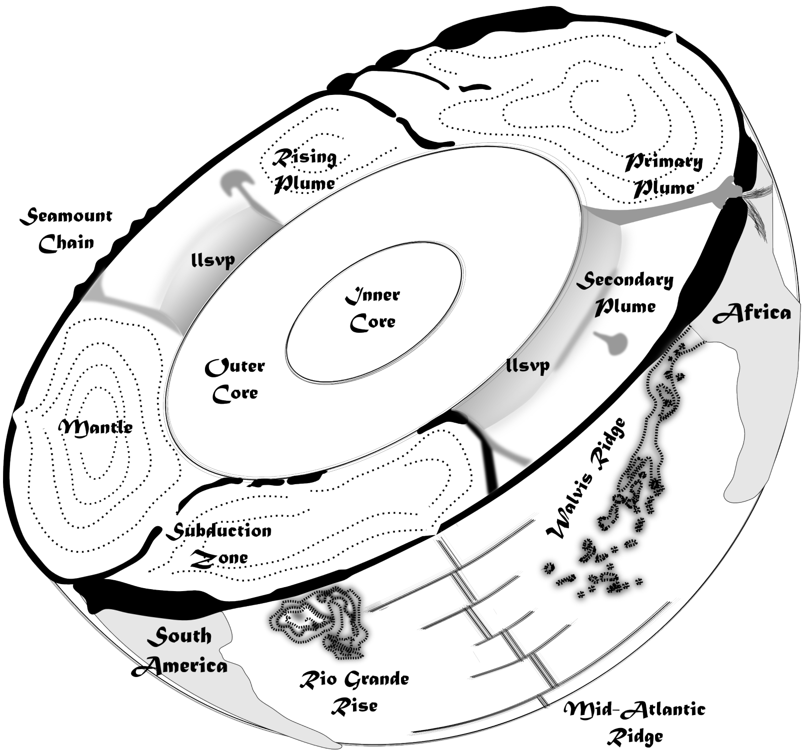
Insights into the temporal and geochemical evolution of the Walvis Ridge

A connection between HIMU and EM I end members in the South Atlantic



Dissertation

zur Erlangung des Doktorgrades

der Mathematisch-Naturwissenschaftlichen Fakultät

der Christan-Albrechts-Universität zu Kiel

vorgelegt von

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Kiel, 2018

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Tag der mündlichen Prüfung..25.05.2018

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PREFACE

The following dissertation is composed of three independent articles that are either accepted for publication or submitted to an international peer-reviewed journal. The first manuscript reviews the distribution of the HIMU mantle end member and presents a conceptual model of a widespread lowermost mantle reservoir in an Archean geodynamical setting. The second paper focuses on late-stage volcanism on the Walvis Ridge in the South Atlantic and the last article summarizes the temporal and spatial geochemical evolution of South Atlantic intraplate lavas.

My dissertation was funded by the German Ministry for Research and Education (BMBF; grants SO233 WALVIS II and SO234 Spaces; 03G0233A) and the GEOMAR Helmholtz Centre for Ocean Research Kiel.

ABSTRACT

The Walvis Ridge, located in the South Atlantic, represents the oldest submarine expression of the Tristan-Gough seamount chain, which extends from the Namibian coast to the active volcanic islands of Tristan da Cunha and Gough. As a reference locality of the EM I end member (enriched mantle one) and a type locality of the classical mantle plume concept, the poorly sampled Walvis Ridge represents an excellent opportunity to examine fundamental geological concepts. To provide further insights into the origin and evolution of the Tristan-Gough seamount chain, my PhD thesis presents a comprehensive geochemical (major and trace elements and Sr-Nd-Pb-Hf isotopes) and geochronological data set ($^{40}Ar/^{39}Ar$ data) of 35 new sample sites from the Walvis Ridge.

The combined results of my bathymetric, geochemical and geochronological data revealed that the Walvis Ridge experienced two magmatic pulses. During the first magmatic phase, the broad ridge crest (basement) was emplaced. These basement lavas have an EM I-type composition and show an excellent age progression of ~31 mm/a along the entire Tristan-Gough hotspot track, indicating relatively constant plate motion over a deep-rooted mantle melt anomaly in the last ~115 Ma. In combination with seismic data (French and Romanowicz, 2015; Schlömer et al., 2017) and high $^{3}He/^{4}He$ ratios (Stroncik et al., 2017), the excellent age progression indicates that the Tristan-Gough mantle plume derive from the margin of the African Large Low Shear Velocity Province (LLSVP) in the lowermost mantle.

A more detailed analysis of the collected lavas revealed that the majority of the superimposed seamounts/ridges on and adjacent to the Walvis Ridge were emplaced 20 to 40 Myr after the formation of the Walvis Ridge basement (EM I), representing the second magmatic pulse. The geochemical signature of these seamounts is characterized

by St. Helena HIMU end member type composition. The long volcanic quiescence and the HIMU-like geochemical signature of the seamounts are unusual for classical hotspot related late-stage (rejuvenated/post-erosional) volcanism, indicating that these seamounts are not associated with the deep-rooted Tristan-Gough mantle plume. HIMU-like lavas along the southwestern African coast have similar emplacement ages (80-50 Ma), suggesting a larger-scale event and possibly mantle upwellings from the internal portions of the African LLSVP.

Based on the characteristic geochemical fingerprints of the South Atlantic intraplate lavas and their position relative to the 1 % ∂V_s velocity contour of the African LLSVP, I propose that the spatial and temporal geochemical heterogeneities in the South Atlantic hotspots ultimately reflects the sampling of different geochemical domains outside and inside the African LLSVP.

I also present new geochemical and geochronological data from the Richardson Seamount in the South Atlantic Ocean and the Manihiki Plateau and Eastern Chatham Rise in the southwest Pacific Ocean. The new data, combined with literature data documents a more widespread (nearly global) distribution of the HIMU end member than previously postulated. The restricted trace element and isotopic composition (St. Helena type HIMU), but the near-global distribution point to a deep-seated, widespread reservoir, which formed most likely in the Archean. In this context I re-evaluate the origin of HIMU in an Archean geodynamic setting.

