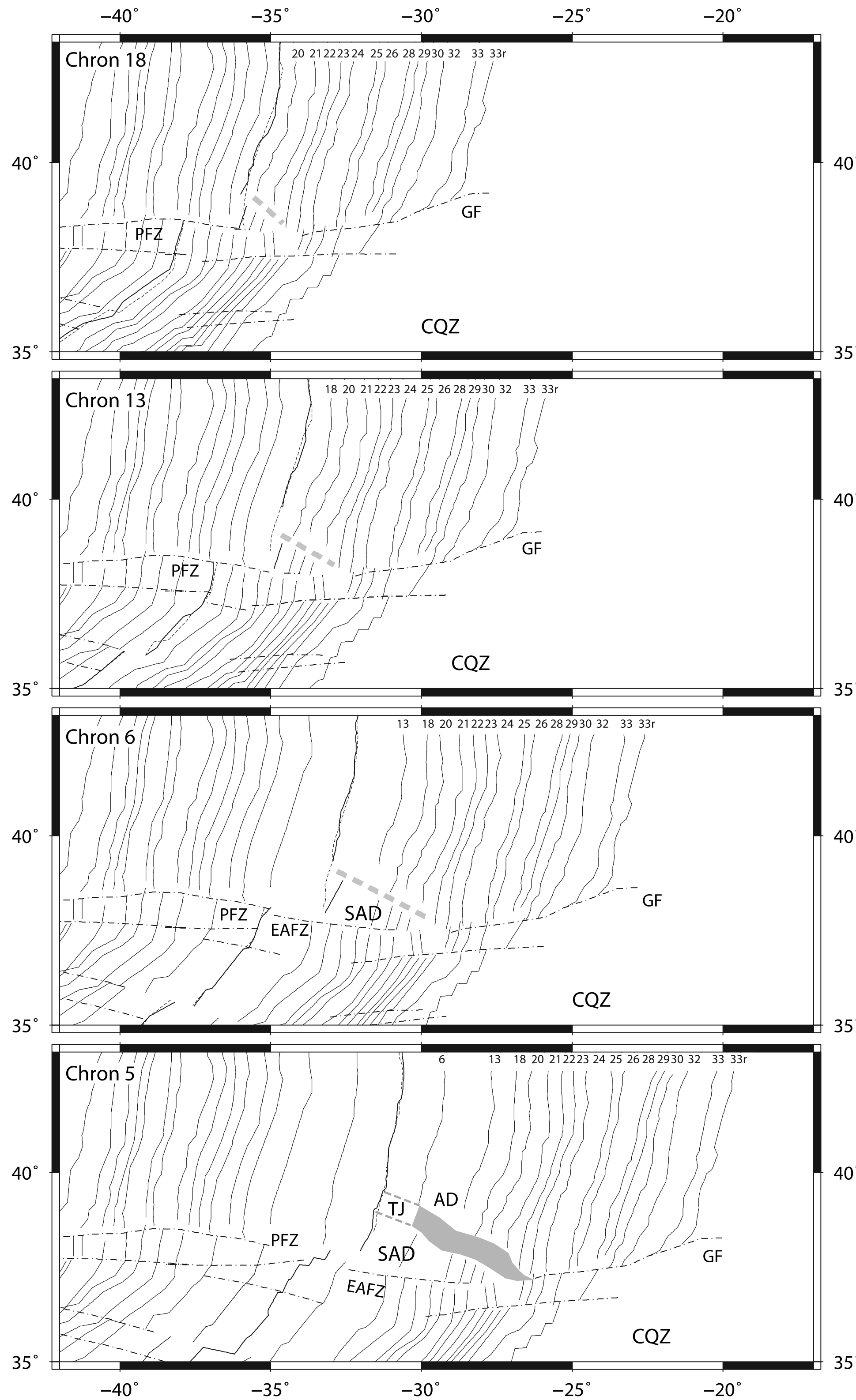

Figure 7. Magnetic reconstructions at times of chrons 18, 13, 6, and 5. The set of rotation parameters used for the Eurasian plate are the ones listed in Table 1; the set of rotation parameters used for Africa and the South Azores domain are taken from *Klitgord and Schouten* [1986]. Anomalies on the South Azores domain are rotated using the same set of parameters as Africa, which corresponds to consider that all any extension between the South Azores domain and the northern border of the African plate is not compensated.

