South Atlantic opening: A plume-induced breakup?

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ABSTRACT

Upwelling hot mantle plumes are thought to disintegrate continental lithosphere and are considered to be drivers of active continental breakup. The formation of the Walvis Ridge during the opening of the South Atlantic is related to a putative plume-induced breakup. We investigated the crustal structure of the Walvis Ridge (southeast Atlantic Ocean) at its intersection with the continental margin and searched for anomalies related to the possible plume head. The overall structure we identify suggests that no broad plume head existed during opening of the South Atlantic and anomalous mantle melting occurred only locally. We therefore question the importance of a plume head as a driver of continental breakup and further speculate that the hotspot was present before the rifting, leaving a track of kimberlites in the African craton.

INTRODUCTION

The processes of lithospheric weakening that finally allow continents to break are still poorly understood and geophysical data constraints are sparse. Various ideas exist about the underlying mechanisms that cause continental breakup, ranging from changing plate boundary forces to mantle dynamics. A much-debated model involves the arrival of a deep mantle plume (e.g., Storey, 1995). Mantle plumes are deep-seated thermal anomalies carrying hot and buoyant material from the core-mantle boundary to the lithosphere-asthenosphere boundary (LAB). The LAB forms a rheological barrier to the plume's further ascent, and so the mantle material spreads out as a large disk (e.g., Griffiths and Campbell, 1991). In the original model, Morgan (1971) postulated that regional uplift and stress induced by thermal doming cracked the continents and pushed them apart. More recent simulations show that plumes also have the potential to thermally and chemically erode the base of the lithosphere (Sobolev et al., 2011) and promote the accumulation of melt that further exacerbates lithospheric weakening. This melt intrudes the crust, partly accumulates at the crust-mantle boundary (Moho), which can be mapped by seismic methods, and partly erupts at the surface as large flood basalt provinces (e.g., Ridley and Richards, 2010). The formation of flood basalt provinces is often in close spatial and temporal proximity to continental breakup, which has led to the controversial concept that the impact of plume heads arriving at the base of the lithosphere initiates continental breakup (e.g., Cande and Stegman, 2011). However, this model is only one possible end member, and global observations from continental margins with and without flood basalt provinces suggest a very different explanation: i.e., preexisting weak zones and a prior history of rifting in combination with general plate movements might be more important factors for breakup (e.g., Armitage et al., 2010; Buiter and Torsvik, 2014).

Here we use seismic refraction data to image the crustal structure associated with a hotspot track and the proposed site of the Tristan plume head impact (Duncan, 1984), the easternmost Walvis Ridge (southeast Atlantic Ocean), including the junction with the Namibian coast (Fig. 1). The area is well covered by four mostly amphibious deep seismic sounding profiles. The data image 2490 km of crust and upper mantle along profiles varying in length from 470 to 730 km. We used 166 ocean bottom stations, 99 land receivers, 12,864 airgun shots, and 13 dynamite shots. One profile is located along the ridge axis and continues onshore, and the other three cross the Walvis Ridge at different angles and locations. The traveltimes of refracted and reflected P-phases were used to derive two-dimensional velocity models using standard modeling procedures. Further details of the analysis and data examples are available in the GSA Data Repository[1].

RESULTS

Our P-wave velocity models (Fig. 2) show that the edifice of the Walvis Ridge consists of closely spaced seamounts and up to 35-km-thick crust. Crustal velocities of 5.5–7.2 km/s point to a gabbroic composition resembling thickened oceanic crust. The ridge is covered by extrusive rocks with velocities of 3.8–5.5 km/s, which we interpret as hyaloclastites and basalt lava flows. The transition from the Walvis Ridge to the adjacent basins reveals drastic differences between the northern and the southern flanks as well as along the axis of the ridge.

While the southern flank gradually converts into the continent ocean transition of the volcanic margin (Fig. 2B), the northern flank is characterized by a sharp transition from 35-km-thick crust below the ridge to 5–6-km-thick oceanic crust in the Angola Basin (Figs. 2B and 2C). This strong lateral variation is limited to the area close to the continental margin. Further offshore (Fig. 2A) both flanks transfer smoothly into oceanic crust, but with some additional volcanism and thickened crust at the northern flank.