KURZFASSUNG

Der Walvisrücken ist die älteste submarine Spur der Tristan-Gough Vulkankette, die sich von der namibischen Küste bis zu den aktiven Vulkaninseln Tristan da Cunha und Gough erstreckt. Trotz seiner Wichtigkeit als südatlantische Typlokalität des geochemisch angereicherten Mantelendgliedes EM I und Teil einer klassischen Hotspotspur, ist der Walvisrücken bislang nur lückenhaft beprobt. Um weitere Einblicke in die Entstehung, sowie in die zeitliche und geochemische Entwicklung der gesamten Vulkankette zu erlangen, wurde im Rahmen der „Expedition SO233" eine detaillierte Beprobung durchgeführt. Meine Doktorarbeit umfasst einen vollständigen geochemischen (Haupt- und Spurenelement, Sr-Nd-Pb-Hf Isotopie) und geochronologischen Datensatz von 35 neuen Beprobungsorte des Walvisrückens.

Batymetrische, geochemische und geochronologische Daten belegen, dass der Walvisrücken von zwei unterschiedlichen magmatische Phasen geprägt ist. Während der ersten magmatischen Hauptphase wurde der breite und plateauähnliche Walvisrücken gebildet, wohingegen in einer Spätphase vereinzelte Vulkane auf und neben ihm entstanden sind. Die magmatische Hauptphase ist durch eine EM I Signatur geprägt und weist eine exzellente Alterprogression von ca. 31 mm/a entlang der gesamten Hotspotspur auf, was auf eine relativ konstante Plattengeschwindigkeit und tiefe Schmelzanomalie (Mantelplume) seit 115 Ma hinweist. Diese exzellente Alterprogression in Verbindung mit seismischen Daten (French and Romanowicz, 2015; Schlömer et al., 2017) und hohen $^{3}He/^{4}He$ Verhältnis (Etendeka; Stroncik et al., 2017) deutet an, dass der Tristan-Gough Mantelplume vom Rande der afrikanischen Large Low Shear Velocity Province (LLSVP) im unteren Erdmantel entstammt.

Eine detaillierte Analyse meines erhobenen Datensatzes zeigt, dass der überwiegende Anteil der Vulkane auf und neben dem Walvisrücken 20 bis 40 Ma jünger

sind als die EM I geprägte Hauptphase. Diese vulkanische Spätphase weist eine St. Helena HIMU Mantelendglied Signatur auf. Die ungewöhnlich späte vulkanische Reaktivierung und die HIMU geprägte Zusammensetzung der Spätphase sind untypisch für Hotspotvulkanismus, was darauf hindeutet, dass diese Vulkane nicht durch den Tristan-Gough Mantelplume entstanden sind. Laven mit HIMU Signatur entlang der südwestafrikanischen Küste sind zeitgleich mit der Spätphase des Walvisrückens eruptiert (80-50 Ma). Dies impliziert ein großräumliches Event und möglicherweise eine tiefe Schmelzanomalie von einer zentraleren Position der afrikanischen LLSVP.

Basierend auf den charakteristischen geochemischen Zusammensetzung des südatlantischen Hotspotvulkanismus und ihrer Position relativ zu der 1 % ∂V_s Kontur der afrikanischen LLSVP, kann die räumliche und zeitliche geochemische Entwicklung im Südatlantik durch unterschiedliche Reservoire außer- und innerhalb der LLSVP erklärt werden.

Des Weiteren umfasst meine Doktorarbeit geochemische und geochronologische Daten vom „Richardson Seamount“ im Südatlantik, sowie vom „Manihiki Plateau“ und östlichem „Chatham Rise“. In Verbindung mit Literaturdaten zeige ich, dass das HIMU Mantelendglied (St. Helena Zusammensetzung) nahezu weltweit verbreitet ist und wahrscheinlich im Archaikum geformt wurde. In diesem Zusammenhang präsentiere ich ein alternatives Modell zur Entstehung eines weitverbreiteten HIMU Reservoirs in einem archaisch-tektonischem Rahmen.

CONTENTS

1. General Introduction

1.1 The geochemical heterogeneity of the Earth's mantle

For several decades, geochemists have recognized that the geochemical signature of volcanic rocks provides insights into the evolution of the Earth. The geochemical fingerprint of volcanic rocks carries information from its petrogenetic evolution and source composition. Based on the Sr-Nd-Pb-Hf isotope systematics of oceanic lavas, four distinct mantle end members were identified, which can describe the large-scale heterogeneity of the Earth's mantle (e.g., Zindler and Hart, 1986; Hofmann, 1997; Willbold and Stracke, 2006; White, 2015). These end members are as follows:

1) Depleted Mantle (**DM**; characterized by relatively unradiogenic Sr and Pb, but radiogenic Nd and Hf isotope ratios)
2) Enriched Mantle type one (**EM I**; characterized by unradiogenic Nd, Hf and $^{206}Pb/^{204}Pb$ but realtively radiogenic Sr, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$)
3) Enriched Mantle type two (**EM II**; characterized by highly radiogenic Sr, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ but relatively unradiogenic Nd, Hf and intermediate $^{206}Pb/^{204}Pb$)
4) Mantle with high time-integrated μ (high $^{238}U/^{204}Pb$ = **HIMU**; characterized by very radiogenic $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$, intermediate $^{208}Pb/^{204}Pb$ and Sr, Nd, Hf isotope ratios projecting beneath the EM-DM mantle array)

Since many MORBs (Mid-Ocean Ridge Basalts) and OIBs (Ocean Island Basalts) converge on an intermediate Sr-Nd-Pb-Hf isotopic composition, a "common" or "prevalent" mantle component (Zindler and Hart, 1986; Hart et al., 1992; Hanan and Graham, 1996), termed PREMA (PREvalent MAntle; Zindler and Hart, 1986), FOZO

(FOcal ZOne; Hart et al., 1992) or C (Common component; Hanan and Graham, 1996) has been proposed. This component is characterized by slightly more radiogenic Sr-Nd-Hf isotope ratios and less radiogenic Pb isotope ratios compared to that of HIMU and has been associated in many cases with high $^{3}He/^{4}He$ ratios (>9R/Ra; Zindler and Hart, 1986; Hart et al., 1992; Hanan and Graham, 1996). Therefore, it has been proposed that it may be a distinct mantle end member rather than a mix of the other end members (e.g., Zindler and Hart, 1986; Hanan and Graham, 1996).

The Sr-Nd-Pb-Hf isotope systematics show that oceanic basalts are derived from chemically and isotopically distinct reservoirs. In turn, these reservoirs reflect the long-time evolution of the Earth, which is mainly characterized by continuous upper mantle depletion and re-enrichment by recycled material (e.g., Armstrong, 1968; Zindler and Hart, 1986). It has been suggested that the different geochemical end members of OIBs (EM I, EM II, HIMU and FOZO/C/PREMA) are derived by various recycled materials (e.g., Zindler and Hart, 1986), which were introduced to the mantle at subduction zones as subducting slabs ± sediments and continental erosion, as well as continental delamination (e.g., Bird, 1979; Stern, 2011). The long-time isolation of these recycled materials led to the characteristic isotope ratios of the respective mantle end members.

