# The "Azores Geosyndrome" and Plate Tectonics: Research History, Synthesis, and Unsolved Puzzles

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## Abstract

The Azores volcanic archipelago, the Azores Plateau (AP) and the Azores triple junction (ATJ) between the Eurasia, North America and Nubia plates occupy the summit of a regional feature we refer to as the '*Azores Geosyndrome*'. Included are anomalies in crustal thickness, rock composition, basement depth, plate boundary morphology, seismicity, gravity and geoid, and upper mantle seismic velocity structure, and there are many similarities between the Azores and Iceland geosyndromes. The location of the Azores in the central North Atlantic, technological advances in marine geophysics as well as logistic, geomilitary and geopolitical motivations and advanced research of island geology/volcanology have contributed to make the ATJ the most studied oceanic triple plate junction. However, a unified understanding of the Azores Geosyndrome awaits future deep crustal boreholes (particularly on the AP) and regional sea-floor seismometer arrays to resolve the seismic velocity

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structure below the AP down to the middle and perhaps lower mantle. Whereas a deep mantle plume appears unlikely to exist below the Azores, it cannot yet be excluded (see O'Neill and Sigloch, Chapter "Crust and Mantle Structure Beneath the Azores Hotspot—Evidence from Geophysics", and Moreira et al., Chapter "Noble Gas Constraints on the Origin of the Azores Hotspot"). What is already clear is that the development and evolution of the Azores Geosyndrome has involved dynamic interactions among the North America-Nubia-Eurasia plates and at least the uppermost mantle below those plates—*even far from the ATJ area*. The plate boundary reorganization that resulted in the triple plate junction jumping from the end of King's Trough south to create the ATJ was largely complete by Chron 6C (23 Ma) and coincided within dating uncertainties with the jump of the spreading plate boundary from the Norway Basin to the new Kolbeinsey Ridge just north of Iceland. Major geological changes in the Pyrenees and Alpine Tethys region at that time have long been known. In fact, the Palaeogene-Neogene boundary, a time of global change in planktonic biogeography, is placed at 23.0 Ma, in the upper part of C6C. Why the ATJ developed where it did and not elsewhere along the MAR suggests the lithosphere and subjacent mantle had already created a region of plate weakness. The subsequent development of the AP, largely

via Mid-Atlantic Ridge spreading, produced a thick crust and more fertile mantle lithosphere-particularly from ca. 12 to 8 Ma. This mantle lithosphere was and continues to be relatively weak and fertile, favouring transtensional fissuring, formation of central volcanoes, as well as oblique hyperslow spreading along the Terceira Rift—particularly in the last 1.5 Ma.

## 1 Introduction

The Azores Archipelago of volcanic islands (Forjaz et al. 2010; Figs. 1 and 2) is the focus of this volume—but these islands collectively form the summit of the much broader regional "Azores geosyndrome", a term we use for an ensemble of spatially and probably causally related anomalies in crustal thickness, depth and gravity/geoid anomaly, upper mantle seismic structure, plate boundary morphology, and rock geochemistry. Whereas this paper focuses on the plate boundaries intersecting at the Azores Triple Junction (ATJ), the anomalous characteristics of the plate

boundaries near the ATJ can only be fully understood within the context of the Azores Geosyndrome, which in many ways resembles similar regional 'geosyndromes' like those centred at Iceland and the Afar Triangle.

The Azores geological literature has exploded, especially in recent years, as obvious from the reference lists in this volume. This poses a challenge for reviews—key publications may be overlooked, while newer data or models are still unavailable to the reviewer. However, our review offers the easily overlooked research history and —we hope- some fresh perspectives on recently published data and interpretations. We cast a wide net and thus inevitably overlap several other chapters in this volume (Fernandes et al., Chapter "The Contribution of Space-Geodetic Techniques to the Understanding of the Present-Day Geodynamics of the Azores Triple Junction", O'Neill and Sigloch, Chapter "Crust and Mantle Structure Beneath the Azores Hotspot—Evidence from Geophysics; Miranda et al., Chapter "The Tectonic Evolution of the Azores Based on Magnetic Data"; and Mitchell et al.,

**Fig. 1** **a** Computer-illuminated seafloor topography from the Azores archipelago and MAR (Mid-Atlantic Ridge) to Gibraltar, derived from satellite radar altimetry and surface ship echo-sounding (from Smith and Sandwell 1997); earthquake epicentres (teleseisms) from 1973 to 2012. See also Simkin et al. (2006) for a generalised global synthesis of plate boundaries, volcanism and seismicity. Known hydrothermal vent fields are numbered: (1) Moytirra; (2) Menez Gwen; (3) Lucky Strike; (4) Lost City; (5) TAG; and (6) Joao do Castro Bank. **b** Seafloor topography and earthquake epicentres of the Azores platform, including the Terceira Rift, the triple junction area, hypothesised Azores microplate, and adjacent parts of the Mid-Atlantic Ridge. Solid line shows axis of Terceira Rift plate boundary after Vogt and Jung (2004), with letters US, G, F, E, D, C, B and A points along the plate boundary topographic profile (Fig. 3a). (The extrapolation of the TR to the MAR (Vogt and Jung 2004) has been revised, reflecting evidence for a diffuse plate boundary (Marques et al. 2013; Miranda et al. 2014). The age '39 Ma' marks the Monaco Bank rock of Beier et al. (2015). Key magnetic lineations (heavy dashed lines) from Luis and Miranda (2008). Red triangles are volcanic centres active since 10 ka (as in Simkin et al. 2006). AB, Azor Bank; PAB, Princess Alice Bank. Inset map (modified from Vogt and Jung 2004), shows other ultraslow spreading axes, with small circles

(on East Pacific Rise) enclosing two postulated microplates at triple plate junctions (See also DeMets et al. 2010). Seismic reflection profile locations (*Vema* and *Gibbs* cruises) correspond to Fig. 2. **c** Seafloor topography, plate boundaries, and earthquake epicentres of the immediate Azores triple junction area. F, Faial; P, Pico; SJ, São Jorge; G, Graciosa; AB, Azor Bank; PAB, Princess Alice Bank. PAR denotes postulated fossil (pre-TR) Prince Alice Rift plate boundary (dashed line). **d** High resolution hillshade seafloor topography of the Azores TJ region (Miranda et al. 2014); image courtesy of J. Luis, Univ. of Algarve. **e** Structural/Tectonic (morpho-structural) interpretation (modified from Miranda et al. 2014) of the Azores TJ region, based on multibeam bathymetry (Fig. **d** and other data), earthquake epicentres, and magnetic anomaly isochrons (numbers denote chrons). Solid lines denote tectonic, and dashed lines, volcanic topographic structures. N1 lineations are abyssal hill fabric exported from the MAR axis; N2 trends are WNW trending normal faults and volcanic fissure eruption trends extending westwards from the islands; N3 denotes NW and conjugate NE trending normal faults attributed to diffuse Eurasia-Nubia motion. Brackets show crust generated ca. 8.2–6.2 Ma, during pole location change and slowdown in Eurasia-North America (Merkouriev and DeMets 2008, 2014b) and Nubia-North America motion (Merkouriev and DeMets 2014a)
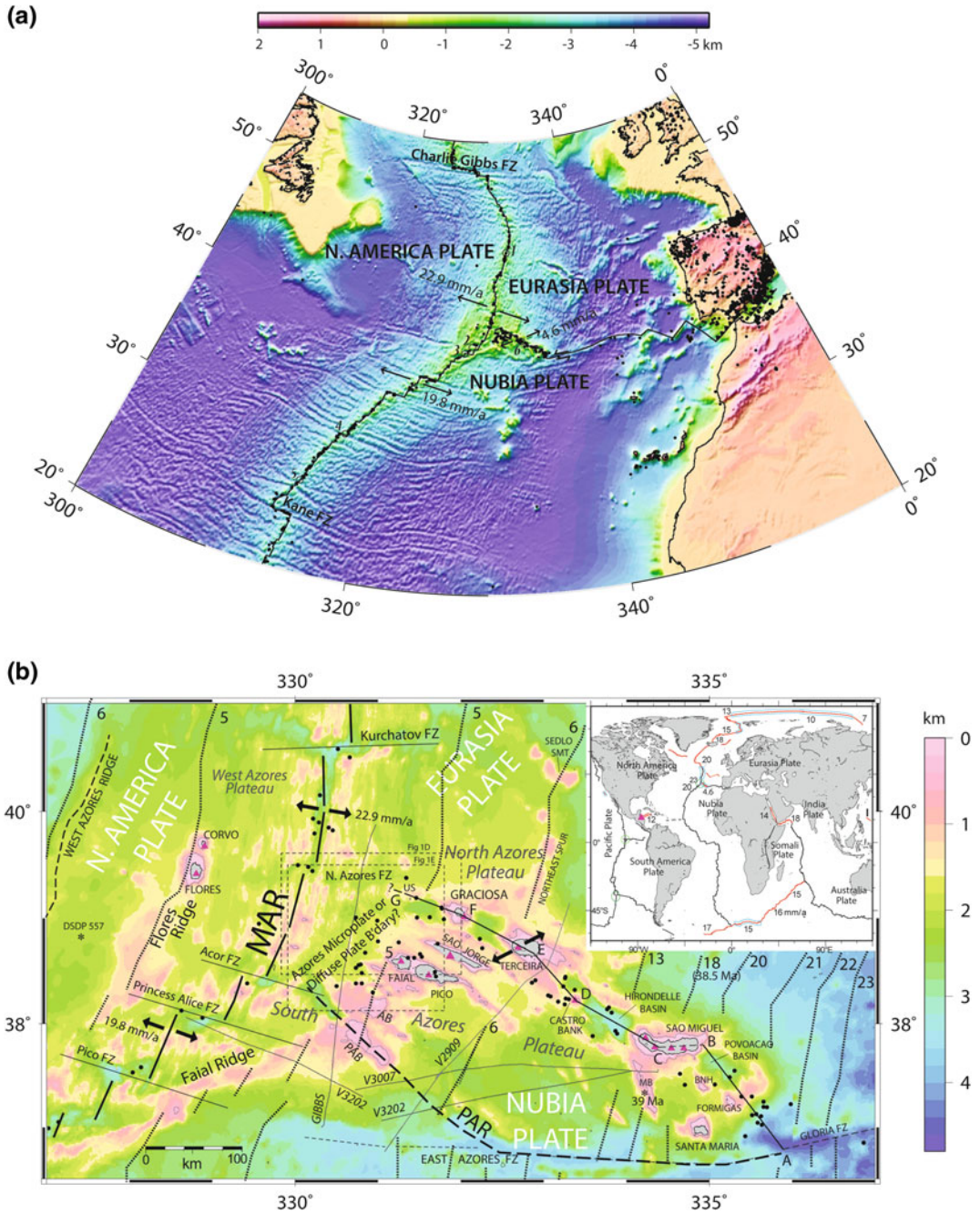
Chapter "Volcanism in the Azores: A Marine Geophysical Perspective"). We trust that any differences in interpretations of the same data will stimulate further discussion and research.

