Journal of Volcanology and Geothermal Research 355 (2018) 2–20

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Invited review article

Origin of the South Atlantic igneous province

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ARTICLE INFO

Article history:
Received 14 March 2017
Received in revised form 5 September 2017
Accepted 11 September 2017
Available online 14 September 2017

Keywords:
Paraná Basalts
Plate hypothesis
Plume hypothesis
Tristan da Cunha
Hotspot

ABSTRACT

The South Atlantic Igneous Province comprises the Paraná Basalts, Rio Grande Rise, Tristan archipelago and surrounding guyot province, Walvis Ridge, Etendeka basalts and, in some models, the alkaline igneous lineament in the Lucapa corridor, Angola. Although these volcanics are often considered to have a single generic origin, complexities that suggest otherwise are observed. The Paraná Basalts erupted ~5 Ma before sea-floor spreading started in the neighborhood, and far more voluminous volcanic margins were emplaced later. A continental microcontinent likely forms much of the Rio Grande Rise, and variable styles of volcanism built the Walvis Ridge and the Tristan da Cunha archipelago and guyot province. Such complexities, coupled with the northward-propagating mid-ocean ridge crossing a major transverse transtensional intracontinental structure, suggest that fragmentation of Pangaea was complex at this latitude and that the volcanism may have occurred in response to distributed extension. The alternative model, a deep mantle plume, is less able to account for many observations and no model variant can account for all the primary features that include eruption of the Paraná Basalts in a subsiding basin, continental breakup by rift propagation that originated far to the south, the absence of a time-progressive volcanic chain between the Paraná Basalts and the Rio Grande Rise, derivation of the lavas from different sources, and the lack of evidence for a plume conduit in seismic-tomography- and magnetotelluric images. The region shares many common features with the North Atlantic Igneous Province which also features persistent, widespread volcanism where a propagating mid-ocean ridge crossed a transverse structural discontinuity in the disintegrating supercontinent.

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1. Introduction

The South Atlantic Igneous Province, ~9000 km broad, includes the Paraná Basalts, alkaline magmatism in the Ponta Grossa Arch, the Rio Grande Rise, the Tristan archipelago including Gough, Inaccessible and the Nightingale Islands, the Walvis Ridge and the Etendeka basalts in Namibia (Fig. 1) (*e.g.*, Courtillot et al., 2003; Fromm et al., 2015; Moore et al., 2008). It has recently been suggested that the province also includes the ~1500-km-long, NE-trending Lucapa zone of carbonatites and kimberlites onshore in Africa extending across Angola and into the Democratic Republic of the Congo (Fig. 2) (Fromm et al., 2015). The attribution of these disparate magmatic rocks to a single generic system is predicated on the assumption that they all arise from a deep mantle plume.

This igneous province is one of only three in the world where emplacement of a flood-basalt was arguably followed by small-volume magmatism in a linear zone in the manner predicted for plume-head/

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https://doi.org/10.1016/j.jvolgeores.2017.09.004
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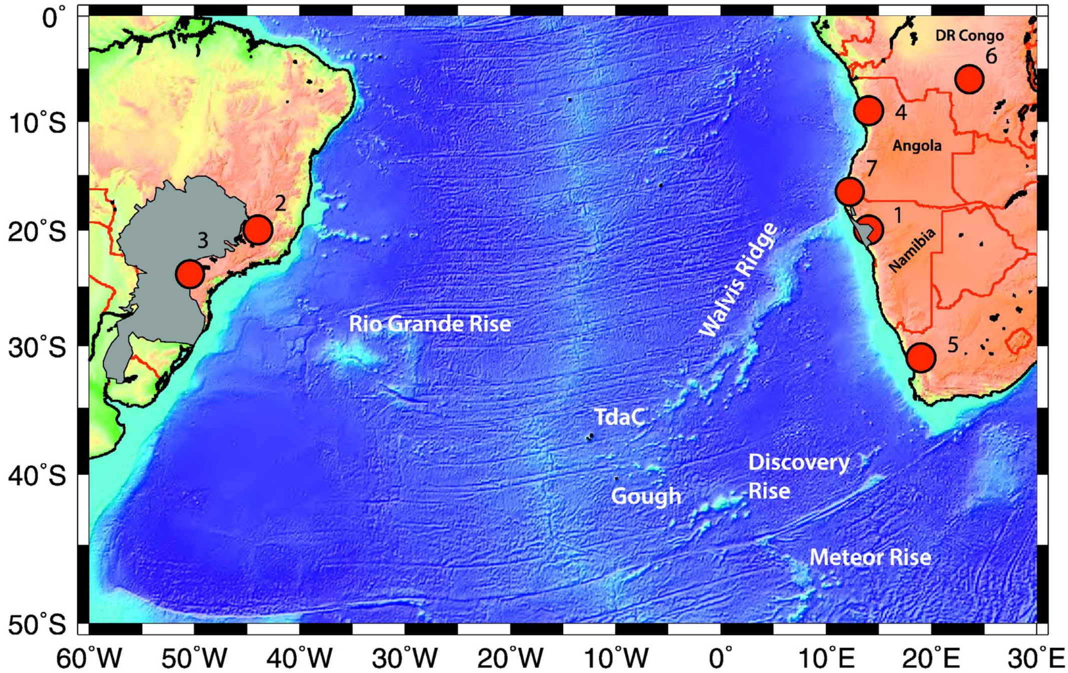

Fig. 1. Bathymetry and topography of the South Atlantic showing the South Atlantic Igneous Province. Red dots: Locations of plume impingement proposed by various authors; 1 = Morgan (1971), 2 = VanDecar et al. (1995), Rocha et al. (2011), Schimmel et al. (2003), 3 = Richards et al. (1989) and many others, 4 = Duncan (1984), 5 = predicted arrival location of the proposed plume calculated by Ernesto et al. (2002) from paleomagnetic reconstructions, 6 = Fromm et al. (2015), 7 = O'Connor and Duncan (1990). Gray: Paraná and Etendeka basalts in South America and Africa respectively, TdaC: Tristan da Cunha island, Gough: Gough island. These islands are two of a number of proposed locations of a present-day plume. DR Congo: Democratic Republic of the Congo.

plume-tail volcanism (Courtillot et al., 2003). The other two cases are the Columbia River Basalts/Eastern Snake River Plain/Yellowstone province in western North America and the Deccan Traps/Laccadive-Maldive-Chagos-Ridge/Réunion province in India and the Indian ocean.

When first proposed (Morgan, 1971), most of the few observations then available from the South Atlantic Igneous Province were consistent with the Plume hypothesis. Many data collected subsequently, however, have either violated the predictions of the original hypothesis or been unexplained by it. This has led to a number of plume variants being proposed, many of which have conflicted with one other and with related work (Lustrino, 2016; Rocha-Júnior et al., 2012). These variants include *ad hoc* lateral flow or plume wandering to explain inconsistencies between the location of volcanism and plume locations predicted by other observations (Fig. 1) (Ernesto et al., 2002), plume locations distant from the contemporaneous location of magmatism (*e.g.*, Duncan, 1984), multiple overlapping plumes (Gibson et al., 1995), and a plume that supplied heat that melted the overlying lithospheric mantle without contributing material (*e.g.*, Comin-Chiaramonti et al., 1997; Peate, 1997). There is no agreement regarding where the postulated plume currently lies and suggestions include beneath the island of Tristan da Cunha, 45 km further south, beneath Gough Island, at the Discovery Rise and at Meteor Rise (Fig. 1) (Schlömer et al., 2017; Sleep, 2002).

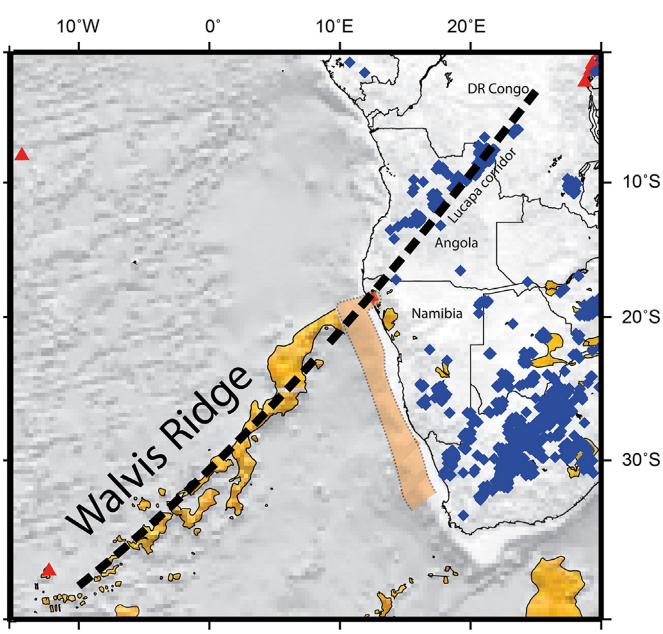

Fig. 2. Postulated track of a Tristan plume. Yellow: shallow bathymetry, pink: surface projection of high-velocity lower crustal body identified by seismology, blue diamonds: carbonatite and kimberlite eruptives onshore.
(From Fromm et al., 2015).

It has also been suggested that, while the Rio Grande Rise and the Walvis Ridge correspond to "plume tail" volcanism, the Paraná and Etendeka basalts do not represent "plume head" volcanism but instead the proposed plume arrived at the base of the lithosphere under central Africa several tens of millions of years earlier (Fromm et al., 2015). In this model, a "plume-head" flood basalt is absent and the Paraná and Etendeka basalts comprise melts from a reservoir at the lithosphere-asthenosphere boundary which were released in response to the rifting that opened the South Atlantic. On the basis of seismic tomography results, VanDecar et al. (1995) postulate that a "fossil" plume tail currently underlies Brazil. Other authors suggest that lateral flow can explain the lack of regular age-progression of volcanics along the Walvis ridge and the two parallel volcano chains emanating from the islands of Tristan da Cunha and Gough (O'Connor and Jokat, 2015). It has further been suggested that, after ~40–44 Ma, the rate of plume migration changed (O'Connor and Jokat, 2015). Temperature anomaly estimates are variable. Temperature excesses of 400 °C have been suggested on geochemical grounds (Thompson and Gibson, 2000) and 150 °C on the grounds of models of melt flow in the proximity of a spreading ridge (Gassmöller et al., 2016).

Data inconsistent with, or unpredicted by, the classical Plume model that require proliferation of mutually exclusive plume variants have become burgeoning. It is thus timely to test other working hypotheses. The Plate model predicts that volcanism occurs where the lithosphere deforms under extension as a consequence of processes resulting directly or indirectly from plate tectonics (Foulger, 2010, Section 1.9). Where volcanism occurs, evidence for lithospheric extension is expected (Foulger et al., 2015). The spatial history of volcanism is predicted to reflect that of extension. Magmatic volumes are controlled by fusibility of the source where decompression melting contributes and by the volume of pre-existing melt in the mantle where that is released (Anderson and Spetzler, 1970; Presnall and Gudfinnsson, 2005; Silver et al., 2006). In the absence of lithospheric extension melt that forms or pre-exists in the mantle does not erupt.