The Walvis Ridge became famous in the early 1980s for representing the EM I reference location in the South Atlantic (e.g., Richardson et al., 1982; Richardson et al., 1984; Zindler and Hart, 1986). This ridge forms part of the geochemically enriched DUPAL anomaly (EM I-type) observed in the South Atlantic and western Indian Ocean MORBs and OIBs (e.g., Hart, 1984). The source of the DUPAL anomaly is often discussed (e.g., Regelous et al., 2009; Class and le Roex, 2011), and the Walvis Ridge represents a perfect observation site to evaluate the origin and heritage of the EM I mantle end member and possibly the entire DUPAL anomaly.

1.2 The mantle plume theory

The seafloor is dotted by innumerous seamounts, which are not related to plate boundaries where magma sources are easy to identify (e.g., subduction zones or mid-ocean ridges). The most striking structures on the ocean floor are linear seamount chains, which extend over several thousand kilometers. The most prominent examples are the Hawaii-Emperor chain in the Pacific Ocean, the Ninety-East Ridge in the Indian Ocean and the Walvis Ridge in the Atlantic Ocean. The origin of these seamount chains is controversial, and two fundamentally different hypotheses exist, which are expressed in "The Great Plume Debate" (mantle plume vs. plate model).

The mantle plume theory is based on the early studies by Wilson (1963) and Morgan (1971). In general, it has been proposed that linear volcanic island chains form by oceanic crust moving over a fixed thermal anomaly, where hot material rises from the deep mantle to the base of the lithosphere (Morgan, 1971). The rising material melts through the crust and forms a volcano and with successive plate motion, the melt supply of the seamount is cut off and a new volcano forms next to the older one; this process results in age progressive volcanic chains with the active volcanic island(s) close to the hotspot position (Fig. 1). In addition to the natural observation that seamount chains are often spatially and temporally associated with flood basalt provinces (Morgan, 1971; Morgan, 1981), the synthesis of laboratory experiments (e.g., Whitehead and Luther, 1975; Farnetani and Richards, 1994), numerical simulations (e.g., McKenzie et al., 1974; Ribe and Christensen, 1999) and seismic data (e.g., Zhang and Tanimoto, 1993; Bijwaard and Spakman, 1999; Montelli et al., 2006; Zhao, 2007) led to the deep-rooted head-tail mantle plume model (e.g., Richards et al., 1989; Campbell, 2007). This hypothesis states that hot material rises from a thermal boundary layer, such as the core-mantle boundary, in a mushroom-like form. When the broad plume head (~1000 km in diameter; Campbell, 2007) arrives at the base of the lithosphere, it spreads out laterally (2000-2500 km; Campbell, 2007) and causes a massive short-lived volcanic outburst (<5 Myr). This initial stage is associated with large igneous provinces (LIPs), such as the Etendeka-Parana or Deccan flood basalt provinces. After the initial plume head stage, the narrow (100-300 km; Campbell, 2007) but long-lived mantle plume tail remains more or less stationary beneath the moving plate causing the age progressive seamount chains (Fig. 1).

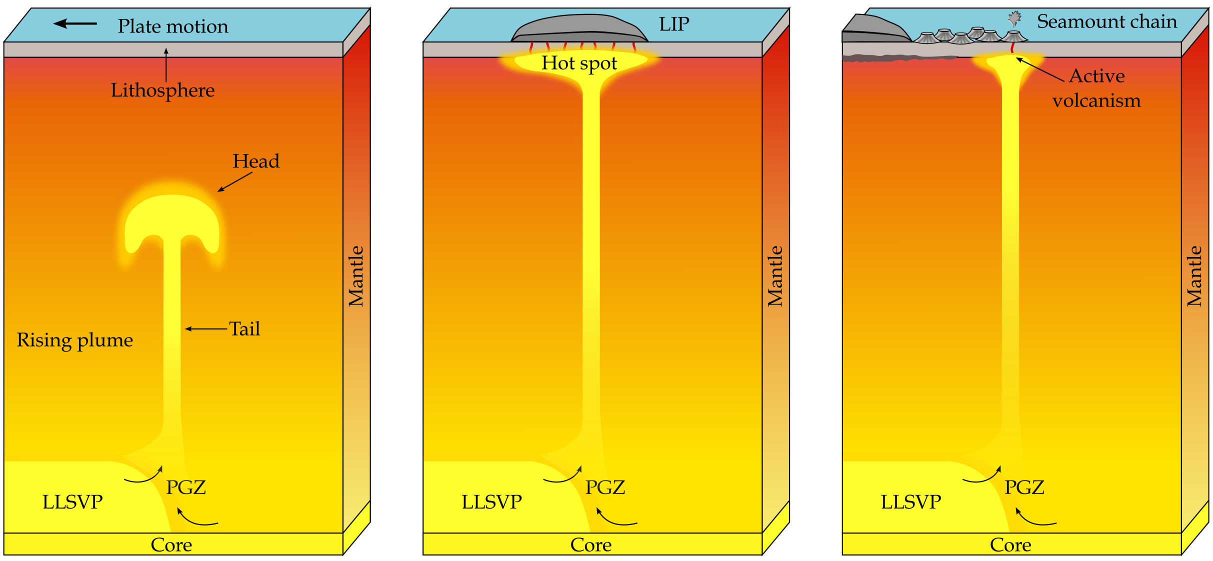

Figure 1: Cartoon of a mantle plume ascending from the lowermost mantle at the boundary of the Large Low Shear Velocity Province (LLSVP), the so-called Plume Generation Zone (PGZ; Burke et al., 2008). A) The mantle plume rises in a mushroom-like shape. B) As the mantle plume head arrives at the lithospheric base it spreads out and cause massive volcanism. C) The plume tail produces a seamount chain as the plate overrides the plume position.