Since the plate tectonic revolution (discussed further below) and the subsequent but still controversial mantle plume/hotspot concept (Morgan 1972), the volcanic Azores islands and plateau have been attributed (e.g., Gente et al. 2003) to the interaction between some type of hotspot/mantle plume/melting anomaly and the triple junction between the North America,
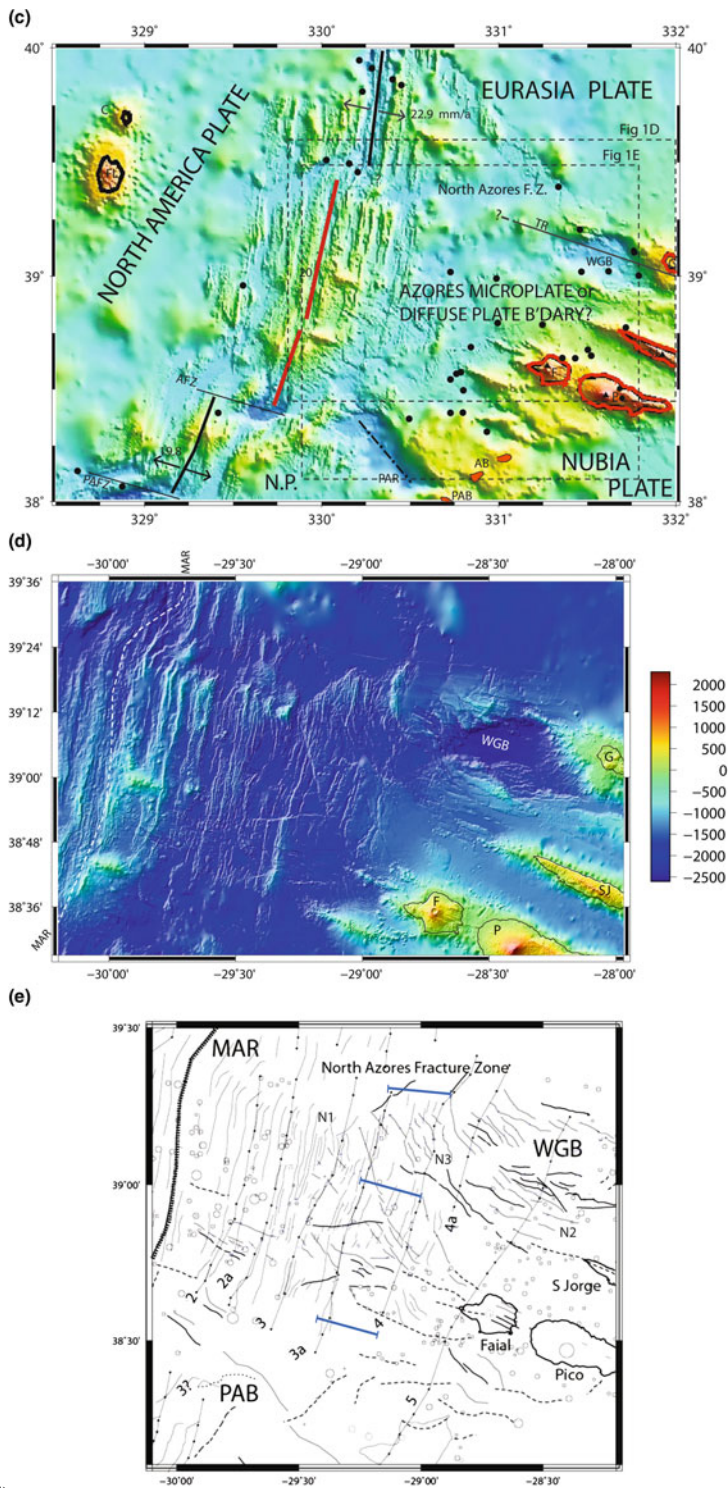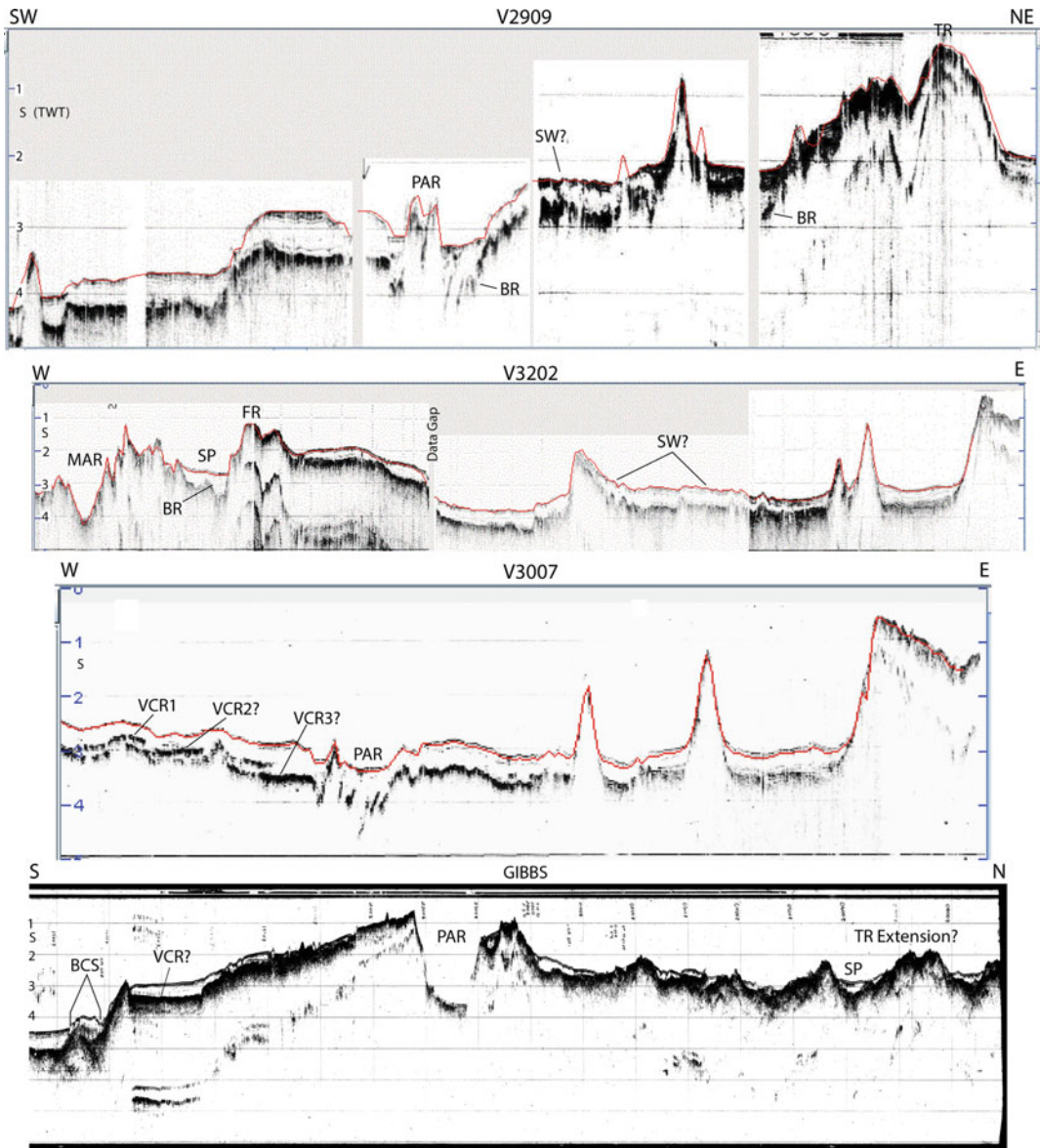
**Fig. 1** (continued)

**Fig. 2** Single channel seismic reflection profiles collected on transits of the Azores Plateau, with vertical scale in two way reflection time. In the acoustically transparent hemipelagic sediments, 1 s is approximately 1 km. Profile locations are shown in Fig. 1b. *R/V Vema* profiles are from GeoMapApp (Ryan et al. 2009); *R/V Gibbs* profile courtesy of National Geophysical Data Center. MAR, Mid-Atlantic Ridge rift valley; FR, Faial Ridge; PAR, Princess Alice rift; TR, Terceira Rift, BCS, bottom current sedimentation and erosion; BR, basement reflector; SP, sediment pond; SW sediment waves; VCR, volcanoclastic reflector. Multichannel seismic profiles were collected (2009) in areas around São Miguel (Weiss et al. 2015b, 2016)

Eurasia, and Africa/Nubia plates (see also O'Neill and Sigloch, Chapter "Crust and Mantle Structure Beneath the Azores Hotspot—Evidence from Geophysics"). Although plume-based numerical models account for some observations (Adam et al. 2013), other numerical models reproduce some features of the Azores Plateau (particularly the trends of the Terceira Rift (TR) and linear volcanic seamounts and islands SW of the TR (Neves et al. 2013) by boundary forces fracturing

the brittle upper plate and providing transtensional conduits for magma ascent.

The anomalous geological and geophysical attributes comprising the "Azores Geosyndrome" include:

- a regional geoid (over +50 m) and corresponding free-air gravity high, which fuses with the highs over Iceland (e.g., Grevemeyer 1999; Rabinowitz and Jung 1986);
- a regional positive oceanic depth anomaly (Louden et al. 2004), which along the Mid-Atlantic Ridge (MAR) axis reaches ca +1.5 km near the ATJ and may extend 3200 km south from the Charlie Gibbs Fracture Zone (FZ) (52°N) to the Kane FZ (Fig. 1a);
- the shallow Azores Plateau (AP), alternatively called platform or rise, with presently thickened (up to 14 km; Escartin et al. 2001; Dias et al. 2007) crust, formed largely from 20 to 7 Ma at the crest of the MAR (Gente et al. 2003; Miranda et al., Chapter "The Tectonic Evolution of the Azores Based on Magnetic Data");
- central volcanoes (Mitchell et al., Chapter "Volcanism in the Azores: A Marine Geophysical Perspective"), rising up to 1105 m above sea level as geologically young (<1 Ma) islands along the Terceira Rift (TR; Graciosa, Terceira, Joao de Castro bank, and São Miguel), and somewhat older ones emplaced in AP crust both west (Corvo, Flores) and east of the MAR axis (Santa Maria, Formigas, Faial, São Jorge, Pico—with its 2351 m summit one of the tallest volcanoes only ca. 150 km from the MAR axis–plus Princess Alice and Azor banks and several guyots);
- a segment of the MAR (ca. 38.7°–39.3°N) near the triple junction lacking a conspicuous rift valley, with comparatively low historical teleseismic activity, and exhibiting, despite the slow (ca. 22 mm/a; Fig. 1c) spreading, well-developed magnetic lineations (Searle 1980; Luis et al. 1994; Miranda et al., Chapter "The Tectonic Evolution of the Azores Based on Magnetic Data") typical of faster-spreading ridges;

- geochemically anomalous (e.g., light-rare-earth-enriched) axial basalts sharply ending just north of the triple junction but gradually towards the south (Schilling 1976; Gente et al. 2003; Fig. 3c) and the heterogeneously sourced (Beier et al. 2008, 2015 and Chapter "Melting and Mantle Sources in the Azores") island volcanoes, and newer data suggesting the Azores overlie a ca. east-west compositional boundary in the underlying mantle (Madureira et al. 2014);
- southward pointing V-shaped Faial and Flores ridges (Vogt 1979, 1986c), formed along the MAR 10–4 Ma (Cannat et al. 1999; Escartin et al. 2001);
- an older set of basement ridges formed along the MAR ca. 20 Ma, plausibly marking the beginning of Azores Plateau formation; and
- a complex low-velocity upper mantle region under AP, and extending from 250 km to at least ca. 400 km depth under or just northeast of the TR according to Yang et al. (2006) and to 250–300 km based on the negative S-wave anomaly (Silveira et al. 2006), with no compelling seismic or other evidence (e.g., Anderson 2005) for a mantle convection plume (Morgan 1972) rising from near the ca. 2900 km deep core-mantle boundary.

Not all features of the ATJ plate boundaries are anomalous, however: The MAR near the ATJ (Fig. 2 of Luis et al. 1994) is segmented at 50–60 km scales, similar to the MAR far from the Azores (Fig. 2 of Vogt 1986a), and includes discontinuities slowly (3 mm/a; Luis et al. 1994) propagating along the axis, of the type also found on the MAR far from the ATJ (Fig. 3 of Vogt and Jung 2005; Schouten et al. 1985), and an axial volcano (minimum depth, 750 m; 38.3°N; Luis et al. 1994) similar to others scattered widely along slow-spreading ridges (Vogt and Jung 2005; Vogt et al. 2008).