This surprising jump in crustal thickness on the Angola Basin side can be explained by the kinematic evolution of the South Atlantic (Fig. 3). The Angola Basin is considerably younger than the Cape Basin (up to 20 Ma; Gee and Kent, 2007; Shipboard Scientific Party, 1984), and the

[1]GSA Data Repository item 2015311, seismic data and model descriptions, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

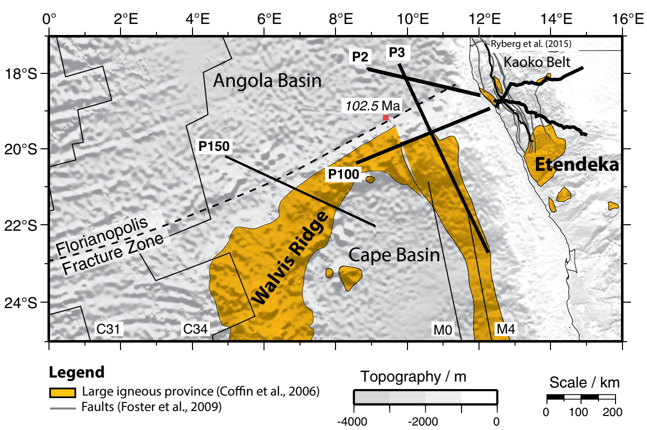

Figure 1. Location of the deep crustal seismic profiles at the Walvis Ridge, southeast Atlantic Ocean. Magnetic anomalies with the ages (Gee and Kent, 2007): C34, 83.5 Ma; M0, 120.6 Ma; M4, 125.7 Ma. Red square marks the dated Deep Sea Drilling Project Site 530 Leg 75 in the Angola Basin (Shipboard Scientific Party, 1984).

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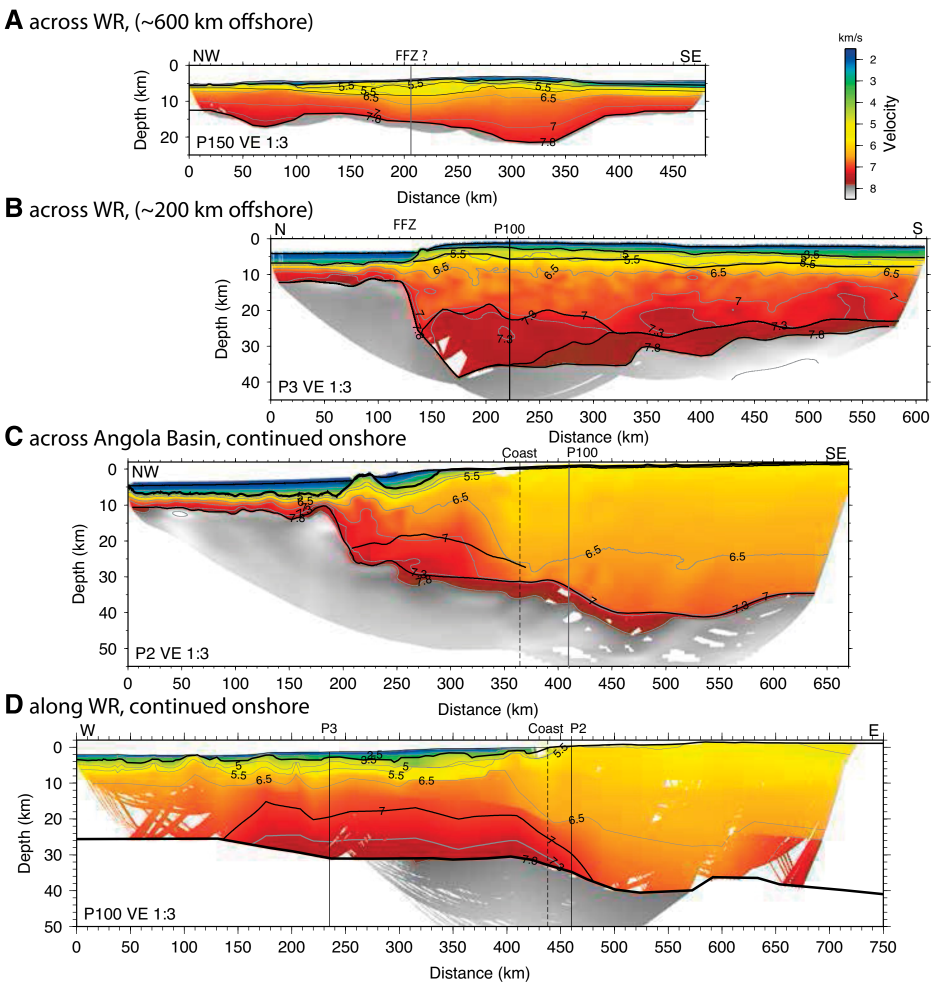