The observations that several seamount chains are neither long-lived (e.g., Ascension, Cape Verde; Courtillot et al., 2003), nor associated with LIPs (e.g., Canary, Cape Verde; Courtillot et al., 2003), whereas some LIPs lack any obvious plume tail trace (e.g., Manihiki plateau; Taylor, 2006) challenged the mantle plume theory. Alternative models, such as the plate model were introduced and are based on tectonic related processes (e.g., Anderson, 2000; Foulger, 2002; Anderson, 2005; Foulger, 2017). The plate model comprises localized processes, such as cracking of the lithosphere or extensional sectors (Gans et al., 2003; Sandwell and Fialko, 2004 Geldmacher et al., 2006), small-scale sublithospheric convection (King and Ritsema, 2000; Geldmacher et al., 2005; Ballmer et al., 2007), lithospheric detachment (e.g., Hoernle et al., 2006; Elkins-Tanton, 2007) and/or heterogeneous upper mantle fertilities (Fig. 2; e.g. Anderson, 2005). For example, Sheth (1999) proposed that age progressive volcanic island chains could be developed by propagating cracks associated with long-lasting stress fields. The formation of LIPs, on the other hand, are attributed to small-scale convection cells in the shallow mantle, which are produced at the base of the lithosphere at steep gradients in lithospheric thickness (e.g. King and Ritsema, 2000).

However, "The Great Plume Debate" does not indicate that all seamounts were formed by deep-rooted mantle plumes or shallow plate-related processes. As noted by Hofmann and Hart (2007), finding an intraplate volcano that is not a product of a mantle plume does not disprove the plume theory. In fact, there are many examples of intraplate volcanoes and even volcanic provinces that are clearly not related to a mantle plume (e.g., Hanan et al., 2004; Hoernle et al., 2011; Kipf et al., 2014). On the other hand, there are also examples, such as Hawaii, that can be more easily explained by the mantle plume model than any alternative. In the context of the two proposed models (plate vs. plume), the geochemical signatures of intraplate lavas are either derived from a shallow- or deep-seated reservoir. Since the enriched mantle end members (EM I, EM II, HIMU and FOZO) are related to various recycled materials, the proposed models have direct implications on the structure and evolution of the Earth.

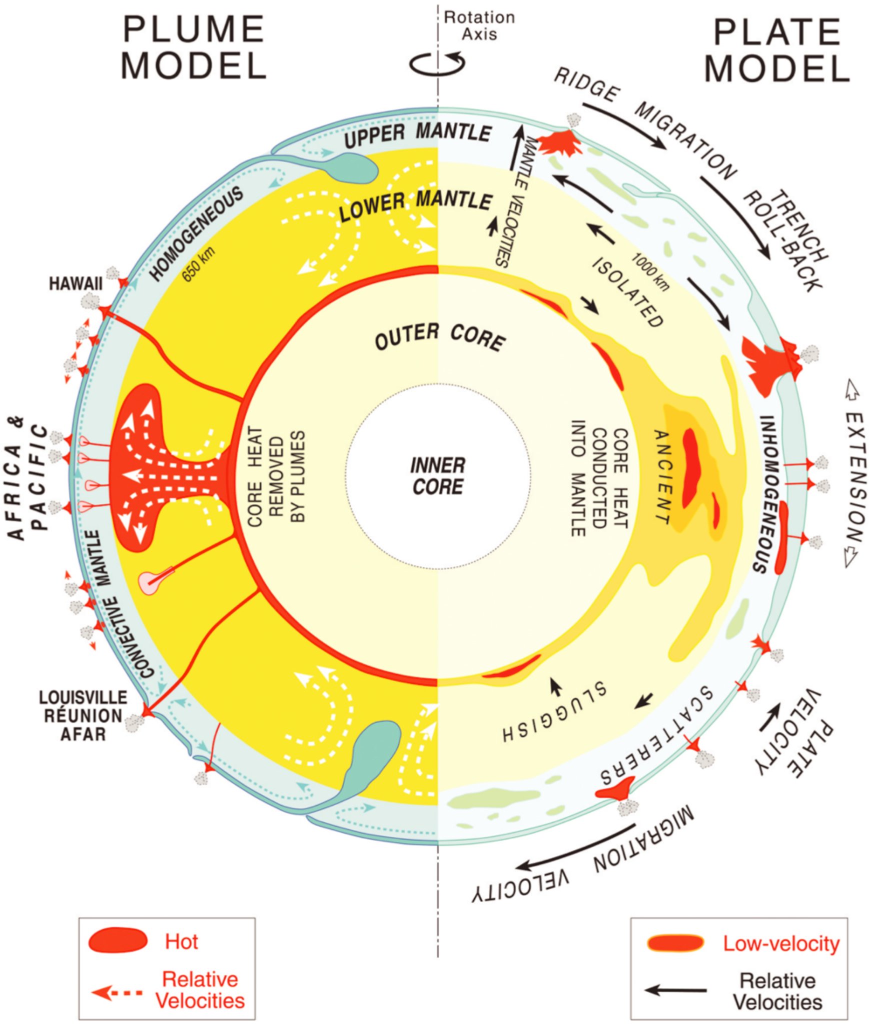

Figure 2: Cartoon of the mantle plume and plate model (Anderson, 2005). The mantle plume model assumes a relatively homogeneous upper mantle, whereas distinct and heterogeneous material is accumulated in the lower mantle, which rises as hot material with deep-rooted mantle up-wellings. In contrast, the plate model predicts an extreme heterogeneous upper mantle and melt anomalies are correlated to localized stress and pre-existing fabric of plates.

1.3 The Walvis Ridge

The Walvis Ridge is the most striking bathymetric anomaly in the South Atlantic and forms the oldest part of the ~3000 km long Tristan-Gough seamount chain. This northeast-southwest trending volcanic chain can be divided as follows: (1) the aseismic Walvis Ridge, which extends from the African coast to the DSDP Site transect and then splits into three ~450 km long ridge-like arms, and (2) the Guyot Province characterized by diffuse and discontinuous chains of seamounts and ridges, which leads to the active volcanic islands of Tristan da Cunha and Gough (Fig. 3). The Tristan-Gough seamount chain can be spatially and temporally extended to Etendeka, which was emplaced at ~132 Ma (Renne et al., 1996; Renne, 2015). The volcanic counterparts on the South American plate are the Rio Grande Rise, an ~800 x 800 km submarine plateau, and the Parana LIP. The Rio Grande Rise can be traced across the South Atlantic along oceanic fracture zones to the central portion of the Walvis Ridge, suggesting a co-genetic origin (e.g., O'Connor and Duncan, 1990).

