1 **Nature and Origin of the Mozambique Ridge, SW Indian Ocean**
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ABSTRACT

The Mozambique Ridge (MOZR) is one of several bathymetric highs formed in the South African gateway shortly after the breakup of the supercontinent Gondwana. Two major models have been proposed for its formation - volcanic plateau and continental raft. In order to gain new insights into the genesis of the Mozambique Ridge, R/V SONNE cruise SO232 carried out bathymetric mapping, seismic reflection studies and comprehensive rock sampling of the igneous plateau basement. In this study, geochemical data are presented for 51 dredged samples, confirming the volcanic origin of at least the upper (exposed) part of the plateau. The samples have DUPAL-like geochemical compositions with high initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7024-0.7050), low initial $^{143}\text{Nd}/^{144}\text{Nd}$ (0.5123-0.5128) and low initial $^{176}\text{Hf}/^{177}\text{Hf}$ (0.2827-0.2831), and elevated initial $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$ ($\Delta 7/4 = 2-16$; $\Delta 8/4 = 13-167$). The geochemistry, however, is not consistent with exclusive derivation from an Indian MORB-type mantle source and requires a large contribution from at least two components. Ratios of fluid-immobile incompatible elements suggest the addition of an OIB-type mantle to the ambient upper mantle. The MOZR shares similar isotopic compositions similar to mixtures of sub-continental lithospheric mantle end members but also to long-lived, mantle-plume-related volcanic structures such as the Walvis Ridge, Discovery Seamounts and Shona hotspot track in the South Atlantic Ocean, which have been proposed to ascend from the African Large Low Shear Velocity Province (LLSVP), a possible source for DUPAL-type mantle located at the core-mantle boundary. Interestingly, the MOZR also overlaps compositionally with the nearby Karoo-Vestfjella Continental Flood Basalt province after filtering for the effect of interaction with the continental lithosphere. This geochemical similarity suggests that both volcanic provinces may be derived from a common deep source. Since a continuous hotspot track connecting the Karoo with the MOZR has not been found, there is some question about derivation of both provinces from the same plume. In conclusion, two possible models arise: (1) formation by a second mantle upwelling (blob or mantle plume), possibly reflecting a pulsating plume, or (2) melting of subcontinental lithospheric material transferred by channelized flow to the mid-ocean ridge shortly after continental break-up. Based on geological, geophysical and geochemical observations from this study and recent published literature, the mantle-plume model is favored.

Key words: Mozambique Ridge – Large Igneous Province (LIP) – Flood Basalts – Continental breakup – Mantle plume – Submarine volcanism – Radiogenic Isotopes

1. INTRODUCTION

Continental breakup leads to the formation of new ocean basins floored by new ocean crust. Breakup forms two types of rifted margins - magma-poor and volcanic-rifted margins (Franke, 2013 and references therein). Magma-poor margins (e.g. the South China Sea) are characterized by low magmatic activity and extensional features such as detachment faults and rotated crustal blocks over wide domains (i.e., >1000 km in the South China Sea). The crust breaks up before the lithospheric mantle extends, which contrasts with the formation of volcanic rifted margins. In the second scenario, initial lithospheric extension preceding crustal breakup leads to extensive magmatism over a short period of time. These large outpourings of magma are generally referred to as Large Igneous Provinces (LIPs) (e.g., Coffin and Eldholm, 1994, Courtillot et al., 1999, Dalziel et al., 2000). As the continental fragments drift apart as a result of new seafloor spreading, the continental crust along the margins cools and subsides, such that the sub-aerially erupted flood basalts on the new continental margins dip seawards, and are known as seaward-dipping reflectors. The super continent Gondwana started to disperse in the Middle Jurassic when Africa, South America, Antarctica, India and Australia rifted apart at different stages. The presence of the 183 Ma-old Karoo (Jourdan et al., 2005) and the 132 Ma-old Paraná-Etendeka (Renne et al., 1996) Continental Flood Basalt (CFB) provinces at the edge of the newly formed continents suggests that magmatic events may have contributed to continental breakup.

The opening of the Southern Ocean results from the fragmentation of Eastern Gondwana (i.e. Africa, Antarctica and Australia; 184-171 Ma, Nguyen et al., 2016). The first oceanic crust between Africa and Antarctica formed at ca. 155 Ma (Jokat et al., 2003). Numerous structures such as the Mozambique Ridge (MOZR), Agulhas Plateau (AGP), Maud Rise, and Madagascar Rise (Figure 1a) were then emplaced between Southern Africa and Antarctica on the newly formed oceanic crust, but little is known about possible links to the Gondwana breakup. The continental margin of the Dronning Maud Land (Antarctica) and its African counterpart have been classified as volcanic-rifted (Jokat et al., 2004, Eagles and König, 2008, Mueller and Jokat, 2017). The nature and origin of these bathymetric highs are

enigmatic due to the lack of detailed marine-based investigations, which has led to opposing models (volcanic plateau versus thinned continental crust) for their formation (e.g., Tucholke et al., 1981, Ben Avraham et al., 1995; König and Jokat, 2010, Gohl et al., 2011). In order to better understand the nature, origin and spatial and temporal evolution of the MOZR and its relationship to Gondwana breakup, the Research Vessel SONNE (expedition SO232 in April-May 2014) carried out a comprehensive bathymetric and seismic reflection survey on the MOZR accompanied by a detailed sampling of the plateau basement, and preliminary sampling of the NW part of the AGP. In this paper we present a comprehensive new geochemical data set for samples from the MOZR and AGP, including major and trace element and Sr-Nd-Hf-Pb (double spike) isotope data.

2. GEOLOGICAL SETTING

The MOZR is an elongated plateau striking roughly parallel to the SE coastline of South Africa between 25° and 35°S (Figure 1). It rises ca. 4000 m above the abyssal plain located at ca. 5000 m below sea level. It is composed of three sub-plateaus, divided by E-W and NW-SE trending valleys: 1) southwestern, 2) central and 3) northern plateaus (Figure 1b). A fourth sub-plateau, in the southeast, is less distinct.

The following section reviews the different models that have been proposed since the early studies in the 1970s on the nature of the MOZR. Laughton et al. (1970) first proposed an origin of the MOZR through thinning of continental crust based largely on its bathymetric connection to the African shelf. This hypothesis was later supported by plate tectonic reconstructions (Tucholke et al., 1981). Several dredges recovered continental rocks from different parts of the MOZR that further supported this hypothesis (Mougenot et al., 1991, Ben Avraham et al., 1995, Figure 1b). The authors described the samples (metapelites, gneiss, metagabbros and anorthosites) as similar to Archean rocks occurring on the African craton. There is some questions as to whether some or all of these samples may have been glacial dropstones from Antarctica. Fresh volcanic glass was also recovered, which was believed to reflect volcanism related to neo-tectonic activity (Ben Avraham et al., 1995). No ages, however, were determined on any of these samples. The southern MOZR, AGP and Madagascar Ridge were also considered to be thinned continental fragments that were stranded after breakup (Ben Avraham et al. 1995).

On the other hand, Green (1972) suggested that the MOZR is an extinct north-south spreading center responsible for the separation of Madagascar from Africa. In this context, others found that the MOZR is in isostatic equilibrium with the neighboring oceanic crust, despite its deep Moho (> 22 km) and thus proposed an oceanic origin (e.g., Hales and Nation, 1973, Chetty and Green, 1977, Maia et al., 1990). Other authors proposed a microplate origin for the MOZR (e.g., Lawver et al., 1999, Marks and Stock, 2001, Marks and Tikku, 2001). Strong evidence for a volcanic nature of at least a part of the northern MOZR came from DSDP Leg 25 (Simpson, 1974; Figure 1b), which recovered Cretaceous tholeiitic basalts at site 249 (Erlank and Reid, 1974, Thompson et al., 1982).