The Plate model predicts that volcanism is a consequence of lithospheric processes and the mantle is a passive source of melt. This is the inverse of the Plume model which proposes that magmatism is actively driven by deep-rooted convection in the mantle with the

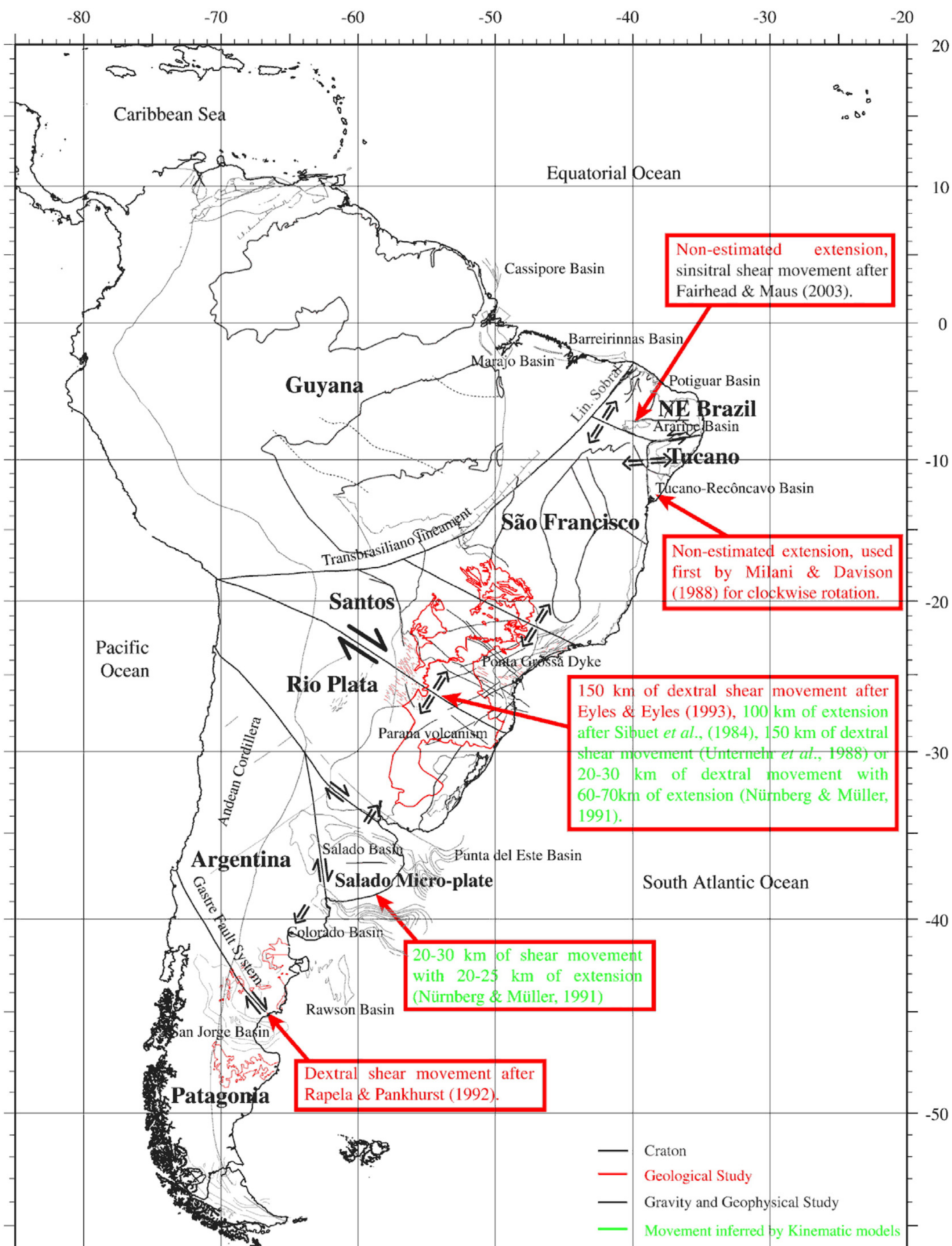

Fig. 3. Structural map in Mercator projection of South America showing data on Cretaceous basins and maximum continental deformation permissible. The type of information used is color-coded (red = geological, blue = geophysical, green = kinematic models). South America is divided into nine blocks: Guyana, NE Brazil, Tucano, the São Francisco craton, Santos, Rio de la Plata, Argentina, Patagonia, and the Salado microplate. Intraplate deformation between these blocks is indicated schematically by black lines.
(From Moulin et al., 2010).

lithosphere being the passive element. Lithospheric influence on volcanism is widely recognized in field observations. In the Plume model this has traditionally been attributed to processes such as *ad hoc* lateral flow or "upside-down drainage" (Sleep, 1996) where plume-supplied material is postulated migrate to thin, weak, or extending places in the lithosphere. Thus, lithospheric control of volcanism has long been recognized but traditionally absorbed into the Plume hypothesis as one of its many variants. In the Plate model, the coincidence of thin, extending regions of the lithosphere and volcanism is attributed to primary causation and not a secondary model feature.

The present paper briefly reviews data from the South Atlantic Igneous Province that must be explained by any successful genesis model. It reviews the evidence for extension in association with the disparate magmatic elements that make up the province and develops a Plate model for the region. Finally, it summarizes the challenges to the Plume hypothesis in this igneous province.

2. A plate model for the South Atlantic igneous province

Extension of the kind predicted by the Plate hypothesis occurred where the Paraná and Etendeka basalts and the Angolan alkaline rocks were emplaced. First, super-continent re-assembly fits require intraplate deformation in both South America and Africa (Fig. 3) (Moulin et al., 2010). Fig. 4 shows the tightest possible reconstructed fit of South America and Africa permitted by geological and geophysical information at the time of eruption of the Paraná Basalts, *i.e.* ~134 Ma (Baksi, 2017; Moulin et al., 2010). This reconstruction recognizes nine separate blocks that may move relative to one another in the South American block and four in the African plate. The best fit of the continental edges requires considerable intra-continental deformation including ~150 km of dextral slip and ~70 km of extension in the Paraná Basin between the Santos and Rio Plata blocks (Fig. 3). The zone of extension extends from the west coast of northern Chile to the east coast

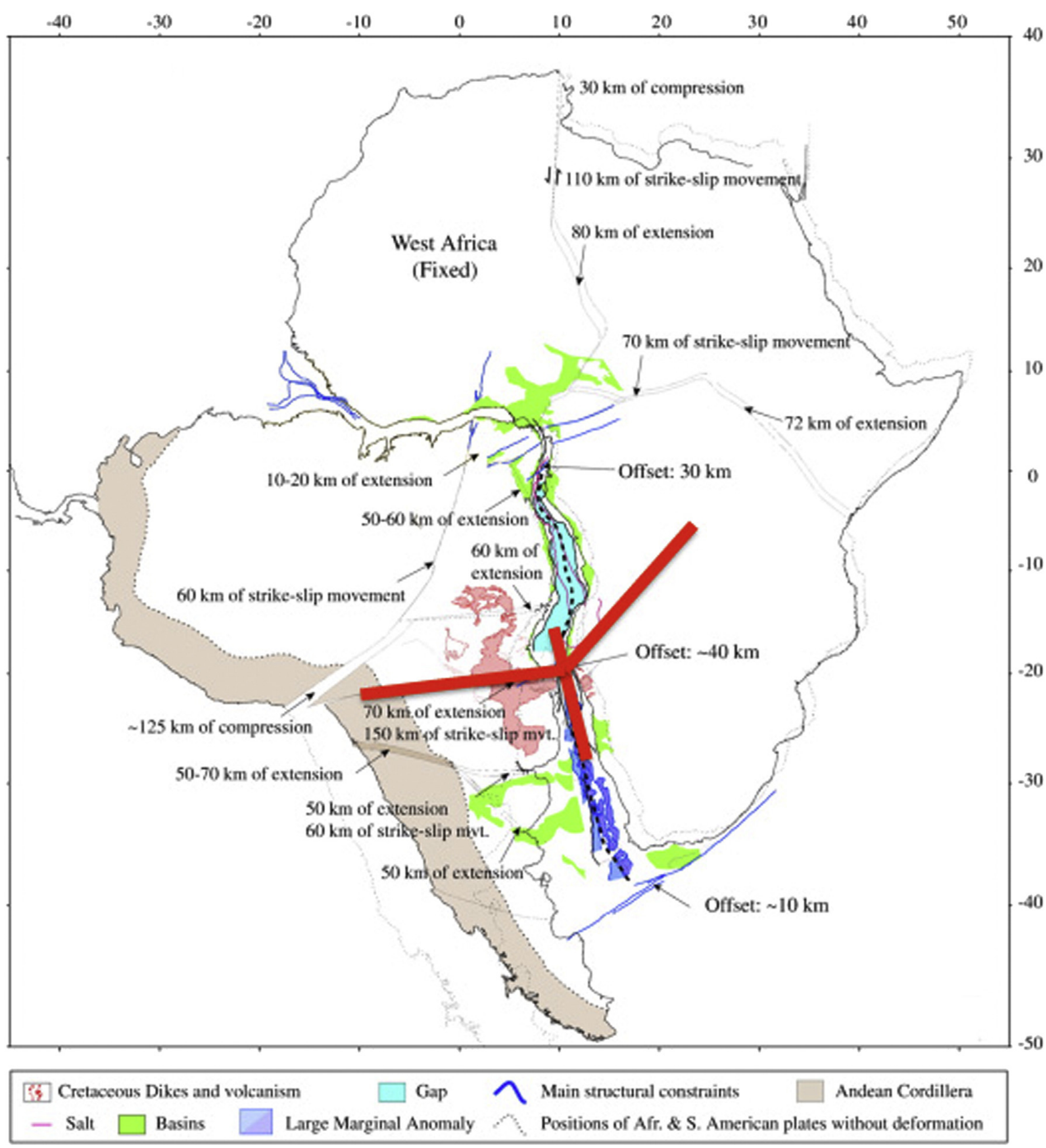

Fig. 4. The tightest possible reconstruction permitted by geological and geophysical data at the approximate time of eruption of the Paraná Basalts, *i.e.* ~134 Ma. Inferred intraplate deformations are indicated in black. Dextral strike-slip movement of 150 km, and 70 km of extension, is required in the Paraná Basin. 125 km of compression occurred in the Andean Mountains and 50–70 km of extension was distributed throughout the Colorado-Salado Basins and the Andes. The West African block is considered fixed (from Moulin et al., 2010. See that paper for additional details). Red lines: mid-Atlantic ridge and transverse structure postulated in the present paper to comprise a locus of extension that allowed volcanism to occur.

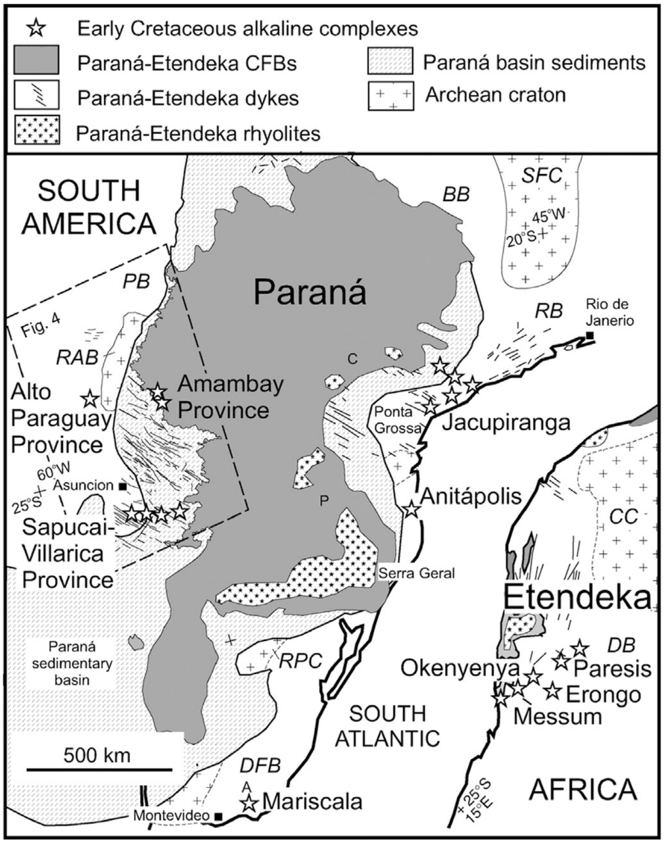

Fig. 5. Distribution of alkaline and tholeiitic igneous rocks in the Paraná-Etendeka flood-basalt province prior to continental break-up. Early Cretaceous alkaline igneous rocks and the approximate locations of cratons and mobile belts are shown. BB: Brasilia Belt, DB: Damara Belt, DFB: Dom Feliciano Belt, PB: Paraguai Belt, RB: Ribeira Belt, CC: Congo Craton, LA: Luis Alves Craton, RAB: Rio Apa Block, RPC: Rio de la Plata Craton, SFC: São Francisco Craton, A: Aiüga rhyolites, C: Chapeco rhyolites, P: Palmas rhyolites.
(From Gibson et al., 2006).

of Brazil where the Paraná Basalts most closely approach the coast. Further evidence for extension is the major margin-perpendicular diking that occurred in the Ponta Grossa zone during a period of a few million years around 131 Ma (Fig. 5) (Renne et al., 1996).

Extension and associated volcanism occurred approximately contemporaneously on the African side. A zone of carbonatites and kimberlites in Angola and the Democratic Republic of the Congo erupted in the Lucapa corridor, a NE-orientated, 300-km-long rift that formed in the Congo craton in the Early Cretaceous at approximately the same time as opening of the South Atlantic (Fig. 2) (De Boorder, 1982; Sykes, 1978). Only a few age dates are available for these volcanics. However, the data that do exist show no evidence of a westerly time-progression but suggest that most of the lavas erupted approximately synchronously with reactivation or formation of the Lucapa rift by the opening of the South Atlantic (Table 1) (Campeny et al., 2014; Robles-Cruz et al., 2012). These rocks are mirrored on the South American side by a ~2000-km-long zone of alkaline carbonatite complexes that extend from the coast to the NW along the Ponta Grossa Arch (Riccomini et al., 2005). These rocks, which date from the Permo-Triassic to the Oligocene, also show no age progression and were related to extensional/subsidence tectonics including arches, rifts, and major dikes (Comin-Chiaramonti et al., 1999; Comin-Chiaramonti et al., 1997). They are thought to have been emplaced along structures active since the Precambrian and reactivated in the Mesozoic (Riccomini et al., 2005).