The longer (ca. 100 km) segmentation wavelengths and pervasive oblique spreading along the TR are also typical of other ultra-slow spreading ridges far from 'hotspots' (Vogt and Jung 2004). While most papers accept the TR as an accreting plate boundary (but see Luis et al.
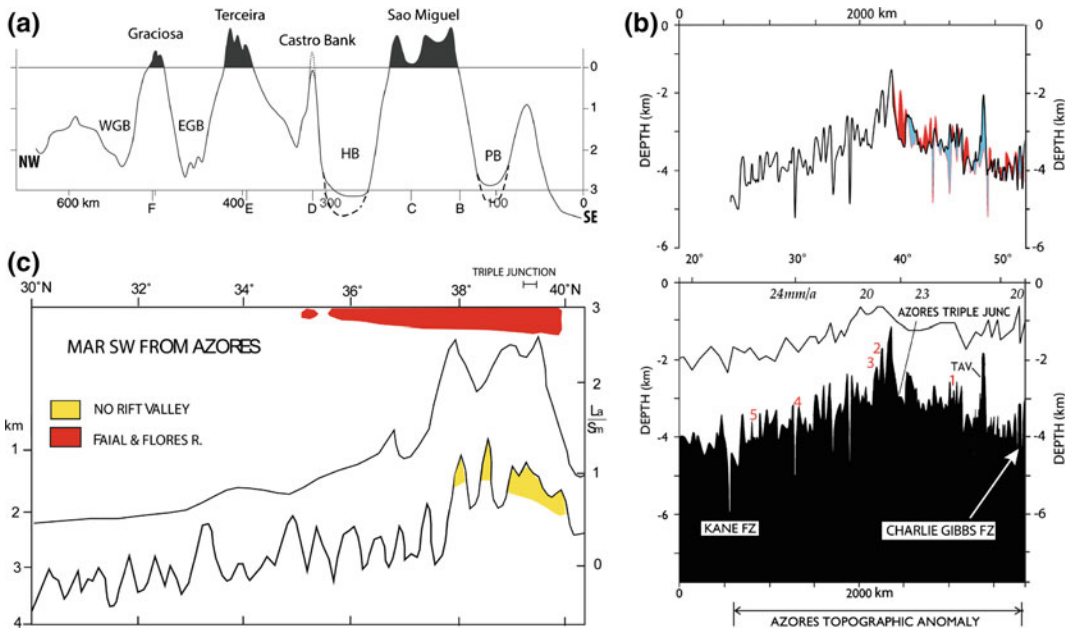
**Fig. 3 a** Along-strike topographic profile along the axis of the Terceira Rift (Fig. 1b), from Vogt and Jung 2004). Letters B, C, D, E and F denote locations where TR plate boundary changes direction. WGB, West Graciosa Basin; EGB, East Graciosa Basin; HB, Hirondelle Basin, and PB, Povoacao Basin. The latter two basins contain at least ca. 500 m sediment (dashed, based on Weiss et al. 2015b). **b** Along-strike topographic profile (lower) along the axis of the Mid-Atlantic Ridge along the Azores and Iceland regional highs (modified from Fig. 9 of Vogt and Jung 2005), suggesting that as much as 3200 km of the MAR (2200 km according to Goslin and Party 1999; Gente et al. 2003) is influenced by the 'Azores Geosyndrome'. Top profiles show southern flank overlapped on

northern flank as a test for north-south along-axis symmetry. TAV is Telegraph Axial Volcano (Vogt and Jung 2005). Known hydrothermal vent fields are numbered: (1) Moytirra; (2) Menez Gwen; (3) Lucky Strike; (4) Lost City; (5) TAG; (6) João do Castro Bank. **c** Along-axis topographic (lower) and La/Sm (upper) profiles from 30°N to just north of the Azores triple junction (reproduced from Fig. 10 of Vogt and Jung 2005; based on Gente et al. 2003, originally from Dosso et al. 1999). Red shows the extent of the paired off-axis V-shaped Faial and Flores ridges, formed at the MAR axis progressively from 10 Ma to 4 Ma (Vogt 1979; Cannat et al. 1999)

1998), the detailed depiction of this boundary varies from author to author. Here we follow Vogt and Jung (2004) who approximated the alternation of volcanic islands and intervening deeps as a serious of strait line segments—in detail many segment transitions are curved (sigmoidal), as is true for the Mid-Atlantic plate boundary where mapped in detail by multibeam bathymetry. GPS data from various Azores islands support a diffuse plate boundary, with the TR itself opening even slower than assumed by Vogt and Jung (2004), perhaps accommodating

only ca. 2–3 mm/a of the total ca. 4.5 mm/a Nubia-Eurasia motion (Marques et al. 2013), as discussed further below.

In this chapter, we review the evolution of understanding, but beginning with the profound advances that set the stage for seafloor spreading and then plate tectonics, and the role of costly technological innovations, driven by geopolitical (mainly military) needs, which made most marine geophysical advances possible. We conclude by summarising some outstanding research problems which remain.

## 2 Preludes to Plate Tectonics (1855 to 1968)

Although the Azores islands have been historically known to mankind since at least the early 15th century, what lay below and beyond the shallow banks and island shelves remained a mystery until the abyss was sounded with long wires (cables), the first in the South Atlantic in 1840 (see also Beier and Kramer, Chapter "A Portrait of the Azores: From Natural Forces to Cultural Identity"). The first crude representation of the north-central Mid-Atlantic Ridge (MAR) was that of Maury (1855), who called this shallower region "Middle Ground". Maury's map also showed, but did not name, the even shallower region around the Azores islands, today known as the "Azores Plateau" (also referred to as a rise or platform, divided in this paper into North, West and South (or East) plateaus; Fig. 1b). Wire soundings proved invaluable for laying of transatlantic telegraph cables, which included a shore station in the Azores.

Higher resolution MAR bathymetry had to await the advent of echo-sounding technology—particularly the southern and equatorial MAR profiles collected by the 1925–27 Meteor expedition (Stocks and Wuest 1935). About the same time, earthquake seismologists discovered that the MAR—including a belt from the Azores region to Gibraltar— was seismically active (Tams 1927; Gutenberg and Richter 1941). The narrowness of these belts would not be discovered until the 1960s.

Alfred Wegener, arguably the father of continental drift (beginning ca. 1913), died on the Greenland ice cap in late 1930, and so never had full access to the new bathymetric and seismologic results, dating from the mid-late 1920s, that bolstered his theory. In the final edition of his book (Wegener 1929), he still believed that the Azores, Iceland, and the MAR were sialic debris, continental material left behind as a kind of 'fossil breakup zone'. Yet, he was obviously troubled by continental reconstruction problems such as posed by Iceland, and by the great width of the Mid-Atlantic Ridge. Wegener did at least consider the possibility that the MAR was of basaltic composition. More important, he attributed the shallower averaged ocean depth of younger ocean basins to thermal expansion of what today would be called the 'lithosphere', thus predating by decades the now well-known 'age-depth' relationships (Sclater et al. 1971). Had Wegener applied his thermal expansion argument to the MAR—plus the new knowledge, acquired after his death, of a central rift valley and earthquake seismicity—Wegener might well have also fathered plate tectonics himself. Simple observation of an intermittently widening, freezing lead between two ice floes—the youngest ice the thinnest—might have inspired this polar scientist to envision continents as frozen into the tops of giant plates, rafting apart along narrow crack-like zones at the axis of the Mid-Oceanic Ridge.

Improvements in paleomagnetism provided the first post-Wegnerian evidence for continental drift, but the new polar wander curves (e.g., Runcorn 1956) did not convince many skeptics. Instead, the next big advance was the formulation of 'sea-floor spreading', a term coined by Dietz (1961), which replaced Wegener's 'sialic' MAR debris with elongate upwelling mantle convection cells below the Mid-Oceanic (and thus Mid-Atlantic) Ridge. Drawing on earlier mantle convection conjectures by Arthur Holmes (1929), Hess first presented the spreading concept two years prior to the Dietz publication (Hess 1959). Ewing and Heezen (1956) had already called attention to the earthquake belt along the MAR crest, with a spur extending towards the Mediterranean from the Azores area. Moreover, Heezen et al. (1959; references therein) had identified the MAR rift valley and, with an early marine magnetometer, found a high positive magnetic anomaly over the rift valley, flanked by negative anomalies.

It took less than a decade for 'sea-floor spreading' to evolve into plate tectonics. During this last pre-plate tectonic interval (1959–1968), linear magnetic anomalies, also called lineations or magnetic striping, were attributed to a combination of sea-floor spreading and magnetic reversals (Vine and Matthews 1963; independently by Morley and LaRochelle 1964). The

reversals of geomagnetic polarity are recorded, largely in the highly magnetised upper 500 m of oceanic crust, as bands of alternately normally and reversely magnetised basalt. The anomalies, small departures of total field strength, depend in their amplitude on distance from the top of the oceanic crust, on the strength of crustal thermoremanent magnetization, and on the relation of a band of crust relative to the present geomagnetic field. In the North Atlantic including the Azores region, positive anomalies approximately overlie bands of normal magnetization. The reversal time scale (e.g., Walker et al. 2012) is divided into 'chrons', with chron numbers approximately equivalent to magnetic anomaly numbers, but include a conspicuous band of largely positive magnetic polarity at the end of a chron, plus the preceding interval of largely reversed polarity. Given the slow spreading rates and frequent reversals for the time of Azores Plateau formation, we use anomaly and chron numbers interchangeably. Magnetic lineations over the Mid-Atlantic Ridge are mostly rather irregular and difficult to identify, a consequence of slow spreading and lava extrusion rates. Thus, Vogt and Ostenso (1966) concluded from a local magnetic-bathymetric survey of the MAR crest north of the Azores (42°–46°N) that convincing evidence for the Vine and Matthews (1963) hypothesis was lacking there.

Wilson (1965) identified and named transform faults—strike-slip plate boundaries along which crust is neither made nor destroyed. However, few obvious transform faults were evident in the complex MAR bathymetry north of the Azores. Menard (1965) identified the active seismic belt and associated rough topography between the Azores and Gibraltar as an 'active' fracture zone, which to first order it turned out to be.

## 3 The Azores Region Interpreted During the Plate Tectonic Era

Interpretations of the Azores region evolved rapidly following the publications of Morgan (1968), Isacks et al. (1968), LePichon (1968), McKenzie and Morgan (1969) and others.

Morgan (1968) proposed the East Azores FZ as the boundary between the African and Eurasian 'blocks' (now called plates). It was early recognised that the Azores platform was too complex to have evolved from a simple ridge-ridge-ridge (r-r-r) triple plate junction. Starting with Krause and Watkins (1970) and continuing with later studies (e.g., McKenzie 1972; Laughton and Whitmarsh 1974) evolutionary models variously incorporated changes from transform faults to rifts, migration of the triple junction along the MAR, and/or jumps in the spreading axis (Searle 1980). Krause and Watkins (1970) applied the idea of a "leaky transform fault" (Menard and Atwater 1968) to what is now called the Terceira Rift. In more recent publications, the "leaky transform" concept has been applied to the central and eastern part of São Miguel (e.g., Sibrant et al. 2016; Weiss et al. 2015b).

Magnetic data available at the time lacked the density and inherent resolution to test aspects of the three basic evolutionary models (Krause and Watkins 1970; McKenzie 1972; Searle 1980). Work in succeeding decades refined these three triple junction evolution models (Neves et al. 2013; Miranda et al. 2014), but resolution of the magnetic stripes is limited by the slow Nubia-Eurasia opening rates within the "Azores Domain" (Luis and Miranda 2008). However, some key NNE-trending magnetic lineations generated at the MAR axis have been identified over parts of the Azores Plateau (Luis and Miranda 2008; Miranda et al. 2014 and Chapter "The Tectonic Evolution of the Azores Based on Magnetic Data"; Fig. 1b, c, e; Miranda et al., Chapter "Volcanism in the Azores: A Marine Geophysical Perspective").

A detailed aeromagnetic survey of the Azores region provided the first evidence for the intermittent (10–3.85 Ma) existence of a separate "Azores microplate" (Luis et al. 1994). DeMets et al. (2010) concluded, from the gradually northward increasing opening rates (since 3.16 Ma) along the MAR from ca. 38.35 ± 0.15°N to 37.7 ± 0.3°N, that such a microplate must on average have existed since then, perhaps with the historically active volcanic islands Faial, Pico, São Jorge, plus Azor and

Princess Alice banks (Fig. 1c), thus forming its present wide, complex eastern boundary. However, in support of earlier studies (Bastos et al. 1998), GPS data from Terceira, São Jorge, Faial, and Pico support distributed (diffuse) deformation, with no microplate required (Marques et al. 2013, 2014), a result corroborated (Miranda et al. 2014) with detailed multibeam topography and earthquake seismicity (Fig. 1e).