Geophysical data support a volcanic nature for the MOZR. Magnetic anomaly data indicate a magmatic origin for the plateau (König and Jokat, 2010), in agreement with similar studies of the AGP and Maud Rise showing that they are all composed of thickened ocean crust (>15 km, which is more than twice the thickness of normal ocean crust), consistent with a LIP origin (e.g., Gohl and Uenzelmann-Neben, 2001, Parsiglia et al., 2008, Gohl et al., 2011). Fischer et al. (2017) favored the LIP hypothesis for the MOZR based on seismic reflection data from the SO232 cruise and estimated volume (3.1×10^6 km³), surface (0.15×10^6 km²) and duration of emplacement (10 Ma) compared to other oceanic LIPs. The MOZR presumably formed 135-125 Ma ago, based on high resolution magnetic anomaly data and tectonic reconstruction (König and Jokat, 2010, Fisher et al., 2017). The MOZR formed during multiple events. It initially began to form in the north at 135 Ma and continued to grow towards the southwest, where the central area formed mainly at ca. 131 Ma with volcanism forming the southwestern sub-plateau lasting until ca. 126 Ma. The less prominent SE plateau may have been emplaced at ca. 125 Ma. One prominent structure is a roughly N-S trending scarp along the eastern margin, which is possibly an elongation of the Andrew Bain Fracture Zone (König and Jokat, 2010). According to Mougenot et al. (1991) and König and Jokat (2010), there is a crustal block located east of the northern plateau that is separated from the main MOZR and may represent a continental fragment, which moved into the oceanic realm during the initial stages of rifting.

3. SAMPLING AND ANALYTICAL METHODS

3.1 Petrography of the samples

Fifty-one successful dredges were carried out during SO232 covering the entire MOZR except the northernmost part (Figure 1b). Massive lavas, mostly sheet and pillow lavas, were recovered in 35 dredges and volcanoclastic rocks from a further 16 dredges. The samples are variably altered with the groundmass ranging from brownish to grayish in color. Mn crusts, present on most samples, and alteration halos were cut off with a rock saw onboard to prepare the least altered inner core of individual rock samples for geochemical analyses. Most samples are aphyric but a few contain relatively fresh millimeter-sized plagioclase phenocrysts. The presence of vesicles is variable in the samples and they are generally filled with secondary minerals. Samples with filled vesicles were avoided when preparing samples for geochemistry. Thin sections of fresh cut blocks show that the matrix is generally composed of plagioclase needles and pyroxene crystals. Some reddish and opaque minerals, and some iddingsitized olivine are observed within the matrix or as phenocrysts. A full detailed sample description and precise sample locations on the plateau basement can be found in the SO232 cruise report (Uenzelmann-Neben, 2014; <http://hdl.handle.net/10013/epic.43724>).

Dredge station DR65 exclusively recovered continental materials, in an area that has been previously described as a continental splinter (Mougenot et al., 1991, König and Jokat, 2010, see also Fig. 5.44 in Uenzelmann-Neben, 2014). DR65-1 is a gneiss, whereas DR65-2 (one meter-sized block) is a Quartz-rich rock, possibly a schist. Both samples have thin Mn-crusts, sharp angular edges and a few freshly broken surfaces (see Supplementary File A1 and Uenzelmann-Neben, 2014). These observations suggest an in-situ origin. Only DR65-1 has been geochemically characterized.

3.2 Analytical methods

In this study 55 samples were analyzed for major elements, trace elements, and Sr-Nd-Pb double-spike (DS) isotopes. A representative subset (32 samples) was selected for Hf isotopes. The full analytical methods including sample preparation and analytical procedures can be found in the Supplementary File A2. All information and geochemical data can be found in the Supplementary Table B1.

4. RESULTS

4.1 Effects of alteration

Because the samples are of submarine origin and have been exposed to seawater for up to ~130 Ma, it is crucial to evaluate the degree of alteration and possible effects of alteration on whole rock chemistry. As stated earlier the thin sections reveal that some of the samples are heavily altered, as highlighted by reddish matrix and altered pyroxenes.

An important criteria for evaluating the freshness of whole rock chemistry is the loss on ignition (LOI), which ranges from 0.5 to 13 wt. %, but 32 out of 55 samples have less than 5 wt. % LOI (Supplementary Table B1). A rough positive correlation between LOI and P_2O_5 is observed ($P_2O_5 = 0.06$ to 15.6 wt. %; plot not shown). Three samples possess LOI > 7.9 and high P_2O_5 contents along with a fourth sample that displays an unusually high CaO contents (~24 wt. %). All four samples have anomalously low SiO_2 contents (< 41 wt. %). Therefore they are excluded from further consideration in this manuscript. A multi-element diagram also provides useful information about the effect of alteration on trace elements (Supplementary Figure A3). The smooth multi-element pattern of glass sample DR14-1G can be considered a reference sample to identify element depletions or enrichments caused by alteration of the whole rock samples. Almost all the whole rock samples display pronounced peaks (Cs, Rb, U and K) for the fluid-mobile trace elements that are commonly taken up by seafloor volcanic rocks during alteration. The peaks in La and troughs in Ce in some samples are also likely to reflect mobilization of these elements. To avoid these alteration effects, the interpretation of this study focus on fluid-immobile incompatible elements and isotope ratios in order to derive information about magmatic processes.

4.2 Major and trace elements

Due to the overall state of alteration of many samples, application of the Total Alkali Silica (TAS) diagram is not suitable. Instead, the Zr/Ti vs. Nb/Y discrimination diagram from Pearce (1996) is used to classify the volcanic rocks (Figure 2). Most of the samples are basalts, but a few plot within the alkali basalt field. All the alkali basalts are from small cones

and/or structures at the summit of the southwestern and central MOZR plateaus likely to represent late-stage volcanism (Figure 1b; Uenzelmann-Neben, 2014). The most evolved sample (DR34-1) with $\text{SiO}_2 = 70$ wt. % plots in the trachyte field. The gneiss sample DR65-1 has a SiO_2 content of 69 wt. %.

All samples form positive correlations on plots of fluid-immobile incompatible element ratios. On the Nb/Yb vs. TiO_2/Yb diagram (Pearce, 2008, Figure 3a), the basalts (henceforth called tholeiites) and the alkali basalts form distinct correlations. Most of the tholeiites plot within the deep melting (OIB) field, suggestive of melting in presence of residual garnet in the source and extend along the plume-ridge interaction trend of Pearce (2008). On a Nb/Yb vs. Th/Yb diagram (Pearce, 2008, Figure 3b), the MOZR and AGP basaltic samples largely overlap with Enriched Mid-Ocean Ridge Basalt (E-MORB) end members with extensions to Normal (N) MORB and Ocean Island Basalt (OIB) end member, whereas the alkali basalt samples lie near OIB. A single sample (DR21-1) has the lowest fluid-immobile incompatible element ratios, below N-MORB composition. On the primitive-mantle-normalized, immobile incompatible element diagram (Hofmann, 1988), all the samples are enriched in incompatible elements (Figure 4). The degree of enrichment of light rare earth elements (LREEs) for the tholeiites lies between E-MORB and OIB reference patterns. From Tb to Yb, the patterns have negative slopes indicating the presence of residual garnet in the source. Sample DR-21-1 has a pattern that runs sub-parallel to the N-MORB reference with a diagnostic depletion in LREE of $(\text{La}/\text{Sm})_{\text{N}} = 0.88$ and a flat HREE pattern (Figure 4a). Ce depletions in some samples indicate post-magmatic mobilization of Ce under oxidizing conditions. Samples collected from a large volcano with a flat top (henceforth called “Tabletop Mountain”) display positive La anomalies reflecting both La uptake and Ce removal. The alkali basalts generally have steeper negative REE slopes, i.e., higher ratios of more to less incompatible elements compared to the tholeiites (Figure 4b) with $(\text{La}/\text{Sm})_{\text{N}} > 2$ and $(\text{La}/\text{Yb})_{\text{N}} > 6$. Trachyte sample DR34-1 shows trace element enrichment similar to the alkali basalt samples. DR65-1 has very depleted HREE with the highest $(\text{Sm}/\text{Yb})_{\text{N}}$ ratio of 4.56 (Figure 4b).