Figure 2. P-wave velocity models. A: P150 across the Walvis Ridge (WR) 600 km offshore. FFZ—Florianopolis Fracture Zone; VE—vertical exaggeration. B: P3 across WR 200 km offshore. C: P2 across Angola Basin and WR with an angle of 45°. D: P100 along axis. All models are plotted with the same scaling and a vertical exaggeration of 3. Major reflectors are marked with thick black lines. White model areas have no ray coverage and are not resolved. The 7.0 km/s contour line is emphasized in P100.

northern flank of the Walvis Ridge is defined by the Florianopolis Fracture Zone. The crust that formed initially to the north of the Walvis Ridge has likely been sheared along the Florianopolis Fracture Zone and transferred to the South American margin as the Sao Paolo Plateau (Fig. 3B). The younger and thinner crust found today in the Angola Basin was formed after the magmatic activity associated with the hotspot was located further westward (Fig. 3C). This implies that the plume tail did not supply sufficient additional melt to thicken the oceanic crust 200–600 km away in the Angola Basin.

In the west-east direction along the axis of the Walvis Ridge the crustal thickness increases from 18 to 30 km toward the coast (Fig. 2D). The continental crust reaches 40 km thickness below the Kaoko fold belt. Further inland, we observe a slight decrease to 36 km and indications for an intrusive body at the edge of the model. This observed crustal root beneath the fold belt is consistent with the findings of profile 2 (Fig. 2C), onshore seismological experiments (Heit et al., 2015), and gravity models (Maystrenko et al., 2013). Close to the coast, the models show high seismic velocities (as high as 7.5 km/s) in the lower crust of the Walvis Ridge. This high-velocity lower crustal body is partly constrained by reflections from the top and otherwise defined by the 7.0 km/s contour line. The high-velocity lower crustal body tapers out ~300 km offshore, much like others found along the southwestern African coast (Bauer et al., 2000; Hirsch et al., 2009; Schinkel, 2006). Compared to these models, where the high-velocity lower crustal bodies terminate 50 km offshore from the coast, the Walvis body continues a few tens of kilometers beneath the continental interior (Fig. 4). Independent onshore seismic profiles indicate that this eastern promontory of the Walvis high-velocity lower crustal body is only 100 km wide (Ryberg et al, 2015); this is considerably narrower than further offshore at P3 (Fig. 2B), where its width is almost equivalent to the bathymetric expression of the Walvis Ridge (160 km). Therefore, compared to the southern volcanic margin, the additional area of intrusive lower crust at the landfall of the Walvis Ridge is at most 100 × 100 km^2 (Fig. 4, inset). According to our data, the continental crust including the root of the Kaoko fold belt has not been significantly modified by the proposed plume head.

DISCUSSION

The intruded area around the Walvis Ridge is surprisingly small in comparison to the often-cited diameters of plume heads, between 800 and 2000 km based on the regional extent of flood basalt volcanism (White and McKenzie, 1989) and theoretical calculations (Tan et al., 2011). However, the exact location of the hotspot during breakup is crucial for the interpretation of our results: a distant location could account for the relatively limited intruded area. The location of the plume impact is not well constrained.

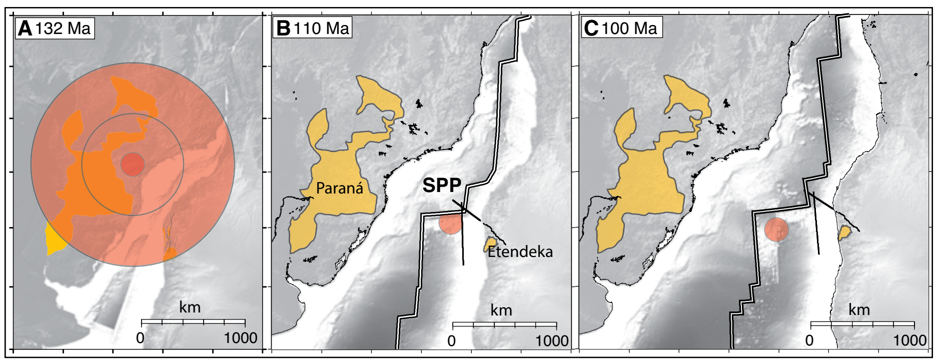

Figure 3. Reconstruction of the South Atlantic opening (Pérez-Díaz and Eagles, 2014). Large red circles in A mark the location of the plume head with 1000 km and 2000 km diameter, respectively (O'Connor and Duncan, 1990). Small red circles denote the location of the plume stem with a diameter of 200 km. Black lines indicate the reconstructed positions of profiles 2 and 3. Thin black lines in A show faults (Foster et al., 2009). Double line marks the spreading center. Yellow areas indicate continental flood basalts (Coffin et al., 2006). SPP—Sao Paolo Plateau.

