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The Terceira Rift as hyper-slow, hotspot-dominated oblique spreading axis: A comparison with other slow-spreading plate boundaries

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Abstract

We suggest the 550 km long Terceira Rift (TR, Azores Plateau) is the world's slowest-spreading (hyper-slow, 4 mm/a plate separation; 2.3–3.8 mm/a perpendicular to oblique axial segments) organized accreting plate boundary. In its slightly sinuous (ca. 300 km radius of curvature) axial trace, its oblique spreading angles (ca. 40°–65°), and in frequency and first motions of earthquakes, the TR resembles better-known 'ultra-' or 'super-' slow spreading ridges (e.g. Gakkel and Southwest Indian ridges). Interpreted simply as volcanically 'unfilled' rift valley segments, the inter-island basins (e.g. the 3200 m deep Hirondelle Basin) are slightly wider (30–60 km), but not significantly deeper (1000–2200 m) than the Mid-Atlantic Ridge (MAR) median valley (20–28 mm/a; 10°N–53°N). However, along-axis segmentation wavelengths (ca. 100 km) are double those along the central MAR, but make TR comparable to the 'ultra-slow' (15–16 mm/a) Southwest Indian and Gakkel (7–13 mm/a) ridges. If this segmentation wavelength reflects Rayleigh–Taylor instabilities, the viscosity contrast between the overlying axial lithosphere and the partial melt zones is about an order of magnitude greater at ca. 4–16 mm/a than at 20–30 mm/a. The TR differs dramatically from ultra-slow ridges only in the large amplitude of along-strike topography (2000–4000 m; 4200 m total variation) owing perhaps to a copious melt flux from the Azores 'hotspot', combined with a spreading-rate-determined greater axial flexural strength and plate thickness, and slower export of volcanics from the rift axis. The probable TR youth (ca. 1 Ma?, requiring less than 4 km new oceanic crust) suggests lack of steady-state spreading conditions, which may explain the published gravity evidence against TR spreading. Absolute plate motions support the creation of the Azores Plateau by successive NE jumps of the rift axis to maintain its position over a fixed 'hotspot'.
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Keywords: Azores; Terceira Rift; slow spreading; triple junction; hotspot; Mid-Atlantic Ridge; rift valley

1. Introduction

A comprehensive model of sea-floor spreading processes must be able to predict a variety of measurable parameters (e.g. rift valley width and relief; crustal and mechanical plate thickness; spacing of volcanic centers; plate boundary geom-

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etry; magma composition; etc.) over the range of present and past spreading rates (here we use total opening rates between two diverging plates). Published models and observations suggest that many parameters are relatively fixed from the highest observed opening rates (ca. 160 mm/a on the East Pacific Rise) down to ca. 20–30 mm/a, below which some parameters (e.g. average crustal thickness; figure 3 of Louden et al. [1]) change rapidly with decreasing rates. Fig. 1, inset, shows the major accreting boundaries, with opening rates (calculated from the NUVEL-1A [2] model) for slow-spreading segments. Probably there is some lower limit of opening rates, below which organized spreading along an identifiable narrow plate boundary is replaced by distributed extension. A search for the slowest-spreading organized boundary is therefore worthwhile – and many authors have examined the Arctic Gakkel Ridge (7–13 mm/a; e.g. [3–6]) and the Southwest Indian Ridge (SWIR; 15–16 mm/a; e.g. [7–11]) with this in mind.

In this paper we argue that the Terceira Rift (TR; Fig. 1) is the world's slowest active discrete spreading plate boundary (ca. 4 mm/a); we compare and contrast the TR with previously recognized slow-spreading ridges. Although the term