4.3 Radiogenic isotopes

In this article, we present and compare radiogenic isotope data of magmatic rocks with different ages, sources and histories. Therefore it is crucial to project all data to a common age as for example in Homrighausen et al. (2019). The MOZR has been estimated to be 135-125 Ma-old (Fisher et al., 2017). A common formation age of 130 Ma is assumed for all samples for the projection of initial isotope ratios. Initial isotope ratios presented in the Supplementary Table B1 and plotted in the diagrams are calculated using the measured Parent/Daughter (P/D) element ratios obtained from unleached powders (i.e. the inductively coupled plasma mass spectrometry (ICPMS) data). This approach assumes that the isotope systems remained closed over 130 Ma and that any postmagmatic alteration occurred shortly after eruption. In order to project literature data of young and variably aged terranes to a common 130 Ma formation age, the following measures were undertaken. For present-day Indian and Atlantic MORB, together with SW Indian OIB, source P/D ratios of depleted mantle (DMM; Workman and Hart, 2005) and OIB (Stracke et al., 2003) were applied to simulate a 130 Ma formation age. Older terranes followed a two-step procedure that first calculates the initial composition at the time of formation and then runs a source correction to 130 Ma using source P/D's from the above mentioned references and those of Willbold and Stracke (2006) for Enriched Mantle 1 (EM-1) (Supplementary Table B7).

Low-temperature and hydrothermal alteration can affect the Rb-Sr, Th-Pb and U-Pb isotope systems in submarine lavas, whereas the Sm-Nd and Lu-Hf systems are much less affected due to their relatively fluid-immobile element behavior. Two major processes contribute to elevated $^{87}\text{Sr}/^{86}\text{Sr}$ values in old, submarine altered rocks: 1) exchange/addition of seawater Sr, and 2) Rb addition as evident from the pronounced Rb peaks in a multi-element diagram (Supplementary Figure A3). Seawater contains ~7 ppm Sr and has strongly elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in comparison to the sub-oceanic mantle (0.709 vs. 0.702-0.706). Mild leaching of rock chips in 2N HCl at 70°C removes possible contamination from sample handling and dissolves any carbonates present, but the treatment is unlikely to significantly alter the overall P/D's ratios. Hot leaching of sample powders in 6N HCL at 150°C will more efficiently dissolve secondary mineral phases. The strong leaching of the powders in hot 6N HCl yielded predominantly lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios compared to those from the mildly leached rock chips (Supplementary Table B1). Two samples (DR87-1 and DR59-1), however, yielded higher values. In order to evaluate effectively the leaching effects, we exclude the three highly altered samples (DR06-1, DR59-1 and DR59-3) and the abnormal $^{87}\text{Sr}/^{86}\text{Sr}_{\text{powder}}$ of DR87-1 from further consideration. The correlation coefficient (r^2) for the measured $^{87}\text{Sr}/^{86}\text{Sr}$ vs. measured $^{143}\text{Nd}/^{144}\text{Nd}$ or measured $^{176}\text{Hf}/^{177}\text{Hf}$ ratios obtained from the mildly leached rock

chips ($r^2 = 0.22$ and 0.16 , respectively) and the strongly leached powders ($r^2 = 0.30$ and 0.28 , respectively) are not indicative of any correlation between Sr, Nd and Hf isotope ratios (Supplementary Figures A4a-b). For Sr vs. Nd isotopes, r^2 improves to 0.38 (chips) and 0.80 (powders), when excluding trachyte DR34-1 (not shown). Similarly, r^2 increases to 0.35 (chips) and 0.65 (powders) for Sr vs. Hf isotopes. Trachyte sample DR34-1, expectedly, has high Rb/Sr ($=1.06$), leading to high post-magmatic radiogenic ingrowth of ^{87}Sr and consequently high measured $^{87}\text{Sr}/^{86}\text{Sr}$. Therefore it is crucial to also consider initial isotope ratios. Correlations of $^{87}\text{Sr}/^{86}\text{Sr}_i$ of mildly leached chips and strongly leached powders against $^{143}\text{Nd}/^{144}\text{Nd}_i$ and $^{176}\text{Hf}/^{177}\text{Hf}_i$ (Supplementary Figures A4c-d) are significantly better for the mildly leached chips ($r^2 = 0.74$ and 0.71 , respectively) than for the strongly leached powders ($r^2 = 0.43$ and 0.51 respectively). The effect of age correction is best seen in sample DR34-1, since its $^{87}\text{Sr}/^{86}\text{Sr}$ (from chips or powder) effectively decreases (Supplementary Table B1). The lower r^2 values for the strongly leached powders mainly stems from over-correction of six samples to very unradiogenic $^{87}\text{Sr}/^{86}\text{Sr}_i \leq 0.702$. Even when filtered, r^2 does not improve to better than 0.61 and 0.60 respectively. ^{87}Sr over-correction most likely reflects using the Rb/Sr ratios from the unleached powders in conjunction with the possibility of significant addition of Rb over the entire life-span of the rocks, and/or partial removal of ingrown ^{87}Sr during acid-leaching as secondary Rb is likely to be bound in secondary minerals. In conclusion, although the net acid-leaching effects on the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are significant for the strongly leached powders (Supplementary Table B1) implying efficient removal of contaminating seawater-Sr, the calculation of the $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratio using the Rb/Sr of the unleached powders leads to over-correction in a few samples due to the inability to trace the combined effects of later Rb addition and the loss of ingrown ^{87}Sr into the acid leachate. Since the $^{87}\text{Sr}/^{86}\text{Sr}_i$ values of mildly leached chips for all samples correlates better with the initial Nd and Hf ratios compared to the $^{87}\text{Sr}/^{86}\text{Sr}_i$ from the strongly leached powders, the $^{87}\text{Sr}/^{86}\text{Sr}_i$ values from the mildly leached chips represent the best possible approximation to the initial magmatic values. Overall it is clear that the $^{87}\text{Sr}/^{86}\text{Sr}_i$ values in the bulk rock analyses have large uncertainties and that the two approaches presented here define the lower and upper limits of $^{87}\text{Sr}/^{86}\text{Sr}_i$. The reasonably good correlations of $^{87}\text{Sr}/^{86}\text{Sr}_i$ using both leaching approaches with the fluid-immobile isotope systems of Sm-Nd and Lu-Hf indicate that primary petrological information can still be derived from $^{87}\text{Sr}/^{86}\text{Sr}$ in aged, seawater altered igneous rocks.

Pb and Th are relatively immobile during low-temperature seafloor alteration processes so that the ^{232}Th - ^{208}Pb decay system can only be disturbed if Pb is mobilized early

in the history of a rock due to hydrothermal alteration. Since no obvious signs of hydrothermal alteration are detected in the samples, the most significant process affecting Pb isotope ratios is U uptake during low temperature alteration / weathering. This is observed as significant positive U-spikes for most samples on a multi-element diagram (Supplementary Figure A3) and is further underpinned by low and highly variable Nb/U ratios ($= 30 \pm 15$) for the sample dataset (Supplementary Table B1) when compared to the canonical values for oceanic basalts (Nb/U = 47 ± 10 , Hofmann et al., 1986) or fresh glass from tholeiite DR14-1G (Nb/U = 46). Since the glass Nd/Pb (17) is very similar to the average whole rock sample Nd/Pb ratio (13 ± 6), we do not believe Pb has been significantly mobilized. In conclusion, U uptake significantly influenced the post-magmatic evolution of Pb in the sample dataset. Since most present-day U is ^{238}U ($^{238}\text{U}/^{235}\text{U} = 138.88$), U uptake will primarily result in the ingrowth of ^{206}Pb throughout the history of these Cretaceous rocks. The reasonably good correlation of $^{206}\text{Pb}/^{204}\text{Pb}_i$ vs. $^{207}\text{Pb}/^{204}\text{Pb}_i$ ($r^2 = 0.68$) and $^{208}\text{Pb}/^{204}\text{Pb}$ ($r^2 = 0.74$) (Figure 5), as well as $^{207}\text{Pb}/^{204}\text{Pb}_i$ vs. $^{208}\text{Pb}/^{204}\text{Pb}_i$ ($r^2 = 0.79$; plot not shown) support the assumption of closed system behavior for U-Pb and Th-Pb in the majority of samples and indicate that most of the alteration of these systems occurred early in the history of the samples.