When did the Azores triple plate junction currently located near 38°50′N, 30°25′W (Gaspar et al. 2015), first form? North Atlantic plate kinematic reconstructions have proved challenging, because slow spreading rates generally produce "noisier" magnetic lineations. The MOR on either side of Iceland is an exception (Vogt 1986b). The first major reconstruction (Pitman and Talwani 1972) was successively refined (e.g., Klitgord and Schouten 1986; Srivastava and Tapscott 1986). The latter two papers conclude that the Azores triple junction originated about anomaly 9 time (ca. 27.5 Ma on the Walker et al. 2012 timescale), when the plate boundary from an earlier MAR triple junction last extended via Kings Trough into the Bay of Biscay and the Pyrenees. About that time, the triple junction jumped south, thereby transferring Iberia to the Eurasia plate, as first suggested by Smith (1971). However, magnetic lineations between #13 and #6 are poorly developed, and King's Trough actually extends west nearly to anomaly #6 (e.g., Fig. 1 of Klitgord and Schouten 1986), so the plate boundary 'jump' might have occurred gradually during the period 27–20 Ma, rather than 'instantaneously'. Geological evidence suggests rifting along King's Trough lasted until roughly 20 Ma (Kidd and Ramsay 1987). Roest and Srivastava (1991) concluded that the triple junction 'jumped' south to the Azores site around anomaly 6C time (23 Ma). The most recent plate kinematic models, based as in earlier models on successively rotating back together crustal isochrons defined by prominent magnetic lineations on both MAR flanks, are by Luis and Miranda (2008) and Merkouriev and DeMets (2008; 2014a, b). We interpret the Northeast Spur and West Azores Ridge, formed around anomaly 6 time (Fig. 1b), as marking the initiation of Azores

Plateau formation, i.e., soon after the triple junction jump (see later discussion). Merkouriev and DeMets (2014b) found small misfits (overlaps) when they rotated magnetic lineations from the one MAR flank to the other. These misfits (20 km for anomaly 6 and 5 km for anomaly 4A) suggest some diffuse 'post-jump' intraplate deformation continued within the Eurasia plate from the triple junction north to 42°N.

The r-r-r type triple junction model (Krause and Watkins 1970) already included a slow-spreading 'Terceira Rift' (TR) crossing the Azores platform. The attempt to measure the TR opening rate using magnetic profiles proved (e.g., Miranda et al. 1991) unconvincing, probably due to the very slow opening rates and wide rift zone, relative to the geomagnetic reversal frequency. If, contrary to Vogt and Jung (2004), the TR is not an established, albeit 'hyperslow' spreading axis, no magnetic lineations would be expected in any case. The opening rates across the slow-spreading, variably oblique TR plate boundary had to be estimated by vector subtraction of the well-constrained North America-Africa motion from the North America Eurasia motion, and basically the same method is still used today. The rifting/spreading half-rate Krause and Watkins (1970) estimated for the TR plate boundary (2.0–2.5 mm/a) is closely comparable to the total opening rates computed for about the middle of the TR from more recent global inversions (e.g., 4.9 mm/a, NUVEL; DeMets et al. 1990; $4.6 \pm 0.2$ mm/a, S64 W $\pm$ 1.3° (MORVEL; DeMets et al. 2010). When only Eurasia-North America and Nubia-North America motion is considered, the "geologic" (since ca. 3.16 Ma) MORVEL inversion yields $4.5 \pm 0.4$ mm/a in the direction S68.1 W $\pm$ 2.8°, and the GPS "present" inversion is closely similar ($4.6 \pm 0.3$ mm/a, S87.9 W $\pm$ 3.3°) but with a Nubia-Eurasia pole ca. 3000 km south of the MORVEL pole. However, inter-island motions measured by GPS indicate that only about half this Nubia-Eurasia motion currently takes place along the TR (Marques et al. 2013; Fernandes et al., Chapter "The Contribution of Space-Geodetic Techniques to the Understanding of the Present-Day Geodynamics of the Azores Triple Junction").

All three types of plate boundaries are represented between the ATJ and Gibraltar (Fig. 1a; e.g., Bezzeghoud et al. 2014). In the west, a rifting/spreading boundary (the TR) extends from the ATJ to about 24°W, SE of São Miguel Island. At that point, the rift intersects the East Azores Fracture Zone, part of which comprises the 400 km long right-lateral strike-slip GLORIA fault (Fig. 1b); east of 18°W the plate boundary becomes an oceanic-oceanic plate convergence zone, with rough, complex sea-floor topography (Fig. 1a).

## 4 Technology and Plate Tectonics —Geopolitical, Economic, Military and Logistic Factors

Whereas the plate tectonics paradigm shift was largely and initially motivated by scientific curiosity, subsequent and very costly technological developments (accurately located earthquake epicentres, focal depths and rupture mechanisms; magnetometers for use on the high seas; multibeam bathymetry; satellite radar altimetry; GPS navigation) that led to our current understanding exemplify 'geopolitical/geomilitary trickledown'. This circumstance contrasts with other areas of geosciences, e.g. magma evolution and geochemistry of Azores volcanic systems (Larrea et al., Chapter "Petrology of the Azores Islands", Beier et al., Chapter "Melting and Mantle Sources in the Azores"), driven mostly by scientific curiosity alone. Marine geophysical understanding of the Azores region was an early and ongoing beneficiary of geopolitically motivated technological advances, most of which had their origins prior to emergence of plate tectonics concepts in the late 1960s.

(1) *WWSSN*: The *World Wide Standardised Seismograph Network* was developed during the early 1960s to improve detection capability for nuclear test ban violations. Particularly in oceanic regions, the WWSSN reduced epicentre location and focal depth errors and threshold magnitudes, while improving the accuracy of first-motion (fault plane) solutions for larger shocks. The more accurately located epicentres

helped refine active plate boundary locations, including in the ATJ-AP region (Fig. 1a), which is seismologically active, creating seismic hazards (e.g., Gaspar et al. 2011, 2015; Hipolito et al. 2013). The epicentre distributions, focal depths, and first-motion/fault plane solutions helped refine and test plate kinematic models, particularly along the tectonically complex Azores-Gibraltar Nubia-Eurasia boundary (Udias et al. 1976; Hirn et al. 1980; Grimison and Chen 1986, 1988; Buforn et al. 1988; Borges et al. 2007; Navarro et al. 2009; Hipolito et al. 2013; Bezzeghoud et al. 2014; Fontiela et al., Chapter "Characterization of Seismicity of the Azores Archipelago: An Overview of Historical Events and a Detailed Analysis for the Period 2000–2012"). Madeira et al. (2015) reviewed the neotectonics (driven by dextral transgressive stress) of the central and eastern islands, estimating slip rates of a few tenths mm to a few mm/a on faults, and maximum expected earthquake magnitudes ca. $M_w = 6$ to 7. Seismographic stations on the Azores islands, OBS (Ocean Bottom Seismometer) deployments on the Azores Plateau (AP; Miranda et al. 1998) and OBH (Ocean Bottom Hydrophone) deployments on the MAR flanks north and south of the ATJ (http://www.ipgp.fr/rech/lgm/MOMAR/) helped make the plate boundaries in the Azores region among the better studied in the world ocean.

(2) *Multibeam bathymetry*: Detailed mapping of ocean-floor topography, especially the active spreading and transform plate boundaries, was not practical until the mid-1960s development of "SASS" (Sonar Array Survey Systems), the world's first hull-mounted multi-narrow-beam bathymetric mapping system, developed for use by the US Naval Oceanographic Office (Glenn 1970). This type of bathymetric mapping is commonly referred to simply as 'multibeam' or 'swath-mapping' to distinguish it from conventional single-beam echo sounding. One of the first scientific applications of the SASS system was mapping the FAMOUS area of the MAR axis (36.4°–37.1°N), not far south of the ATJ (Phillips and Fleming 1978). The narrow axial "Neo-Volcanic Zone" rising from the floor of the rift valley was one of the notable discoveries, and

played a large role in planning *ALVIN* submersible dives. A somewhat smoothed version of otherwise classified SASS bathymetry shows the Kurchatov Fracture Zone area (40.3°–40.7°N), immediately north of the ATJ (Fig. 8 of Vogt and Tucholke 1986).

Starting in the later 1970s, multibeam technology spread into the commercial and thereby academic communities, leading by the 1990s to detailed Portuguese multibeam mapping of the ATJ-AP area (e.g., Lourenco et al. 1998). While the gridding-based 'hillshade' images (computer-illuminated perspective-view topography) convey much of the topographic information at grid spacings of ca. 1 km (e.g., Fig. 1b, c), their full spatial resolution (e.g., Miranda et al. 2014) requires grid spacings of ca. 50–100 m on the relatively shallow Azores Plateau. Figure 1b–d illustrate the gaps—some filled in 2009 (Weiss et al. 2015a, b) in detailed multibeam coverage. In the Azores Plateau area and elsewhere near actively spreading plate boundaries, multibeam bathymetry has yielded a treasure of previously unresolved volcano-tectonic features, notably distributions and morphometry of small seafloor cones, fissure eruptions, and faults, and the bathymetric modifications of these features by mass-wasting and sedimentation processes (e.g., Weiss et al. 2016; Mitchell et al., Chapter "Volcanism in the Azores: A Marine Geophysical Perspective").

A high-resolution hillshade map of the ATJ area, derived from gridded multibeam data, is shown in Fig. 1d (courtesy of J. Luis, Univ. of Algarve). Compared to most oceanic regions, the relatively shallow ATJ-AP region requires closer track spacing (typically ca. 4 km) for complete swath coverage, but the spatial resolution is proportionately higher. By 2014, ca. 150,000 km$^2$ of the Azores Plateau had been swath-mapped by the Portuguese Navy and academic institutions (J. Luis, personal communication, 2014). See also Weiss et al. (2015a, b, 2016), Casalbore et al. (2015), and Mitchell et al. (Chapter "Volcanism in the Azores: A Marine Geophysical Perspective") for other multibeam mapping.

(3) *Seismic reflection* profiles were collected on an opportunity basis on transits across the Azores Plateau in the 1960s–1970s, primarily by Lamont Doherty Earth Observatory (Fig. 2). These single-channel (or two-channel) profiles, using mostly airguns as sources, readily resolve an acoustically transparent, ca. 100–400 m thick hemipelagic sediment cover, which has been ponded in intermontane valleys due to slumping from nearby topographic highs (Fig. 2) and locally sculpted by bottom currents (Weiss et al. 2016). The frequent high earthquake-generated accelerations in the Azores area (e.g., Matias et al. 2007) have likely helped prevent sediments from accumulating on seamounts and any other steep topographic slopes. In 2009, the University of Hamburg collected ca. 1000 km of 2D multichannel seismic reflection profile and multibeam bathymetry data NW, SE, SW, and S of São Miguel Island. The processed data resolved seismic reflectors to ca. 1 km below the ocean floor, revealing a complex history of explosive submarine and subaerial volcanism (Weiss et al. 2015a) and mass wasting (Weiss et al. 2016), and providing a record of TR volcano-tectonic evolution (Weiss et al. 2015b).

(4) *Sidescan sonar* mapping, images based on the strength of backscattered or reflected acoustic returns, has higher spatial resolution but cannot be as objectively interpreted as water depth. Sidescan sonar images can be made from surface-towed, deep-towed or deep autonomous systems, but can also be derived from hull-mounted multibeam data if the entire echo, not just the first arrival, of each ping is recorded for each beam. The GLORIA towed sidescan system, developed from World War II antisubmarine sonars, provided an early view of the entire GLORIA fault, a key element of the plate boundary east of the TR (Laughton and Whitmarsh 1974), with the tectonic fabric of the MAR in the ATJ area mapped by Searle (1980). A comparison between GLORIA sidescan and SASS multibeam bathymetric contours over the Kurchatov FZ (Fig. 8 of Vogt and Tucholke 1986) illustrates the complementary nature of the data, with sidescan imagery most diagnostic for MAR axial tectonics (fault-controlled escarpments typically 5 km apart). To date, few multibeam-derived or other sidescan sonar maps

have been published for the ATJ-AP region. Backscatter mapping of Condor Seamount (Tempera et al. 2013) and near São Miguel (Weiss et al. 2015a) are exceptions.