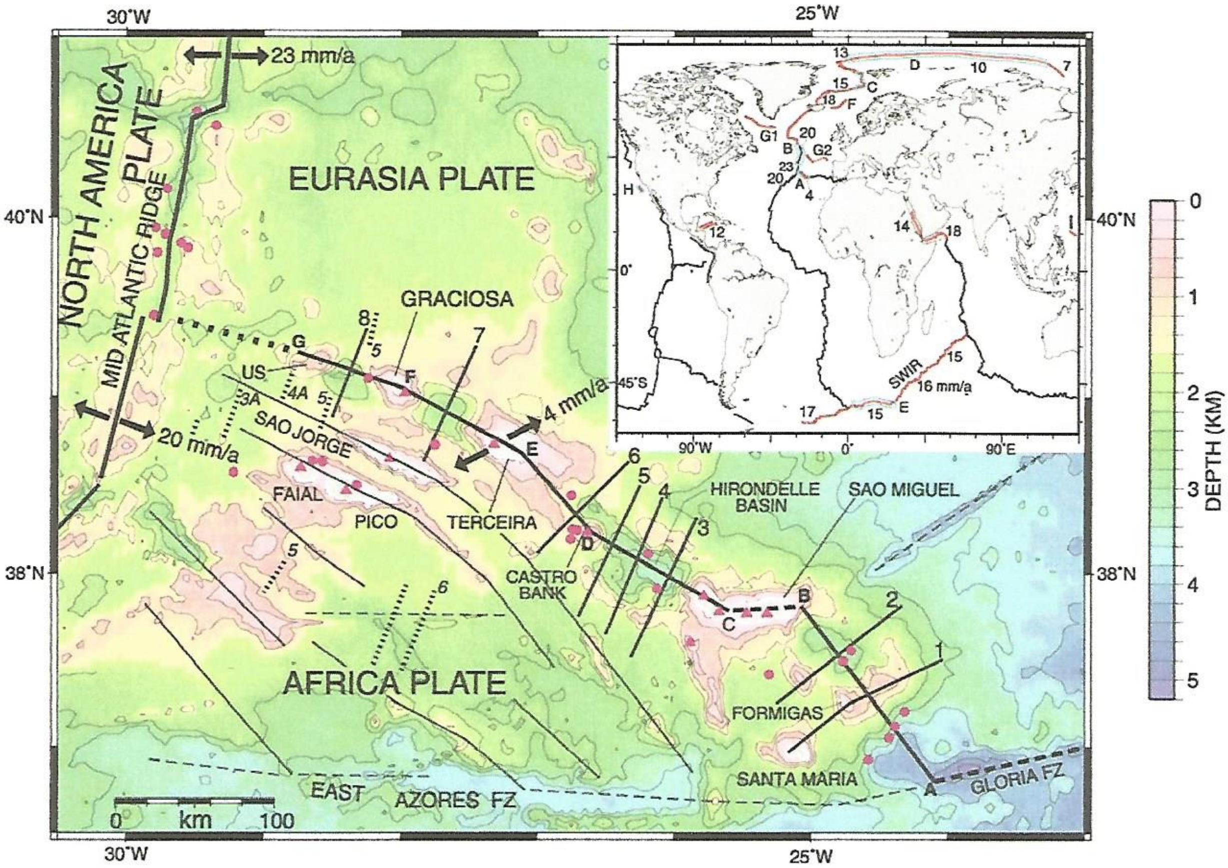

Fig. 1. Bathymetry of Azores Plateau area (from [32]), showing interpreted Terceira Rift and Mid-Atlantic Ridge plate boundaries (solid, spreading ridges; dashed, transform faults; dotted, uncertain boundary). Red dots are teleseisms (courtesy of National Geophysical Data Center) and triangles are active and dormant volcanoes. Thin solid and dashed lines show possible extinct, pre-TR plate boundaries. Dotted lines are sea-floor spreading type magnetic lineations (modified from [20]). Numbered lines show locations of bathymetric profiles, and letters denote points along longitudinal profile (Fig. 2). Inset map shows world's major spreading boundaries, with total opening rates (mm/a) for slow ridges. Lettered blue boxes outline locations of ridge segments reproduced in Fig. 4 and others discussed in text: A, Terceira Rift; B, Mid-Atlantic Ridge; C, Mohns–Knipovich Ridge; D, Gakkel (Nansen) Ridge; E, Southwest Indian Ridge; F, extinct Aegir Ridge; G1, extinct Mid-Labrador Sea Ridge; G2, King's Trough; H, Guadalupe Island and extinct axis; I, extinct West Philippine Sea axis.

'Terceira Rift' has been used in earlier papers [14], we propose that this feature has been the active accreting plate boundary long enough (≥1 Ma) for simple extension by normal faulting ('rifting' in the old sense) to have progressed to 'sea-floor spreading' (creation of new oceanic crust), although this requires proof. We represent our pick of the center line of the TR plate boundary as a segmented line (Fig. 1), but do not imply that magmatism is sharply concentrated there. Extinct ('fossil') spreading axes (e.g. the Aegir Ridge, ca. 8 mm/a or less [12]; the Mid-Labrador Sea ridge (ca. 7 mm/a or less [1]; and the West Philippine Basin axis [13]) may also offer some constraints on the structure of very slow-spreading plate boundaries. However, 'live' parameters such as seismicity and thermal structure can no longer be measured, and the actual spreading-rate history in the final stages of spreading cannot be recovered, owing to lack of resolution of magnetic reversals at very low opening rates, which prior to extinction must have dropped below TR rates on their way to zero.

While opening rates also cannot be resolved by magnetic anomalies along the active TR, they can be calculated from plate closure about the Azores triple junction. At 3–4 mm/a, the TR is spreading at only 25–50% the rates of the 'ultra-' [5,11] (also called 'very' [9] and 'super-' [10]) slow SWIR and Gakkel Ridge (Figs. 1 and 2). Accordingly, the TR spreading rates are here termed 'hyper-slow' (< 5 mm/a).

2. Terceira Rift: a hyper-slow oblique spreading axis?

The TR is a 550 km long, generally ESE trending line of alternating volcanic massifs (of which Graciosa, Terceira and Sao Miguel islands are the highest) and basins (Figs. 1 and 2). The TR crosses the Azores Plateau, of which it is an integral part, and except in the earliest years of plate tectonics (e.g. [15]) has been considered by many (first by Krause and Watkins [16]) the third arm of a simple RRR triple junction involving the North America, Africa, and Eurasia plates (e.g. [17–19]). However, detailed aeromagnetic surveying of the MAR in the Azores area suggests the existence of a separate Azores plate at least from 10 to 3.85 Ma, with post-2.45 Ma Azores movement as part of the Eurasia plate [20]. Based on analysis of TR gravity data, in comparison with MOR (Mid-Ocean ridge) results, Luis et al. [21] conclude that the TR is 'mainly a zone of intense volcanism' and that there is 'no gravity evidence for the existence of a spreading axis.' (They inferred this from the mantle Bouguer anomaly – which is inconsistent with a typical thermal model for steady-state spreading. The TR gravity anomalies instead can be modeled by elastic loading of a ca. 10 Ma old lithosphere [2].) Considerable Quaternary to Recent island and submarine volcanism has occurred southwest of the TR axis (e.g. on Sao Jorge, Pico and Faial islands; Fig. 1) and west of the MAR plate boundary (Corvo and Flores islands). This distributed volcanism has complicated the interpretation of the TR as the primary Eurasia–North America plate boundary. The formation of the Azores Plateau and its complex volcano-tectonic fabric and relatively thick (twice normal oceanic) crust has been attributed to the effects of an Azores mantle hotspot, which, as in the case of Iceland, affects the morphology and average axial elevation for great distances (ca. 1500 km – three times the length of the TR – along the MAR on either side of the Azores triple junction). The 'absolute motion' model of plates relative to fixed hotspots [22] predicts that both sides of the TR are moving in a SW direction over the hotspot, with the plate boundary itself moving ca. S55°W at ca. 20 mm/a (Fig. 3B). If the TR plate boundary is trying to maintain itself over the hotspot, it must jump towards the NE at least every few Ma.

The TR axis is a portion of the Azores–Gibraltar plate boundary between the Africa and Eurasia plates (Euler pole ca. 21.0°N, 20.6°E; NUVEL-1A [2]). East of the TR, the plate boundary is transform (GLORIA fault; [23]), and SW of the Iberian peninsula partly transpressional (e.g. [24]). The GLORIA transform strikes ca. N77°E at 23.5°W [25], near its intersection with the TR (Fig. 1). Motion along the transform averages about 3 mm/a [2], about an order of magnitude less than the San Andreas fault. There has been no significant historical (last 75 yr) seismicity along the GLORIA fault, either due to aseismic/sub-teleseismic slip or to low recurrence frequency. By contrast, the TR (Fig. 1) exhibits high seismicity of moderate magnitude [21,24] with normal or transform-type fault mechanisms and an average axis of horizontal extension oriented N25°E [26,27]. The low levels of TR seismicity near the triple junction (e.g. [21]) probably relate to the thin, young, weak lithosphere. Two published focal depths (12 ± 5 and 15 ± 5 km; [27]) for normal faulting events along the TR support a rigid axial plate thickness greater than typical for the MOR and perhaps to be expected from the hyper-slow opening.