The MOZR, Tabletop Mountain and AGP samples form a reasonable good negative correlation ($r^2 = 0.74$) on a $^{87}\text{Sr}/^{86}\text{Sr}_i$ vs. $^{143}\text{Nd}/^{144}\text{Nd}_i$ isotope diagram (Figure 6a) and a similarly good positive correlation ($r^2 = 0.75$) on the $^{143}\text{Nd}/^{144}\text{Nd}_i$ vs. $^{176}\text{Hf}/^{177}\text{Hf}_i$ isotope diagram (Figure 6b). The Tabletop Mountain samples have the most enriched isotope ratios (radiogenic Sr and unradiogenic Nd-Hf), together with one tholeiite (DR44-2) and one alkali basalt (DR72-1). On the other hand, the DR21-1 and AGP samples plot at the depleted end of the array and two other alkali samples also have depleted isotope ratios. When considering the initial Pb isotope data, the samples display elevated $^{207}\text{Pb}/^{204}\text{Pb}_i$ and $^{208}\text{Pb}/^{204}\text{Pb}_i$ ratios at a given $^{206}\text{Pb}/^{204}\text{Pb}_i$ ratio with respect to the Northern Hemisphere Reference Line (NHRL; i.e. high $\Delta 7/4$ and $\Delta 8/4$ ratios, Hart, 1984). The AGP samples have the most radiogenic Pb isotope ratios and sample DR21-1 has very low $\Delta 7/4$ and $\Delta 8/4$ ratios (Figure 5). The gneiss sample (DR65-1) has radiogenic $^{87}\text{Sr}/^{86}\text{Sr}_i$ of 0.7097, unradiogenic $^{143}\text{Nd}/^{144}\text{Nd}_i$ of 0.5115, and very unradiogenic Pb ($^{206}\text{Pb}/^{204}\text{Pb}_i = 16.04$, $^{207}\text{Pb}/^{204}\text{Pb}_i = 15.29$ and $^{208}\text{Pb}/^{204}\text{Pb}_i = 36.69$; Figure 7).

5. DISCUSSION

5.1 Nature of the MOZR: Evidence for excess volcanism

The exact nature of the MOZR is controversial, and contradicting models (i.e., volcanic versus continental) have been proposed. DSDP Leg 25 (Site 249) on the MOZR northern plateau (Figure 1b) was the first sampling attempt of the plateau basement and Cretaceous tholeiitic rocks were recovered (Thomson et al., 1982). In contrast, several cruises in the late 1980s dredged continental crustal rocks (Figure 1b). Mougenot et al. (1991) dredged gneiss, metagabbros and anorthosites samples, with similar features to the nearby African cratons. Ben Avraham et al. (1995) described small rock fragments of garnet-bearing metapelites and gneiss along with fresh volcanic glass from a single location at the SW margin of the plateau. In the absence of radiometric ages, the glasses were interpreted to be very young (not more than tens of thousands years old). However, none of these studies could convincingly exclude a dropstone origin for the continental rocks recovered via dredging at four locations.

The new study at hand presents the first comprehensive basement sampling of the MOZR, which primarily recovered volcanic and volcanoclastic rocks (Uenzelmann-Neben, 2014). The gneiss sample (DR65-1), which has lower continental crust type isotopic composition, was recovered close to the northern plateau in an elongated block-like structure earlier identified as a continental block by Mougenot et al. (1991) and König and Jokat (2010). This structure is clearly separated from the MOZR plateau, as evident from bathymetric mapping (Fig. 5.53 in the cruise report; Uenzelmann-Neben, 2014). The exclusive association with other continental like rocks in dredge 65 (seven samples - DR65-2 to -8 - in Uenzelmann-Neben, 2014) suggests that DR65 sampled the talus at the base of a slope. Except for sample DR44-5, a rounded plutonic pebble interpreted as being an ice-rafted dropstone, surprisingly no other continental rocks were recovered during SO232. Another interesting sample is DR18-1 from the southern margin of the MOZR, which shows a microcrystalline structure in thin section indicative of a plutonic or subvolcanic origin. Its mantle-like geochemistry suggests that this dolerite formed in an oceanic setting. Numerous morphologic structures, such as small cones, scattered on the plateau, probably reflect late-stage volcanism, as they appear to intrude the sediment cover (Uenzelmann-Neben, 2014, Fischer et al., 2017).

In summary, although a few presumably in-situ continental rocks were found at the base of a morphologically separated ridge close to the northern plateau margin, extensive sampling of the entire exposed (upper) plateau basement and bathymetric data obtained during cruise SO232 provide strong evidence for a primarily volcanic origin of the MOZR. Moreover, no serpentinites or related rocks were recovered precluding the model of Zhou and Dick (2013) suggested for the nearby Marion Rise that such bathymetric highs could be exhumed altered mantle rocks.

5.2 Mantle source components at the Mozambique Ridge

At the southernmost end of the MOZR, an unusual depleted rock sample (DR21-1) was recovered from a seamount (Figure 1b). This sample is characterized by the lowest fluid-immobile incompatible element ratios (Figures 2-4) and depletion in MORB-like LREEs. Similarly, its isotopically depleted Sr-Nd-Hf ratios (Figure 6) and unradiogenic Pb along with the lowest $\Delta 7/4$ and $\Delta 8/4$ (Figure 5) indicate derivation from a depleted source. Considering that it was sampled at the lower edge of the SW plateau, it is possible that this sample is derived from uplifted ocean crust and thus provides us with an idea of the upper mantle composition close in time to the formation of the SW plateau but it does not necessarily represent a component involved in the formation of the MOZR. In contrast, the Tabletop Mountain samples have the most enriched Sr, Nd and Hf isotopic compositions, and the most elevated $\Delta 7/4$ (Figures 5, 6). Finally, the AGP samples plot at the depleted end of the Sr-Nd-Hf array (Figure 6) but have the most radiogenic Pb isotope ratios (Figure 5).

5.2.1 Comparison of the MOZR with (local) Indian Ocean sources (MORBs and OIBs)

The MOZR samples might be expected to have similar geochemical compositions with surrounding Indian intraplate (OIB) volcanoes (e.g. Bouvet, Crozet, Marion, and Prince Edward islands). Data from these Indian intra-plate volcanoes do not overlap with the MOZR data on Sr-Nd (Figure 6a), Nd-Hf (Figure 6b) and uranogenic Pb isotope diagrams (Figure 5a). The MOZR samples overlap with the SW Indian MORB field on Sr-Nd-Hf and on the

thorogenic diagrams, but have distinctively higher $\Delta 7/4$ compared to most SW Indian MORBs (Figure 5a). We also note that they have higher $\Delta 8/4$ at the unradiogenic end of the thorogenic Pb isotope diagram than local MORB (Figure 5b). These observations are surprising, especially when comparing nearby OIBs with the SW Indian MORBs, which overlap in all isotope systems. Therefore the source of the 130 Ma MOZR volcanism was different to what is now the source of SW Indian OIB volcanism.

5.2.2 Comparison of the MOZR with South Atlantic-type sources (MORBs and OIBs)

Elevated $\Delta 7/4$ values are a common feature of oceanic volcanic rocks in the southern hemisphere compared to those of the northern hemisphere (e.g., Dupré and Allègre, 1983). South Atlantic MORB has higher $\Delta 7/4$ but similar $\Delta 8/4$ compared to SW Indian MORB (Figure 5). However, the higher $\Delta 7/4$ occur primarily at the unradiogenic $^{206}\text{Pb}/^{204}\text{Pb}$ end of the MORB arrays, whereas the MOZR samples have elevated $\Delta 7/4$ for the entire $^{206}\text{Pb}/^{204}\text{Pb}$ range. Therefore the more radiogenic Pb component is likely to come from a distinct source (e.g., the subcontinental lithospheric mantle (SCLM) or a deep source) and thus excludes mixing of the two MORB domains to form the MOZR data array.

Ocean island volcanoes are thought to be products of mantle plumes (e.g. Richards et al., 1989). In classical models, the plumes rise from either the upper/lower mantle or mantle/core boundary (e.g. Courtillot et al., 2003). In the South Atlantic, the Tristan-Gough hotspot track, including the Walvis Ridge, Rio Grande Rise and the Paraná-Etendeka flood basalts, are a prominent example of plume volcanism being associated with continental break up (e.g. Hoernle et al., 2015, Stroncik et al., 2017, Homrighausen et al., 2019). Interestingly, the MOZR samples have similar Sr-Nd-Pb-Hf isotopic compositions to most of the Walvis Ridge (Figures 5, 6) and the Gough sub-track of the Guyot Province (Richardson et al., 1982, Gibson et al., 2005, Salters and Sachi-Kocher, 2010, Rohde et al., 2013a, Hoernle et al., 2015, Homrighausen et al., 2019). South of the Walvis Ridge, the Discovery Seamount chain (Schwindrofska et al., 2016) and Shona hotspot (Hoernle et al., 2016) have isotopic compositions that plot largely within the Gough component of the Tristan-Gough hotspot track (Figures 5, 6; Homrighausen et al., 2019). Although there is considerable overlap, overall the MOZR samples tend towards lower $\Delta 8/4$ than the South Atlantic array (Figure 5b), suggestive of a different geochemical “flavor” with lower long-term Th/Pb ratios (i.e.

resulting in lower $^{208}\text{Pb}/^{204}\text{Pb}$ ratios) but similar U/Pb ratios (i.e. resulting in similar $^{207}\text{Pb}/^{204}\text{Pb}$ ratios) and similar Sr-Nd-Hf isotope ratios.