(5) **GPS (Global Positioning Satellites)**: The application of earth-orbiting satellite technology for accurate surface ship and aircraft navigation, independently by the US and the USSR, was another costly military technology that has come to play large roles in marine geophysics. No marine survey would be conducted today without GPS navigation. Moreover, a network of fixed GPS stations made it possible, beginning in the 1990s, to measure present motions between and among the tectonic plates, and to compare these motions with the 'geologically recent' rates from ca. post-3 Ma magnetic lineations recorded by the oceanic crust. These advances are evident in comparing the latest global model for current plate motions (MORVEL; DeMets et al. 2010) with earlier models (Minster and Jordan 1978; NUVEL model of DeMets et al. 1990). Temporary and permanent GPS stations on various Azores islands have enabled measurement of inter-island (Fernandes et al. 2006; Marques et al. 2013) and intra-island (Terceira: Miranda et al. 2012; São Jorge: Mendes et al. 2013) motions. These new data (Fernandes et al., Chapter "The Contribution of Space-Geodetic Techniques to the Understanding of the present-day geodynamics of the Azores Triple Junction") show that at least in recent decades, the Nubia-Eurasia plate boundary in the Azores area is diffuse—a band ca. 100–140 km wide (Fig. 1b; Marques et al. 2013; Miranda et al. 2014)—and contrary to morphologic predictions (Vogt and Jung 2004) Graciosa is moving with the Eurasia plate.

(6) **Radar altimetry**: First proposed in the late 1960s, microwave altimetry from earth-orbiting satellites began (late 1970s) to map geoid undulations recorded (upon correction for other signals) by the shape of the sea surface. This originally military technology, used as a navigation aid, began to constrain submarine crustal density structures, especially seafloor topography (seamounts, rift valleys, transform fracture valleys, etc.) and its compensation. Satellite altimetry, combined with surface ship soundings,

is integral to modern ocean floor maps over much of the world ocean (e.g., Smith and Sandwell 1997). The spatial resolution, however, is only ca. 10–20 km, ca. 100–1000 times coarser (depending on water depth) than multibeam bathymetry. In the Azores region, areas mapped in part from satellite altimetry are thus easily distinguished from areas fully mapped by multibeam bathymetry (Fig. 1a, b).

(7) **Exclusive Economic Zones (EEZ)**: The 1958 United Nations Law of the Sea (UNCLOS) Convention and the succeeding LOS treaty (e.g., Knauss 1986), still a 'work in progress', have led to coastal states claiming legal (not necessarily physiographical or geological) extensions of their "continental shelf", in which these nations exercise certain sovereign rights over resources in the water column and on/under the seabed. The large extension of the claimed 'Portuguese Continental Shelf' surrounding the Azores (1.3 million $km^2$) includes the Azores Plateau and parts of the MAR both north and south of the triple junction. The need to support the claim with data has motivated extensive detailed Portuguese multibeam and magnetic mapping (e.g., Fig. 2 of Luis and Miranda 2008; Miranda et al. 2014; Fig. 3d), making the ATJ region one of the best-charted parts of the Mid-Oceanic Ridge and oceanic-crust-floored parts of the world ocean.

(8) **Logistics:** Few parts of the oceanic plate boundaries are as easily accessible to shipborne and airborne geophysical mapping as is the Terceira Rift and the MAR near the ATJ. As a result, the ATJ is the best-studied fully oceanic triple junction. Many research vessels have taken on fuel and supplies, and allowed exchange of scientific parties at Ponta Delgada (São Miguel), and the MAR aeromagnetic surveys reported in Phillips et al. (1975) and Luis et al. (1994) would not have been possible without the Lajes (Terceira) airfield, which was constructed in 1945 and served as a base for anti-submarine-warfare patrols by NATO aircraft during the Cold War. Of course, the fact that central volcanoes have grown above sea level along the TR (Terceira, São Miguel, Graciosa) and elsewhere on the AP has greatly facilitated research (e.g., Catalao et al. 2006; Sibrant et al. 2016; other chapters in

this volume) compared to what would practically be possible had these seamount summits today been submerged below the sea (e.g., Condor Seamount (Guyot), Tempera et al. 2013).

(9) *Radiometric dating*: Due to excellent subaerial exposures of intrusive and extrusive rock, the Azores Plateau, and particularly the Terceira Rift, have benefited much more from radiometric dating (Holmes 1929; Dalrymple 1991) compared to the average submerged Mid-Oceanic Ridge. Abdel-Monem et al. (1975) published the first radiometric ages of Azores islands (Santa Maria, the Formigas, and São Miguel). Some of their ages, determined by K/Ar, have proven much too old, for example their 4.01 Ma, versus less than 900 ka (Johnson et al. 1998) for the oldest volcanics on São Miguel. Prior to 1975, the only age constraint for pre-historic Azores volcanism was a biostratigraphic 'Mid-Miocene' age (shown by Hildenbrand et al. 2014, to be latest Miocene to earliest Pliocene) for a coquina on Santa Maria (see Avila et al., Chapter "Petrology of the Azores Islands"). A good geochronology of Azores island volcanism has been developed in recent years, as summarised below. In recent decades, K/Ar whole-rock dating, which often yielded erroneous ages, has been complemented by $^{39}Ar/^{40}Ar$ ($^{39}Ar/^{40}Ar$) dating (e.g., Larrea et al. 2014; Beier et al. 2015). However, improved K/Ar dating methods are still used (e.g., Hildenbrand et al. 2014), especially when combined with geochemical analysis.

(10) *Marine magnetometry*: The technology to measure the strength of the earth's magnetic field from ships and aircraft (see Vogt 1986b for a historical review) was perhaps the greatest single technological development which later lead to acceptance (by ca. 1968) of seafloor spreading and plate tectonics. Detecting enemy submarines by their magnetic anomaly, as well as prospecting for mineral resources, motivated the development of field magnetometers. In the first years after WWII, fluxgate magnetometers were tried at sea, with the first magnetic field strength profile across the Mid-Atlantic Ridge measured not far south of the Azores in 1948. In later years the sensor of choice for marine work became the proton precession magnetometer, invented by Victor Vacquier in 1939 but classified during World War II. Most of the now vast but still incomplete total field strength magnetic anomaly database (e.g., Luis and Miranda 2008; Miranda et al. 2015) has been collected from research vessels towing sensors far enough behind the ship to reduce anomalies caused by the vessel. Large, nowadays gridded databases are now available to plate kinematicists, much of the data with GPS vessel navigation accuracy. These databases enabled progressively improved plate kinematic reconstructions which include the Azores region (e.g., Pitman and Talwani 1972; Klitgord and Schouten 1986; Srivastava and Tapscott 1986; Roest and Srivastava 1991; Luis et al. 1994; Luis and Miranda 2008; Merkouriev and DeMets 2014a, b, Miranda et al. 2015 and Chapter "The Tectonic Evolution of the Azores Based on Magnetic Data").

## 5 Some Modern Research Issues

*Location of TR and non-TR volcanic islands*: Vogt and Jung (2004) nominated the TR as the world's slowest-spreading organised (discrete) spreading axis, and noted that very slow inter-plate extension is more typically associated with broad (diffuse) belts of deformation (see Simkin et al. 2006). One possible explanation for the discrete character of the TR builds on Vink et al. (1984), who suggest typical oceanic mantle lithosphere is stronger, due to the greater strength of ultramafic materials at a given temperature, compared to deep continental crust, and that this difference might explain the preference for new rifts to develop just inside continent-ocean crustal transitions to form microcontinents. We speculate that the thickened AP crust (14 km was measured by Escartin et al. 2001) produced at the MAR axis, i.e., a weaker lithosphere, somewhat resembles continental crust and thus breaks more easily along a discrete axis, versus diffuse rifting. Together with compositionally different (more residual melt inclusions) and possibly warmer AP mantle lithosphere, this might explain why the TR developed only within the pre-existing

Azores Plateau (Fig. 1a, b). The same factors—including a more fertile mantle lithosphere—might also explain why young non-TR volcanic islands (São Jorge, Pico, Faial, Condor Seamount (a guyot; Tempera et al. 2013), as well as Azor and Princess Alice banks grew on the Faial Ridge, while Corvo and Flores rose on the Flores Ridge. The absence of large volcanoes on the intervening younger (largely post-8 Ma) MAR flanks (e.g., Fig. 1e) poses a problem for the model of Neves et al. (2013) unless this crust and associated mantle lithosphere is less vulnerable to transtensional fissuring.

The time of TR origin and the degree of sea-floor spreading (besides rifting of pre-existing AP lithosphere) remain to be quantified, and a dynamic model developed to explain why the Nubia-Eurasia boundary jumped to the TR site.

***TR along-axis volcanic relief***: If the TR is a spreading axis, what accounts for its great along-axis relief? Western São Miguel volcanoes rise about 4200 m above the adjacent Hirondelle Basin (Fig. 3a), which along with the Povoação Basin SE of São Miguel contains at least 500 m sediment (Weiss et al. 2015b). Copious melt production, combined with very slow export of volcanoes out of the plate boundary zone might help explain such great relief (Vogt and Jung 2004), but simple Pratt isostasy is probably the simplest explanation. Following Vogt (1974), Vogt et al. (2008) showed that maximum along-axis relief of MOR axial volcanic edifices increases systematically with decreasing opening rates (Fig. 4), so the TR volcanoes may represent an end member on this roughly linear distribution of maximum heights versus model axial plate thickness (based on Phipps Morgan and Chen 1993). The slower the spreading, the thicker the axial plate, and the higher the lower-density magma conduit can rise (given sufficient magma) in isostatic balance with adjacent more normal oceanic crust. A thicker TR lithosphere is also consistent with inferred lower degrees of partial melting and a lack of connection between adjacent magma systems (Beier et al. 2008). If it accounts for only ca. 2–3 mm/a of the Eurasia-Nubia separation (Marques et al. 2013),
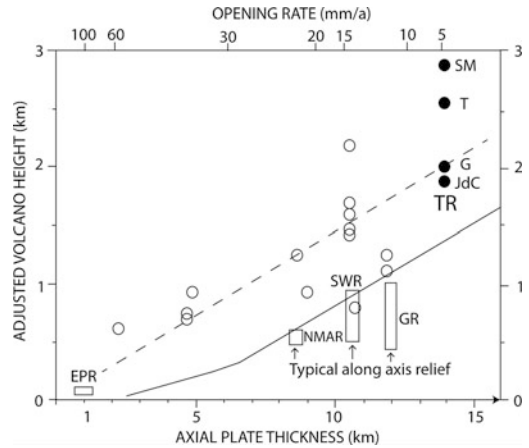


**Fig. 4** Maximum (circles) and typical (rectangles) Mid-Oceanic Ridge axial volcano heights (adjusted to remove buoyancy effects of water column) versus opening rates (top) and axial plate thickness (based on Phipps Morgan and Chen 1993). EPR, East Pacific Rise; NMAR, Northern Mid-Atlantic Ridge; SWIR, Southwest Indian Ridge; GR, Gakkel Ridge; TR, Terceira Ridge: Graciosa (G), Terceira (T), João de Castro Bank (Seamount) (JdC) and São Miguel (SM) island points based on highest elevations. Dashed (ultramafic crust) and solid (normal oceanic crust) lines predict maximum volcano heights based on Pratt isostasy, relative to adjacent plate boundary. Adapted from Vogt et al. (2008); see also Vogt (1974)

the TR spreading rate is only half of the 'hyper-slow' rate assumed by Vogt and Jung (2004) and in Fig. 4. Pratt isostasy suggests that most of the TR axial volcanoes are near their final maximum heights, so additional magmas would likely be preferentially injected into flank dikes or form new conduits, versus erupting from summit calderas.

Data on erupted versus intruded magma fluxes versus time are needed to test whether island volcanoes have reached their maximum 'Pratt' heights. The Pratt isostasy approximation needs to be adjusted for the effects of flexural isostasy.

***Age of TR and non-TR island volcanism***: The TR cannot be younger than the oldest exposed rocks, and radiometric dating in recent years suggests the TR and the volcanoes formed along it are all less than ca. 1 Ma in age: The oldest outcropping lavas, on eastern São Miguel, were erupted 780–880 ka (Johnson et al. 1998). The oldest outcropping lava succession on

Graciosa was dated at $1057 \pm 28$ ka (Larrea et al. 2014) and probably more accurately at $702 \pm 10$ ka by Sibrant et al. (2014). On Terceira Island, the oldest measured radiometric age is only $401 \pm 6$ ka (Hildenbrand et al. 2014; see also Calvert et al. 2006). The oldest known volcanics on non-TR islands were erupted 850 ka on Faial (Hildenbrand et al. 2014), 1.2–1.2 Ma on São Jorge (Hildenbrand et al. 2008) and 5.3–5.7 Ma on Santa Maria (Sibrant et al. 2015).