The extensional deformation that occurred in the South American and African continental lithosphere indicates the style in which Pangaea disintegrated at this latitude. It did not break up simultaneously along the entire length of the South Atlantic. Indeed, breakup by rift propagation is required by plate divergence about a pole of rotation. The South Atlantic unzipped in jumps from south to north (Fig. 6) (Franke, 2013; Franke et al., 2010; Franke et al., 2007). Rifting started at the Falkland-Agulhas Fracture Zone, currently at ~45°S, and propagated north episodically in discrete segments separated by transfer zones, *i.e.* zones that delay the rift-to-drift transition. Abrupt changes in the volumes of the volcanic margins occur across these zones. Franke (2013) describes three discrete segments in which spreading onset at ~137, 133 and 128 Ma (Fig. 6). Extension in the southernmost segment followed oblique and magma-poor rifting, creating thin crust (Fig. 6A). At this time, small-volume intracontinental volcanism was already underway further north and ~4 Ma later magma-rich rifting began in the middle segment (Fig. 6B). Emplacement of the Paraná-Etendeka flood basalts and rifting and magmatism in Angola occurred at this time. Spreading in the northernmost segment (Fig. 6C) followed after another ~5 Ma and propagated quickly to reach the transfer zone that bounds the southern and central South Atlantic oceans. Seaward-dipping reflectors detected in offshore seismic surveys, that represent volcanic margins, exceed 10 km in thickness and were emplaced episodically from seaward-migrating centers.

Propagation of the new rift across the activated extensional transverse zone between the Santos and Rio Plata blocks and in the Lucapa corridor likely led to complexities at this latitude. Volcanism is unusually distributed compared with the passive margins and ocean to the north and south and there is likely a continental fragment beneath the Rio Grande Rise (Sager, 2014). These complexities may also have bequeathed on-going, low level plate boundary instability at this part of the new spreading plate boundary resulting in second-order disequilibrium and persistent deformation of the oceanic crust that formed.

Fairhead and Wilson (2005) studied the Walvis Ridge and Rio Grande Rise using high-resolution gravity data (Sandwell and Smith, 1997) enhanced to ~10 km resolution (Fig. 7). They suggest these bathymetric features formed as a consequence of periodic release of intraplate stress via shear faulting. Release of time-varying stress in the African plate is reflected in variations in the stratigraphic record of sedimentary basins in Africa and development of the East African rift system (Bailey, 1992; Bailey and Woolley, 1999; Fairhead et al., 2013). Corresponding processes in the oceanic part of the plate are revealed in the fabric of the ocean crust. Release of stress occurs preferentially at places of lithosphere weakness and this process may have formed and shaped the Rio Grande Rise and the Walvis Ridge (Fig. 7). Periodic transtension on transform faults may be responsible for the staircase-like morphology of the latter.

Table 1
Ages of kimberlites in Angola, listed in order from north to south.

Location	Age, Ma	Method	References
Catoca kimberlite	117.9 ± 0.7	U-Pb	(Robles-Cruz et al., 2012)
Chicuatite kimberlite	372 ± 8	K-Ar	(Egorov et al., 2007)
Luxinga cluster	145–113		(Eley et al., 2008)
Val do Queve	133.4 ± 11.5	Fission tracks	(Haggerty et al., 1983)
Bié Province, Central Angola	238	U–Pb and mica-in-kelyphite Ar–Ar geochronology	(Jelsma et al., 2013)

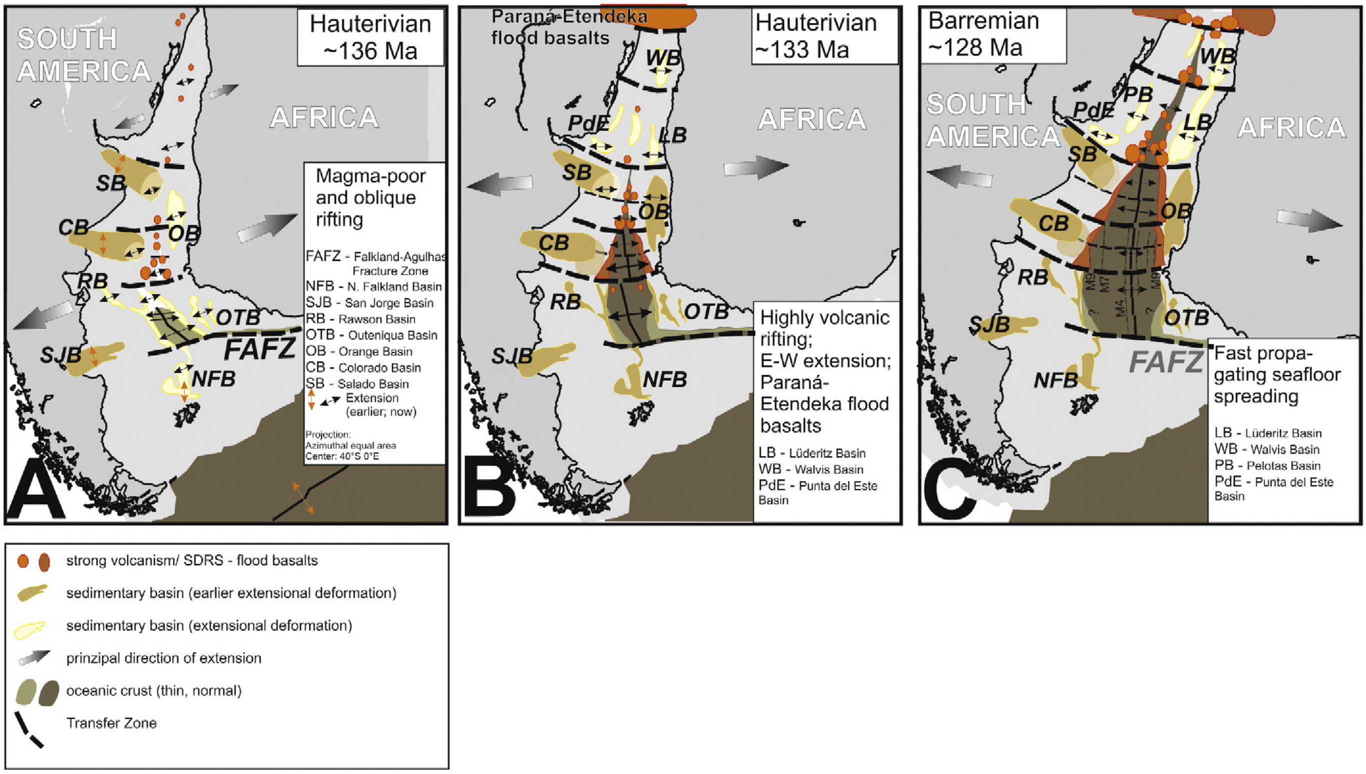

Fig. 6. The early evolution of the South Atlantic at (A) ~137 Ma, (B) ~133 Ma, and (C) ~128 Ma. (From Franke, 2013).

The Paraná Basalts erupted ~5 Ma before the South Atlantic at the same latitude opened. It seems unlikely that Paraná volcanism was unrelated to breakup. In general, there are two options for extension-related volcanism:

1. Melt accumulated over a longer time than eruption and accumulated in a reservoir, possibly at the base of the lithosphere, and escaped rapidly when permitted by lithospheric extension (Silver et al., 2006); and
2. Melt was produced on the same time-scale as eruption by decompression melting.

Long-term melt accumulation in reservoirs is difficult to argue on theoretical grounds. However, two lines of observational evidence suggest that it does occur in nature and that such reservoirs can drain to the surface quickly and form flood basalts. First, the volumes and eruptive rates of the largest flood-basalt provinces known cannot be reproduced by numerical modelling of decompression melting in upwelling mantle for any reasonable temperature anomaly. For example, the majority of the ~4 × 10^6 km^3 Siberian Traps, the largest continental flood basalt on Earth, are thought to have erupted in just one or a few million years (*e.g.*, Ivanov, 2007). Decompression melting in a rising hot diapir or mantle plume stalled at the base of thick lithosphere such as that on which the Siberian Traps erupted can only account for production of up to ~1 × 10^6 km^3 in such a short time-period (Cordery et al., 1997). It thus seems required that the melt formed over a longer time period than it took to erupt.

Second, long-term melt accumulation and rapid release is required for several flood basalts in southern Africa (Fig. 8). Silver et al. (2006) studied the Ventersdorp (2.71 Ga), Great Dyke (2.57 Ga), Bushveld (2.06 Ga), and Soutpansberg Trough (1.88 Ga) flood-basalt provinces. These erupted onto thick continental lithosphere shown, using lithospheric mantle xenoliths, to have remained intact before, during and after the events. Thus, enhanced adiabatic decompression melting facilitated by thermal erosion allowing hot asthenosphere to rise to shallow depth could not have occurred. This rules out both mantle plumes and delamination of the lower lithosphere. Accumulation of melt in sublithospheric reservoirs over a longer period than eruption, followed by short-duration drainage events, is required.

Lithospheric control of these flood basalts is clear. They erupted almost synchronously with the formation of collisional rifts associated with subsequent major orogens. The magmatism followed pre-existing lithospheric structure and exploited pre-existing mechanical anisotropy in the lithospheric mantle.

Estimates of the total volume of the Paraná Basalts range from 1.3–0.6 × 10^6 km^3 (Frank et al., 2009; Piccirillo and Melfi, 1988; Renne et al., 1992). This is small compared with the largest flood basalts, and comparable with estimates of the volumes of the Afar basalts and Deccan traps (Foulger, 2010, p. 82). Only under exceptional circumstances could this volume be produced sufficiently rapidly in a rising plume head.

The second option, formation of melt on the same time-scale as eruption, requires lithospheric thinning and the rising to shallow depth of material that decompresses and melts. A possible process that could enable this in the absence of sea-floor spreading is depth-dependent lithospheric extension (Fig. 9). Numerical modelling of the onset of continental breakup suggests that in some cases up to 250 km of lithosphere extension can occur over a period as long as 25 Ma prior to the onset of sea-floor spreading (Huismans and Beaumont, 2008). The required circumstance is low coupling between the crust and mantle lithosphere so the latter can extend and move laterally before the crust ruptures.

This model fits the South Atlantic particularly well (Huismans and Beaumont, 2008). It predicts wide regions of strongly thinned crust and relatively thin overlying synrift sediments, some of which are deposited in shallow seas. The zone of thinned continental crust is predicted to be up to several hundred kilometers broad, with faulted early synrift sedimentary basins and undeformed late synrift sediments. Extension in this style, prior to breakup, can occur if the crust is weak

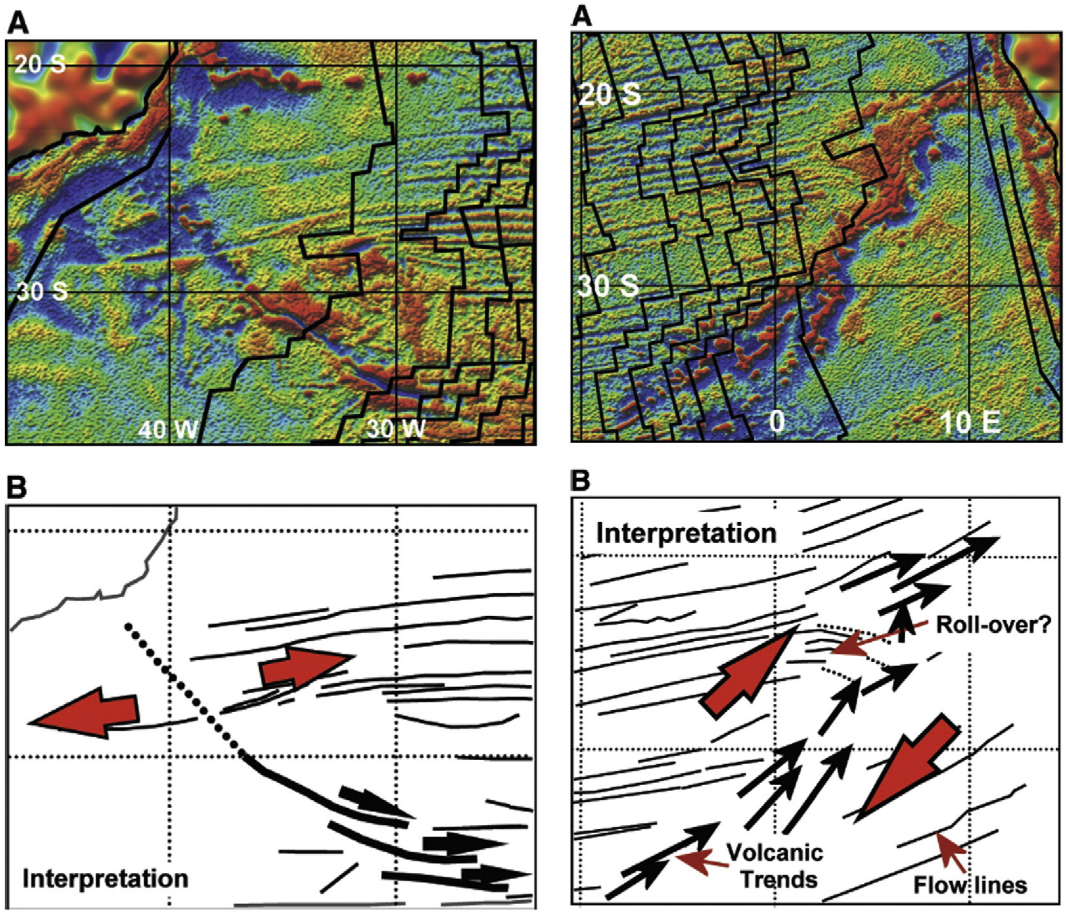

Fig. 7. Left panels: (A) Satellite-derived free-air gravity map of the Rio Grande Rise, (B) its interpretation in terms of stress release in dextral shear movements and extension. Dashed black line shows the Trinidade-Martin Vaz seamount trail. Thin black lines: major flow lines, thick black lines: segmented structure of the Rio Grande Rise. Right panels: (A) Satellite-derived free-air gravity map of the Walvis Ridge, (B) its interpretation in terms of stress release in dextral shear movement (red arrows) and formation of roll-over structures. Black arrows represent volcanic lineaments propagating away from the Mid-Atlantic Ridge at the time of magmatism.
(From Fairhead and Wilson, 2005).