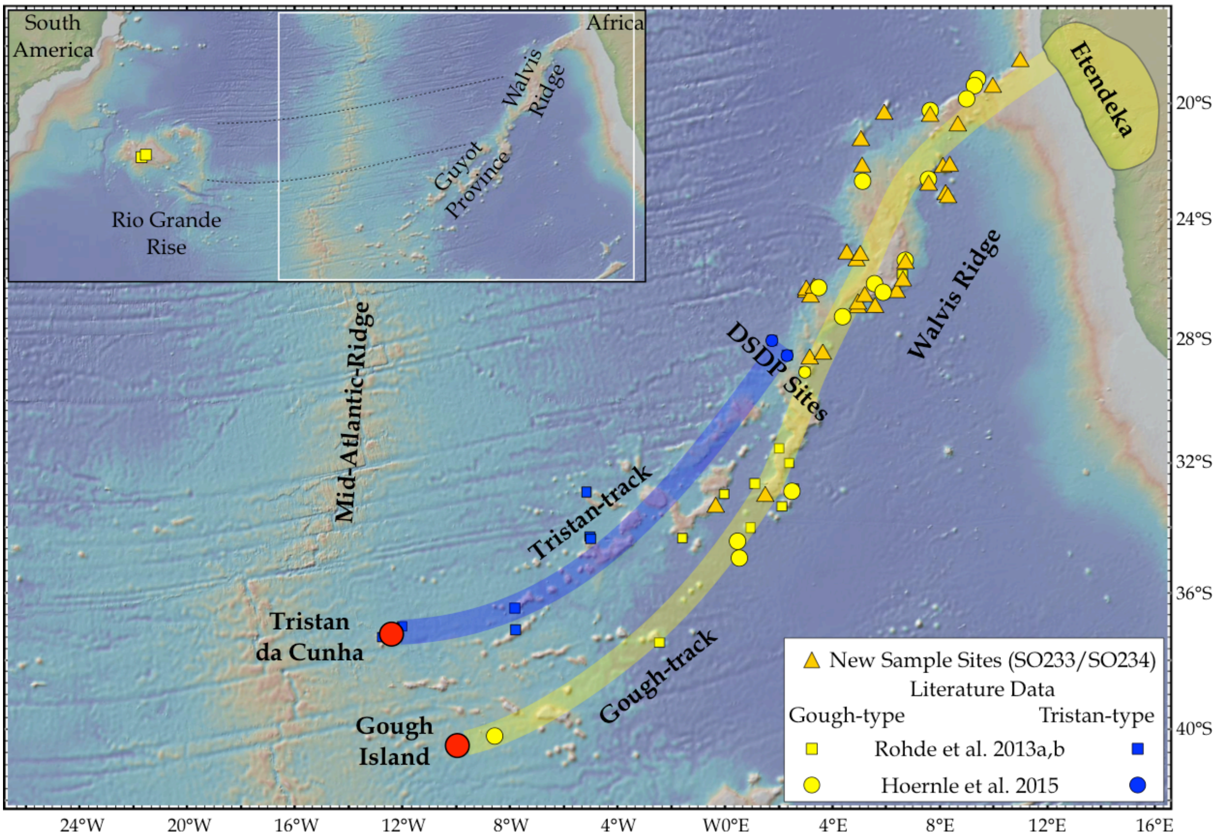

Figure 3: Map of the Tristan-Gough seamount chain with main geological structures and sample sites from SO233 and SO234 (WALVIS II; new sample sites) and from WALVIS I (Rohde et al., 2013a; Rohde et al., 2013b; Hoernle et al., 2015). The blue and yellow lines show the spatial geochemical zonation.

The Tristan-Gough seamount chain is one of the rare structures, that exhibits a spatial and temporal connection between an LIP (Etendeka-Parana) and an active volcanic island (Tristan-Gough). It is considered one of the seven primary hotspots, after Courtillot et al. (2003), which originated from and samples the lowermost mantle. After the classical head-tail mantle plume model (e.g., Wilson, 1963; Morgan, 1971; Wilson, 1973; Richards et al., 1989), the deep-rooted Tristan-Gough hotspot system was initiated by an upwelling mantle plume head that caused a massive volcanic outburst, which formed the continental flood basalt province Parana-Etendeka (135-132 Ma, Renne et al., 1996; Renne, 2015). Due to the opening of the South Atlantic, the LIPs were separated and then the mantle plume interacted with the newly evolved Mid-Atlantic Ridge (MAR), forming the Walvis Ridge and Rio Grande Rise (e.g., Humphris and

Thompson, 1983; O'Connor and Duncan, 1990; O'Connor and Jokat, 2015b). The Walvis Ridge and Rio Grande Rise split apart between 80 and 60 Ma by several ridge jumps (e.g., Humphris and Thompson, 1983; O'Connor and Duncan, 1990; O'Connor and Jokat, 2015b). After ~60 Ma, the plume conduit migrated beneath the African plate and formed the scattered Guyot Province.

The preceding project WALVIS I, which focused on the Guyot Province, yielded two fundamental results. First, the Tristan-Gough volcanic chain shows a linear age progression from the active volcanic islands to the southern Walvis Ridge (DSDP Sites) and can be extrapolated to the African coast and the Etendeka LIP (Rohde et al., 2013b). If the Rio Grande Rise is rotated back along the oceanic fracture zones, the $^{40}Ar/^{39}Ar$ age data fit the calculated age progression of the Tristan-Gough track (Rohde et al., 2013b). Therefore, the age progressive trend with high precision $^{40}Ar/^{39}Ar$ age data supports the deep-rooted mantle plume theory and the simultaneous evolution of the Walvis Ridge and Rio Grande Rise.

Secondly, Rohde et al. (2013a) showed that the proposed Tristan-Gough hotspot track exhibited spatial geochemical zonation over the last 70 Ma, which can be divided into the Tristan and Gough tracks (Fig. 3). The Gough-type composition has higher $^{207}Pb/^{204}Pb$ ratios, but similar $^{208}Pb/^{204}Pb$ ratios at a given $^{206}Pb/^{204}Pb$ isotope ratio and extending to lower $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ ratios and higher $^{87}Sr/^{86}Sr$ values in relation to the chain leading to Tristan da Cunha (Rohde et al., 2013a; Hoernle et al., 2015). Northward of the DSDP sites (>70 Ma), the Walvis Ridge seems to be entirely composed of the EM I Gough-type composition (Rohde et al., 2013a; Hoernle et al., 2015).