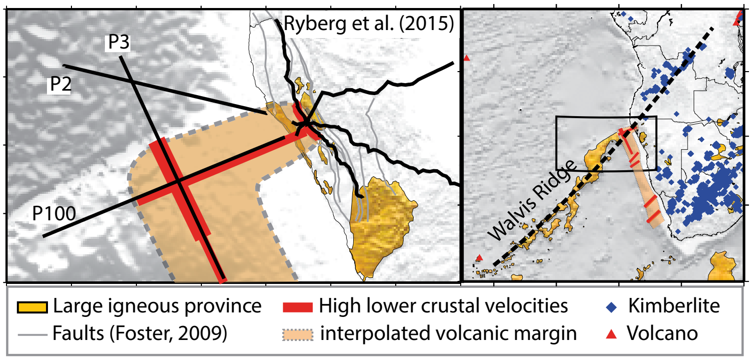

Figure 4. Track of the Tristan-Gough hotspot extended on the African continent. The dashed line follows the axis of the Walvis Ridge and coincides with kimberlite intrusions onshore. Together with the narrow track-like promontory of the high-velocity lower crustal body in prolongation of the Walvis Ridge, it indicates that both volcanic features might be related. The inset magnifies the distribution of the high-velocity lower crustal body observed in the presented models and demonstrates its relation to onshore faults and flood basalts.

Some place it at the South America plate near the Paraná flood basalts (O'Connor and Duncan, 1990; VanDecar et al., 1995); others locate it at the African plate (Duncan, 1984; White and McKenzie, 1989). More recent findings indicate a position near Paraná, although this solution cannot be achieved with a fixed hotspot position (Ernesto et al., 2002). In this case, the Namibian margin would have only been influenced by the outer ambit of the plume head and we would expect a different geometry for the affected area. The limited encroachment into African continental crust may be explained by greater distance from the center, but then it is reasonable to expect a much wider shape than the observed 100 km resembling a large-diameter circle (Fig. 3A). Furthermore, the area of the intruded lower crust onshore, formed during impact of the proposed plume head, should be greater than offshore, because the latter was formed after the plume head had dissipated. It is thought provoking that we find the contrary, i.e., attenuated magmatism during continental breakup and increased magmatism during the formation of the easternmost portions of the Walvis Ridge. Instead, the confinement of intruded continental crust to a narrow strip in the landward prolongation of the Walvis Ridge seamount chain suggests a hotspot track origin and is not a signature of a plume head.

Our observations are inconsistent with a significant impact of the Tristan plume as a driving force in the opening of the South Atlantic. The absence of a large plume head signature can be interpreted in terms of (1) the non-development of a head during plume ascent, or (2) the preexistence of a hotspot before the time of breakup. The development of headless plumes is at odds with current models of mantle dynamics and a different melt source for the flood basalt provinces would be needed. Continental rifting can trigger significant partial melting if the ambient mantle temperature is 100–150 °C warmer than normal (Rey, 2015). Supercontinents in general might be underlain by increased temperatures (Coltice et al., 2009), and the Etendeka volcanics imply a mantle source (1490–1540 °C) that is warmer than normal (~1400 °C) but cooler than plume settings (Tp > 1550 °C; Hole, 2015). In such a case, only the plume tail would leave a hotspot track, but is otherwise not needed for the breakup process.

In the alternative scenario, a hotspot was already established a long time prior to the breakup, but its volcanic manifestation was suppressed due to the thickness and strength of the African lithosphere. An indication for such a preexisting hotspot is the geometry of the continental high-velocity lower crustal body and its relation to continental fault systems. In Namibia, the northern Etendeka basalts are associated with deep-reaching coast-parallel faults (Foster et al., 2009) that extend well beyond the area of basalt outcrops and intruded lower crust. Even if the surface basalts were eroded, the geometry of the intracrustal intrusions would remain unaltered. In the plume head scenario it is difficult to explain why only this localized crustal portion was affected, even though the faults are much longer and would have been completely underlain by the plume head (Fig. 3A). Despite the fact that the continental crust shows preexisting weak zones and was weakened by rifting, volcanism was suppressed. The hotspot-derived mantle melts had limited ability to actively impinge the continental crust unless given an easy conduit to the surface, such as a major basement-penetrating continental fault, an oceanic spreading center, or a fracture zone.