(low viscosity), *e.g.*, in the presence of wet quartz, and can decouple from the mantle lithosphere over a broad region. Such conditions might exist in old sutures which are frequently re-activated by continental breakup (Lundin and Doré, 2005; Lustrino, 2005; Sykes, 1978).

Lithospheric stretching is enhanced if, in addition, the mantle is weakened by high water content. This allows small-scale convective instability in the rising asthenosphere which enhances erosion of the mantle lithosphere. The asthenosphere can then rise to shallower depths which enhances decompression melting and encourages melting of the lithospheric mantle.

Such a process can account naturally for a number of geochemical observations from the South Atlantic Igneous Province. The Paraná Basalts exhibit high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ which, together with their trace-element patterns, do not fit any model for melting of the asthenospheric mantle even if continental lithospheric contamination is permitted (*e.g.*, Comin-Chiaramonti et al., 1997; Ernesto et al., 2002; Peate, 1997; Piccirillo et al., 1989; Regelous et al., 2009; Turner et al., 1996). Both the northern high-Ti and southern low-Ti Paraná Basalts require the presence of the components EM-I and EM-II. These are thought to correspond respectively to ancient lower continental crust or metasomatized lithospheric mantle, and to upper continental crust and pelagic sediments or metasomatized oceanic lithosphere. These materials could have been introduced into the mantle by Neoproterozoic subduction (*e.g.*, Rocha-Júnior et al., 2013; Rocha-Júnior et al., 2012).

The geochemistry of basalts from Walvis Ridge and the Rio Grande Rise suggests inclusion in the source of detached continental lithospheric mantle eroded off during continental break-up and mixed with typical oceanic MORB source (Comin-Chiaramonti et al., 1999; Comin-Chiaramonti et al., 1997; Comin-Chiaramonti and Gomes, 1996; Comin-Chiaramonti et al., 2007; Hawkesworth et al., 1988; Hawkesworth et al., 1990; Hawkesworth et al., 1986; Ussami et al., 2012). The basalts from both regions are inconsistent with derivation from a similar source to Tristan da Cunha basalts which are significantly more radiogenic (LeRoex et al., 1990; Milner and LeRoex, 1996; Peate and Hawkesworth, 1996; Weaver et al., 1987). In addition, Re-Os isotope data for basalts from Tristan da Cunha show that they have suprachondritic osmium isotopes (initial γ^{187}Os values from $+15$ to $+80$) that are more radiogenic than Paraná Basalts (initial γ^{187}Os values from -1 to $+3$). This shows that the Paraná Basalts and Tristan da Cunha cannot derive from the same source either (Rocha-Júnior et al., 2012).

These observations are readily explained by mechanical or thermal erosion of the sub-continental lithospheric mantle. This could have occurred as a consequence of extension of the continental mantle lithosphere and lower crust prior to sea-floor spreading as modelled by Huismans and Beaumont (2008). When a continent breaks up, and asthenosphere rises beneath the center of the newly forming ocean, descending convection-current limbs are predicted to form in the mantle at the new continent edges. These convection limbs are expected to erode the mantle lithosphere and recycle it back into the asthenosphere beneath the center of the new ocean. Incorporation of that eroded material into the melt column, possibly along with Neoproterozoic material recycled in the asthenosphere, would have provided water that

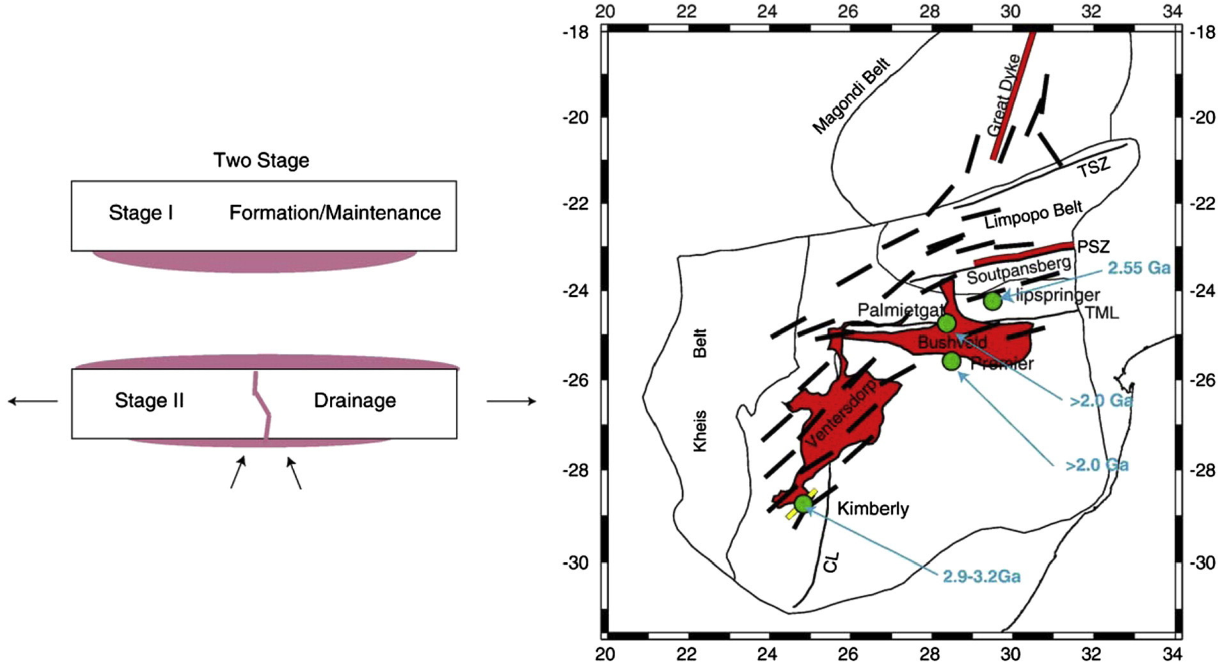

Fig. 8. Left: Two stages of the model of Silver et al. (2006) whereby a reservoir of melt accumulates at the base of the lithosphere over a long period of time (Stage I) and drains rapidly when orogenic activity creates a trans lithospheric fracture (Stage II). Right: Map of southern Africa showing the Great Dyke, Ventersdorp, Bushveld and Soutpansberg magmatic provinces. TSZ: Triangle shear zone, PSZ: Palala Shear Zone, TML: Thabazimbi Murchison. Lineament, CL: Colesberg Lineament.
(From Silver et al., 2006).

enhanced mantle flow by lowering the viscosity. Additional evidence for such lithospheric entrainment is found in seismic tomography images. Conjugate high-velocity "drips" are imaged beneath the current continental edges (Fig. 10) (King and Ritsema, 2000) This process also increases the amount of melt produced at the onset of sea-floor spreading, and can account for most of the magma volumes in the volcanic margins (Fig. 11).

Fig. 4 shows a simple schematic of extending zones around the time the Paraná Basalts were emplaced. The main locus of continental break-up crossed a transverse zone of weakness at the latitude of the Paraná Basalts. This resulted in mechanical complexities. Onset of sea-floor spreading was delayed as a result of depth-dependent extension facilitated by the availability of fluids. Distributed extension and volcanism occurred, along with fragmentation of the continental crust resulting in the setting adrift of continental microcontinents. One of these may comprise part of the Rio Grande Rise and others may underlie the easternmost part of the Walvis Ridge.

Voluminous basaltic volcanism somewhat prior to the onset of major extension or sea-floor spreading is not unusual. The Columbia River Basalts (volume: 0.15×10^6 km^3) erupted at ~17 Ma, immediately prior to the onset of distributed (basin-range) extension throughout much of the western USA. The Deccan Traps (volume: 0.5×10^6 km^3) erupted at ~67–60 Ma, commencing about 1 Ma prior to formation of the Carlsberg Ridge which separated the Seychelles microcontinent from India. The Afar flood basalt (volume: 0.35×10^6 km^3) erupted at ~31–28 Ma, ~11 Ma prior to the onset of spreading in the Gulf of Aden. In the case of the Paraná Basalts (volume: 0.78×10^6 km^3), the delay between eruption and adjacent sea-floor spreading was ~5 Ma. Despite the variable delays, it seems unlikely that the eruptions of these flood basalts and subsequent extension or spreading are unrelated.

3. Challenges to the mantle plume model

In order to naturally fit a modern generic mantle plume model, observations from the Paraná-Tristan-Etendeka region should match its primary predictions. These have recently been defined as (Campbell, 2007; Campbell and Kerr, 2007):

- Precursory, kilometer-scale domal surface uplift in response to plume-head impingement on the base of the lithosphere;
- Eruption of flood basalts a few, or a few tens of millions of years after the onset of uplift;
- As a result of the plume being fixed relative to other plumes, a time-progressive chain of volcanoes oriented in the appropriate azimuth will develop on the moving, overhead plate;
- A temperature anomaly of the order of hundreds of degrees C in the mantle melt source; and
- A hot conduit forming a plume tail extending from the surface to the core-mantle boundary.

Many variants of this model have been proposed for the South Atlantic Igneous Province because observations often fit these predictions poorly. Maturation and second-order adjustments of a model in the light of new findings is natural, but these adjustments must make predictions that can themselves be confirmed by observation. Difficulties with variant plume models for the South Atlantic Igneous Province is that many are mutually exclusive, none fits all the observations successfully, and the adjustments are often *ad hoc* and do not improve a generic model that can explain other proposed plume localities:

- The Paraná Basalts erupted in a subsiding intracratonic Palaeozoic sedimentary basin (Fig. 12) (Peate, 1997). This basin had been subsiding since the Early Paleozoic and filled to a depth of ~3.5 km up to early Cretaceous times. The oldest sediments are marine, grading up into subaerial, fluvial and aeolian deposits laid down under desert conditions. The earliest Paraná volcanics overlie these. The broader region thus underwent uplift over a period of several hundred million years, much longer than expected for a plume impinging in the Early Cretaceous, with concurrent local subsidence where the sedimentary basin formed and the Paraná flood basalts were emplaced (Fúlfaro, 1995). The thickest part of the flood basalt (~1.5 km) coincides with the deepest part of the basin.