Although the Tristan-Gough volcanic chain shows many characteristic features of a classical mantle plume, there are several critical observations. Compared to other mantle plume reference locations (e.g., Hawaii, Ninetyeast Ridge) the structure of the Tristan-Gough track is characterized by a broad region with scattered seamounts at the younger end. The active volcanic islands of Gough and Tristan da Cunha lie 400 km apart from each other, and thus, it seems implausible that a 200 km wide mantle plume conduit, as predicted by the plume model, forms the two volcanic islands. On the other hand, only five ages are available for the Walvis Ridge between the Deep Sea Drilling Project Sites and the northeastern end of the Walvis Ridge (Fig. 2) (Rohde et al., 2013b; O'Connor and Jokat, 2015a), which cover ~1500 km of the entire track. Of these five ages, only two were close to what was expected for a linear age progression. In fact, three samples are ~30 Ma younger than the predicted age progressive trend (Rohde et al., 2013b; O'Connor and Jokat, 2015a). Such an exceptionally long volcanic quiescence is unusual for hotspot tracks or ridges (e.g., Clague and Dalrymple, 1987; Hoernle and Schmincke, 1993; Geldmacher et al., 2005; Garcia et al., 2010). Finally, Hoernle et al. (2015) argued that the Tristan- and Gough-type components represent distinct mantle sources, implicating that the DUPAL anomaly inherited various EM I-types.

In conclusion, the origin of the Tristan-Gough volcanic chain and especially the temporal and geochemical evolution of the Walvis Ridge remain controversial (e.g., Rohde et al., 2013b; Foulger, 2017; O'Connor et al., 2018). Therefore, systematic sampling of the Walvis Ridge combined with geochemical and geochronological analyses provide not only further insights into the formation of the Tristan-Gough seamount chain but also the origin of the EM I mantle end member(s) and the possibly the origin of the entire South Atlantic DUPAL anomaly.

1.4 Main objectives

The aim of my thesis is to evaluate the origin and the temporal and geochemical evolution of the Walvis Ridge and to identify potential associations to other proposed hotspots in the South Atlantic. The main objectives are as follows:

1. Is the Tristan-Gough volcanic chain formed by a classical mantle plume?
2. What is the geochemical signature of the Walvis Ridge and when does the geochemical zonation of the Tristan-Gough track start?
3. Do the distinct Tristan- and Gough-type compositions contain temporal or spatial variations? What are the potential source components?
4. Is the geochemical signature of the Walvis Ridge associated with other intraplate lavas in the South Atlantic?
5. What is the geochemical fingerprint of the lavas with anomalously young ages?
6. How old are the seamounts on and next to the Walvis Ridge? Are they related to the emplacement of the Walvis Ridge basement?
7. Does the temporal and spatial evolution of the Tristan-Gough track yields further insights into the origin of the geochemical heterogeneity of the South Atlantic intraplate lavas?

To answer these research questions, I processed and evaluated major and trace element data, Sr-Nd-Pb-Hf isotope ratios and $^{40}Ar/^{39}Ar$ age data from 35 new sample sites, which were recovered through dredging at the following areas: 1) steep scarps on the margins of the ridge, 2) walls of cross-cutting graben systems, and 3) seamounts on and nearby the Walvis Ridge. A detailed description of the sample sites is presented by Hoernle et al. (2014) and Werner and Wagner (2014). Together with Walvis I, which focused on the volcanic province south of the Walvis Ridge, the recovered lavas represent one of the best sample collections worldwide of an oceanic seamount chain and provide unique insights into its origin and temporal evolution. The next chapter contains the three independent articles accepted for publication or submitted to international scientific journals. The last chapter summarizes the conclusions and gives an outlook for further research.

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2. CONTRIBUTION TO SCIENTIFIC JOURNALS

GLOBAL DISTRIBUTION OF THE HIMU END MEMBER: FORMATION THROUGH ARCHEAN PLUME-LID TECTONICS

Stephan Homrighausen, Kaj Hoernle, Folkmar Hauff, Jörg Geldmacher, Jo-Anne Wartho, Paul van den Bogaard, Dieter Garbe-Schönberg

accepted for publication in Earth Science Reviews

We present new major and trace element, Sr-Nd-Pb-Hf isotope and geochronological data from the Walvis Ridge and Richardson Seamount in the South Atlantic Ocean and the Manihiki Plateau and Eastern Chatham Rise in the southwest Pacific Ocean. Our new data, combined with literature data documents a more widespread (nearly global) distribution of the HIMU end member than previously postulated. The restricted trace element and isotopic composition (St. Helena type HIMU), but the near-global distribution point to a deep-seated, widespread reservoir, which formed most likely in the Archean. In this context we re-evaluate the origin of HIMU in an Archean geodynamic setting.

I wrote the manuscript with contributions from all of the co-authors. Kaj Hoernle supervised the work and was Chief Scientist during Cruise SO233. I prepared the samples for the geochemical analyses. Folkmar Hauff and I performed the isotope measurements. Paul van Bogaard and Jo-Anne Wartho performed the Ar-Ar and Dieter Garbe-Schönberg the trace element determinations. Kaj Hoernle, Folkmar Hauff and Reinhard Werner conceived the project.

UNEXPECTED HIMU-TYPE LATE-STAGE VOLCANISM ON THE WALVIS RIDGE

Stephan Homrighausen, Kaj Hoernle, Jörg Geldmacher, Jo-Anne Wartho, Folkmar Hauff, Maxim Potnyagin, Reinhard Werner, Paul van den Bogaard, Dieter Garbe-Schönberg

accepted for publication in Earth and Planetary Science Letters

We present the first comprehensive data set of $^{40}Ar/^{39}Ar$ ages, trace element and Sr-Nd-Pb-Hf isotopic data from seamounts on and next to the Walvis Ridge. Based on an average age offset of 20-40 Myr from the local Walvis Ridge basement and a distinct composition compared to the EM I-type basement, we conclude that the seamounts are not related to the Tristan-Gough mantle plume. The HIMU-like signature was most likely derived from the lowermost mantle. We propose that the EM I signature was derived from the margin of the African Large Low Shear Velocity Province, whereas HIMU rose from a more central portion.

I wrote the manuscript with contributions from all of the co-authors. Kaj Hoernle supervised the work and was Chief Scientist during Cruise SO233. Reinhard Werner was Chief Scientist during Cruise SO234. I prepared the samples for the geochemical and geochronological data and performed the isotope measurements. Paul van Bogaard and Jo-Anne Wartho performed the Ar-Ar and Dieter Garbe-Schönberg the trace element determinations. Kaj Hoernle, Folkmar Hauff and Reinhard Werner proposed the project.