The presence of a well-established hotspot producing mantle melts prior to continental breakup implies that the Walvis Ridge hotspot track might extend onto the African continent. A recent seismological study revealed high Vp/Vs (compressional to shear wave velocity) ratios in prolongation of the Walvis Ridge, which might be related to a thermal mantle anomaly (Heit et al., 2015). Further volcanic features onshore include a lineament of kimberlites, scattered along the eastward-extrapolated ridge axis (Fig. 4). Such rocks have long been associated with hotspots under thick continental lithosphere and indicate the presence of a thermal anomaly beneath the craton (e.g., Crough et al., 1980). Some of the rocks show age progression similar to hotspot tracks (Crough et al., 1980), although the progression is not as clear as for oceanic island chains, or even absent (Bailey and Foulger, 2003). If these features were formed in coincidence with the Tristan hotspot, the onset of the Walvis Ridge cannot mark the beginning of the Tristan hotspot chain (Fig. 5). Furthermore, the

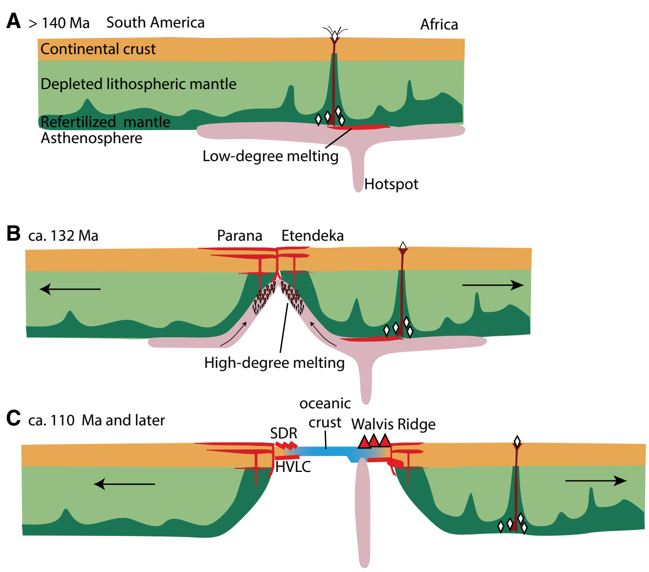

Figure 5. Sketch of the proposed breakup model. A: The hotspot existed prior to the rifting and formed low-degree melts at the hotspot location. Lithospheric structure focused intrusions venting to the surface and marking the hotspot trail by kimberlites. B: Changing plate boundary forces (Jokat et al., 2003) stretched the lithosphere and initiated rifting. Decompression melting at the thinned areas generated large volumes of melt, which formed the large flood basalt provinces. The following onset of seafloor spreading was characterized by excessive melt extraction building the volcanic margins. C: Further plate movement over the hotspot formed the Walvis Ridge. HVLC—high-velocity lower crustal body; SDR—seaward dipping reflectors.

hotspot-derived mantle melts could not actively erode the thick lithosphere beneath the craton, and intruded into the lithosphere only at preexisting weak zones. This implies that the source for the large volumes of melt required for the flood basalt volcanism was ponded hotspot material at the base of the lithosphere, as previously suggested (Sleep, 2006). With the onset of rifting in response to changing plate boundary forces driven by spreading systems in the young ocean basins around Antarctica (Jokat et al., 2003), new melt pathways became available for the ponded melt to migrate to the surface and form the large flood basalt provinces and the volcanic margins. The asymmetric distribution of the continental flood basalts might be explained with regional geology and rift history. The Paraná flood basalts are located at a major deformation zone, the Paraná-Chacos shear zone, which has also been interpreted as a failed rift arm of a triple junction. Extension of as much as 150 km of shear movement occurred here (Moulin et al., 2010), and might have focused magmatism at this location.

In conclusion, we do not find traces of large-scale intrusions within the continental crust at the junction with the Walvis Ridge, which would indicate important plume head–lithosphere interaction during South Atlantic breakup. It therefore seems unlikely that the arrival of the Tristan plume head initiated the opening of the South Atlantic Ocean.

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