Although there must obviously be older eruptives and intrusives deeper inside all island edifices, such rocks cannot be much older than the oldest surface materials, provided the average magma flux ($F$) remained relatively constant: For an assumed conical edifice of slope $s$ and height $h$ ($t$), $\frac{dh}{dt} = \frac{F}{\pi h} \tan^2 s$. According to this relation, an edifice grows rapidly in height at the beginning and much more slowly later—e.g., at the present elevations of the TR volcanic islands above the adjacent rift valleys, $\frac{dh}{dt}$ would be only 5–10% of what it was at 1 km edifice heights. $F$ of the order 1 $km^3$/ka would suffice to produce one of the TR islands in about 1 Ma (Vogt and Jung 2004).

By how much does the TR (>1 Ma) predate the oldest island volcanoes? A wide range of ages have been postulated for the TR, but with Sibrant et al. (2015) we consider ages greater than 3 Ma implausible. Miranda et al. (2015) suggested the TR originated when the Nubia-Eurasia plate boundary jumped from the Princess Alice Bank rift (Fig. 1b) to the TR. Sibrant et al. (2015) used tectonic extension measured by normal fault displacements to conclude the TR formed by rifting between 1.4 and 2.7 Ma. However, before sea-floor spreading is discounted entirely, boreholes are needed to date the basement in the apparently rifted belt. Some post-3 Ma spreading from a TR axis appears consistent with the bathymetry in the Formigas area (Fig. 1c). The Formigas islets appear symmetrically located as far from the present TR axis as a paired modest bathymetric high northeast of the axis—somewhat resembling the 'split axial volcanoes' locally present along the MAR (Vogt and Jung 2005) and there formed by an alternate

dominance of volcanism and rifting. The lesser East Formigas High (Weiss et al. 2015b) appears also to have a split "twin". These features are hard to explain entirely by tectonics, with no spreading. Moreover, the Big North and North Hirondelle bathymetric highs (Weiss et al. 2015b) might also have formed along or near the earliest TR axis, perhaps with subsequent off-axis volcanism enhancing early asymmetry. Indeed, unless the TR island volcanoes are entirely loaded on older crust, they must themselves represent axial accretion of new crust, balanced by stretching (rifting) in adjacent rift valleys. Topographic asymmetry (higher peaks south of the TR axis vs. on the north side in this case) is common on slow-spreading plate boundaries north of Iceland (Vogt et al. 1982) and thus possible in the Azores. Multibeam bathymetry and seismic reflection profiles across the submerged TR on either side of São Miguel reveal a terrain peppered with volcanic cones (Weiss et al. 2016) and laced with faults typically spaced 1–2 km apart (Weiss et al. 2015b), and thus similar to the axis of a slow-spreading ridge whose rift valley is partially filled with sediments —for example the Knipovich Ridge southwest of Svalbard.

What can have happened during the later Pleistocene and Recent that might explain so much geologically young volcano-tectonic activity, especially along the TR? A geologically recent change in plate motions or plume activity is one possibility. Hinting at such a change is the location of the present (GPS-based) Eurasia-Nubia plate rotation pole some 3000 km south of the MORVEL (3.16 Ma-present average) pole for the same pair of plates (Marques et al. 2013), although the opening rates happen to remain nearly the same in the ATJ area.

Carminati and Doglinoni (2010) have speculated on a different reason for globally increased Pleistocene volcanism: The Mid-Pleistocene Transition (ca. 1.25–0.8 Ma, most recently dated to 0.9 Ma by Elderfield et al. 2012), shifted glacial-interglacial climate cycles from moderate amplitude (in terms of ice sheet volume, hence sea level) 40 ka to high-amplitude 100 ka cycles. This shift increased the amplitude of

glacioisostatic loading placed on the mantle by northern ice sheets and to some extent the global ocean, thus forcing a more vigorous upper mantle flow. Could such changes in pressure and flowage have stimulated magma production and migration in mantle regions close to their pressure-melting points distant from the ice sheets? The probable initiation of major edifice construction along the TR is suggestive enough to warrant additional dating and numerical modelling. Relatively short episodes (ca. 850, 700, 400, 200, 120, 50 and 0 ka according to Hildenbrand et al. 2014) of coeval volcanism on several Azores islands exhibit episodicity on time scales comparable to that of major post-Mid Pleistocene glacial cycles. However, the episodicity of Azorean volcanism may simply reflect the time scale of some local upper mantle process, such as Rayleigh-Taylor instabilities in the asthenosphere. Mid-Oceanic Ridge axial volcanism appears locally non-steady state, forming successions of axial volcanoes which are then split to form half-volcanoes on similar time scales of ca. 0.1–1 my (Vogt and Jung 2005).

***Azores mantle plume?***: Wilson (1963) first postulated that movement of the earth's crust over localised anomalous melt sources relatively fixed in the cores of mantle convection cells could explain the age progression and trends of Pacific island and seamount chains like the Hawaiian-Emperor chain. The sites where anomalously prolific melts, derived by partial melting of mantle material, rise to the surface to create volcanoes came to be called 'hotspots' because it was first assumed only higher mantle temperatures could be the cause. Morgan (1972) modified this concept by proposing that 'hotspots'—by then including the Azores—actually represent deep mantle convection plumes rising from the core-mantle oundary. Such plumes would be relatively fixed relative to the lithospheric plates moving across them. However, due to the lack of credible evidence, the deep mantle plume concept remains controversial (e.g., Anderson 2005) after nearly a half century of research and numerous publications, many of which modified the plume model, using newer seismic tomography and numerical modelling.

For example, Courtillot et al. (2003) classified 49 postulated hotspots into three types: (1) 'primary' hotspots may originate at the core-mantle boundary; (2) secondary hotspots originate at the base of the seismic transition zone; and (3) the remainder are the consequence of plate tectonics. Davaille et al. (2005) placed the Azores at the edge of a large deep mantle source domain called the "Indo-Atlantic Box". Based on numerical convection modelling and seismic tomography, they interpreted Iceland as a narrow deep mantle plume and the Azores as a "secondary plume" rising from a large plume head ponded in the seismic transition zone. Silveira et al. (2006) observed a region of anomalously slow S-waves below the Azores lithosphere down to ca. 250–300 km depths. They suggested this region comprises the remains of a dying plume.

A conservative term for features like the Azores is simply 'melting anomaly': Excessive melting is not necessarily- and can often be shown not to be- due to higher mantle temperatures, but rather to anomalous composition or even just to decompression melting by magma rising where the lithosphere is rifted by tectonic forces (Beier et al. 2015). Although given (Anderson 2005) a score of only 2+ (out of 12), and rated only 12th among a list of 60 proposed deep mantle plume sites in terms of observational support, the Azores region is still considered by many the surface expression of at least a shallow or secondary mantle plume, perhaps more 'wet' than 'hot' (Metrich et al. 2014; Beier et al. 2012). The geochemistry of Azores volcanic rocks suggests heterogeneous, poorly mixed, and not particularly hot mantle sources, ultimately recycled (previously subducted) oceanic crust (Beier et al. 2008, 2015).

How old is the Azores 'hotspot'? Gente et al. (2003) argue that an Azores hotspot/plume has existed since 85 Ma, but only began to influence the MAR when the latter began to migrate near it. Beier et al. (2015) inferred from a 39 Ma lava dredged on Monaco Bank that the Azores plume already existed below the area at the time, because the lava is rich in radiogenic isotopes, similar to modern São Miguel volcanics. The

date—about the crustal age predicted by magnetic lineations—is consistent with an abstract by Campan et al. (1993), who suggested the MAR-Azores plume interaction began 36–39 Ma. The 39 Ma sample may have come from an old NW trending Monaco Bank seamount, constructed near the MAR axis and unrelated to formation of the AP. However, the sample was recovered from depths of 250–500 m (Beier et al., personal communication, 2016), much too shallow for post-39 Ma crustal subsidence of MAR generated crust.

While not discounting the possibility of older antecedents, we propose the origin of the Azores Plateau was 'recorded' (Fig. 1b) by formation of the West Azores Ridge (WAR) on the west flank of the MAR, and by the Northeast Spur—at least partly a belt of small seamounts—on the east flank. Both features also mark a shallowing of the Mid-Atlantic Ridge to form the AP. Magnetic lineations identified by Luis and Miranda (2008) suggest the WAR was formed ca. 18 Ma, slightly postdating anomaly 6 and as implied by its northward divergence from that lineation (Fig. 1b) propagating northwards along the MAR axis. On the east MAR flank, the Northeast Spur appears to coincide with anomaly 6 (19 Ma).

How is formation of the AP related to the southward jump of the triple junction from ca. 45°N (King's Trough) to ca. 39°N (Azores)? The jump ended a period of compressional deformation in the Pyrenees and transferred Iberia from the Africa (Nubia) to the Eurasia plates (Srivastava et al. 1990). This event was dated to anomaly 9 time (Srivastava and Tapscott 1986; Klitgord and Schouten 1986) and later to anomaly 6C time (23 Ma), or at least predating anomaly 6 time (Srivastava et al. 1990; Roest and Srivastava 1991). Most of the change in Eurasia-North America plate motion had happened by anomaly 6C time according to Luis and Miranda (2008). Although the jump and AP development were not instantaneous, the similarity in timing between the AP and the jump is suggestive. However, the AP appears to have developed after the jump, and thus perhaps triggered by it. If the AP developed from a mantle

plume below the plates, an improbable coincidence is required for a plume 'happening' to rise into a new triple junction.

Whereas many modern triple junctions (e.g., Fig. 1b inset map) are not associated with 'melting anomalies', and modelling (Adam et al. 2013) does not require such a correlation, Sager (2005) noticed that several Pacific oceanic plateaus also 'happened' to form at triple junction jumps: Were mantle plumes—including secondary plumes Davaille et al. (2005)—responsible for oceanic plateau initiation, this would have been extremely unlikely. A plate tectonic origin might explain the correlation, by decompression melting, at a new triple junction, given the existence of an anomalous asthenosphere susceptible to increased melting under small stress perturbations (Sager 2005). Although this also might explain AP formation soon after the triple junction jump, some underlying asthenosphere anomaly is still required.

The triple junction jump from the King's Trough to the Azores sites coincided, within age-dating uncertainties, with the axis boundary jump from Aegir Ridge in the Norway Basin to the Kolbeinsey Ridge axis just north of Iceland around anomaly 6C time. The oldest clearly recognizable lineation (Vogt 1986b) on the east flank of that ridge is 6B (22 Ma). This seems also the most likely time the Iceland melting anomaly greatly increased its output to begin generating Iceland and its associated platform. Based on the shoaling (over time) of the Reykjanes Ridge, Saemundson (1986) concluded this happened sometime between 19.5 and 35.5 Ma. Luis and Miranda (2008) found a rapid northward motion of the Eurasia-North America plate rotation pole during the C11/12 to C6C interval (31–23 Ma) and continuing after that time. Formation of the Azores triple junction largely by C6C time (23 Ma) was thus an expression of a regional plate kinematic reorganization, and this necessarily also involved at least the upper mantle. This also corresponds to the Neogene-Palaeogene boundary (23.0 Ma, near the end of C6C; Walker et al. 2012), a time long recognised as marking major geological and paleontological changes in the Alpine-Tethys

region (Earnes 1970) and a 'major change in global planktonic biogeography' (Kennett 1978). How the plate kinematic changes at C6C time relate to the Neogene-Paleogene boundary is a problem inviting collaboration among geophysicists, geologists and palaeontologists.

Where is the present centre or apex of the Azores melting anomaly, whatever its mantle source may be, and how wide is this centre? The most concentrated off-ridge volcanism would place this Pleistocene-Holocene "volcanic centre" in the area of Pico, Faial, and São Jorge. However, along the MAR axis, the centre corresponds to the shallowest crestal topography, a ca. 80 km long MAR segment also lacking a prominent rift valley (just east of the label 'MAR' in Fig. 1b) and located ca. 150 km WNW of the 'volcanic centre'. The along-axis geochemical anomaly (Schilling 1986) peak corresponds (Fig. 3c) to the segment lacking a rift valley, but crustal thickness there is not particularly thick, compared to the 14 km under Faial Ridge (Escartin et al. 2001). Does the Azores volcanic centre represent a 'second type of hotspot island' (Morgan 1978), supplied by asthenosphere flow from a ridge-centred plume near the MAR axis? If this accounts for the 150 km distance between the Azores 'volcanic centre' and the anomalous MAR axial segment, what explains a similar relationship at ca 45°N, where MAR axial geochemical and topographic anomalies (Schilling 1986) lie 300–350 km west of the tip of the long extinct (ca. 20–25 Ma) King's Trough? Broad regions of anomalous asthenosphere might explain these relationships, or also remnants of dying plumes (e.g., Silveira et al. 2006) but only if such anomalies are elongated in an EW direction. As discussed previously, the Azores 'volcanic centre' simply reflects preferential transtensional fracturing of an anomalously thick and weak lithosphere produced by the MAR ca. 12–8 Ma (the oldest part of the Faial Ridge) as part of the diffuse Nubia-Eurasia plate boundary.

