South Atlantic opening: A plume-induced breakup?


1 Alfred-Wegener-Institut für Polar- und Meeresforschung, Am Alten 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 (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; Buijter 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 (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

†Current address: Bundeswehr Technical Center WTD71, Research Department for Underwater Acoustics and Marine Geophysics, Berliner Strasse 115, D-24340 Eckernförde, Germany.

*E-mails: Tanja.Fromm@awi.de; Wilfried.Jokat@awi.de

©2015 Geological Society of America. Gold Open Access: This paper is published under the terms of the CC-BY license.

GEOLOGY, October 2015; v. 43; no. 10; p. 931–934 | Data Repository item 2015311 | doi:10.1130/G36936.1 | Published online 28 August 2015

931
This observed crustal root beneath the Kaoko fold belt. Further inland, we observe a slight decrease to 36 km and indications for an intrusive body near the edge of the model. This observed crustal root beneath the fold belt is consistent with the findings of previous studies (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), whereas its width is almost equivalent to the bathymetric expression of the Walvis Ridge (160 km). Therefore, compared to the northern volcanic margin, the additional area of intrusive lower crust at the landfall of the Walvis Ridge is much thinner (~100 × 100 km²) (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-quoted 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 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.

**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.
mantle temperature is 100–150 °C warmer than
inces would be needed. Continental rifting can
different melt source for the flood basalt prov-
with current models of mantle dynamics and a
The development of headless plumes is at odds
ancestors before the time of breakup. It is thought
ition and is not a signature of a plume head.
structure of the intracrustal intrusions would remain
etry of the intracrustal intrusions would remain
ormal (Rey, 2015). Supercontinents in general
might be underlain by increased temperatures
(1490–1540 °C) that is warmer than normal (~1400 °C) but cooler
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 sup-
pressed due to the thickness and strength of the
African lithosphere. An indication for such a
preexisting hotspot is the geometry of the con-
tinental 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 geo-
metry of the intracrustal intrusions would remain
unaltered. In the plume head scenario it is dif-
icult 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 preex-
isting weak zones and was weakened by rifting,
vulcanism was suppressed. The hotspot-derived
mantine melts had limited ability to actively im-
pinge the continental crust unless given an easy
conduit to the surface, such as a major base-
ment-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 is-
land chains, or even absent (Bailey and Foulger,
2003). If these features were formed in coinci-
dence with the Tristan hotspot, the onset of the
Walvis Ridge cannot mark the beginning of the
Tristan hotspot chain (Fig. 5). Furthermore, the

Figure 4. Track of the Tristan-Gough hotspot extended on the African
continent. The dashed line follows the axis of the Walvis Ridge and coinci-
des 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 Dun-
can, 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 Namib-
ian 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 continen-
tal crust may be explained by greater distance
from the center, but then it is reasonable to ex-
pect 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 mag-
matism during the formation of the easternmost
portions of the Walvis Ridge. Instead, the con-
finement 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 sig-
nificant 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 preex-
istence 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 prov-
inces would be needed. Continental rifting can
trigger significant partial melting if the ambient
mantle temperature is 100–150 °C warmer than

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.
Low-degree melting 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.
Compression melting at the thinned areas generated large volumes of
melt, which formed the large flood basalt provinces. The following on-
set of seafloor spreading was characterized by excessive melt extraction
building the volcanic margins. C: Further plate movement over the Walvis
Ridge. HVLC—high-velocity lower crustal body; SDR—seaward dipping reflectors.
hotspot-derived mantle melts could not actively erode the thin 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 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 flood 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 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 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, J0-19/15–1), 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