The MOZR is located in the center of the so-called DUPAL anomaly (Dupré and Allègre, 1983, Hart, 1984) and the MOZR and AGP samples have typical DUPAL-like isotope signatures. The DUPAL anomaly is a geochemical domain located in the southern hemisphere, characterized by enriched isotopic compositions (radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and elevated $\Delta 7/4$ and/or $\Delta 8/4$). The origin of the DUPAL anomaly is still controversial, but many studies favor a recycled continental lithospheric component (lower crust and/or SCLM) to explain the enrichment. Two opposing recycling models exist to explain the formation of the DUPAL anomaly. The first envisions shallow recycling of the lower continental lithosphere through the asthenospheric mantle resulting from delamination of the SCLM during the breakup of Gondwana (Geldmacher et al., 2008, Hoernle et al. 2011). The second model argues for a deep origin of the enriched recycled lower continental lithospheric component that roots DUPAL in the African low shear velocity province (LLSVP; Castillo, 1988, Class and Le Roex, 2011, Rohde et al., 2013a, Hoernle et al., 2015, White, 2015). The models are not mutually exclusive and both shallow and deep recycling of SCLM $\pm$ lower crust are likely.

Over the last decade, new models have argued that the LLSVPs are the sources of mantle plumes forming CFBs (e.g., Paraná-Etendeka, Karoo; Figure 1a). Upwelling of hot material is postulated to have occurred at the margins of these long-lived thermo-chemical anomalies at the base of the lower mantle (Torsvik et al., 2006, 2008, Burke et al., 2008, Steinberger and Torsvik, 2012, French and Romanowicz, 2015). Plumes sampling the boundary of the African LLSVP may be responsible for the long-lived geochemical zonation of the 70 Ma Tristan-Gough and 40 Ma Discovery hotspots (Rohde et al., 2013a, Hoernle et al., 2015, Schwindrofska et al., 2016). The Gough-type EM-1 component, believed to be derived from the African LLSVP, is common to the Tristan-Gough, Discovery and Shona hotspot tracks (Homrighausen et al., 2019). Two other EM-1-type components (Tristan and Southern Discovery) may also be derived from the African LLSVP, suggesting that it is heterogeneous (Schwindrofska et al., 2016). The overlap of the MOZR on most isotope diagrams with the South Atlantic hotspot fields suggests that the MOZR source material could also originate from the African LLSVP.

HIMU-type lavas have also been documented at the Walvis Ridge (Homrighausen et al., 2018), which are 20-40 Ma younger than the Walvis basement. Therefore, the authors

suggested that the mantle plume source of Walvis volcanism first tapped the EM-1 component in the LLSVP, then late-stage volcanism tapped a different reservoir, possibly HIMU. The AGP samples have low $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratios of ca. 0.7028 and have more radiogenic Pb than the rest of the MOZR ($^{206}\text{Pb}/^{204}\text{Pb}_i > 18.72$; Figures 5-6). Based on geophysical data, the AGP is believed to be ~90 Ma-old, thus is ~30-40 Ma younger than the MOZR (Gohl et al., 2011). This observation may point toward similar mantle plume dynamics beneath the MOZR, where an EM-1 mantle component first dominates the geochemical signature, which then becomes more influenced by a HIMU-like mantle component. Another possibility for the higher $^{206}\text{Pb}/^{204}\text{Pb}$ component would be FOZO, an ubiquitous mantle component with isotopic compositions intermediate between the mantle end members (DM, EM1, EM2 and HIMU) that differs from HIMU by slightly less radiogenic Pb isotope signatures (Stracke et al., 2005). However clear mixing trends to either HIMU or FOZO are not observed in both thorogenic and uranogenic Pb isotope diagrams.

5.2.3 Comparison of the MOZR with subcontinental lithospheric mantle-type component

The enriched components, responsible for the MOZR geochemical variations, could also be present in the upper mantle. In other places such as the Christmas Island Seamount Province in the Eastern Indian Ocean, where there is no evidence for the presence of a long-lived mantle plume, it has been shown that shallow recycling of subcontinental lithospheric mantle (SCLM) can occur via off axis volcanism near mid-ocean ridges connected with continental rifting (Hoernle et al., 2011). Notably, the Christmas Island Seamount Province was formed in close connection with continental break-up and the movement of SCLM material $\pm$ lower crust. The delaminated lithospheric material then welled up beneath the newly formed spreading center and melted by decompression to form the Christmas Island seamounts and former ocean island volcanoes (now guyot seamounts). Enriched lavas have also been found on portions of the SW Indian Ridge (39-41°E, Mahoney et al., 1992) and the SE Indian Ridge (123-130°E, Hanan et al., 2004). Geochemically, SCLM is difficult to trace as it represents a reservoir beneath thick continental crust that is rarely tapped by magmatism. Lamproites and/or kimberlites are infrequent volcanic rocks that are only found on continents and are believed to derive from the SCLM (Fraser et al., 1985). They generally have very enriched Sr-Nd isotopic compositions but possess variable Pb isotope ratios, ranging from

highly radiogenic to highly unradiogenic $^{206}\text{Pb}/^{204}\text{Pb}$ ratios but generally elevated $^{207}\text{Pb}/^{204}\text{Pb}$ ratios (with the exception of e.g., the Smoky Butte lamproites, Fraser et al., 1985) and elevated $^{208}\text{Pb}/^{204}\text{Pb}$ ratios compared to N-MORB at a given $^{206}\text{Pb}/^{204}\text{Pb}$ ratio. Lamproites and kimberlites from Gondwana, i.e., Antarctica (Gaussberg; Murphy et al., 2002), South Africa (Finsch Mine; Fraser et al., 1985, Nowell et al., 2004) and Australia (Eastern and Western domain; Fraser et al., 1985, Nelson et al., 1986), all have higher Sr and lower Nd isotope ratios than the MOZR (Figure 7a) and lie on the extension of the Sr-Nd MOZR array. The Tabletop Mountain samples of the MOZR have the most enriched Sr-Nd-Hf isotopic compositions and the highest $\Delta 7/4$, which could be explained by higher amounts of SCLM in their magma source (Figure 7). On a Sr vs. Nd isotope diagram, any of these SCLM compositions would be suitable as an enriched end member for all these previously mentioned regions, except perhaps for the Eastern Australian lamproites. The Gaussberg samples lie almost on an extension of the MOZR array except on the uranogenic Pb isotope diagram (Figure 7). On both Pb-Pb isotope diagrams (Figures 7b-c), the Finsch Mine samples largely overlap the low $^{206}\text{Pb}/^{204}\text{Pb}_i$ end of the MOZR array. The Western Australia and Gaussberg samples have elevated $\Delta 7/4$ and $\Delta 8/4$ but none of the MOZR samples form a clear trend toward one of these compositions (Figures 7b-c). Overall, Smoky Butte or Leucite Hills (Mirnejad and Bell, 2006) have the closest EM-1 Pb isotope signature to serve as component for the unradiogenic end of the MOZR array. In conclusion none of the SCLM components alone can serve as mixing end member for the MOZR but a mixture of e.g. Leucite Hills $\pm$ Gaussberg lamproites could potentially serve as the end member with the appropriate unradiogenic Pb isotope composition.

Summarizing the last two sections, we note that the isotope and fluid-immobile incompatible-element ratios (Figures 3-7) could be explained by mixing of three components:

- (1) A component depleted in trace elements and similar to N-MORB (=D-MOZ), with low $^{87}\text{Sr}/^{86}\text{Sr}$, $\Delta 7/4$ and $\Delta 8/4$, and high $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios, is most likely similar to the composition of the ambient depleted upper mantle (possibly SW Indian MORB). This component is best represented by the seamount sample DR21-1.
- (2) A component with low $^{87}\text{Sr}/^{86}\text{Sr}$ but radiogenic Pb isotopic ratios (=F-MOZ), broadly similar to a FOZO- or HIMU-like component (Hart et al., 1992, Stracke et al., 2005). This component is best represented by the AGP samples.

