South Atlantic opening: A plume-induced breakup?


1 Alfred-Wegener-Institut für Polar- und Meeresforschung, Armin Hafen 26, D-27568 Bremerhaven, Germany
2 GEOMAR, Helmholtz Centre for Ocean Research Kiel, Wischhofstrasse 1-3, D-24148 Kiel, Germany
3 Helmholtz-Centre Potsdam–German Research Centre for Geosciences (GFZ), Telegrafenberg, D-14473 Potsdam, Germany
4 University of Potsdam, Institute of Earth and Environmental Science, Golm, D-14471 Potsdam, Germany

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 (Solobev 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 basalts provinces (e.g., Ridley and Richards, 2010). The formation of flood basalts 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 basalts 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; Buijten 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 amphidaptic 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.

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
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 previous models. This observed crustal root is consistent with the findings of previous models.

In the west-east direction along the axis of the Walvis Ridge 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 previous models.

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 our results: a distant location could account for

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).
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
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 flow basalts 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 flow basalts provinces and the volcanic margins. The asymmetric distribution of the continental flood basalts might be explained with regional geology and rift history. The Paraná flow 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 largescale 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.

ACKNOWLEDGMENTS

We thank the German Research Foundation for funding this project (grants BE 1041/29–1, JO-191/15–1), the South Atlantic Margin Processes and Links with onshore Evolution (sample SPP), the crew of the R/V Maria S. Merian, and the onshore field party. Seismic instruments onshore were provided by the Geophysical Instrument Pool Potsdam (GIPP); those offshore were provided by GEOMAR, Kiel.

REFERENCES CITED


Manuscript received 2 May 2015 Revised manuscript received 10 August 2015 Manuscript accepted 14 August 2015 Printed in USA
South Atlantic opening: A plume-induced breakup?


Geology 2015;43:931-934
doi: 10.1130/G36936.1

Email alerting services  click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article
Subscribe  click www.gsapubs.org/subscriptions/ to subscribe to Geology
Permission request  click http://www.geosociety.org/pubs/copyrt.htm#ga to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

© 2015 Geological Society of America