Except for the eastern end of Sao Miguel (which we suggest follows a small transform; Fig. 1) the volcanics exposed or cored along the TR islands are no older than Brunhes (0–0.71 Ma; reviewed by [28]). At historical eruption rates

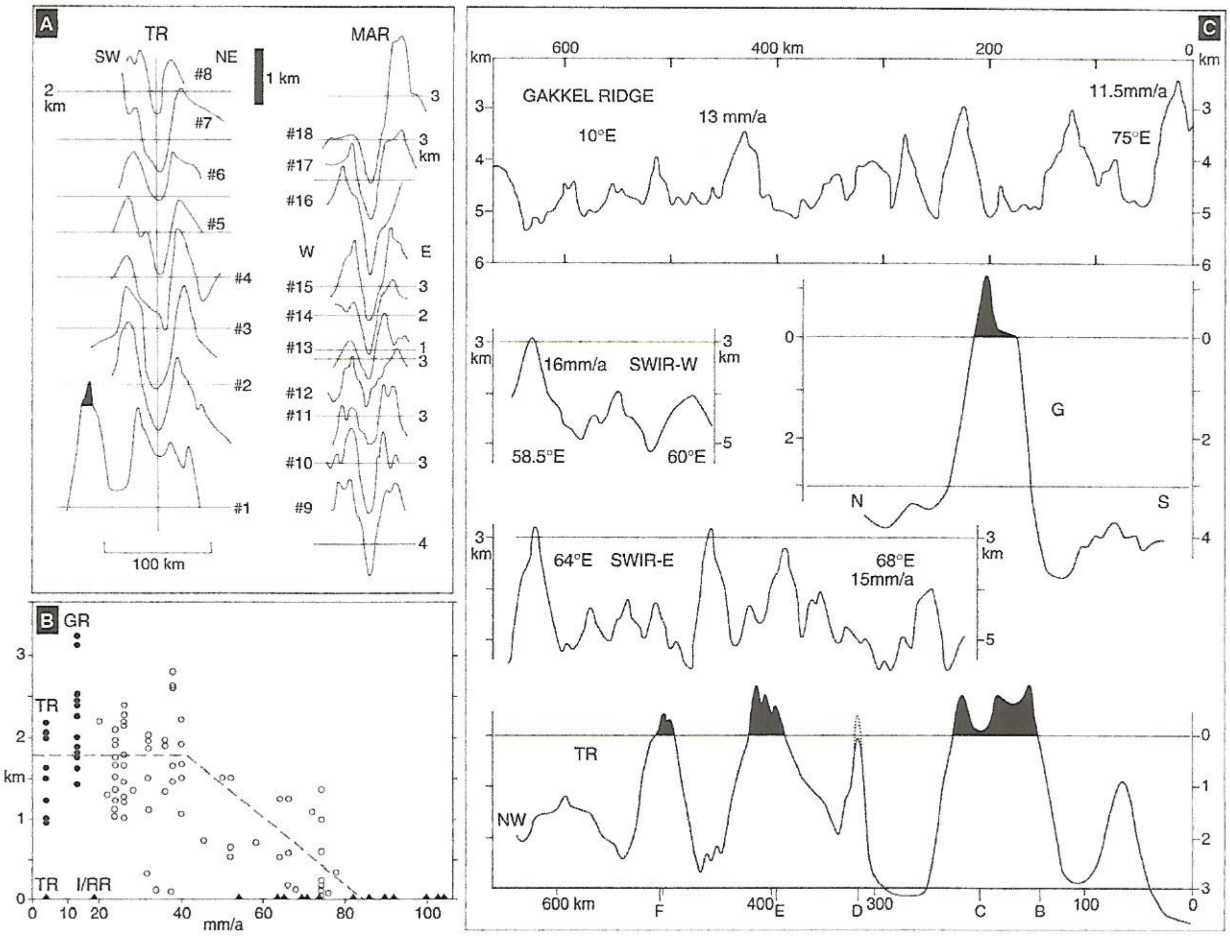

Fig. 2. Bathymetry along Terceira Rift. (A) Comparison between TR profiles #1–8 (Fig. 1) with selected profiles across Mid-Atlantic (#9–15) and Gakkel (#16–18) ridge rift valleys. The horizontal lines are 2 and 3 km isobaths. From south to north, profiles 9–18 (oriented in direction of plate motion) start on the North American plate at 15.5°N, 47°W (#9); 22.75°N, 45.8°W (#10); 26.5°N, 45°W (#11); 37.3°N, 32.7°W (#12); 42.4°N, 29.8°W (#13); 47.37°N, 27.85°W (#14); 49.47°N, 29°W (#15); 50.2°N, 29.6°W (#16); 86.2°N, 19°E (#17); 87.5°N, 65°E (#18). (B) (Modified from [33].) Plot of maximum rift valley relief vs. opening rate, with spreading axes lacking rift valleys shown by black triangles (TR, Terceira Rift volcanic islands; I/RR, Iceland and the northern Reykjanes Ridge). Open circles (maximum rift valley relief) denote Mid-Atlantic Ridge; closed circles show Gakkel Ridge [3] and TR (profiles #1–8). (C) Longitudinal profiles along axis of TR, Southwest Indian Ridge (SWIR-W [8] and SWIR-E[10]; Gakkel Ridge [5]; and Guadalupe extinct rift (G). Land above sea level is black.