COMPARISON OF NEW AGE AND GEOCHEMICAL DATA FROM THE WALVIS RIDGE WITH OTHER SOUTH ATLANTIC HOTSPOTS: MAPPING THE BASE OF THE LOWER MANTLE BENEATH THE SOUTH ATLANTIC

Stephan Homrighausen, Kaj Hoernle, Folkmar Hauff, Jo-Anne Wartho, Paul van den Bogaard, Dieter Garbe-Schönberg

submitted to Geochimica et Cosmochimica Acta

We report Ar-Ar age data combined with geochemical data from the Walvis Ridge, which shows an excellent age progression supporting the deep-rooted mantle plume model. The geochemical data confirm that the Gough-type composition is the long-lived component of the Walvis Ridge, which is also identified at the Discovery and Shona hotspot tracks. Mixing of Gough-type material with continental crust and a FOZO-like component can reproduce the geochemical heterogeneity in the South Atlantic DUPAL region. We present a model where the geochemical compositions of the South Atlantic Ocean island basalts reflect sampling from different portions of the African LLSVP and the surrounding ambient lower mantle.

I wrote the manuscript with contributions from Kaj Hoernle, Folkmar Hauff and Jo-Anne Wartho. Kaj Hoernle supervised the work and was Chief Scientist during Cruise SO233. I prepared the samples for the geochemical and geochronological data. Folkmar Hauff and I performed the isotope measurements. Paul van Bogaard and Jo-Anne Wartho performed the Ar-Ar and Dieter Garbe-Schönberg the trace element determinations. Kaj Hoernle, Folkmar Hauff and Reinhard Werner proposed the project.

3. Conclusions and Outlook

3.1 Conclusions

The aim of my PhD thesis was to provide further insights into the origin and the temporal and geochemical evolution of the Walvis Ridge. By collecting new bathymetric data and combining them with geochemical and geochronological analyses from 35 new sample sites on and next to the Walvis Ridge I could address all my objectives (see section 1.4. and below).

Is the Tristan-Gough volcanic chain formed by a classical mantle plume?

Based on bathymetric and geochemical data, I could identify at least two magmatic events, that were confirmed by the $^{40}Ar/^{39}Ar$ age data. Together with the literature data (Rohde et al., 2013; O'Connor and Jokat, 2015a, b), the basement samples with EM I-type compositions of the entire Tristan-Gough seamount chain display an excellent linear age progression (Fig. 6 in section 3.3). This array can be extrapolated to the Etendeka flood basalts (135-132 Ma; Renne et al., 1996; Renne, 2015) and the active volcanic islands of Tristan da Cunha and Gough (0.12 -2.6 Ma; Maund et al., 1988; Hicks et al., 2012), providing further support for the age progression. The age progression is the strongest evidence that a deep-rooted mantle plume formed the track. Recent seismic tomographic data supports this conclusion, which images a low-velocity conduit-like structure with a radius of 100 km down to a depth of 250 km just to the southwest of Tristan da Cunha (Schlömer et al., 2017). This shallow velocity anomaly lies above a broader vertically continuous conduit-like structure with ∂V_S ratios of < -0.5 % at a depth range of 1000-2800 km (French and Romanowicz, 2015). Furthermore, Stroncik et al. (2017) report high $^3He/^4He$ ratios (> 10 R_A) from the Etendeka flood basalt province, which additionally support a lower mantle origin. The fan-out mechanism of the Guyot Province towards the active volcanic islands remains enigmatic but could be related to a weakening mantle plume (Rohde et al., 2013).

What is the geochemical signature of the Walvis Ridge and when does the geochemical zonation of the Tristan-Gough track start?

The majority of the new basement samples from the Walvis Ridge lie within the Gough compositional domain, confirming that the Walvis Ridge is primarily composed of this EM I-type composition (Fig. 5 in section 3.3). Nevertheless, a few samples either expand the Gough-field towards the Tristan compositional field, or the first appearance of the Tristan-type material can be extended to approximately 90 Ma. Interestingly, these lavas are from the eastern side of the Walvis Ridge and suggest the local presence of Tristan-type material before the hotspot track became zoned. Finally, there is not enough data (samples from only two sites have been reported thus far; Rohde et al., 2013a) to evaluate whether Tristan-type compositions are present on the Rio Grande Rise or Sao Paulo plateau.

Do the distinct Tristan- and Gough-types compositions contain temporal or spatial variations? What are the potential source components?

Since the Gough-type composition represents the long-lived mantle plume component, I focused on this compositional type. The vast majority of the Walvis Ridge is characterized by tholeiitic compositions and relatively depleted incompatible trace element concentrations, whereas the Gough-type Guyot Province lavas are overall alkalic and relatively enriched in trace elements (Figs. 3-4 in section 3.3). The geochemical variations along the track are consistent with the change from plume-ridge interaction during the Walvis Ridge formation to intraplate volcanism, with an increase in lithospheric thickness resulting in higher pressure and lower melting degrees. The Nb-Ta systematics (e.g., Nb/Th) indicate that the Gough-type composition reflects the mixing of two distinct components. In accordance, mixing of a lower continental crust component with a mixture of recycled oceanic crust (FOZO) ± sediments (EM II) can reproduce the Gough domain in multi-isotope space (Figs 5, 7-8 in section 3.3). The Guyot Province lavas seem to have an overall higher imprint of the FOZO-EM II component (e.g., higher $^{206}Pb/^{204}Pb_{60Ma}$), compared to the Walvis Ridge lavas, which could be coupled to the melting degree. One possible explanation could be that the Walvis Ridge lavas preferentially sample the lower continental crustal component, whereas at lower degrees of melting (alkaline lavas, which primarily occur in the Guyot Province and Gough Islands) sample mainly recycled ocean crust ± sediments, possibly in the form of eclogite/garnet pyroxenite.

Is the geochemical signature of the Walvis Ridge associated with other intraplate lavas in the South Atlantic?

The Gough-type component can also be identified in the Discovery and Shona mantle plumes, indicating that these hotspots sample the same reservoir (Figs. 7-8 in section 3.3). The various EM I-type flavors in the South Atlantic can be reproduced by the mixing of Gough-type composition with the following: 1) FOZO to produce the Tristan-type composition, 2) upper continental crust to yield the Southern Discovery-type composition and 3) depleted mantle to cover the compositional domain of the Shona lavas (Figs. 5,7-8 in section 3.3). Therefore, it seems that the Gough-type composition represents the common and widespread EM I-type in the South Atlantic DUPAL anomaly.