The fixed mantle plume hypothesis predicts an age progression, with the youngest magma generation located over the plume core. Nearly all the known volcanic activity ages associated with the putative plume or hotspot/melting anomaly cluster around ca. 6–4 Ma and again 1.5–0 Ma (e.g., Beier et al. 2015; Hildenbrand et al. 2014; Sibrant et al. 2015), with no clear age progression and thus not supporting a fixed mantle plume model. A widespread flood basalt episode (Beier et al. 2015) would not be expected from the dying plume idea of Silveira et al. (2006). As noted by Hildenbrand et al. (2014), multiple coeval volcanic episodes on several islands is also not explained by the plume model but would require modulation by other processes. However, an age progression would not be easy to detect if the postulated plume head is broad and motion of a plate across the head is slow and poorly constrained (as is the case for the Nubia plate; Gripp and Gordon 2002, and for the Afar triple junction magmatism; Corti 2008). Age dates from within Faial, São Jorge and Terceira (Fig. 2 of Hildenbrand et al. 2014) do suggest age progressions of the order 1–10 cm/a, but younging in the direction of the MAR axis. Such age progression might reflect crustal fracture propagation or plate movement relative to magma sources, but is inconsistent with the motion of the Nubia plate relative to a fixed hotspot or plume (Gripp and Gordon 2002, see below). Moreover, in the MORVEL-based No-Net-Rotation reference frame, the TR region is moving at ca. 20 mm/a in a NE direction (Fig. 1 of Argus et al. 2011), opposite to that predicted by Gripp and Gordon (2002).

Only a few observations support a mantle source (such as Morgan's 1972 deep mantle plume) fixed below the plates in the Azores area. Relative to a set of assumed fixed hotspots (Gripp and Gordon 2002), the TR should be moving ca. 20 mm/a ('absolute' motion, i.e. relative to a relatively fixed mantle below the plates) in the direction S55 W (Fig. 3b of Vogt and Jung 2004), consistent with seismic tomographic evidence for a mantle plume (at least to 400 km depth) now located under or just northeast of the TR (Yang et al. 2006). This direction of absolute motion is consistent with the apparent ca. 150 km NE jump (equivalent to ca. 8 m.y. of 20 mm/a absolute plate motion) of the rift axis from the extinct Princess Alice Rift (Fig. 1b) to the present

TR location. Miranda et al. (2015) also suggested such a jump ca. 3 Ma. The diachronous Faial and Flores ridges (Fig. 1b; Vogt 1979; Cannat et al. 1999) suggest mantle flow away from a fixed upwelling located near the Azores triple junction, but the ridge geometry could alternatively be explained by MAR axis motion across a NE elongated compositional or/and thermal anomaly (Fig. 8B of Vogt and Jung 2005).

A careful search for anomalously high heat flow and/or young volcanism or intrusives on the Eurasia plate just northeast of the TR, particularly around small seamounts north of Terceira (the Northeast Spur in Fig. 3c) and NE of São Miguel, might help determine if the TR and eastern Azores Plateau are being displaced southwestwards relative to a melting anomaly currently below the plates. We consider this possible but unlikely. Detailed magnetic, seismic reflection, multibeam and borehole investigations of the Northeast Spur and the West Azores Ridge are needed to evaluate our suggestion of a TR origin ca. 20 Ma.

We remain agnostic on deep mantle plumes but agree with many other authors that compositionally or thermally anomalous mantle must have existed at least since 20 Ma, and still exist below the AP and surroundings. Needed for future knowledge advances are: (1) improved seismic tomography using broadband OBS and OBH arrays distributed over the seafloor around the Azores Plateau to help resolve what lies at depth (particularly below ca. 300–400 km) in the mantle below the AP (Silveira et al. 2006); (2) detailed mapping and borehole sampling around the western end of King's Trough and along the Northeast Spur and West Azores Ridge to determine more accurately the timing of the triple junction jump and its relation to origin of the AP and to apparently coeval events in the Iceland area; (3) data-based dynamic models predicting why the triple junction and new plate boundary jumped south specifically to the Azores-Gibraltar region.

***The Azores Plateau crust: What exactly is it?***
If the apparently NE-trending, MAR-generated sea-floor spreading magnetic lineations on much of the Azores Plateau (Fig. 1b; Luis and Miranda

2008; Miranda et al., Chapter "The Tectonic Evolution of the Azores Based on Magnetic Data") have been correctly identified, why has subsequent Azores magmatism (e.g., Weiss et al. 2015b; Beier et al. 2015 and Chapter "Melting and Mantle Sources in the Azores") not obscured the older MAR-derived magnetic lineation signature? If the linear volcanic ridges (including the TR) dominating the modern plateau formed by eruptions controlled by transtensional crustal fractures (Neves et al. 2013), did much of the eastern AP form from extrusive and intrusives emitted along these fissures? The age-dating reported by Beier et al. (2015) suggests much of the elevated AP south of the TR (labeled South Azores Plateau in Fig. 1b to distinguish it from the North Azores Plateau) is underlain by flood basalts erupted during the interval ca. 6–4 Ma, although their dredges likely did not recover the initial stages of this episode. The amount of anomalous AP crustal thickening attributable to such post-MAR igneous 'overprinting' also remains unknown. However, the previously discussed 39 Ma lava from Monaco Bank, compositionally similar to young volcanics on São Miguel (Beier et al. 2015), implies that the overprinting eruptives are at least locally thin.

The existence of the Flores Ridge (Vogt 1979) on the West Azores Plateau, i.e., the west flank of the MAR, capped by two volcanic islands (Flores and Corvo), suggests that anomalously thick crust (Escartin et al. 2001) was already being formed at the MAR axis during the period ca. 12–7 Ma (Fig. 1b), but that this crust and mantle lithosphere was fertile, perhaps also more heterogeneous- to account for geochemical differences among various AP magmas (Beier et al. 2008, 2015 and Chapter "Melting and Mantle Sources in the Azores"), and subsequently more easily fractured. Flores and Corvo are relatively circular islands, located on the North America plate, and thus form a control for the Neves et al. (2013) model, insofar as the Flores Ridge was not subjected to transtensional shear, and therefore island lavas were not erupted from fissures.

Forming the eastern edge of the North Azores Plateau (Fig. 1b), the Northeast Spur, especially Sedlo Seamount, may in part represent off-axis

AP volcanism similar to that forming Corvo and Flores islands. However, the Northeast Spur has a twin (West Azores Ridge, WAR) on the opposite flank of the MAR (Fig. 1b). The WAR must have (like the Flores and Faial ridges) largely formed on or near the MAR axis, but earlier.

The three peaks of Sedlo Seamount (Santos et al. 2010), a guyot, range from 950 to 660 m in summit depth. These volcanoes, located on ca. 20 Ma crust, probably formed as small islands at least partly off-axis—otherwise they would have thermally subsided ca. 1300–1600 m together with the adjoining oceanic MAR crust. If post-volcanic erosion beveled these islets by 5 Ma, subsequent crustal subsidence could account for the present summit depths. Although not yet mapped in detail, much of the WAR was first formed ca. 10 Ma prior to the first Faial and Flores ridges, which based on the locations of magnetic anomalies 5 and 6, formed during the period ca. 12–8 Ma (Fig. 1b). Although Beier et al. (2015) attempted to recover unaltered samples from Northeast Spur, there are no igneous rock ages from this feature, Sedlo Seamount, and the WAR.

In any case, the existence of MAR-parallel magnetic lineations over parts of the South Azores Plateau (Fig. 1b, c; Miranda and Luis 2013; Miranda et al., Chapter "The Tectonic Evolution of the Azores Based on Magnetic Data") suggests that an original MAR-generated basement topography (e.g., Fig. 2) was buried in lava flows and volcaniclastic debris, much of which must have been shed by the linear, island-capped volcanic ridges. Such randomly oriented debris—even strongly magnetised clasts—would not create a significant thermoremanent (TRM) magnetic anomaly signature and therefore would not obscure the original MAR-generated sea-floor spreading anomalies. Do the flat, acoustically opaque reflector below some sediment ponds (Fig. 2; Weiss et al. 2015b) represent anomalously flat, rapidly erupted MAR flood basalts, or has an original MAR type basement topography been buried and thus obscured under sheet-type lava flows or sills (largely 6–4 Ma; Beier et al. 2015) or by rapidly deposited volcaniclastic debris flows?

Coring is needed to calibrate the reflection seismology of the thick (up to ca. 1 km) sediments in the intermontane valleys (e.g., of Weiss et al. 2015b) and sample, age-date and measure the magnetic polarities of the AP flood basalt sequence down to and including the original MAR-generated basement. Boreholes could map the AP and MAR flank geochemical anomalies over space and time, building on the complex results from DSDP Site 556 (typical MORB recovered from 31 Ma MAR flank crust west of the AP) and DSDP Site 557 (Fig. 1b; LREE-enriched or 'E-type' basalt from 17 Ma AP crust east of the WAR). We suggest an entire ODP drilling leg be planned for the Azores Plateau.

***Azores microplate, diffuse plate boundary, or both?*** The scattered seismicity and volcanism in the ATJ-AP area (Fontiela et al., Chapter "Characterization of Seismicity of the Azores Archipelago: An Overview of Historical Events and a Detailed Analysis for the Period 2000–2012") suggests that the plate boundary—particularly the Nubia-Eurasia one—is somewhat diffuse (distributed) there, as has long been known. GPS technology (e.g., Fernandes et al., Chapter "The Contribution of Space-Geodetic Techniques to the Understanding of the Present-Day Geodynamics of the Azores Triple Junction") has opened the door to measurement of the present Azores inter-island displacement field. Fernandes et al. (2006) reported 1993–2001 displacements among the islands. Although the measured rates are generally consistent with global models for geologically recent plate motions, some of the islands did not move consistent with a simple triple junction, but supported a model of distributed elastic deformation within the Azores Plateau (Bastos et al. 1998). While as expected, Santa Maria moved with the Nubia plate, Graciosa moved with Eurasia, and the others (São Jorge, Pico, Terceira and São Miguel) moved in ways somewhat intermediate between Eurasia and Nubia. However, the displacement of Pico and São Jorge were closer to Nubia, the plate on which they to first order reside. The intermediate displacements of Terceira and São Miguel are to be expected, given their location on the immediate TR plate

boundary. The most surprising motion is that of Graciosa, located on the TR but moving entirely with Eurasia. Subsequent work (Marques et al. 2013), based on 35 new GPS stations occupied during 2001–2013, on Terceira, Faial and Pico (the latter two located on same volcanic ridge; Fig. 1b), plus fifteen GPS velocities on São Jorge (Mendes et al. (2013) refined these results: Terceira: Thirteen stations show slow (1–2.8 mm/a) westward motion relative to Eurasia, consistent with location on a very slow-spreading TR plate boundary; São Jorge: Fifteen GPS sites moved WSW at $2.7 \pm 0.7$ mm/a relative to the Eurasia plate; and Faial and Pico moved WSW at ca. 2–4 mm/a, with average separation of Faial/Pico from São Jorge ca. 1 mm/a. Faial/Pico moved largely, but not entirely, as if fixed to the Nubia plate (Marques et al. 2013).