(3) A component with elevated $^{87}\text{Sr}/^{86}\text{Sr}$ and $\Delta 7/4$, low $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (=EM-MOZ), similar to the EM-1 composition. This component is most clearly observed in the MOZR Tabletop Mountain samples. Such source material could reflect either mixtures of different SCLM end member compositions transferred into the upper oceanic mantle by delamination during continental breakup (Hoernle et al., 2011) or EM/DUPAL deep mantle sources, as observed for South Atlantic hotspot volcanics (Rohde et al., 2013a, Hoernle et al., 2015, 2016, Schwindrofska et al., 2016, Homrighausen et al., 2019).

5.3 Geodynamic implications

LIPs are often associated with continental breakup (e.g., the Greenland-North Atlantic Magmatic Province in the North Atlantic, and the Paraná and Etendeka regions on both sides of the South Atlantic Ocean; Coffin and Eldholm, 1994, Courtillot et al., 1999). Jokat et al. (2004) and Eagles and König (2008) classified the Dronning Maud Land margin and its African counterpart as volcanically rifted margins. Initial opening of the southern Ocean occurred 184-171 Ma ago (Nguyen et al., 2016), and some authors have related the breaking up of Eastern Gondwana to the 183 Ma Karoo CFB event (Courtillot et al., 1999, Dalziel et al., 2000). Moreover, Mueller and Jokat (2017) estimated that the volcanic activity related to the Gondwana breakup along the central coast of Mozambique could have lasted until 157 Ma but then ceased due to southward motion of the magmatism.

In light of the new geochemical data from the MOZR, we will now address the question of how the 140-120 Ma-old MOZR fits into the geodynamic evolution of the Southern Ocean and the breakup of Gondwana. In the following sections, we will first investigate potential links between the Karoo CFB and the MOZR before discussing the preferred model for the formation of the volcanic basement of the MOZR.

5.3.1 Karoo CFB geological setting and geochemistry

The Karoo CFB province, which extends from South Africa to Botswana and Mozambique, was formed by extensive volcanism between 183-178 Ma-ago (e.g., Jourdan et al., 2005). The Karoo volcanism has typical intraplate geochemical characteristics with a strong crustal and/or subcontinental lithospheric mantle component in the erupted tholeiitic rocks (e.g., Hawkesworth et al., 1984, Sweeney et al., 1994, Jourdan et al., 2007). Some authors suggest that the Karoo source contained small amounts of sediment and/or a weak subduction component (e.g., Jourdan et al., 2007, Neumann et al., 2011, Heinonen et al., 2014). Karoo-related outcrops are also found in the western Dronning Maud Land of Antarctica (Vestfjella) and the samples are mostly high MgO picrites, picrobasalts and basalts. They are believed to be free of crustal interaction and therefore may provide insights into the sub Gondwanan mantle reservoir from which they were extracted (e.g. Heinonen and Luttinen, 2008, Heinonen and Kurz, 2015, Riley et al., 2005, Heinonen et al., 2010, 2013, 2014, 2015,). Two main source components are observed: a depleted component similar to the SW Indian MORB, and a relatively enriched component that may be associated with a pyroxenitic source, which is based on high Ni contents in olivine, high whole-rock Zn/Fe ratios and low whole-rock CaO contents (Heinonen et al., 2013). On the other hand, Coltice et al. (2009) proposed, and demonstrated through modeling, that long-lived mantle insulation beneath super continents such as Gondwana leads to extreme internal heating below the continental lithosphere and can trigger melting without the presence of a plume. Their numerical model was successfully applied to the Karoo CFB. Nonetheless some authors favor the plume model hypothesis based on geophysical data, which shows a plume currently beneath southern Africa extending to the African LLSVP (Torsvik et al., 2006, 2008). However, Heinonen and Kurz (2015) analyzed the most magnesian-rich lavas from the Karoo and showed that the $^3\text{He}/^4\text{He}$ isotopic ratios ($R/R_a = 7.03 \pm 0.23$) are similar and undistinguishable from the SW Indian MORBs ($R/R_a = 6.4-7.6$). They concluded that, although a mantle plume cannot be totally excluded, a mantle insulation model seems more appropriate. However, the lack of an elevated $^3\text{He}/^4\text{He}$ (i.e., >upper mantle values) does not rule out the presence of a plume. As shown by Stroncik et al. (2017) for the Etendeka flood basalts, only very rare picritic samples preserve elevated (>10) $^3\text{He}/^4\text{He}$ ratios and most of the mafic rocks from Etendeka also have MORB-like $^3\text{He}/^4\text{He}$ ratios.

5.3.2 Relationship of the MOZR with the Karoo CFB

The MOZR data are now compared with published literature data from the Karoo-Vestfjella CFB (Figure 7). The African Karoo data overlap with the MOZR data but extends towards much more enriched compositions, e.g. higher Sr, and lower Nd and Pb isotope ratios, which are typical for rocks interacting with the continental lithosphere (crust and/or SCLM). The MOZR data plot at the depleted end of Sr-Nd isotopic array, overlapping the Vestfjella data which are believed to represent the pristine mantle reservoir with little to no continental lithospheric influence. On the Pb isotope diagrams, both Karoo and Vestfjella data deviate towards lower $^{206}\text{Pb}/^{204}\text{Pb}_i$, $^{207}\text{Pb}/^{204}\text{Pb}_i$, and $^{208}\text{Pb}/^{204}\text{Pb}_i$ ratios. The MOZR data could represent the sublithospheric source mantle with no or little continental influence, similar to what has been proposed for the extreme variations seen in the Paraná-Etendeka CFB, i.e., interaction between the Tristan-Gough plume and the African lithosphere. For Etendeka (Africa) and Paraná (South America), it has been shown that Sr isotope ratios increase and Nd isotope ratios decrease with increasing degree of lava differentiation, consistent with crustal assimilation (Hoernle et al., 2015 and references therein). Pb isotope ratios also show evidence of continental lithospheric assimilation in more evolved samples. The most mafic Etendeka and Parana samples overlap completely with the submarine lavas from the Tristan-Gough-Walvis hotspot track and samples with high $^3\text{He}/^4\text{He}$ ratios (Stroncik et al., 2017) have compositions similar to the submarine samples from the hotspot track. Therefore there is strong evidence that the Paraná/Etendeka CFBs were formed by a mantle plume from the lower mantle which interacted with the Gondwana continental lithosphere. Considering the similarities in the composition and compositional range of the Etendeka/Parana and the Karoo/Vestfjella CFBs, it is likely that the Karoo/Vestfjella CFBs formed by a similar process. Plate tectonic reconstructions, however, do not place the Karoo/Vestfjella CFBs near the MOZR or on an extension of it, but rather in the vicinity of the Shona hotspot track (Figure 1a; see Torsvik et al., 2008 for further explanations), which has a similar composition to the Walvis Ridge and thus could serve as a depleted (plume) end member for the Karoo/Vestfjella CFBs, with the two enriched components reflecting interaction with the upper and lower Gondwana continental crust and/or lithospheric mantle.