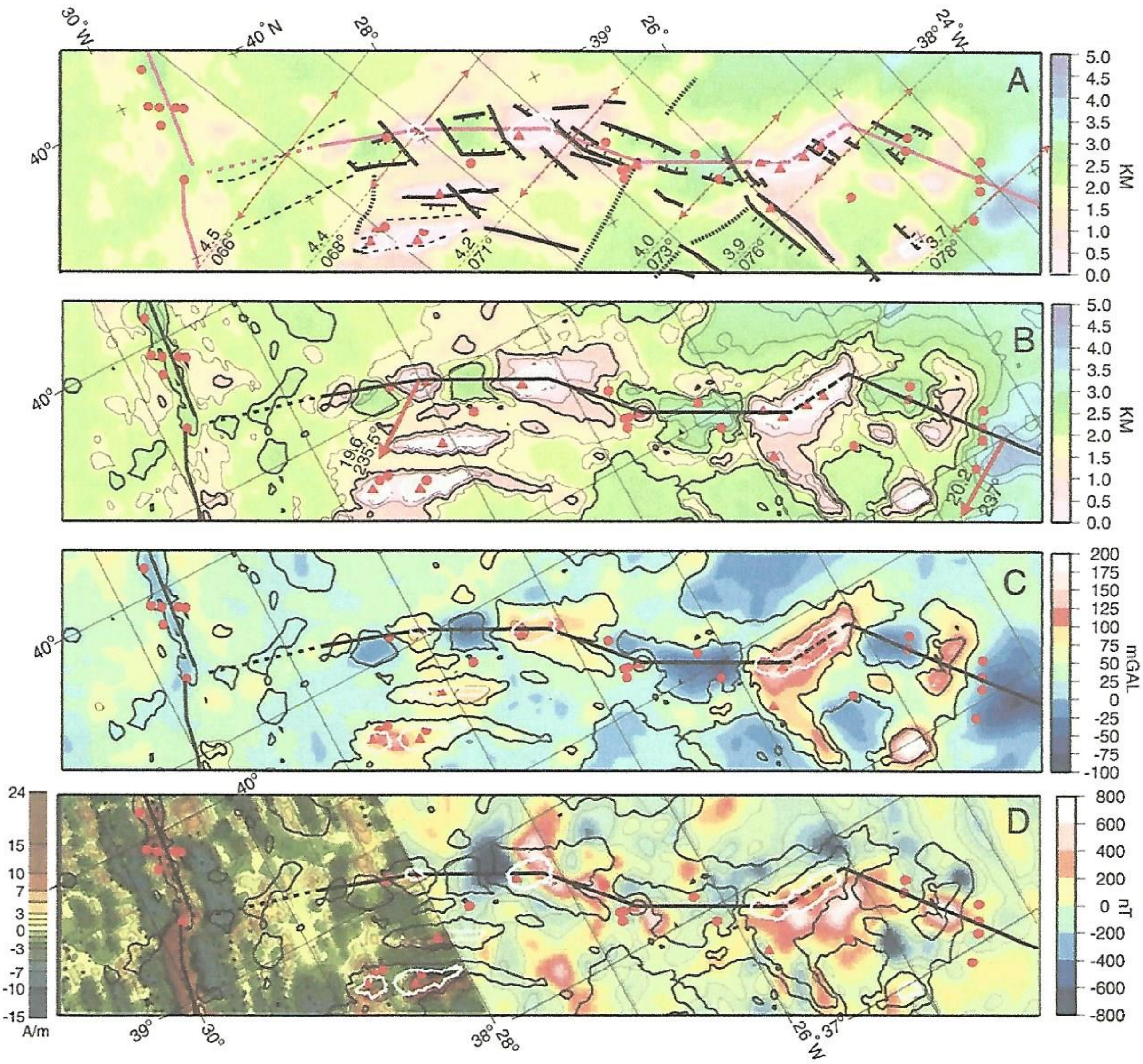

Fig. 3. Morphotectonic (panel A, with our choice for plate boundary in pink, and structural lineations after [14]), bathymetric (panel B), free-air gravity (panel C; [44]); and magnetic anomaly (panel D; [45], except in west from [20]) expressions of TR region. In panel A, structural lineations are from [14] and (for comparison) TR spreading fabric calculated at arbitrary points along TR from NUVEL-1A [2] plate rotation pole (21°N, 20.6°W). Thick red arrows (panel B) show absolute motion of TR plate boundary relative to hotspots [22]. In panel C, 1000 m and 2000 m depth contours have been added to the gravity map. Inversion of detailed aeromagnetic data to crustal magnetization (in A/m; [20]) have been substituted for anomaly contours over westernmost TR. Red triangles are active or dormant volcanoes and red dots are teleseisms.

of the order 1 km^3/ka per island, the TR volcanic islands and their submarine pedestals (each of the order 100–1000 km^3) could have been formed since ca. 1 Ma, consistent with a Quaternary age for the TR. If the parallel WNW volcano-tectonic trends to the SW of the TR ([14]; Figs. 1 and 3) represent short-lived older, abandoned rift axes (as elaborated later), the Azores Plateau evolved by successive NE jumps of the rift axis. Taken together, all evidence suggests the Azores Plateau began to form about or just prior to 10 Ma [20,23,28–30].

Examined in greater detail (Fig. 3A), the TR is slightly sinuous, but all along its length is oblique to the direction of current (and Quaternary) plate motion, as predicted by the NUVEL-1A plate motion model [2]. Whereas the very slow opening along TR readily accounts for the lack of an identifiable magnetic anomaly 'stripe' pattern associated with spreading along the TR (Fig. 3D), the rate and direction are readily predicted from plate motion closure about the triple junction, given the well-constrained relative plate motions of Africa–North America and Eurasia–North America. According to the NUVEL-1A model (with the Eurasia–Africa Euler pole at ca. 21°N, 20.6°W), the relative motion at Castro Bank, near the middle of the TR (Fig. 1), is 4 ± 0.8 mm/a in a direction N72°E ± 3°. The predicted opening rates along the TR decrease from 4.5 mm/a near the triple junction to 3.9 mm/a at the eastern end of the Azores Plateau (Fig. 3A). We have interpreted the TR axis as a segmented continuous line, the segments varying in their obliqueness relative to the direction of opening. Except for the short Sao Miguel 'leaky transform', we avoid the term 'discontinuity' (whether the more oblique segments should be called 'discontinuities' is a semantic distinction). Incorporating the variation of predicted relative motion with the varying strikes along the TR segments, we calculate the following obliqueness angles α (where $\alpha = 90°$ means perpendicular to the direction of relative plate motion) and corresponding projected components of perpendicular opening, Sp: Starting from the southeast end of the Azores Platform and progressing westwards towards the triple junction, we measured the first segment (150 km), from the middle Sao Miguel 'neck' to the intersection of the TR with the GLORIA transform. This segment trends ca. N42°W, implying $\alpha = 61°$ Sp = 3.3 mm/a. The eastern part of Sao Miguel (60 km) trends N77°W, implying a negligible angle of only 2 ± 5°, from the NUVEL-1A-predicted direction of present plate motion, and parallel to the western end of the GLORIA transform [25]. We interpret this 45 km long segment as a short 'leaky' transform along which magma has risen. From the Sao Miguel 'neck' to Castro Bank the TR trends ca. N60°W for 100 km ($\alpha = 47°$; Sp = 2.9 mm/a). A 65 km long segment trends N44°W from Castro Bank to Terceira Island ($\alpha = 64°$; Sp = 3.8 mm/a); from Terceira to Graciosa the TR trends N63°W (48°; 3.2 mm/a), and from Graciosa to an unnamed seamount ('US') at 39.23°N, 28.88°W, the trend is N73°W (40°; 2.9 mm/a).