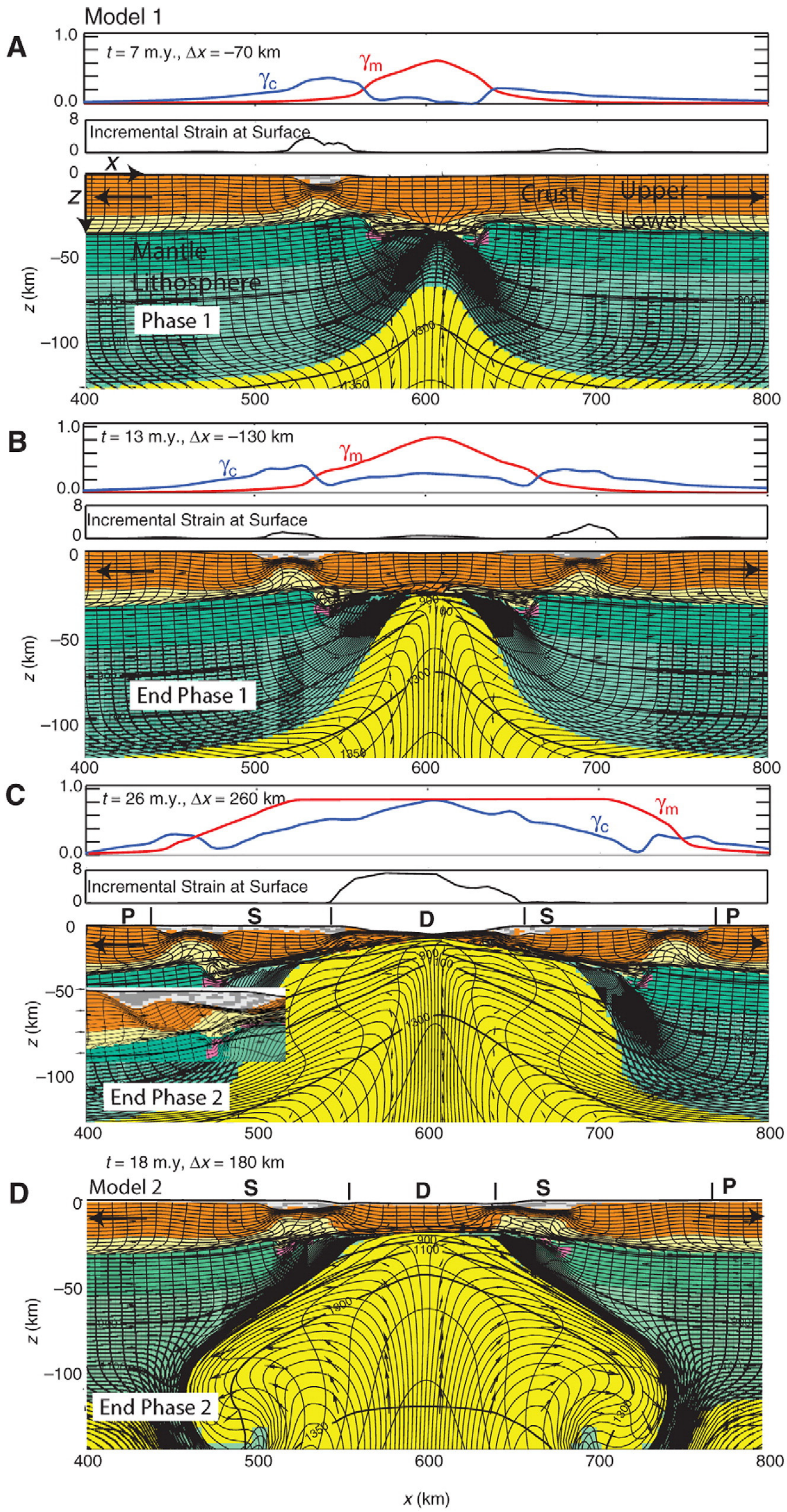

Fig. 9. Numerical thermo-mechanical models of lithospheric extension. A–C: Model 1. Panels show deformed Lagrangian mesh, velocity, and temperature. Increment in strain at surface is with respect to the previous panel. Total extension velocity is 1 cm/a. Materials deform plastically or viscously. Model 1: phase 1–wide zone of crustal extension, matched by narrow zone of mantle necking. Phase 2–crustal extension focuses in distal margins and rift axis and mantle lithosphere is translated laterally. D: Model 2, Phase 2: convective removal of mantle lithosphere. P–proximal, S–sag, D–distal.
(From Huismans and Beaumont, 2008).

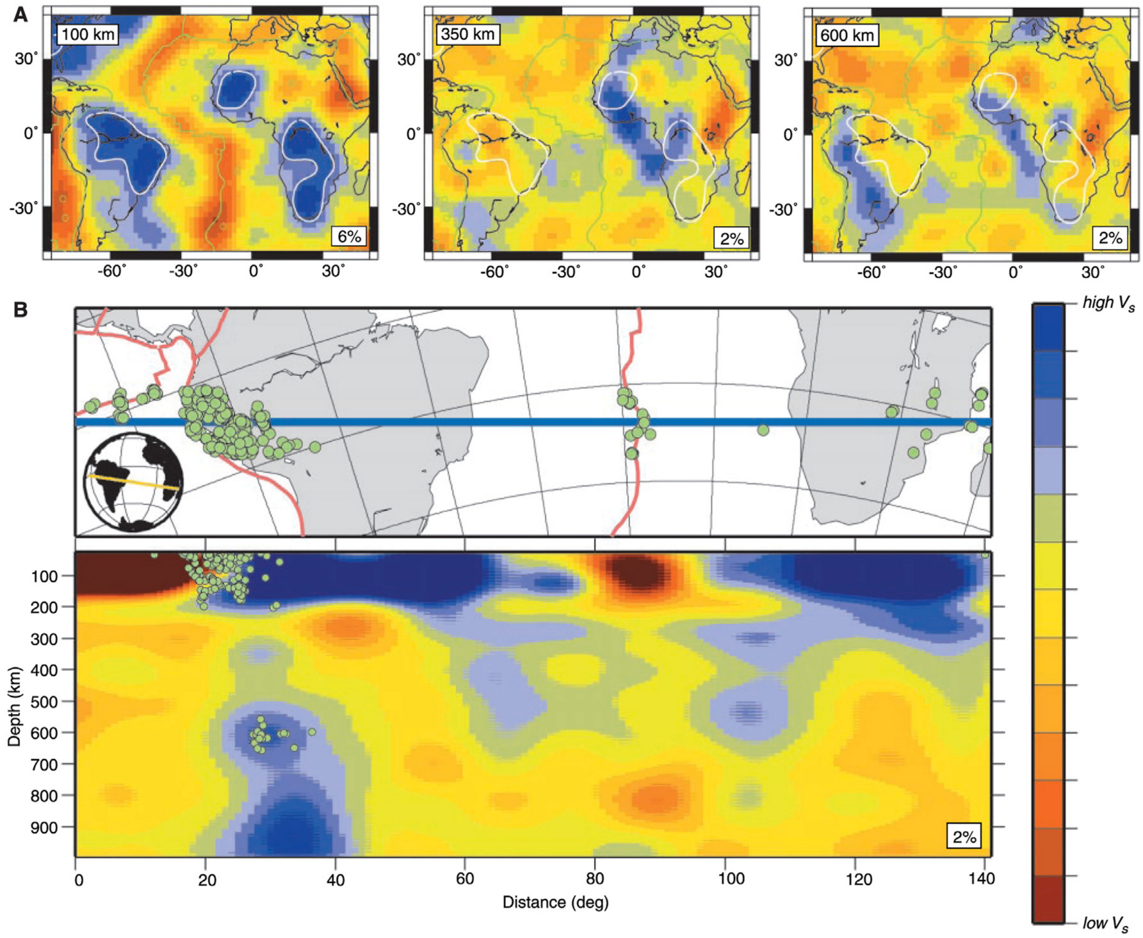

Fig. 10. (A) Horizontal cross sections through mantle tomography model S20RTS at the depths indicated. Velocity anomalies are relative to the PREM standard Earth model. White contours indicate where the anomaly is >4%. (B) Cross section along blue line in upper part of panel. Green circles: earthquakes from the Harvard Centroid Moment Tensor catalog. The high-velocity (blue) "drips" that underlie the eastern edge of South America and the western edge of Africa in the depth range ~200–600 km are interpreted as the remnants of downgoing convection currents that may have eroded the continental lithosphere at the time of breakup and recycled it into the upper mantle beneath the center of the new South Atlantic ocean.
(From King and Ritsema, 2000).

Vertical movements in the critical few tens of millions of years prior to flood-basalt eruption have been investigated using apatite fission track analysis. Conclusions drawn from this work suggest two periods of basin-wide, kilometer-scale uplift, the first in the period 84–90 Ma and the second in the Tertiary (De Oliveira et al., 2000; Hegarty et al., 1995). Both of these occurred well after eruption of the Paraná Basalts and may account for the present-day high elevation of the area (Hegarty et al., 1995). There is no evidence for regional uplift on a time-scale of a few tens of Ma immediately preceding emplacement of the Paraná Basalts. Rivers in the Paraná region typically flow away from the continental margin, an alternative location suggested for an arriving plume, but there is no evidence that this drainage developed prior to the eruptions. Even if it did, it is then unclear why, in the context of the Plume hypothesis, the Paraná Basalts are centered ~500 km from the Brazilian continent-ocean boundary in the direction towards which the rivers flow.

- There is disagreement regarding whether the Paraná Basalts represent plume-head volcanism or not. They mostly erupted in ~1 Ma from ~134–135 Ma (Baksi, 2017; Baksi, 2005; Baksi, 2007a; Baksi, 2007b) and are, counter-intuitively, relatively small in volume. They are typically ~0.7 km thick which is thin compared with the volcanic margins that were emplaced along the edge of the continent ~5 Ma later when breakup occurred. Those are commonly >10 km thick and almost certainly emplaced as a direct consequence of continental breakup (Franke, 2013).

Fromm et al. (2015) interpret the seismic structure on the African side, where the Walvis Ridge juxtaposes the continent, as lacking the voluminous intrusives expected for plume-head magmatism. They point out that the Etendeka basalts of Namibia are associated with major faults that run parallel to the coast and extend much further than associated subsurface structure. On these grounds they suggest that the Etendeka and Paraná flood basalts do not represent plume-head volcanism and that the postulated plume arrived much earlier and beneath what is now the Democratic Republic of the Congo in the center of the African continent. They interpret the zone of carbonatites and kimberlites in the Lucapa corridor that extends from there through Angola and almost to the coast as an older, continental volcanic chain representing a plume tail (Fig. 2). They suggest that no initial flood basalt formed because the thickness and strength of the African lithosphere suppressed it.

This model is at odds with structural models of the region and conflicts with observations from other flood-basalt provinces where eruption occurred over thick lithosphere (Silver et al., 2006). The Lucapa corridor and most of the volcanics it contains are thought to have formed contemporaneously with, or later than, opening of the ocean (Campeny et al., 2014). The sparse age data available for the kimberlites, which form the northeasterly volcanics, do not suggest age progression (Section 2; Table 1). The dates from Central Angola are older than those further to the northeast, the reverse of what would be expected for a plume. The more southwesterly, carbonatitic

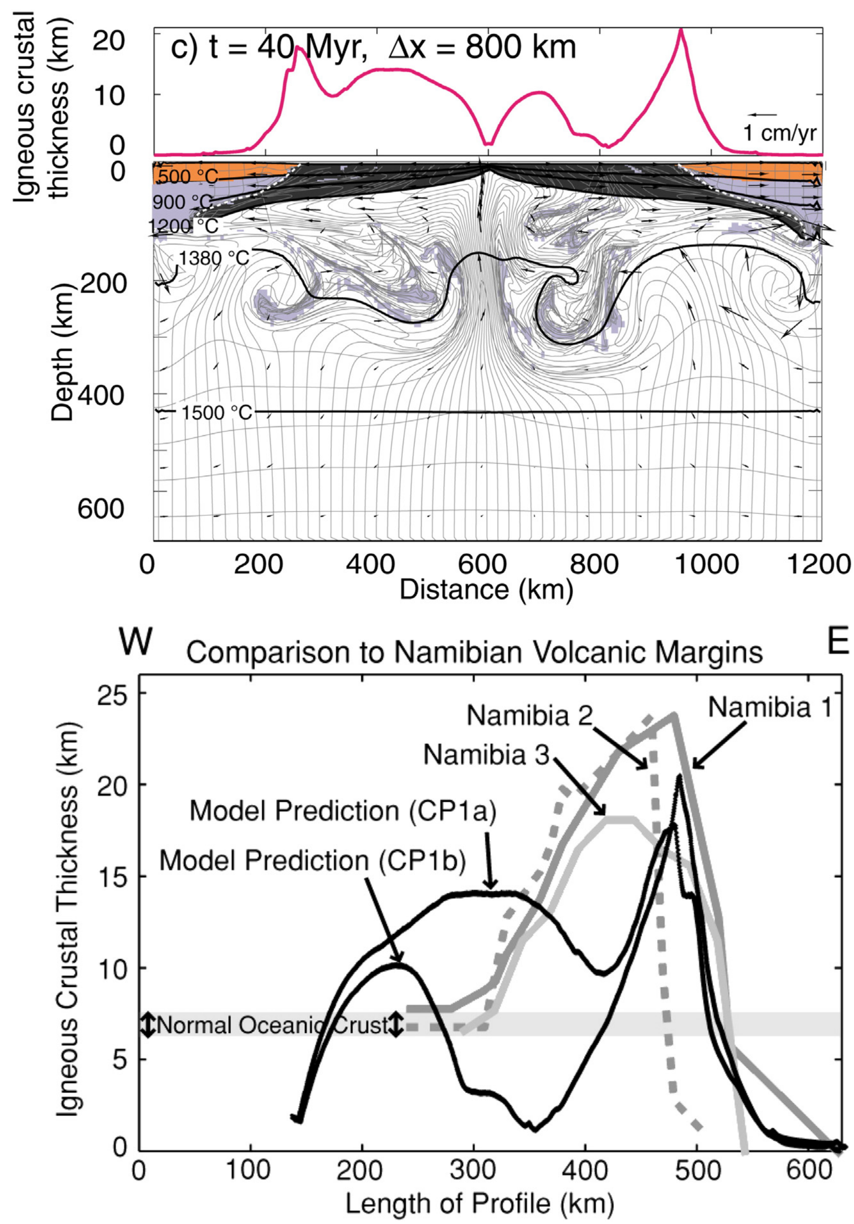

Fig. 11. Dynamics of an opening ocean underlain by wet lithosphere with a temperature anomaly of +50 °C. Top: Evolution of melt production in a model with a strong component of buoyant upwelling owing to small-scale convection and a wet-olivine mantle-lithosphere rheology. Full extension velocity: 2 cm/yr. Deformation in the asthenosphere is shown as a deforming Lagrangian grid along with the velocity field and igneous crustal thickness at 40 Ma. Orange: continental crust, mauve: mantle lithosphere, white: sublithospheric mantle, dark gray: sublithospheric mantle at a temperature of <1200 °C, representing oceanic lithosphere. Dashed white line bounds the rifted continent. Bottom: Comparison of the model results with profiles of the igneous thickness of the Namibian volcanic margin from Gladczenko et al. (1998) and Bauer et al. (2000).
(From Simon et al., 2009).

volcanics have not yet been dated but are thought to have been emplaced approximately contemporaneously with the kimberlites (Campeny et al., 2014).