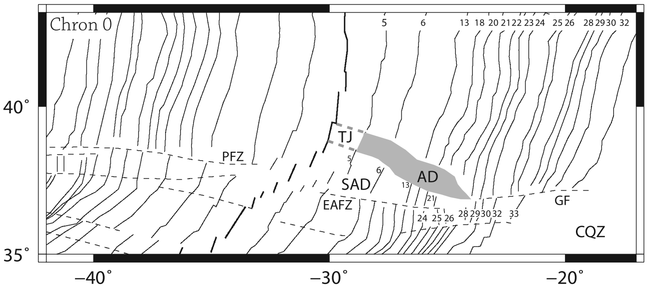

Figure 8. Reconstitution of the Eurasia-North America-Africa triple junction area for chron 0 (present time). Magnetic chrons are approximately identified south of the Azores. SAD, South Azores domain; AD, Azores domain; CQZ, Cretaceous Quite Zone; EAFZ, East Azores Fracture Zone; GF, Gloria Fault; PFZ, Pico Fracture Zone; TJ, Triple Junction area.

Azores Fracture Zone. The result is shown in Figure 7 for the chrons 5, 6, 13, and 18.

6. Discussion and Conclusions

[31] Marine magnetic anomalies, when accurately mapped, still represent the best source of information to infer the time evolution of complex geological domains, as is the case of the Azores Triple Junction. Up to now the possibility to get a clear picture based on the combination of magnetism and plate kinematics has been difficult to achieve because of the lack of well controlled sets of Euler rotations that reconcile Iberian and North American magnetic chrons within the 35°N–47°N area.

[32] *Srivastava et al.* [1990a] divided the eastern flank of the Mid-Atlantic Ridge into four distinctive zones: zone 1 between Charlie-Gibbs Fracture Zone and ~46°N latitude, zone 2 between this latitude and Kings Trough Azores-Biscay Rise, zone 3 between this limit and Azores-Gibraltar Fracture Zone–Gloria Fault and zone 4 south of this limit [*Srivastava et al.*, 1990a]. Because of the size of each zone and the detail of geophysical data available they considered an approach were the Iberian plate is considered attached either to the Eurasia or to the African plate, with a jumping plate boundary. They argued against the use of either Gloria Fault or Kings Trough as strong constrains because of the amount of overprint by younger tectonic activity. Within this approach they concluded that Iberia could be considered attached to Africa from Late Cretaceous to middle Eocene. From middle Eocene to late Oligocene it should be consider almost as an independent plate with slight motion relative to Africa, while the northern border along Kings Trough concentrated most of the deformation. Since late Oligocene it moves as part of the Eurasian plate [*Srivastava et al.*, 1990a].

[33] We are mainly interested in the interaction between Africa plate and the *Srivastava et al.* [1990a] zone 3, where the development of the Azores took place. To fulfill this need, we applied a slightly heterodox approach, enhancing magnetic anomaly identification with a continuous reduction to the pole technique that takes into account the magnetic latitude variation within the study area and the direction of remnant magnetization vector assuming that all magnetic rocks were generated in the ridge and acquired magnetization according to the geocentric dipole approach. This allowed us to "pick" a large number of magnetic anomalies and to compute a new set of poles, which global validity is constrained by the size of our study area, but that describe well the Iberia–North America relative motion.

[34] As can be observed from Figure 6, the major kinematic change took place between chron 11–12 (~30 Ma) and 6C (~24 Ma). While chron 11–12 is impossible to be fitted both north and south of King's Trough that is not the case of chron 6C, as was suggested by *Srivastava et al.* [1990a]. We conclude that the attachment of Iberia to Eurasia took place between the upper Oligocene and the lower Miocene. It marks a major change in the kinematics of the Eurasian-African-North American triple junction that ultimately led to the formation of the Azores plateau.