The exact course of the TR plate boundary from US to the triple junction is unclear, but based on our choice for the triple junction (ca. 39.4°N, 29.7°W), corresponding to a short offset of the MAR axis and a change from an axial high to a rift valley (Figs. 1 and 3A) the trend is somewhat north of west and may currently be transform in character. However, other interpretations for this westernmost segment are possible (e.g. [24]). Luis et al. [21] suggest the plate boundary shifts from Terceira via en echelon Sao Jorge and Faial–Pico segments to intersect the MAR southwest of our suggested triple junction. This and our (Fig. 1) boundaries may both be active, defining a small triangular microplate. While alternative interpretations cannot be discounted, we suggest that the volcanoes forming Sao Jorge, Faial and Pico developed or continued to grow within extinct rifts (Fig. 1), as has happened repeatedly in the Eastern Pacific [31]. In that case Sao Jorge and Faial–Pico are analogs of Guadalupe Island (Fig. 4H).

We used the bathymetric chart of Lourenco et al. [14] and the gridded global database of Smith and Sandwell [32] to examine the gross morphology of the TR rift (Figs. 1–3). As suggested by Saemundsson [28], the deep basins separating the islands and seamounts along the TR may well simply be the 'holes left vacant by volcanoes during volcano growth around them', vs. formed by sagging and extension as first suggested by Krause and Watkins [16]. We regard the basins simply as 'unfilled' segments of what otherwise would be a continuous TR rift valley. Topographic profiles across the basins (#2–8, Fig. 2) show valley widths (between adjacent topographic highs, interpreted as equivalent to the rift mountains of common slow-spreading ridges) from 30 to 60 km, and valley depths (relief) from 1000 to 2200 m. The basin floors range from ca. 2000 to 3300 m (Hirondelle Basin) in water depth. An along-

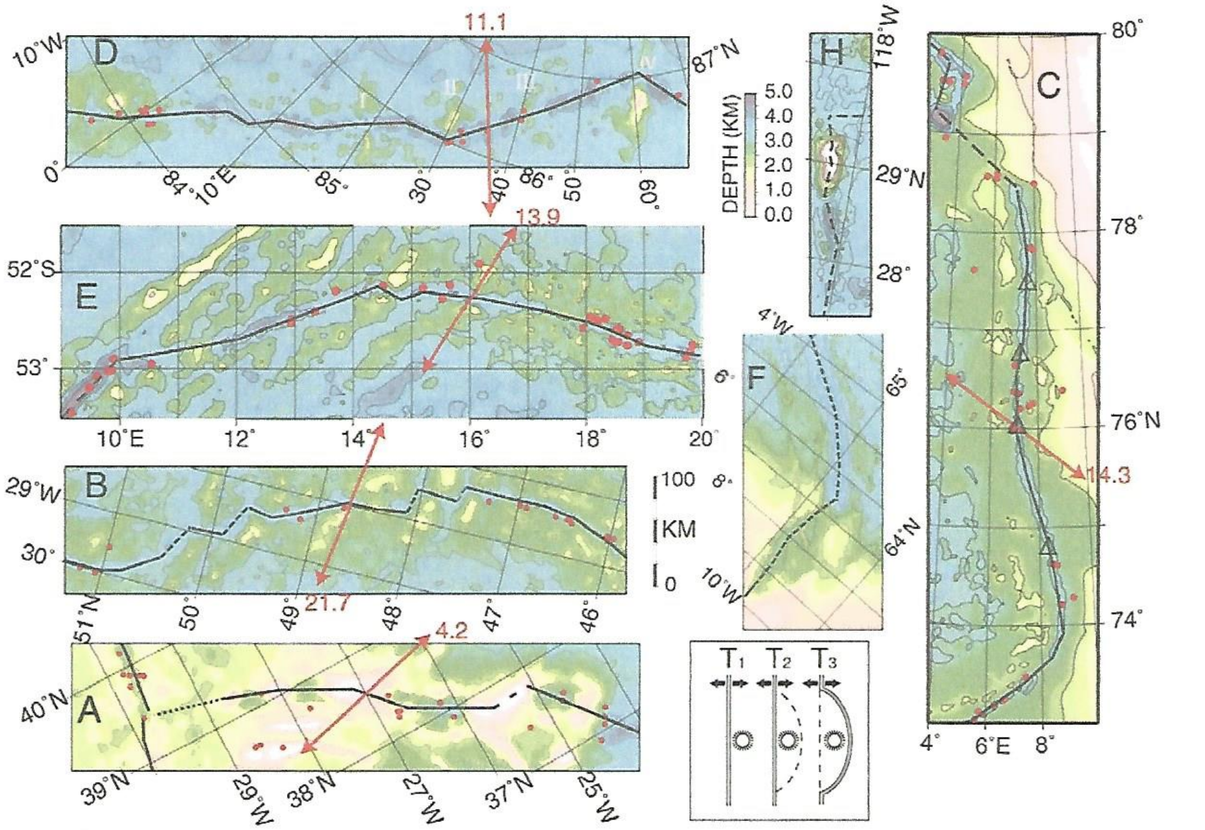

Fig. 4. Comparison between topography along TR (A) and selected other slow-spreading ridge segments (see Fig. 1 inset for area locations): (B) Mid-Atlantic Ridge; (C) Mohns–Knipovich Ridge (triangles show magmatic centers [39,40]); (D) Gakkel Ridge (I–IV show several off-axis highs); (E) Southwest Indian Ridge; (F) extinct Aegir Ridge; (H) extinct Gadalupe axis and volcanic island. Bathymetry based on [44], except Gakkel Ridge from IBCAO [49]. Red arrows and numbers show opening directions and rates [2]. Schematic illustrates how an arcuate spreading axis may have been created as a response to large volcanic or tectonic load placed near – and thereby cracking – the trailing (spreading) edge of a plate.

axis topographic profile (Fig. 2C) shows dominant wavelengths of ca. 100 km, and relief amplitudes of ca. 2000–4000 m. (There is a ca. 4200 m elevation difference between the highest point on Sao Miguel to the bottom of Hirondelle Basin, a distance of only 100 km.) From about Graciosa Island westwards towards the triple junction, valley depth (relief), width, and along-strike relief all decrease and the TR loses its identity, at least from available data (Figs. 1 and 3). We interpret the southeastern segment of the TR to cross a saddle in the elevated area northeast of Formigas islets. If this is correct, the Formigas represent the equivalent of uplifted rift mountain summits to the SW of the TR axis (Profile #1, Fig. 2A).