The entire zone is mirrored by similar rocks on the South American side that comprise a longer, more voluminous suite, also lacking time progression. Those rocks are clearly associated with pre-existing structure that was re-activated in extension at the time of eruption and continued to be active as late as the Oligocene (Riccomini et al., 2005). In addition, a plume model for the Angola kimberlite/carbonatite lineament provides no explanation for the parallel zone of kimberlites that traverses South Africa, Botswana, Zimbabwe and Zambia, 1300 km to the southeast in the strike-perpendicular direction (Fig. 13). That line does not appear to continue offshore (Moore et al., 2008). A more likely explanation for the kimberlites and carbonatites of the Lucapa corridor is localization of extensional strain associated with the opening of the South Atlantic Ocean along a pre-existing trans lithospheric structural discontinuity (*e.g.*, Jelsma et al., 2009).

- Time-progressive volcanism is observed in some parts of the province but not in others. The islands of the Tristan da Cunha archipelago mostly yield young ages–0.02–0 Ma for Tristan da Cunha itself (McDougall and Ollier, 1982) and 2.5–0.12 Ma for Gough Island (Maund et al., 1988). Nightingale Island, a heavily eroded volcanic remnant, has yielded ages as old as 18 Ma (Geraldes et al., 2013; Miller, 1964) but these are suspect. The samples are not well documented or described and since the ages were derived using the K-Ar method over 50 years ago they could have large errors resulting from loss of Ar in the sample (Jim Natland and John O'Connor, personal communications). Such great ages would be surprising for a volcanic island still exposed above sea level so it must be concluded that dating Nightingale Island reliably remains to be done.

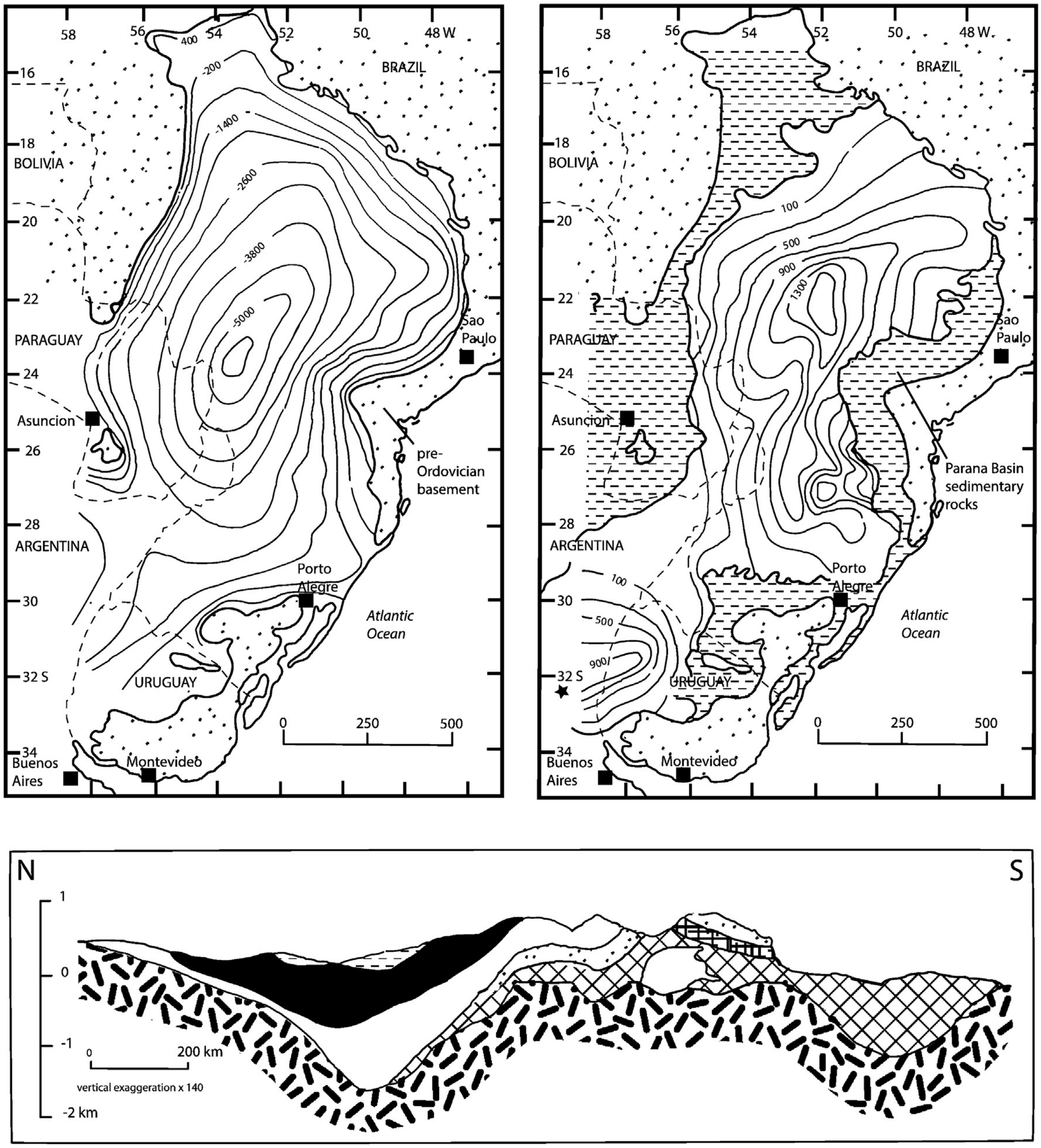

Fig. 12. Top left: Depth to pre-Ordovician basement rocks beneath the Paraná sedimentary basin. Contours at 600-m intervals. Top right: Isopach map of Paraná lavas with contours at 200-m intervals (from Peate et al., 1992). Bottom: Schematic N-S cross section through the Paraná lavas. Stratigraphic units defined by magma compositions and correspond to the Urubici, Palmas, Ribeira, Gramado, Paranapanema and Pitanga magma types (in approximate order of younging) capped by sedimentary rocks (see Peate et al., 1992 for details).

Ar-Ar dates for basement samples from ~20 sites on the Walvis Ridge show regular time-progression from the Tristan da Cunha archipelago eastward for about half its length, a distance of ~1750 km, albeit at a variable rate (Fig. 14) (O'Connor and Jokat, 2015). The 400-km breadth and diffuse volcanism of this part of the Walvis Ridge is not predicted by the classical Plume hypothesis, but requires variants that are unnecessary at other proposed plume localities. The ~900 km of the ridge onward to the east is not time-progressive but rather characterized by simultaneous activation along its entire length for ~23 Ma. Sparse dates from the easternmost ~400 km, including the Etendeka basalts, are consistent with continuation of the age progression of the youngest half of the ridge.

Very few samples from the Rio Grande Rise have been dated. Those available suggest two periods of basaltic volcanism at ~84–90 Ma and ~40 Ma (Bryan and Duncan, 1983; Fodor and Thiede, 1977; Mohriak et al., 2010). There is thus currently no evidence for time-progressive volcanism on the Rio Grande Rise and no volcanic chain connects it with the Paraná Basalts (Fig. 1). The lack of seamounts between the Rio Grande Rise and Tristan da Cunha has been explained by the postulated plume crossing the mid-ocean ridge at ~80 Ma (Sleep, 2002), which is approximately the time at which the Walvis Ridge bifurcated (Fig. 14). In the context of the Plate hypothesis, this would be interpreted as the South American plate stabilizing and intraplate deformation of the ocean floor on the African plate becoming more distributed. If a plume is responsible for the current volcanism at the Tristan da Cunha archipelago, it cannot have been fixed relative to others proposed since if it arrived at ~134 Ma it would have impinged on the Pangaean lithosphere ~1000 km south of the Paraná Basalts (Ernesto et al., 2002).

- Continental break-up did not start from the Paraná-Etendeka region and propagate north and south as would be expected if triggered by the arrival of a plume (Franke et al., 2007). Instead it started

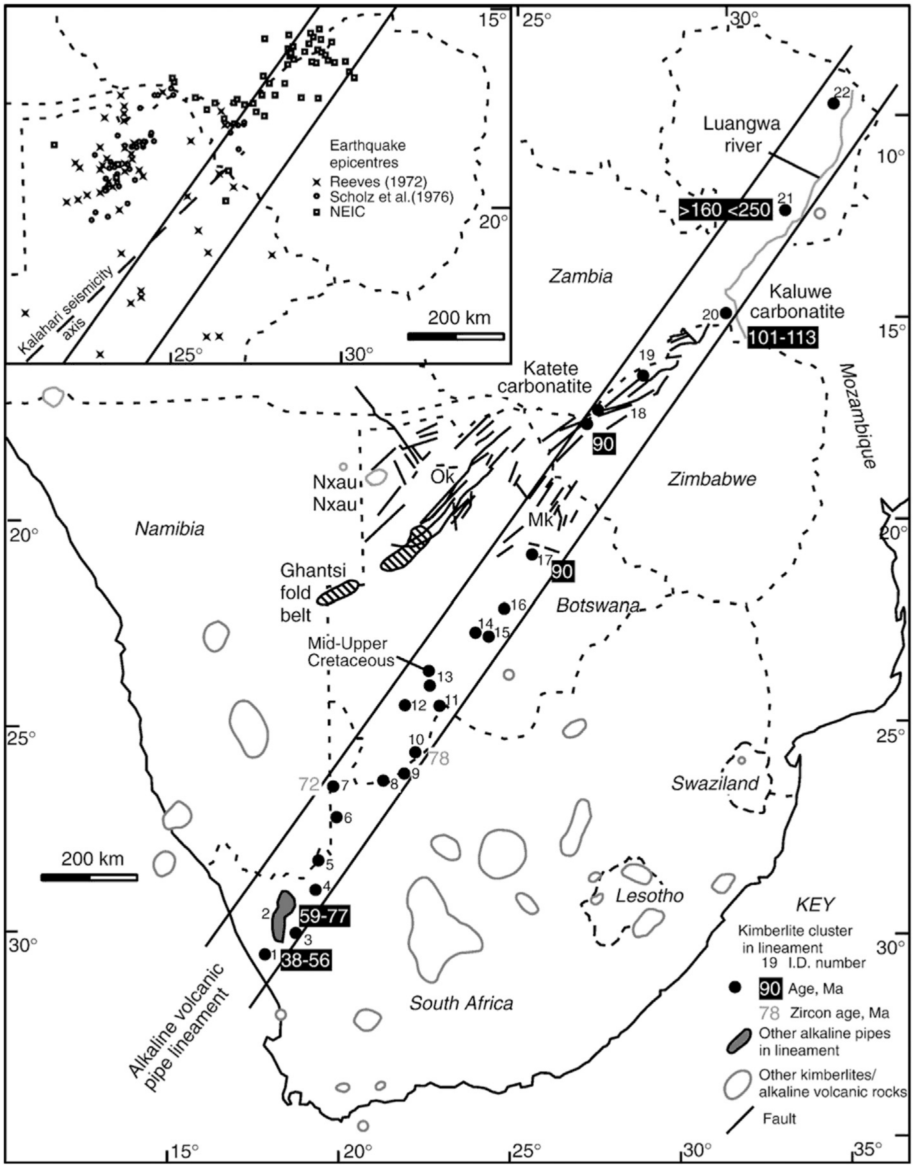

Fig. 13. The alkaline volcanic pipe lineament that extends from the west coast of South Africa into the Zambezi and Luangwa rifts of Zimbabwe and Zambia. The dates available for volcanic rocks on the lineament indicate a systematic increase in age to the NE. This lineament is approximately parallel to that crossing Angola and extending into the Democratic Republic of the Congo (Fig. 2) where sparse age data do not show such a time-progression (from Moore et al., 2008). Extensive regions of kimberlites and alkaline volcanic rocks that do not lie on this lineament are outlined by gray lines.

2500 km further south and was intrinsically linked with the development of the global plate boundary system. Studies of the mid-Atlantic spreading axis show that there is no systematic decrease in crustal thickness or magma volume north and south of the latitude of Tristan da Cunha as would be expected if a mantle plume currently underlay that region (Franke et al., 2010).