DeMets et al. (2010) observed that opening rates along the MAR do not change abruptly from south to north anywhere between ca. 38° and 40°N near ATJ, but rather increase gradually from the Nubia-North America rate to the Eurasia-North America rate. They interpreted this gradual variation in rate as evidence for a separate Azores microplate, with its eastern edge presumably in the volcanic and seismically active island group from Graciosa through São Jorge to Pico-Faial. If a microplate exists, there must be three triple plate junctions, not just one. However, GPS stations on Faial-Pico, São Miguel, and Terceira (Marques et al. 2013), the sea-floor structures mapped by multibeam (Miranda et al. 2014), taken together with long-known mid-plate seismicity (Fig. 1e) make a convincing case for a diffuse triple junction, as suggested by Bastos et al. (1998). High resolution multibeam data (Fig. 1d, e; Miranda et al. 2014) do not support the speculative extension of the TR from West Graciosa Basin to the MAR axis suggested by Vogt and Jung (2004).

Presumably the magnetic data can also be interpreted in terms of a systematically deforming region, as suggested by Bastos et al. (1998). DeMets et al. (2010) used the 3.16–0 Ma interval on slow spreading ridges like the MAR to facilitate anomaly picks, with 3.16 Ma being the magnetic anomaly low in the middle of the anomaly 2A sequence. Perhaps a careful re-examination of the 38°–40°N magnetic anomaly data first reported by Luis et al. (1994), plus any newer and higher-resolution data, together with careful magnetic anomaly modelling which includes multibeam-defined seafloor topography, would yield an acceptably accurate rate for just the 0.78–0 Ma interval (0.78 Ma is the older limit of the Brunhes normal chron, recorded by the oceanic crust as anomaly #1). This time interval is closer to the period represented by earliest exposed Terceira Rift island volcanism. This rate might show an opening rate gradient more compatible with the GPS results for the present time and indicate that a change in kinematics has occurred, as in fact might be expected if the TR is only ca. 1 Ma old and was formed because of the change. Alternatively, if no such change has occurred, the northern edge of the microplate (from Graciosa to the MAR) might simply have been locked (seismically inactive) during the WWSSN observation period (i.e., since the early 1960s). Microplates are known at two triple plate junctions in the eastern Pacific (Fig. 1b inset), but are not there clearly associated with excess magmatism.

While the morpho-structural trends mapped by multibeam (Fig. 1c, d, e) and the earthquake epicentres (Fig. 1e) support diffuse deformation, the observed seismicity generally does not correlate with the structures, except for some epicentres clustering around an extension of São Jorge, and around Condor Seamount. Most of the epicentres are actually located on crust with only abyssal hill (MAR-generated) structures (N1, Fig. 1e). Future seafloor OBS and OBH campaigns will be necessary to obtain more accurate hypocentre locations and thus test whether the topographic structures mapped e.g. by Miranda et al. (2014) are tectonically active, perhaps showing that the diffuse triple junction actually comprises a series of smaller, fault-bounded blocks.

Distributed deformation probably also accounts for the misfit (over-rotation) of magnetic lineations from the Azores Triple Junction north ca. 300 km to ca. 42°N prior to ca. 7–8 Ma, i.e., prior to the MAR spreading rate slowdown (Merkouriev and DeMets 2014b)

discussed further below. The misfits range from ca. 5 km at C4A to ca. 20 km at C6. 42°N also marks the approximate northern edge of the North Azores Plateau (Fig. 1a, b).

Probably the microplate and the elastic intraplate deformation models are not mutually exclusive, and if the regional tectonic patterns change frequently over human time scales, future geophysicists will have no lack of research material.

## 5.1 The MAR Spreading Deceleration ca. 8–6 Ma

By careful mapping and back-rotating isochrons represented by magnetic anomalies, Merkouriev and DeMets (2008, 2014b) concluded that Eurasia-North America motion was essentially constant from 19.7 Ma (Chron C6n) to ca. 7 Ma and again from ca. 6 Ma to the present (See Vogt 1986c for a review of differing earlier results). However, during the 7–6 Ma interval the plate rotation rate slowed by ca. 20%, while the rotation pole migrated south ca. 1000 km. Using the same techniques, Merkouriev and DeMets (2014a) showed closely similar kinematic behaviour of Nubia-North America motion: Motion was steady from ca. 20 to 8.2 Ma; a deceleration by 25% happened during the interval 8.2–6.2 Ma, with motion subsequently steady. A deceleration ca. 7 Ma had previously been demonstrated from magnetic surveys along the 28–29°N part of the MAR (Sloan and Patriat 1992). The slowdown was accompanied by an end to the diffuse deformation on the MAR from the present triple junction north to 42° (Merkouriev and DeMets 2014b). Merkouriev and DeMets (2014a) speculate that the close coupling between the two plate motions might have resulted from changes in frictional forces along the Nubia-Eurasia plate boundary.

There are several implications of these results for the Azores Geosyndrome problem: First, Eurasia-Nubia motion—along the Azores plate boundary—must have slowed by similar amounts during this interval. Second, the 'deceleration crust' (Fig. 1e) includes most of the

N2 and N3 morphostructures mapped by Miranda et al. (2014)—this observation coupled with fairly low historical seismicity (Fig. 1e) leaves open the possibility that the structures were formed as a MAR plate boundary response to past changes in plate motion, and may therefore not all be active parts of the present diffuse boundary. Third, the deceleration crust forms the eastern edge of relatively normal, albeit shallow, oceanic crust. Evidently generation at the MAR axis of very anomalous Azores Plateau crust constituting the Fayal and Flores ridges (Vogt 1979, 1986c) and their cargo of younger volcanoes ceased. Perhaps this change in magmatism was some sort of response to the 8–6 Ma change in plate motion. Alternatively, perhaps the location of the deceleration band is a clue that the deceleration was itself driven by a change (reduction?) in mantle convection associated with a dying (Silveira et al. 2006) Azores plume. Azores. A slower convection and a less melt-rich asthenosphere (i.e., a higher viscosity) might have caused the deceleration. Numerical models of mantle convection its consequences for plate boundary forces can test this speculation.

## 6 Conclusions

For logistic reasons, the Azores triple plate junction and associated "geosyndrome" are among the best studied such features on the planet. Yet, despite great advances in seismic tomography and numerical modelling of mantle processes, advances have mainly refined earlier (1970s–1980s) interpretations.

Several of the geophysical research methods used to date have reached the point of diminishing marginal returns. A detailed surface ship or aeromagnetic survey of the North Atlantic is unlikely to provide a plate kinematic model greatly improved over (and different from) those of Luis and Miranda (2008) and Merkouriev and DeMets (2008, 2014a, b). GPS data on "present day" inter-island motions (e.g., Fernandes et al. 2006 and Chapter "The Contribution of Space-Geodetic Techniques to the Understanding of the Present-Day Geodynamics of the Azores Triple

Junction"; Marques et al. 2013) and intra-island deformation (e.g., Miranda et al. 2012) cannot detect temporal variations on time scales of centuries to millennia until far in mankind's future. However, 'paleostress' parameters can be recovered by age-dating of faults or dikes, as done for Graciosa (Hipolito et al. 2013), São Miguel (Carmo et al. 2015) and Santa Maria (Sibrant et al. 2015). Where fault or dike orientations changed over time (e.g., between 5.3 and 4.3 Ma on Santa Maria), were these just a local or regional volcano-tectonic effects or were they responses to changes in relative plate motions?

Seismic tomography could in principle resolve mantle anomalies, if any, deeper below the Azores region, particularly below ca. 400 km depths (Yang et al. 2006) and settle the long-standing controversy over the existence of a mantle plume or plume head. However, further progress is limited by current global and regional seismic coverage. A costly network of broadband stations both on the islands and on the wider seafloor region surrounding the AP would be needed (Silveira et al. 2006). Advancing from kinematics to dynamic modelling (e.g., Magde and Sparks 1997; Adam et al. 2013) will remain problematic until the structure, composition, and physical state of the mantle below the Azores are better constrained. This applies not only to the AP region, but also to the apparently vast geographic extent (Fig. 3b) of the Azores Geosyndrome particularly southwest along the MAR from the ATJ. Does partially molten mantle flow southwest, from an upwelling region under the Azores, in the triangular pipe-like region of enhanced melting (hence reduced viscosity) which must exist at depth under the MAR, as proposed by Vogt (1976)? The Faial and Flores ridges (Vogt 1979, 1986c; Cannat et al. 1999; Figs. 1b and 3a), which are not propagating rifts of the sort described by Hey (1977), as well as the SW geochemical gradient (Schilling 1976, 1986; Dosso et al. 1999; Fig. 3a) possibly remain the only expressions of such flow.

Meanwhile, rock sampling and geologic mapping have for practical reasons been almost entirely restricted to the Azores islands and immediate submarine plate boundaries, providing a necessarily biased 'zero age'

geochemical/petrologic snapshot of the Azores geosyndrome and its mantle origins (e.g., Beier et al. 2008, 2015, Chapter "Melting and Mantle Sources in the Azores"; Larrea et al., Chapter "Petrology of the Azores Islands", Madureira et al. 2011, 2014; Metrich et al. 2014) and other chapters in the present volume). In terms of magma extraction from the upper mantle, the TR islands themselves probably represent at most 10% of the roughly 0.05 $km^3$ annual crustal production along the 500 km long TR and 2000 km (conservatively assumed) length of MAR lithosphere produced by the "Azores melting anomaly".

Even along these narrow plate boundary belts, only the most recent eruptive products have been sampled at most sites, while off the axis the igneous crust lies buried under sediment, or where exposed is highly altered. More research boreholes are clearly needed to penetrate the Azores island edifices and, particularly, the surrounding submarine and largely sub-sedimentary AP crust to resolve processes of tectono-magmatic evolution, especially on time scales shorter than those resolved by magnetic lineations generated at low spreading rates (roughly on the order one to a few Ma). Owing to their high costs, boreholes into igneous volcanic islands and AP oceanic crust need to be carefully planned, with detailed 'site surveys'.

Less expensive coring from drilling vessels, penetrating and recovering primarily seafloor sediments, for example the up to ca. 1 km thick (e.g., Weiss et al. 2015b) largely hemipelagic sediment accumulations in Azores Plateau valleys (e.g., Fig. 2), recover not only the paleo-oceanographic history of the AP region, but also the volcano-tectonic history of the islands, as recorded by ash falls from subaerial and submarine explosive eruptions (e.g., Weiss et al. 2015a), volcaniclastic and other debris flows (e.g., Weiss et al. 2016), faulting (e.g., Weiss et al. 2015b) and infrequent but spectacular flank collapses from large edifices (e.g., Sibrant et al. 2014, 2015; Costa et al. 2014). Age dating (i.e., calibrating the seismic stratigraphy) would depend on a combination of sediment biostratigraphy and radiometric dating of

volcanogenic clasts from debris flows or ejecta. DSDP Leg 43 sediment cores adjacent to two of the New England Seamounts (DSDP sites 382 and 385) and adjacent to the Bermuda pedestal (DSDP site 387) exemplify this combined dating approach (Tucholke and Vogt 1979).

The demonstration from MAR flank magnetic lineations that both Nubia-North America motion (Merkouriev and DeMets 2014a) and Eurasia-North America (Merkouriev and DeMets 2008, 2014b) simultaneously slowed during the period ca. 8.2 to 6.2 Ma indicates that plate motions are coupled, perhaps controlled by Eurasia-Nubia convergence (Merkouriev and DeMets 2014a, b) or perhaps a regional change in mantle convection associated with the Azores geosyndrome.

The most intriguing, interdisciplinary question concerns the relation between AP formation and the triple junction jump ca. 23 Ma (chron 6C; Walker et al. 2012), closely coeval with plate reorganization in the Iceland area and more widely the 23.0 Ma Paleogene-Neogene boundary, a time of major global environmental change caused by the tectonic opening or closing of an oceanic 'watergate'. The formation of the AP in association with the jump is similar to what Sager (2005) found for other oceanic plateaus in the Cretaceous Pacific, and can scarcely be explained by coincidental rising of deep mantle plumes into newly formed triple junctions. The AP seems to have begun forming AFTER the jump and must thus be a consequence. However, because triple junctions do not REQUIRE excess magmatism (e.g., Georgen and Sankar 2010; Adam et al. 2013), an anomalous source mantle is still required. A secondary plume-type blob present below that part of the MAR would explain many of the observations, especially if the blob or plume 'head' is now slowly dying (Silveira et al. 2006) after creating the Flores and Faial ridges ca. 12–8 Ma. However, the great spatial extent of the MAR axial topographic high and the associated geoid high (e.g., Grevemeyer 1999) suggest that this Azores blob or secondary plume rose from the top of a much larger mantle anomaly (e.g., Davaille et al. 2005).

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