Lourenco et al. [14] have interpreted the bathymetry and island geology in terms of 'morpho-structural' lineations. We have superposed this volcano-tectonic fabric on the topography along the TR, adding a 'predicted' plate tectonic fabric comprising lineation trends both parallel and perpendicular to the opening directions calculated from NUVEL-1A [2] (Fig. 3A). A number of the volcano-tectonic lineaments are parallel to subparallel to the trend normal to the NUVEL-1A opening direction. This trend was called the 140°–150° 'Azores trend' by Lourenco et al. [14]. Their 'main trend' (110°–120°; figures 4 and 5 of [14]) corresponds to most of what we interpret as obliquely spreading axial volcanic edifices (mostly islands) and the edges of basins we interpreted as oblique rift valley segments. These two main trends (spreading-normal and oblique-spreading), with few or no 'transform' lineations closely correspond to the volcano-tectonic 'fabric' of Knipovich [39,40] and other slow, oblique-spreading ridges.

The location of the TR near the northeastern edge of the Azores Plateau (Fig. 1) raises the possibility of asymmetric spreading, with higher rates on the southwest flank of the TR. However, we find no evidence for any asymmetry along the immediate TR axis. The asymmetric location of the TR is therefore better explained by successive NE jumps of the rift axis, as elaborated later.

3. TR morphology compared to other slow-spreading axes

Although the two MAR rifting arms of the Azores triple junction are opening much faster (20 mm to the south and 23 mm to the north) than the TR, at least the gross rift valley morphology is similar. In particular, the inter-island basins (Figs. 1–3A), interpreted as short 'unfilled' rift valley segments, are only slightly wider (30–60 km) than the MAR rift valley (20–40 km between 10°N and 53°N [33]), and the relief from adjacent peaks to basin floors (ca. 1000–2200 m) falls within the range of MAR valley relief (1000–2800 m [33]; Fig. 3B). Further, the water depth of the TR rift basins (2100–3300 m) lies within the range of the MAR median valley within 500 km of the triple junction. Although there are several types and scales of along-strike discontinuities along spreading axes [34], the primary MAR segmentation wavelength is about 55 km on average [33], about half of the ca. 100 km spacing along the TR (Fig. 3C). The MAR segmentation is a combined plate-tectonic (transform) and magmatic effect, whereas no transforms appear to be present along the TR, with the possible exception of eastern Sao Miguel (Figs. 1 and 3A). Only in the amplitude of along-strike plate boundary elevation changes (Fig. 3C) is there a dramatic difference between the TR (2000–4000 m) and the MAR (300–600 m; maximum 1300 m).

The 'ultra-slow' SWIR (Figs. 2C and 4E; 15–16 mm/a) and Mohns–Knipovich Ridge (Fig. 4C; 15–16 mm/a) MOR segments both contain segments which, like the TR and many other slow-spreading ridges (e.g. [35]), are strongly oblique to the direction of relative plate motion. TOBI side-scan imagery and detailed bathymetry along the ca. 200 km long oblique ($\alpha = 50°–55°$) SWIR segment between ca. 58°E and 60°E [8] revealed three major volcanic centers ('main axial volcanic ridges'), ca. 60–80 km apart, individually elongated perpendicular to plate motion, and rising 500–2000 m above the ca. 5000 m deep intervening basins (Fig. 2C, SWIR-W). The latter authors attribute the placement of these compound edifices to magmatic rather than to the tectonic processes which control the orientation of fissure eruptions and minor axial volcanic ridges. To the east, Mendel et al. [10] mapped 1400 km of the 'super-slow' SWIR, showing similar gross along-strike axial morphology (partly reproduced as SWIR-E in Fig. 2C). A long oblique-spreading segment of the SWIR (Fig. 4E), west of SWIR-W, has not been mapped at high resolution, but as depicted on lower-resolution maps appears similar (Fig. 4E). The Mohns–Knipovich ridges (Fig. 4C; [36–40]) closely resemble oblique SWIR segments, with the Molloy Ridge to the north analogous to 'normal' segments of the SWIR. NUVEL-1A present opening rates (from 15 mm/a along the central Mohns Ridge down to 14 mm/a along the northern Knipovich Ridge) and obliquities ($\alpha = 40°–80°$; [36,37]) are similar to those along the oblique segments of the SWIR. Volcanic centers segment the boundary at intervals from ca. 30 to 150 km along the Knipovich valley, as shown by the triangles in Fig. 4C. At least the more prominent volcanic centers are individually elongated perpendicular to plate motion, and rise ca. 500–1000 m above the ca. 3500–3700 m deep basins [36,39,40]. Were Quaternary continent-derived sediments stripped from the Knipovich valley, along-strike relief would probably increase by at least 500 m, and basin floors deepen to 4000–4500 m in some areas [36].

Farther north, in the Arctic Basin, the Gakkel (also called Nansen, or Mid-Arctic Ridge); Fig. 4D) is said to be 'the slowest active spreading portion of the global mid-ocean ridge system' [4], with total opening rates ranging from 14 mm/ a north of Spitzbergen to around 7 mm/a where the plate boundary crosses into the Siberian shelf [2]. (As discussed previously, the TR (Fig. 3A) is opening at only 25–50% the rate of Gakkel Ridge.) However, middle Tertiary rates along the Siberian end of Gakkel Ridge (ca. 20–30 Ma) were probably as low (e.g. [37]) as along the present TR. Near the Spitzbergen end of Gakkel Ridge, aeromagnetic and submarine-based bathymetric data [3] showed the ridge axis to exhibit strong along-strike central magnetic anomaly amplitude variations (from 50 to 500 nT), correlating with dramatic variations of rift valley depth, from 3700 to 5200 m, the latter significantly deeper than typical at opening rates of 20–30 mm/a. Feden et al. [37] attributed this variability to 'varying basalt productivity associated with the slow spreading'. Modeling gravity anomalies measured over several portions of Gakkel Ridge, Coakley and Cochran [4] inferred an abnormally thin crust. Michael et al. [5] mapped and sampled the western 1000 km of this ridge. They found magmatic segmentation, unrelated to transforms, at 40–160 km spacing along most of the axis (Fig. 2C), with a total along-strike relief approaching 3000 m. Elevation changes just off the Gakkel axis are even more dramatic – we attribute these (e.g. I–IV in Fig. 4D) and similar off-axis features along Knipovich Ridge (Fig. 4C) to the exported remains of axial magmatic centers and/or to tectonic uplifts similar to the 'inside corner highs' associated with typical transform faults. The wavelengths of this along-strike topographic variability are thus about 50–100 km along Gakkel Ridge (Fig. 2C), comparable to the Southwest Indian 'ultra-slow' ridge and the TR, but somewhat greater than along the slow MAR, for which Macdonald [34] calculated an average segment length of 55 km between 10°N and 53°N.