What is the geochemical fingerprint of the lavas with anomalously young ages? Are they related to the Tristan-Gough seamount chain? What is the origin of the seamounts next to the Walvis Ridge? Do they belong to a later stage of volcanism?

The combined analyses of bathymetric, geochemical and geochronological data demonstrate that the majority of seamounts on and close to the Walvis Ridge belong to a later volcanic activity. The sampled seamounts are 20-40 Ma younger than the age progressive Walvis Ridge basement, and the isotopic compositions of the seamounts extend from the St. Helena HIMU end member to E-MORB (Figs. 5-7 in section 3.2). Based on the unusually long volcanic quiescence and HIMU-like composition, I concluded that these seamounts were derived from a distinct source and are not related to the Tristan-Gough mantle plume.

Does the temporal and spatial evolution of the Tristan-Gough track yield further insights into the origin of the geochemical heterogeneity of the South Atlantic intraplate lavas?

Based on the temporal and spatial evolution of the Tristan-Gough hotspot track and the characteristic geochemical fingerprints of the South Atlantic hotspots relative to their position to the 1 % ∂V_S velocity contour of the African Large Low Shear Velocity Province (LLSVP), I propose that the spatial and temporal geochemical heterogeneities in the South Atlantic hotspots ultimately reflect sampling from different geochemical domains outside and within the African LLSVP. The model shows that the Gough-type composition of the Tristan-Gough, Southern Discovery and Shona hotspots was derived from the outer margins of the LLSVP, whereas St. Helena and Ascension hotspots and late-stage Walvis and Shona volcanism sample HIMU from inner portions of the LLSVP (Fig. 9 in section 3.3). The ambient lowermost mantle outside of the LLSVP consists of subducted ocean crust (FOZO), as sampled by the Bouvet hotspot, and subducted marine sediment or continental crust, as sampled by the Southern Discovery hotspot.

HIMU-type volcanism

Finally, I used selected submarine samples from the Walvis Ridge, Shona track, Eastern Chatham Rise and Manihiki plateau combined with a literature data survey to demonstrate a more widespread (nearly global) distribution of the HIMU end member than previously postulated (Fig. 6 in section 3.1). This survey shows that HIMU is generally associated with low-volume alkaline, carbonatitic and/or kimberlitic intraplate volcanism, consistent with the derivation through low degrees of melting of CO_2-rich sources. The majority of end member HIMU locations can be directly related to hotspot settings. The restricted trace element and isotopic compositions (St. Helena-type HIMU) but near-global distribution, point to a deep-seated, widespread reservoir, which most likely formed in the Archean. In this context, I re-evaluated the origin of a widespread HIMU reservoir in an Archean geodynamic setting. In my PhD thesis, I note that the classical oceanic crust recycling model cannot be applied in a plume-lid dominated tectonic setting and propose that delamination of carbonatite-metasomatized subcontinental lithospheric mantle could be a suitable HIMU source (Fig. 10 in section 3.1). In contrast, hydrothermal alteration of the ocean crust and dehydration during subduction gives the ocean crust the appropriate composition to evolve HIMU-like (FOZO-type) compositions. Therefore our model invokes a different origin for the HIMU (through carbonate metasomatism and detachment/delamination of SCLM during Archean plume-lid tectonics) and FOZO (Proterozoic and later recycling of ocean crust during modern-style tectonics) mantle end members.

3.2 Outlook

The recovered lavas during WALVIS I and II represent one of the best worldwide sample collections from a submarine volcanic chain. My PhD thesis demonstrates a more complex volcanic history, as previously thought, and raises further questions. The majority of seamounts and ridges on and close to the Walvis Ridge have a HIMU-type composition and were emplaced 20 to 40 Ma after the underlying or nearby EM I-type basement. Based on two magmatic lineaments with similar ages and isotopic compositions, I proposed a genetic relationship and a widespread volcanism between 80 and 50 Ma. However, the geochemical and geochronological data of this area are sparse, and a detailed sampling of the Mocamedes Arch and volcanic edificies along the East African coast could clarify the situation. Rock samples from potential late-stage volcanism from the Etendeka LIP have already been collected to test this hypothesis (Hoernle pers. comm.).

In the last few decades, the Tristan-Gough seamount chain (Etendeka-Walvis Ridge-Guyot Province) was always related to Tristan da Cunha. My thesis shows that the Gough-type composition represents the long-lived mantle plume component, and further seismic observations should focus on Gough Island. Overall, increased seismic tomographic resolution would help to understand the recent structure of the Tristan-Gough mantle plume. Does the mantle plume split into two arms? Where? Or does the mantle plume consist of numerous rising "blobs"?

The geochemical heterogeneity of the South Atlantic DUPAL anomaly can be explained by Gough-type composition flavored with FOZO and continental material. Note, that the majority of our lavas are differentiated ($MgO<5wt.\%$) and were affected by varying degrees of alteration, which could decouple the trace element signature from the isotopic fingerprint. To test the mixing hypothesis, more fresh and primitive materials are required. Additionally, Stroncik et al. (2017) showed that some Gough-type lavas from Etendeka have high $^{3}He/^{4}He$ ratios (> 10 R_A). Until now, only lavas with extremely low $^{3}He/^{4}He$ ratios (< 6 R_A; Kurz et al., 1982) are reported from Tristan and Gough, and further work could provide new insights. Based on the presented model (Tristan = Gough-type + FOZO), I would expect even higher $^{3}He/^{4}He$ ratios at Tristan compared to Gough (if FOZO is characterized by high helium ratios). Furthermore, new samples from Rio Grande Rise and especially the Sao Paulo plateau could provide further insights into the evolution of the Tristan-Gough mantle plume. Where does the geochemical zonation start? Is there also widespread late-stage volcanism, and what is the geochemical signature? If HIMU-type late-stage lavas can be recovered from the Rio Grande Rise, HIMU could be part of the Tristan-Gough mantle plume. In this case, the mechanism of late-stage volcanism remains enigmatic but could indicate an even closer association between HIMU and EM I.

Finally, the spatial and temporal geochemical evolution of the South Atlantic mantle plumes could be used to map the lowermost mantle. A comparison of the DUPAL anomaly from the South Atlantic and Indian Oceans could provide further insights into the spatial geochemical heterogeneity of the African LLSVP and ambient lowermost mantle. For example, the geochemical composition of some Kerguelen lavas overlaps with the Gough-type composition and could indicate that the Gough-type composition is also present in Indic mantle plumes. In this case, the Gough-type composition is not limited to the westernmost margin of the African LLSVP.

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