- The geochemistry of the eruptives throughout the province is not consistent with a single source and the majority are not of the composition expected of plumes. The Paraná flood basalts almost certainly arise from remelted continental lithosphere and not from an ocean-island-basalt-like source (Section 2). They share affinity with basalts from the Walvis Ridge and the Rio Grande Rise so none of these lavas are consistent with the expectations of plume theory. They do not share a source with lavas from the Tristan da Cunha archipelago. A variant of the classic Plume hypothesis that has been suggested to account for this is that it contributed heat but not material to the Paraná Basalts (Ernesto et al., 2002), but this model does not fit other continental flood basalts.
- There is no unequivocal evidence for a high-temperature source for the Paraná flood basalts or lavas from the Tristan da Cunha archipelago and the surrounding guyot province. Petrological approaches that calculate temperature using crystalline picrites, for example, assume that they represent uncontaminated original melt compositions (*e.g.*, Thompson and Gibson, 2000). Such an assumption is only reliable for picritic glass samples and these have nowhere been found in the South Atlantic Igneous Province (Foulger, 2012).
- A continuous structure corresponding to a plume tail extending from the surface to the core-mantle boundary beneath the Tristan da Cunha region has not been detected. The most detailed study conducted to date is a multi-disciplinary marine survey that deployed dense arrays of ocean-bottom seismometers and electromagnetometers.
Data were recorded for a year on the 24-station, 400 × 500-km-broad array of ocean-bottom seismometers. These data sampled the upper mantle well beneath much of the array in the depth interval ~150–400 km and were used to derive the seismic structure using teleseismic tomography. Schlömer et al. (2017) conclude that the results image a mantle plume but this inference relies on parts of their image that lie outside the well-sampled region (Foulger et al.,

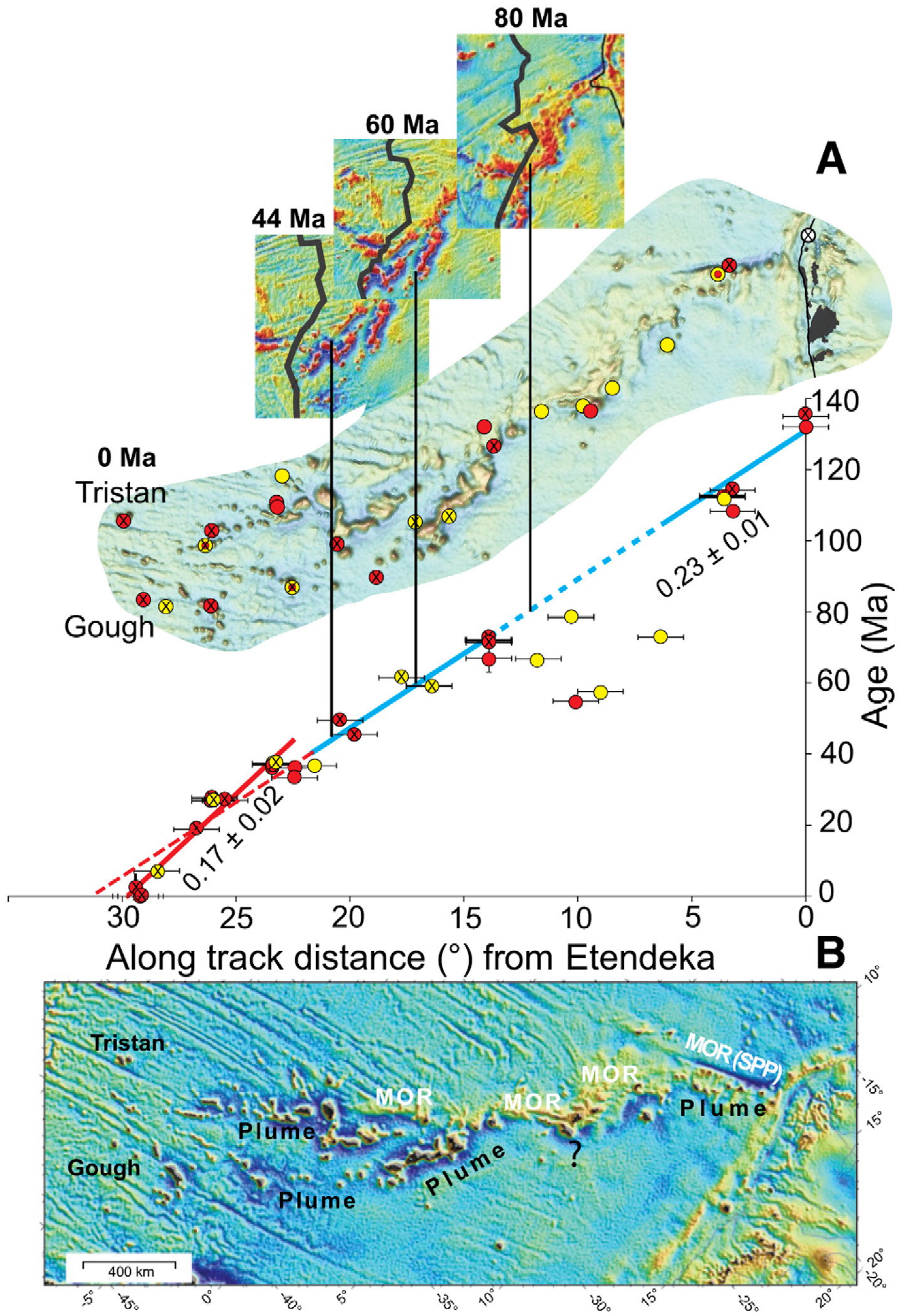

Fig. 14. A: $^{40}Ar/^{39}Ar$ isotopic ages *vs.* sample site distance from the Etendeka continental flood basalt in Namibia (white filled circle at 18.2°S, 12.5°E) using an age of 135–132 Ma. Red and yellow circles represent sample site locations. Blue and red lines show faster (0.23° ± 0.01°/Ma) and slower (0.17° ± 0.02°/Ma) fitted age progressions, respectively. Regressions are fitted to the oldest along-ridge ages (x symbols). Dashed red line: extrapolation of the faster migration rate to the present. Top panels show locations of the spreading plate boundary relative to the inferred location of volcanism. B: Free-air gravity map in an oblique Mercator projection showing bathymetry around the Tristan archipelago. MOR–mid-ocean ridge. (From O'Connor and Jokat, 2015).

2013). Within the well-sampled region no low-velocity conduit is imaged.

Up to a year of usable electromagnetic measurements were also collected and a three-dimensional image of the electrical conductivity structure was calculated to a depth of ~450 km (Baba et al., 2016). This a similar region to that studied with seismic tomography. A high-conductivity layer at ~120 km depth beneath the region was detected but no structure that could be interpreted as a plume was found. Baba et al. (2016) suggest that either a plume too small to be resolved lies within the study volume, or else a plume elsewhere feeds volcanism in the Tristan da Cunha archipelago by lateral flow. They do not consider the possibility that there may be no plume.

Several teleseismic tomography studies of Brazil (Rocha et al., 2011; Schimmel et al., 2003; VanDecar et al., 1995) report low-V_P and V_S anomalies throughout a cylindrical region ~150 km wide with wave-speeds depressed by up to ~1% in V_P and 2% in V_S (Fig. 1). This anomaly is imaged to extend from the near-surface down to the base of the upper mantle at ~650 km. It was interpreted first by VanDecar et al. (1995) as a "fossil plume"–the tail of an early postulated Tristan plume that became entrained in the root structure of the Archaean São Francisco craton and sheared off by plate motion. Other suggested interpretations include an artifact of the method used, which estimates seismic velocities relative to an assumed average starting model and is susceptible to smearing imaged anomalies

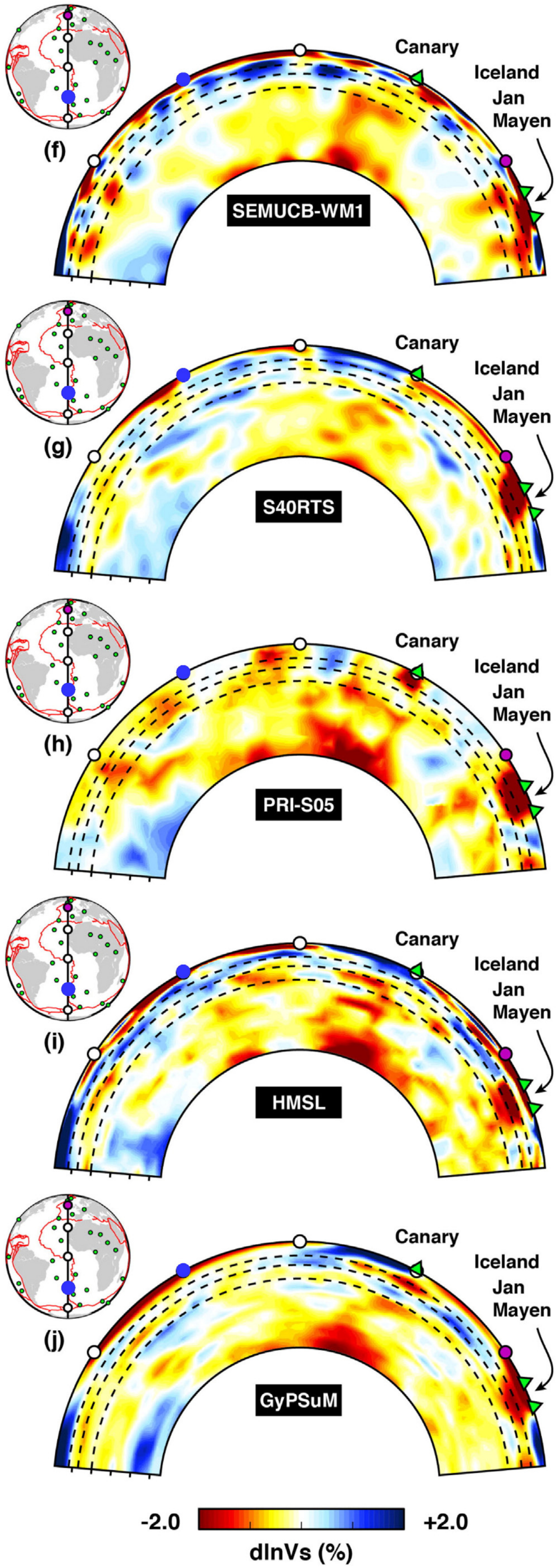

Fig. 15. Cross sections passing near Tristan da Cunha through several global tomography images. Lines of section are indicated in the inset maps. Blue circles indicate approximate position of Tristan da Cunha. Shown are relative shear-wave velocity (V_S) anomalies in models SEMUCB-WM1 (French and Romanowicz, 2015), S40RTS (Ritsema et al., 2011), PRI-S05 (Montelli et al., 2006), HMSL-S06 (Houser et al., 2008) and GyPSuM (Simmons et al., 2010). The five models are broadly compatible with each other but none shows a downward-continuous low-shear-wave velocity anomaly beneath Tristan da Cunha.
(From French and Romanowicz, 2015, supporting on-line material).

vertically (Schimmel et al., 2003). Correlations between V_P and V_S and with surface volcanic features suggest the anomaly may represent chemical variations and not high temperature (Rocha et al., 2011). Brazil has drifted several thousand kilometers west subsequent to formation of the Paraná flood basalts at ~134 Ma, it is unclear how the entire upper mantle section of a plume could become sheared off, and such a process has not been invoked to explain observations elsewhere. A "fossil plume" model does not accord with the hypothesis that current plume volcanism is occurring in the Tristan/Gough area. Whole-mantle tomography is not expected to have sufficient resolution to detect a mantle plume tail in the lower mantle if it has a diameter of only a few hundred kilometers (Hwang et al., 2011). This method is more sensitive to structure in the upper mantle. A strong upper-mantle low-velocity anomaly has been reported beneath the North Atlantic/Iceland region (Foulger et al., 2001; Hung et al., 2004), but no such feature is observed beneath the Tristan region (Fig. 15) (French and Romanowicz, 2015).