We conclude that the TR resembles other very slow ridges in terms of obliqueness (40°–65°), rift valley relief (1000–2200 m) and width (30–60 km), and magmatic segmentation wavelength (100 km).

Recent MOR studies (e.g. [4–11]) have emphasized the role of sub-axial mantle convective processes, not tectonics, as the primary control on MOR segmentation where no major transforms exist. However, what controls the segmentation wavelength? If Rayleigh–Taylor instabilities (caused by higher-density crust overlying lower-density partial melts) are the basic process (e.g. [41,42]), the observed apparent INCREASE of wavelength at LOWER spreading rates helps constrain the physics. Previous researchers have assumed the buoyant melt layer to be less than 10% of the thickness of the overlying denser layer, and this would be even more likely to apply at very slow spreading. Then the instability wavelength reduces to $\lambda = (2\pi h/2.15)(\mu_1/\mu_2)^{1/3}$, where h is the buoyant layer thickness and μ_1 and μ_2 are the viscosities of the upper and lower layers [41]. A wavelength ratio of 2 for ultra-slow (4–16 mm/a) vs. slow (20–30 mm/a) opening rates requires the viscosity ratio or the melt layer thickness (or their product) to be greater for ultra-slow vs. slow ridges. A melt layer thickening with decreasing opening rate is very unlikely, leaving a higher viscosity ratio as the plausible alternative. Physically this makes sense – at slow opening rates the upper layer can cool more effectively, and viscosity has a strong inverse dependence on temperature. A viscosity ratio of about 8 (i.e. an order of magnitude) could then account for the factor of two wavelength ratio discussed above.

4. Extinct ('fossil') spreading axes

Abandoned (extinct or fossil) spreading centers may relate to the TR not only because their opening rates are presently zero (by definition), i.e. even lower than the TR, but because during the process of deceleration to zero, the rates must have for some time (however briefly) equaled that of the present TR. Therefore extinct rifts may preserve some aspects of ultra- and hyper-slow modern spreading axes. Because (as along the present TR) magnetic lineations cannot be resolved at very low rates, direct measurement of the slowdown process is impossible. However, the integral of $V\mathrm{d}t$, where V is the opening rate, can be measured from the youngest identifiable anomaly to the extinct axis. Extrapolation of the last measurable rate to the axis gives an upper (older) limit to the time of extinction, and an upper limit to the final opening rate – under the assumption of abrupt cessation. It is also possible to calculate rates prior to extinction if plate kinematics can be reconstructed from other boundaries. A major disadvantage is that extinct spreading axes lack many of the parameters that can be used to characterize active ones, e.g. seismicity, geometry of melt chambers, and thermal structure; 'post-mortem' gravity and axial magnetic anomalies have also changed over time.

In the North Atlantic region (Fig. 1, inset map), the Aegir (Fig. 4F; [12]) and the Mid-Labrador Sea (Ran) Ridge [1] were spreading at rates of 7–8 mm/a or less prior to extinction. Both exhibit wider rift valleys than the present MAR, and in this respect resemble the active TR. The last phases of Labrador Sea spreading consisted primarily of crustal stretching [1]. Both extinct axes were significantly oblique, similar to the TR, in plan view. Similarly, the last phase of spreading along the West Philippine Basin (WPB) fossil axis (I in Fig. 1 inset map) involved amagmatic extension of ca. 15–20 km from 30–33 Ma to 26 Ma [13], at an average rate of 2–5 mm/a – about the same as the present TR rates. The WPB axis was similarly oblique (30°–50°) as the TR.

While none of the above fossil axes sported major volcanic massifs in their respective valleys, this is not true for several extinct centers in the eastern Pacific [31]. Evidently some extinct rifts passed over hotspots or otherwise offered favorable pathways for mantle-derived melts to reach the surface – such that volcanic edifices began to rise from the rift valleys and in some cases emerged as islands (e.g. Guadalupe Island, Figs. 2G and 4H). In terms of topographic amplitude and along-strike wavelength, such features are morphologically identical to parts of the TR.

5. Sinuosity of slow, oblique-spreading axes

Several of the oblique-spreading portions of the MOR axis are irregular to widely curved in plan view (Fig. 4), a characteristic not observed along fast-spreading ridge segments. The TR (Hirondelle Basin to US) curvature radius of ca. 300 km is comparable to, although somewhat greater than, radii for the Mohns–Knipovich bend (ca. 150 km; Fig. 4C), the middle Knipovich bend (ca. 300 km; Fig. 4C), three bends (ca. 150, 300 and 400 km) along the ultra-slow (13–10 mm/a central section) Gakkel Ridge; and the bend in the MAR axis from 46°N to 48°N (21–22 mm/a, 300 km; Fig. 4B). A similar bend (radius ca. 200 km) is executed by the southern Aegir Ridge (Fig. 4F), an extinct axis that was opening at 8 mm/a or less in the last few Myr prior to extinction ca. 25 Ma. On Iceland, the Eastern Neovolcanic Zone (19 mm/a) bends from NE to N with a radius of ca. 150 km. The western portion (15 mm/a) of the ultra-slow SWIR (Fig. 4E) executes a broad bend of ca. 500 km curvature radius. Of the almost unlimited variety of gross ridge axis configurations geometrically possible, we note that ridge crest sinuosity with radii of ca. 150–500 km appears to characterize many ultra-slow (4–20 mm/a) spreading axes, including the TR. Perhaps these are preferred 'minimum work' configurations (e.g. [43]) that can alternate with adjoining 'zed' configurations with normal segments offset by transforms (e.g. Fig. 4C). Alternatively, the irregular/sinuous configurations have simply been inherited and replicated from past magmatic/tectonic events or initial-rift geometries.

Fig. 4I suggests one mechanism for creating an arcuate boundary: Because the trailing edges of plates are nearly stress-free, an unusual load (e.g. a massive volcanic or tectonic pile) imposed near the spreading boundary might cause an arcuate fracture within the plate. If active spreading is then transferred to this new zone of weakness, an arcuate plan view would result, and then might be replicated by continued spreading. This mechanism is at least consistent with preferential placement of significantly higher topography on the concave sides of arcuate spreading centers at 74°N in Fig. 4C, at points I, II and IV in Fig. 4D, and in Fig. 4F. In the case of the TR, we note that Sao Jorge, Pico and Faial islands are also located on the concave side of the arcuate segment of TR west of Castro Bank (D in Fig. 1).