5.3.3 Nature and origin of the MOZR

The new geochemical data from the igneous portions of the MOZR and comparison with literature data suggests mixing of at least two components: an enriched continental type material similar to EM-1 (EM-MOZ) and a component with high Pb isotope ratios similar to FOZO/HIMU (F-MOZ). Although the MOZR array forms a two-component mixing on the Sr-Nd-Hf isotope diagrams (Figure 6), a third component (D-MOZ), reflecting the ambient SW Indian upper mantle, is likely to be present on the Pb isotope diagrams (Figure 5). It would explain the spread of the data in $\Delta 7/4$ and $\Delta 8/4$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$, which deviates from the upper mantle toward more enriched compositions. This spread could be explained if the MOZR was formed through interaction of a spreading ridge with plume or SCLM material. We can model the MOZR array by mixing the F-MOZ with EM-MOZ components (Figure 8; Supplementary Table B8). In addition, the D-MOZ could be mixed with any proportion of the F-MOZ-EM-MOZ mixing. Two types of models are envisaged to achieve mixing and melting the EM-MOZ component with the F-MOZ component: A) Shallow (within the upper mantle), or B) deep (within the lower mantle, possibly LLSVP) through recycling of the enriched component(s). In A), the EM-MOZ component could be similar to different lamproitic compositions, e.g. Leucite Hills-type or Gaussberg-type. On the Sr vs Nd (Figure 8a) and thorogenic Pb isotope diagram (Figure 8c), less than 10% of a Gaussberg-type composition would explain the MOZR array. However, a Leucite Hills-type end member is needed to explain the uranogenic diagram (Figure 8b). Therefore, none of these lamproitic compositions work on all the diagrams. Of course, the SCLM beneath the MOZR at the time of formation could be a mixture of these SCLM compositions. In B), the EM-MOZ component could be similar to the EM-1 component sampled by South Atlantic hotspots, tapping different reservoirs of the LLSVP (Homrighausen et al., 2019). When choosing a composition close to the low- μ Gough described in Homrighausen et al. (2019), mixing lines nicely overlap the MOZR data on all isotope diagrams (Figures 8d, e, f). We note, however, that the isotopic composition of these end member could be much more different, as the LLSVP is likely to be heterogeneous (e.g. Balmer et al., 2016). Therefore, the amount of enriched material added is likely to significantly change. Finally, although we favor a FOZO-like end member, an HIMU-like end member appears to be a possible mixing candidate, since the Walvis-HIMU data lie on an extension of the MOZR array. In contrast to the Walvis Ridge, however, no true HIMU signature has been sampled in the MOZR-AGP system.

The shallow recycling model involves delamination of the subcontinental lithospheric mantle (SCLM) $\pm$ lower crust during continental breakup in the Cretaceous, followed by successive upwelling and melting of the continental material beneath or near the mid-ocean ridge. The MOZR could have formed at, or near, the SW Indian mid-ocean ridge, since it is located on the Andrew Bain Fracture Zone (König and Jokat, 2010). This model is roughly similar to that proposed for the origin of the Christmas Island Seamount Province (Hoernle et al., 2011), except that a larger volume of excessive volcanism was produced over a smaller region at the MOZR compared to the Christmas Island Seamount Province. The MOZR could have formed at, or near, the SW Indian mid-ocean ridge, since it is located on the Andrew Bain Fracture Zone (König and Jokat, 2010). Still this hypothesis does not account for the fact that excessive volcanism occurred at the MOZR over a relatively short period of 10 Ma in a fairly restricted area (450 x 450 km, i.e., ca. $0.15 \times 10^6 \text{ km}^2$; Fisher et al., 2017), in contrast to the Christmas Island Seamount Province which formed over a much longer period (136-47 Ma) and covered a fivefold larger area (1,800 x 600 km, i.e. ca. $1 \times 10^6 \text{ km}^2$; Hoernle et al., 2011) at apparently much lower volumes. In conclusion, formation of the MOZR through shallow recycling of SCLM would require high volume channelized flow of such material into the ocean realm over a limited period unlike low volume detachment of SCLM over longer periods as proposed for the Christmas Island Seamount province (Hoernle et al., 2011).

The second model calls upon the recycling of enriched continental material through the lower mantle via subduction, possible storage in the deeper mantle (e.g., LLSVP), and its return to the surface via a mantle plume fed from the LLSVP. Geophysical studies suggest that other structures in the South African gateway (AGP, Maud Rise, and Georgia Rise in the South Atlantic) could belong to a single magmatic unit, referred to the African Super LIP (e.g., Gohl and Uenzelmann-Neben, 2001, König and Jokat, 2010, Parsiglia et al., 2008, Gohl et al., 2011). The MOZR displays LIP characteristics such as large volume ($3.1 \times 10^6 \text{ km}^3$) and aerial extent ($0.15 \times 10^6 \text{ km}^2$) comparable to other oceanic plateaus (Fischer et al., 2017). According to Bryan and Ernst (2008), a LIP is characterized by short pulses ($\sim 1\text{-}5 \text{ Ma}$) with a maximal lifespan of $\sim 50 \text{ Ma}$. Fisher et al. (2017) demonstrated that the timing of emplacement was short (10 Ma) with several magmatic pulses forming the sub-plateaus. Moreover, most of the MOZR samples have elevated TiO_2/Yb ratios suggestive for deep melting (Figure 3a, Pearce, 2008). The MOZR samples that trend toward the shallow melting field may indicate plume-ridge interaction (Pearce, 2008) a likely scenario considering

formation of the MOZR shortly after continental breakup. The mantle plume hypothesis can also better explain the positive bathymetric anomaly and excess volume of magmatism produced to form the MOZR, and the similarity between the radiogenic isotopic compositions (EM-1 type) with nearby South Atlantic volcanic structures and southern African CFBs. The good to excellent age progressions of the Tristan-Gough, Discovery and Shona hotspot tracks in the South Atlantic and evidence for high $^3\text{He}/^4\text{He}$ ($>10 R_A$) in the Etendeka flood basalts (Stroncik et al., 2017) and in lavas from the SMAR adjacent to the Discovery and Shona hotspot tracks provide strong support that these volcanic tracks were formed by mantle plumes (O'Connor et al., 2012; Rohde et al., 2013b; O'Connor and Jokat, 2015; Schwindrofska et al., 2016). Plate reconstructions for the formation of the MOZR suggests a southerly directed younging of the direction of plate motion, which is also consistent with formation from a mantle plume (Fischer et al., 2017). Therefore the similarity in EM-1 type composition of the MOZR to the Tristan-Gough, Discovery and Shona hotspot tracks, and to the more depleted end of the Etendeka/Paraná and Karoo/Vestfella CFBs, is consistent with derivation of all these volcanic tracks and provinces from mantle plumes that originated from the margins of a chemically heterogeneous EM-1 type African LLSVP reservoir (Figure 1a).

6. CONCLUSIONS

This study presents the first comprehensive geochemical data set (major and trace elements, and Sr-Nd-Pb-Hf isotopes) from an extensive sampling campaign (SO232) of the Mozambique Ridge. We conclude the following:

(1) The evidence for a volcanic nature for the MOZR is clearly supported by material recovered through dredging during the SO232 cruise. With the exception of exclusively continental material from a suspect continental block immediately north of the MOZR, volcanic rocks were recovered across the entire MOZR. The recovered samples, combined with estimated volumes ($3.1 \times 10^6 \text{ km}^3$) and aerial extent ($0.15 \times 10^6 \text{ km}^2$) (Fisher et al., 2017), are consistent with the MOZR being a LIP.

(2) The geochemical data are consistent with the MOZR lavas being derived through mixing of a FOZO-like and enriched (delaminated continental lithospheric $\pm$ lower continental crustal) sources. The MOZR has an EM-1-type geochemical flavor similar to the Tristan-Gough-Walvis, Discovery and Shona hotspot tracks that are interpreted to have been

formed by mantle plumes beneath the South Atlantic (Rohde et al., 2013a, Hoernle et al., 2015, 2016, Schwindrofska et al., 2016). The MOZR, however, has lower $\Delta 8/4\text{Pb}$ than the aforementioned locations, indicating lower time-integrated source Th/Pb ratio.

(3) The MOZR data plot at the depleted end of the Etendeka/Paraná and Karoo/Vestfella CFB arrays.

(4) Combined with recent studies (Fisher et al., 2017), the new data suggests two possible models: Formation of the MOZR from (1) channelized transfer of subcontinental lithospheric material to the mid-ocean ridge during continental break-up, in contrast to dispersed, low volume outflow of such material as proposed for the Christmas Island Seamount Province (Hoernle et al. 2011), or 2) a deep-seated mantle plume, derived from the African LLSVP, which has also been proposed for the South Atlantic EM-1-type hotspots and the CFBs. The overall LIP characteristics (aerial extent, volume, and timing), the excessive crustal thickness, the (although vague) spatial age progression during plateau formation, and the geochemical similarities with South Atlantic hotspots are indicative for a mantle plume to have caused formation of the MOZR.