- Although the Walvis Ridge on the African plate and the Rio Grande Rise on the South American plate have been postulated to be complementary time-progressive volcanic chains, their morphologies are significantly different. The eastern half of the Walvis Ridge comprises a ~ 100–150 km broad, ~1300-km-long topographic ridge that has the morphology of a tilted block with a steep north-facing slope and a gently dipping south-facing slope (Fig. 1) (Fromm et al., 2015). It is not linear, but has a staircase-like shape. At its western end, this ridge bifurcates and still further west it trifurcates. At its westernmost end it comprises a ~400-km-wide region of diffuse guyots with only a few volcanoes exposed above sea level. This diffuse morphology and the geochemical variations over the province have led to a number of different proposals for the dynamics and morphology of the hypothesized plume. These include a laterally migrating plume that became chemically zoned halfway through its lifetime and bifurcated upwards along the compositional boundary (Hoernle et al., 2015) and a multiple-conduit plume (Sleep, 2002). Schlömer et al. (2017), in contrast, suggest on the basis of their seismic tomography results that the plume bifurcates downwards. Baba et al. (2016) suggest, on the basis of electromagnetic data, that the presumed plume is too small to be seen because it is dying. Rocha-Júnior et al. (2013, 2012) argue that the geochemical evidence suggests it had no plume head. The Rio Grande Rise on the South American plate, in contrast, comprises mostly a quasi-circular, broad region of shallow sea floor ~1000 km in diameter, bisected by a NW-trending rift. Few samples have been dated and there is no bathymetric anomaly between the Rise and the mid-Atlantic ridge, a distance of ~1300 km. The recent discovery of granite on the Rise calls into question how much of it represents basaltic volcanism younger than the surrounding sea floor and suggests that much of it may instead be a continental microcontinent. The Rio Grande Rise thus departs from the expectations of basaltic, time-progressive plume-tail volcanism.

4. Comparison with the North Atlantic volcanic province

The North Atlantic Volcanic Province has many similarities with the South Atlantic Igneous Province (*e.g.*, Koopmann et al., 2014; Scotchman et al., 2010). The former is better studied than the latter, despite the fact that much of Greenland is hidden by an icecap, because the Atlantic is

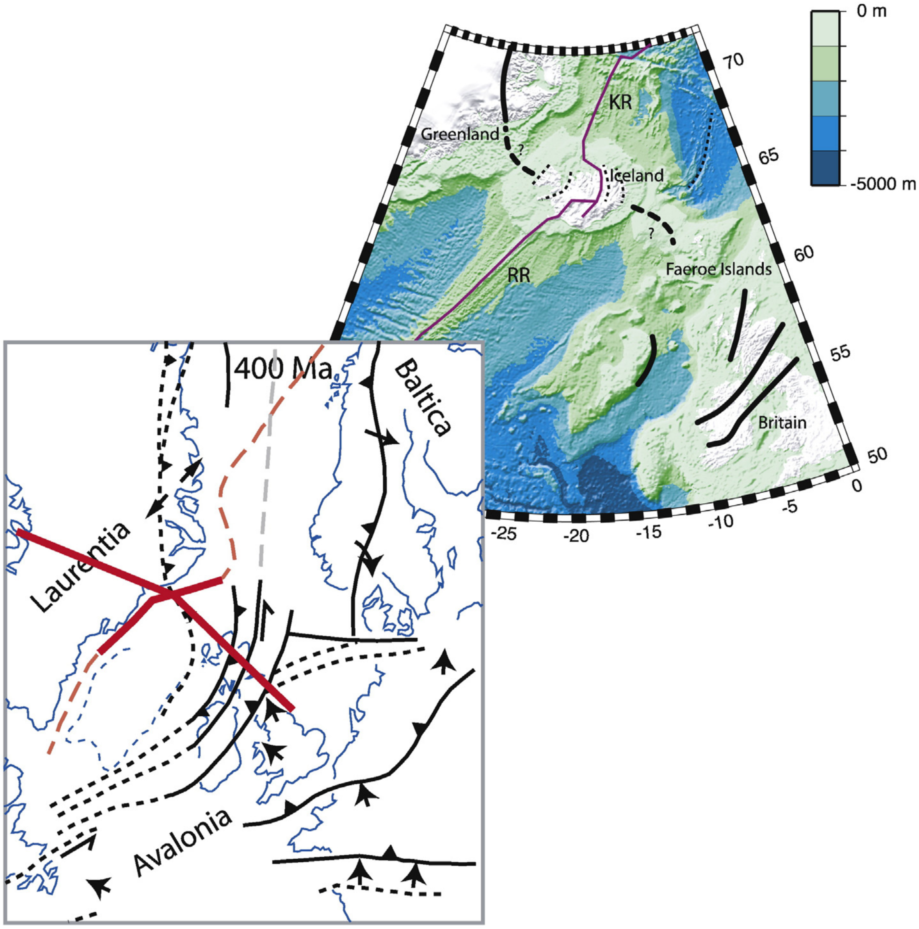

Fig. 16. Top right: Present-day bathymetry of the North Atlantic. Thin magenta line: MOR, thin dashed black lines: extinct ridges, thick lines: faults of the Caledonian collision zone from Soper et al. (1992), thick dashed line: inferred trend of the western frontal thrust of the Caledonian collision zone crossing the Atlantic Ocean. Bottom left: Caledonian collision zone associated with the closure of the Iapetus ocean at 400 Ma by convergence of Laurentia, Baltica, and Avalonia. Arrows: convergence directions, thick lines: faults and orogenic fronts. Black triangles indicate sense of thrust faults. Slabs were subducted beneath Greenland, Baltica and Britain. Red dashed line indicates position of MOR that formed at ~54 Ma (from Foulger et al., 2005). Thick red lines show mid-Atlantic ridge and transverse structure postulated to comprise a locus of extension allowing volcanism to occur.

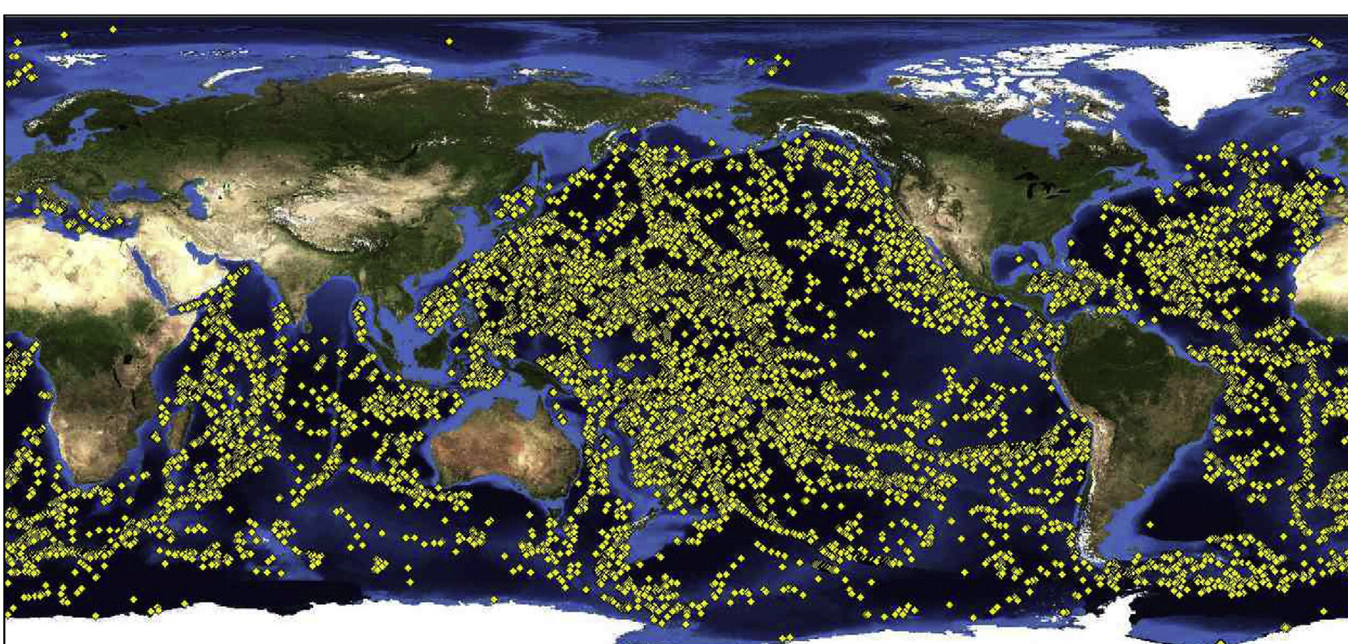

Fig. 17. Global distribution of seamounts over 1.5 km high (Clark, 2009).

narrower in the north, it has been of commercial and strategic importance to Europe and Scandinavia for more than a millennium, and a large expanse of the spreading plate boundary is exposed above sea level in Iceland. Extensive commercial exploration of the hydrocarbon-bearing Scandinavian and British shelves has been done.

As is the case for the South Atlantic Ocean, significant magmatism occurred prior to the onset of sea-floor spreading in the form of eruption of the Thulean Line (Hall, 1981). This occurred at 62–58 Ma, several million years prior to continental breakup at 56–53 Ma. Thulean volcanism includes intense NW-SE-orientated dike swarms in Britain and the North Sea and magmatism in both west and east Greenland. Lundin and Doré (2005) attribute it to Thulean-Line-normal extension that destabilized the region prior to development of the mid-Atlantic ridge. As is the case for the Paraná-Tristan-Etendeka zone, the activated Thulean Line also follows a significant transverse structural zone that later remained persistently anomalously magmatic–the Greenland-Iceland-Faeroes zone. In the North Atlantic this zone corresponds to the western frontal thrust of the ~400 Ma Caledonian collision zone where the it crosses from Greenland to Britain (Fig. 16) (Foulger and Anderson, 2005; Foulger et al., 2005).

It is not known whether depth-dependent extension occurred prior to the onset of sea-floor spreading at the latitude of Iceland. The amount of internal continental deformation that occurred before formation of the oldest oceanic crust is not accurately quantifiable because re-assembly fits for the North Atlantic are hampered by lack of detailed knowledge of the exact locations of the continent-ocean boundaries and the amount of lithospheric stretching. There is an apron of sediment-draped shallow bathymetry between Greenland and the Iceland shelf (Fig. 16), but crustal and mantle structure beneath it have been relatively little studied. A preliminary interpretation of a 300-km-long seismic line extending from the east coast of Greenland to the Icelandic shelf (the Sigma 1 line) suggests that the crust is up to ~30 km thick there (Holbrook et al., 2001). Receiver function work conducted onshore in East Greenland detects structures interpreted as the remnant of an Iapetus slab which is continuous with a similar structure beneath northern Britain–the Flannan Reflector (Schiffer et al., 2014; Schiffer et al., 2015a; Schiffer et al., 2015b).

As is the case for the South Atlantic, the North Atlantic formed by rift propagation. In the case of the latter, rifting likely propagated from both the north and the south (Gaina et al., 2009). The propagating ridge tips overlapped at the latitude of present-day Iceland but did not join to form a continuous rift. Instead, a region of tectonic complexity developed which has persisted to the present day. Spreading along multiple parallel zones, diffuse deformation, lateral ridge jumps, ridge migrations, and general southward migration of the overlapping rift tips have occurred, capturing continental crust in the form of the Jan Mayen microcontinent (Gernigon et al., 2012; Nunns, 1983) and possibly beneath Iceland (Foulger, 2006). Persistent tectonic disequilibrium inherited from continental breakup across major older lithospheric structures is likely the root cause of ongoing excess magmatism in both the Iceland and Tristan da Cunha regions.

5. Concluding remarks

Like most volcanic provinces, when studied in detail, the South Atlantic Igneous Province is seen to be far more complex than can satisfactorily be explained with a simplistic model that assumes simple and homogeneous lithospheric structure and deformation, and simple mantle convection. The data require strong control by pre-existing variations in lithospheric strength, complex local fragmentation of the continent, and responsive magmatism. The anomalous magmatism on both the South American and African continents occurred in zones of intracontinental lithospheric extension that were activated at the time. The history of offshore basin formation, evidence from seismic tomography, and numerical modelling are consistent with ongoing extension of the lower lithosphere for several million years prior to the onset of seafloor spreading. It was during this period that the Paraná Basalts, a modest volume of magma compared with later-emplaced volcanic margins, erupted.

Subsequent seafloor spreading at this latitude was complex. If indeed continental fragments were rafted into the new ocean, forming a block under the Rio Grande Rise and possibly also under the Walvis Ridge, distributed spreading and volcanism would be required in a similar fashion to that which occurred in the North Atlantic and is still ongoing in Iceland today. The low-level distributed volcanism that persists in the Tristan da Cunha archipelago and surrounding guyot province suggests that second-order deformations of the sea floor persist (Fairhead and Wilson, 2005). The world's oceans are host to ~3500,00 seamounts and volcanic islands rising over 0.5 km above the surrounding sea floor, and the Atlantic alone contains 2694 that rise over 1.5 km (Fig. 17) (Hillier, 2007). Only for a fraction of a percent of these is it reasonable to consider a mantle plume origin and the Tristan da Cunha guyot province most plausibly falls in the majority category.

Acknowledgments

This paper is based on an oral presentation at the 2015 Fall Meeting of the American Geophysical Union, invited by Edgardo Cañón-Tapia, who also suggested several improvements to the manuscript. Andy Moore provided valuable input regarding the kimberlites and carbonatites of Africa. The paper benefited from helpful discussions with Bruce Julian, Jim Natland, John O'Connor, Anthony Koppers and Susan Schnur. Reviews by Valdecir Janasi and Eduardo R.V. Rocha-Júnior significantly improved the manuscript. Ritske Huismans kindly provided the color version of Fig. 11. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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