6. Discussion and summary

Our synthesis of the morphology and geophysics of the TR reinforces its claim to being the slowest-spreading ('hyper-slow') organized plate boundary, with opening rates (ca. 4 mm/a) less than half of those along the 'ultra-' slow Southwest Indian (14–16 mm/a; [2]) and Gakkel ridges (7–13 mm/a; [2]). In particular, the depth and relief of the basins (e.g. Hirondelle Basin) separating the volcanic islands show them to be comparable to the nearby MAR rift axis. Including data from the TR and Gakkel Ridge suggests that rift valley relief is not a function of opening rate, once rift valleys begin to form at and below ca. 40 mm/a (Fig. 2B). While the TR rift valley is somewhat wider than its MAR counterpart (Fig. 2A), this can be attributed to the very slow opening rate, and therefore thicker axial lithosphere. The TR rift valley width is close to that of the extinct Guadalupe ([30]; Fig. 4H) and Aegir rifts [12], which, like all extinct rifts, must at one time, however briefly, have opened at the rate of the TR. The volcano-tectonic topographic 'fabric' [14] is dominated by lineations either parallel to the oblique-spreading segments or normal to the calculated direction of opening (Fig. 3A), as observed on well-studied oblique, slow-spreading ridges[39,40]. 'Transform' lineations are rare or absent.

Magmatic activity along the TR is spaced quasi-regularly at about 100 km intervals (Fig. 2C), comparable or somewhat greater than along the very slow Gakkel Ridge (Fig. 4D) and SWIR (Fig. 2C), and about twice that reported for the MAR north of the Equator (55 km; [33]). If this 'spreading cell' (e.g. [7]) spacing is the result of Raleigh–Taylor instabilities (low-density partial melts overlain by dense, solid axial lithosphere; e.g. [41,42]), three conclusions can be drawn: (1) The viscosity ratio between the overburden and partial melt layers is about an order of magnitude greater for very slow spreading (ca. 4–15 mm/a) than it is for slow spreading (ca. 20–30 mm/a); (2) because the TR magmatic center spacing is similar to that on the relatively magma-starved Gakkel Ridge and SWIR, mantle fertility ('hotspot' effects) either does not play a major role or happens to be subdued [30]; and (3) because the TR is probably not much older than the volcanic islands, the time scale for Rayleigh–Taylor instability development is likely much less than 1 Ma.

Seismic activity along the TR – including a mixture of normal and more complex fault-plane solutions – is typical for slow-spreading, oblique-spreading centers. The two TR focal depths [27] somewhat deeper than typical for the MOR suggest ultra-slow axes 'freeze' to greater depths, as to be expected. Sub-teleseismic activity appears to extend further from the TR axis [20] than common along the MOR.

Only in the RELIEF of its along-strike topography (ca. 3000–4000 m) does the TR contrast with other very slow ridges (ca. 500–3000 m; e.g. Fig. 2C), although the extinct Guadapupe rift, with its post-rift volcanic island, is closely similar (Fig. 2C). Further geophysical and modeling studies are needed to determine the relative importance of (1) stronger and thicker axial elastic plate, due to slow spreading (e.g. SWIR [10]); (2) slower export of volcanics from the rift zone, due again to slow spreading; or/and (3) unusually fertile mantle, presumably associated with an Azores hotspot.

Like several other slow-spreading boundaries, the TR is irregular to gently curved in plan view (Fig. 4), an observation which merits further investigation (Fig. 4I shows one possible mechanism). The absence of decipherable TR-parallel magnetic lineations is also readily accounted for by the slow spreading rates; both magnetic anomalies (Fig. 3D) and radiometric dating [28] suggest a Brunhes age for the volcanoes that 'fill' the rift valley.

The lack of gravity anomaly evidence for spreading [21] may reflect the relative youth of the TR, i.e. the TR has not had time to develop steady-state conditions in the crust and mantle. If the TR originated ca. 1 Ma, only 4 km extension has occurred, putting an UPPER limit of 4 km for the width of new oceanic crust generated. If the entire Azores Plateau began to form by similar processes and rates starting ca. 10 Ma, then only about 40 km of oceanic crust could have formed by spreading (the Azores triple junction may be older; see below). Since the SW–NE width of the plateau is practically an order of magnitude greater, we infer that most of the plateau is in fact oceanic crust formed at the MAR axis and then modified by loading by and intrusion of Azores-hotspot generated magmas, to generate the present thick, elevated crust. The presence of some MAR-parallel magmatic lineations ([20]; Fig. 1) within the Azores Plateau supports this interpretations. We propose that the plateau was formed by successive NE jumps of the oblique spreading axis – the present TR being the latest stage – the axis at each stage trending NW and intersecting the East Azores fracture zone. This is similar to the evolutionary model first proposed by Ridley et al. [17] (see their figure 26), the primary difference being our suggestion of successive NE jumps in the rift. These jumps may have occurred in response to the average ca. SW motion (ca. S55°W, ca. 20 mm/a, based on [22]) of the Africa–Eurasia plate boundary over an Azores hotspot. Continued SW motion of the TR will then some day result in a new rift to the northeast of the present TR.

Possible traces of earlier rifts are shown in Fig. 1. The NE–SW width of the Azores Plateau in the region of Faial and Graciosa is about 200 km, consistent with 10 Myr 'absolute' motion at the 20 mm/a predicted by the Gripp–Gordon [22] model. The physical reasons why intact continental lithosphere is weaker than oceanic lithosphere [46] also make lithosphere topped by thickened oceanic crust, such as Iceland and the Azores Plateau, easier to rift than normal oceanic lithosphere: because olivine-rich mantle lithosphere is stronger than the lower crust [46] at comparable pressures and temperatures, the larger the crustal component of the lithosphere, the weaker the lithosphere will be.

A detailed comparison of the TR with the extinct King's Trough/Azores–Biscay Rise [47] plate boundary (G2 in Fig. 1 inset) would be instructive. Geometrically and kinematically similar to the present TR–GLORIA transform, this slow plate boundary and associated MAR triple junction formed the previous northern edge of the Africa plate, starting ca. 50 Ma and ending 26 Ma [48] (16–20 Ma according to [47]). King's Trough, a wide, continuous rift valley similar to the Aegir rift valley [12], differs from the TR primarily in the absence of regularly spaced high-relief volcanic centers, suggesting that the mantle underlying King's Trough was less fertile.

The TR, particularly the inter-island basins, is an ideal 'natural laboratory' for comparative studies of active hyper-slow spreading and the formation of young intra-oceanic rifts and evolution into steady-state spreading centers in a hotspot-influenced environment. The first priority should be geophysical studies, and deep boreholes in the basins to establish how the ca. 4 km/Ma opening has been distributed between normal faulting (extension) and magmatic intrusion (e.g. dikes).

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