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FIGURE CAPTIONS

Note: Color should not be used in the print version

Figure 1

(a) Regional map showing the South African gateway (modified from Torsvik et al., 2008). White labels show some of the prominent bathymetry anomalies mentioned in the paper. The black box shows the location of the Mozambique Ridge (MOZR). The orange circle shows the approximate location of dredges performed on the Agulhas Plateau (AGP). The white dotted line shows the approximate location of the Andrew Bain Fracture zone (see König and Jokat, 2010 for further details). The dark grey lines show the 1% slow contour of the African LLSVP. The two green circles show the reconstructed LIP eruption sites for Karoo (KR) and Paraná-Etendeka (P-E) discussed in the paper. (b) Bathymetric map showing the SO232 dredge locations (blue circles = tholeiites; red circles = alkali basalts; brown squares = Tabletop Mountain). The purple stars and yellow triangle show the dredge locations of recovered continental blocks (Mougenot et al., 1991, Ben Avraham et al., 1995). The red square with a cross in it is the continental-like sample recovered from an elongated block distinct from the main plateau. The blue square shows the location of DSDP Leg 25 Site 249 (Simpson, 1974).

Figure 2

Nb/Y versus Zr/Ti classification diagram (after Pearce, 1996), showing the geochemical range of the recovered samples during cruise SO232. The samples are overall very mafic, ranging from basalt to alkali basalt. One sample (DR34-1; blue diamond with a bar in it) is more evolved with $\text{SiO}_2 = 70$ wt. % and plots within the trachyte field. The blue star denotes DR21-1, the most depleted sample analyzed.

Figure 3

(a) Nb/Yb versus TiO_2/Yb diagram after Pearce (2008). The MOZR tholeiites reflect a mixture of shallow and deep melting material. Moreover, they form a separate trend from the alkali basalts. The arrow represent the plume-ridge interaction as shown in Pearce (2008).

Note that trachyte DR34-1 plots at the lower limit TiO_2/Yb due to fractionation of Ti bearing mineral phases. (b) Nb/Yb versus Th/Yb diagram after Pearce (2008). All samples fall on the mantle array, except the Tabletop Mountain samples and one alkali basalt sample, which have slightly elevated Th/Yb ratios. The tholeiites show E-MORB compositions, but the alkali basalts tend to OIB type compositions. DR21-1 has an N-MORB type composition. The solid squares represent the three end members of Pearce (2008). The red square with a cross is the gneiss sample (DR65-1) with continental affinities.

Figure 4

Primitive-mantle normalized immobile incompatible element diagram (Hofmann, 1988) showing (a) the tholeiites from the MOZR plateau and the Tabletop Mountain, and (b) the alkali basalts, AGP plateau and continental sample DR65-1. The mafic samples have compositional characteristics between those of OIB and E-MORB. The alkali basalts have steeper slopes than the basalts.

Figure 5

$^{206}\text{Pb}/^{204}\text{Pb}_{130\text{Ma}}$ versus (a) $^{207}\text{Pb}/^{204}\text{Pb}_{130\text{Ma}}$ and (b) $^{208}\text{Pb}/^{204}\text{Pb}_{130\text{Ma}}$. The Pb isotope ratios are typical for DUPAL-like volcanism with high $\Delta 7/4$ and $\Delta 8/4$. Almost all MOZR samples have higher $\Delta 7/4$ than the nearby Indian Ocean OIBs or SW Indian MORB field but overlap the field for the Walvis Ridge and other S Atlantic hotspots. The samples have similar $\Delta 8/4$ to the SW Indian OIBs and MORBs but extend to lower $\Delta 8/4$ than the Walvis Ridge and Discovery Seamounts but largely overlap the field for the Shona hotspot track. The Walvis Ridge data are from Rohde et al. (2013a), Hoernle et al. (2015), and Homrighausen et al. (2018, 2019). The Discovery Seamounts data are from Schwindrofska et al. (2016). Shona data are from Hoernle et al. (2016). Data sources for MORBs and OIBs are from PetDB (<http://www.earthchem.org/petdb/>) and Georoc (<http://georoc.mpch-mainz.gwdg.de/georoc/>) (Complete references in Supplementary File C). SW Indian MORB (39-41°E) values are from Mahoney et al. (1992). NHRL = Northern Hemisphere Reference Line from Hart (1984). The dashed field and the arrow represent the location of 130 Ma-corrected FOZO/HIMU end members of Stracke et al. (2005). All Literature data are also projected to 130 Ma.

Figure 6

(a) $^{87}\text{Sr}/^{86}\text{Sr}_{i_{130\text{Ma}}}$ versus initial $^{143}\text{Nd}/^{144}\text{Nd}_{i_{130\text{Ma}}}$ of the MOZR samples form a negative correlation ($r^2 = 0.74$), consistent with two-component mixing between a depleted and an enriched source. The Tabletop Mountain samples, as well as one basalt and one alkali basalt, have the most enriched isotopic compositions, whereas basalt sample DR21-2 has the most depleted composition. The compositional range of the MOZR is similar to the SW Indian and S Atlantic MORBs, nearby OIBs and the Walvis Ridge. (b) $^{143}\text{Nd}/^{144}\text{Nd}_{i_{130\text{Ma}}}$ versus $^{176}\text{Hf}/^{177}\text{Hf}_{i_{130\text{Ma}}}$ form a positive correlation ($r^2 = 0.64$), overlapping the SW Indian and S Atlantic MORB fields. Data sources are the same as Figure 5. All Literature data are projected to 130 Ma.

Figure 7

(a) $^{87}\text{Sr}/^{86}\text{Sr}_{i_{130\text{Ma}}}$ versus $^{143}\text{Nd}/^{144}\text{Nd}_{i_{130\text{Ma}}}$, (b) $^{206}\text{Pb}/^{204}\text{Pb}_{i_{130\text{Ma}}}$ versus $^{207}\text{Pb}/^{204}\text{Pb}_{i_{130\text{Ma}}}$ and (c) $^{206}\text{Pb}/^{204}\text{Pb}_{i_{130\text{Ma}}}$ versus $^{208}\text{Pb}/^{204}\text{Pb}_{i_{130\text{Ma}}}$. In all three diagrams, the Karoo samples extend to much more extreme isotopic compositions (e.g. radiogenic Sr and unradiogenic Pb), which is typical for magma interaction with continental lithosphere. The mantle source responsible for the Karoo volcanism could be the same for the MOZR and AGP (excluding continental crust interaction). Alternatively, SCLM similar in composition to Finsch Mine, South Africa and Smoky Butte lamproites/kimberlites could represent possible enriched end members. Data source for Karoo-Vestfjella are from Hawkesworth et al. (1984), Sweeney et al. (1994), Jourdan et al. (2007), Neumann et al. (2011), Heinonen and Luttinen (2008), Heinonen et al. (2010, 2013, 2014). Data from lamproites/kimberlites are from Fraser et al. (1985), Nelson et al. (1986), Murphy et al. (2002), and Nowell et al. (2004). All Literature data are projected to 130 Ma.

Figure 8

(a; d) $^{87}\text{Sr}/^{86}\text{Sr}_{i_{130\text{Ma}}}$ versus $^{143}\text{Nd}/^{144}\text{Nd}_{i_{130\text{Ma}}}$, (b; e) $^{206}\text{Pb}/^{204}\text{Pb}_{i_{130\text{Ma}}}$ versus $^{207}\text{Pb}/^{204}\text{Pb}_{i_{130\text{Ma}}}$, and (c; f) $^{206}\text{Pb}/^{204}\text{Pb}_{i_{130\text{Ma}}}$ versus $^{208}\text{Pb}/^{204}\text{Pb}_{i_{130\text{Ma}}}$. The diagrams show that the MOZR array can be explained by a two-component mixing between two end members: F-MOZ (orange stars) and variable EM-MOZ (geochemical composition in Supplementary Table B8). Model A: mixing lines between F-MOZ and E-MOZ represented

by two types of lamproitic compositions, (1) Gaussberg-type (light grey lines and stars) or (2) leucite Hills-type (dark grey lines and stars). None of them fits as unique end member in multi Pb-Pb isotope space nor does a mixture of them. Model B: mixing lines between F-MOZ (orange stars) and a Walvis-type composition (black lines and stars) representing the E-MOZ end member. The SW Indian MORB (D-MOZ, dashed field) may play an additional role, especially in Pb isotopes (grey arrows) to cause deviation from the mixing lines. Each increment are 10%.

Figure 1

Figure 2

Figure 3

Figure 3

Figure 4

Figure 4

Figure 5

Figure 5

Figure 6

Figure 6

Figure 7

Figure 7

Figure 8