[35] *Freire Luis et al.* [1994] tried to characterize the approximate location of the Azores "Triple Junction" on the basis of the identification of an independent behavior, with respect to the three megaplates, of the so-called "Azores block," between chron 5 and chron 3 (10.1–3.85 Ma). It was concluded that the Eurasian-African-North American triple junction was located already north of the East Azores Fracture Zone between anomaly 4 and anomaly 3A times, approximately at 38°20′N, 30°15′W (Eurasia fixed coordinates) and proposed a present-day location close to 38°55′N, 30°00′W (Eurasia fixed coordinates), after anomaly chron 2A, approximately 2.45 Ma ago. These conclusions were based solely on the magnetic anomalies up to chron 5 so excluding most of the Azores plateau.

[36] The first question addressed here regards the location, in the Iberian plate, of the newly formed Azores lithosphere. In principle, the easiest way to answer this question would be the mapping of magnetic anomalies in the plateau and the identification of magnetic striping subparallel to the Azores trend. This has been looked for since *Krause and Watkins* [1970] but was never found for the whole plateau. The compilation presented here shows why: the Azores plateau displays two different magnetic zones, one roughly north of 38°N where "Azorean" magnetic anomalies, close to the topographic heights and with no systematic organization (Azores domain) and the other, south of this limit (South Azores domain) where magnetic anomalies are MAR-like. The obvious conclusion is that the newly formed Azores lithosphere is presently located in the Azores domain.

[37] The second question concerns the relationship between the Pico Fracture Zone and the East Azores Fracture Zone between chrons 22 and 5. The similarity between the trend of the magnetic anomalies, north of the Azores, and the trend of the South Azores domains anomalies, favors the conclusion that they correspond to the same spreading regime. This means that the homologues of each North American chrons 5 to 22 can be found in the Eurasian plate, split by the Azores extensional processes into two branches, one now located north of the Azores plateau and the other within the South Azores domain. This conjecture is confirmed by the similarity between the distances from the southern tips of the rotated North American chrons (Figure 8) with the width of the South Azores domain for a similar longitude value. Figure 7 shows the successive configurations of the Azores plateau, where it can be (quantitatively) seen that at the time of chron

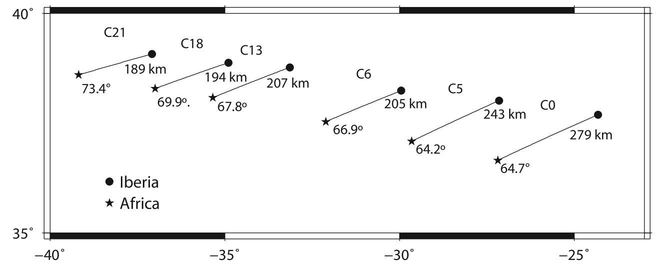

Figure 9. Time evolution of a segment that links two points fixed to the Iberian and African plates for the period between chron 21 and chron 0, respectively. The length is indicated in kilometeers and the azimuth in degrees.

13 both Pico Fracture Zone and East Azores Fracture Zone have spatial continuity.

[38] The third question regards the onset of Azores spreading. To better understand the extension applied to the Azores by the differential motion between the Iberian and African plates, we computed the successive dimensions and strikes of a segment that connects the southern end of the Iberian chron 21 with the northern end of the African chron 21. The time evolution of this segment, that presently crosses S. Miguel Island, gives an interesting ‘‘lagrangian’’ description of the changes in stretching and in the direction of extension. Results are plotted in Figure 9, where it can be seen that only after chron 6 significant extension took place in the Azores. Its average value can be simply estimated from the data plotted in Figure 9, as close to 4.1 mm/a for the period C6–C5 and 3.5 mm/a for the period C5–C0. The direction of extension can also be estimated as close to N50 for the period C6–C5 and N68 for the period C5–C0. So, the onset of the Azores extensional regime appears to follow the welding of Iberia to Eurasia, corresponding to a sharp change of extensional velocity.

[39] One can make an argument parallel to *Searle* [1980] that used chron 13 poles by *Sclater et al.* [1977] to compute the average opening rate for the Azores, concluding for an approximate age of 36 Ma, to ensure compatibility with his estimation of 160 km for the width of the Azores spreading center. From the results presented here we concluded that the extension of the Azores domain has been active since chron 6 at an average velocity of 3.8 mm/a, giving a total of ~75 km. It is also shown in the reconstructions at the time of chron 13 and chron 18 (Figure 7) that there is a residual misfit of ~30 km that can be considered an evaluation of the width of the previous Eurasian lithosphere now within the Azores domain. The sum of these two factors reaches 105 km, which is close to the average width of the Azores domain as depicted in the gray area of Figure 8. We should however keep in mind that this is a simplification as a part of the Iberian-African deformation occurs at the East Azores Fracture Zone (see the magnetic map in Figure 4).

[40] The development of a large lithospheric block at a very slow rate didn't generate the conventional magnetic stripping that is characteristic of very even slow spreading regimes (e.g., Southwest Indian Ridge). From the magnetic compilation it is clear that only the most recent magnetic epochs (Brunhes and Matuyama) are reflected in the Azores domain and mainly at its northern limb. This identification, which can simply be deduced from the large intensity mapped in Figure 4, was already checked independently in the Islands of Faial [*Miranda et al.*, 1991], S. Miguel [*Johnson et al.*, 1998] and S. Jorge (P. Silva, personal communication, 2007). This favors the interpretation that the evolution of the Azores plateau had two different phases: the first one, where no coherent discrete magmatic features where created, predominantly extensional and most probably related with the development of the deep basins along the whole central and southern areas of the Azores domain. The second and very recent one concentrated on the northern limb of the Azores domain that is associated with the present active axis, the seismicity, the larger topographic masses, and where the magmatic processes are coherent enough to allow the presence of a sharp magnetic signature. The shift between the two phases could be related with small changes in Eurasia-Africa spreading direction, velocity or changes in magma supply.

[41] Even if the attempt by *Freire Luis et al.* [1994] to establish a rigid Eulerian description for the behavior of the small Azores block has some inherent limitations due to the size of the study area, its main conclusions remain: Eurasian stable plate can today be found north of the Azores domain, stable African behavior can be found south of East Azores Fracture Zone–Gloria Fault. Within the Azores area, the now slowly developing spreading regime, affects a large area that encloses newly formed lithosphere (Azores domain) and previous Eurasian lithosphere split by the Azores extension and dragged by the stable African plate. To describe the motion of the Azores domain by a set of rigid Eulerian rotations, we need a set of parameters that is different from the stable Iberian and African plates.

[42] This interpretation resembles the Searle's interpretative sketch [*Searle*, 1980, Figure 11] where the time evolution is more constrained, the development of the buildup of the Azores domain occurs off the Mid-Atlantic Ridge, connected not by a discrete transforming boundary but by a more complex tectonic domain. The lack of evidence for a discrete triple junction already suggested [*Searle*, 1980; *Freire Luis et al.*, 1994; *Lourenço et al.*, 1998] and the amount of extension taking place on the Azores domain either magmatic or amagmatic, reinforces the characterization made by *Lourenço et al.* [1998] and *Vogt and Jung* [2003] for the Azores axis as a plate boundary acting both as an oblique, ultraslow spreading center and a transfer zone accommodating dextral differential Eurasian-African shear motion.

[43] To reconstruct the past locations of the South Azores domain, we used African poles. As can be observed in Figure 7 the reconstructed positions of South Azores

domain chrons do not match the corresponding North American anomalies showing systematically a significant angular misfit. This misfit is a consequence of two tectonic phenomena: the northward migration of the Eurasia-North America-Africa triple junction and the distribution of Eurasia-Africa extension between the Azores and the East Azores Fracture Zone–Gloria domain.

[44] The northward migration of the triple junction implies that there is pure Eurasia behavior north of 38°55′N, and so chrons older than 5 are unaffected; there is pure African behavior south of 38°3′N. Between these two latitudes there is a mixed behavior, with westward migration of some segment of the MAR (e.g., Menez Gwen) which generates the impossibility to get a god fit using either African or Eurasia poles only. The extension along the East Azores Fracture Zone cannot be studied using magnetic data alone. The tectonic mechanism that accommodates the northward migration of the southern branch of the Mid-Atlantic Ridge and the split of the extension between the different elements of the broad triple junction can only be assessed by combined structural and geophysical investigation.

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