Geochemistry of Etendeka magmatism: Spatial heterogeneity in the Tristan-Gough plume head

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Abstract

The origin and distribution of geochemically distinct source components in continental flood volcanism (generally associated with the initial phase of a mantle plume head) are poorly understood. Here we present new geochemical (major and trace element and Sr-Nd-Pb-Hf isotope) data from the Etendeka flood basalts and associated dikes from northern and central Namibia that are believed to have been produced during the initial stage of the Tristan-Gough hotspot. Following earlier studies, the Etendeka lava flows and dikes are divided into high-Ti and low-Ti groups. The trace element and isotopic composition of the high-Ti tholeiitic basalts, exclusively outcropping in northern Etendeka (northwestern Namibia), are similar to the Gough-type enriched mantle I (EMI) composition found on the Walvis Ridge (the Atlantic type locality for the EMI end member). The low-Ti tholeiitic basalts, primarily outcropping in Southern Etendeka (central western Namibia), have higher $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ but lower $^{208}\text{Pb}/^{204}\text{Pb}$ ratios than the Gough composition. Combining our data with newly published $^3\text{He}/^4\text{He}$ data and estimates of the magma source's potential temperature from 1520-1680°C, we conclude that the source of the low-Ti basalts was also intrinsic to the Tristan-Gough plume, consistent with a spatially-

zoned plume head. The low-Ti basalts were derived from a distinct EMI-type source component that has thus far only been detected in the initial Tristan-Gough plume head (~132 Ma), but not the later submarine hotspot track.

Keywords: Sr-Nd-Pb-Hf isotope ratios; Etendeka flood basalts; Large Igneous Province (LIP); Namibia; plume zonation; Gough

1. Introduction

The South Atlantic is considered a classic example of continental breakup associated with large-scale magmatism, resulting in conjugate large igneous provinces. The magmatism comprises the voluminous Paraná - Etendeka flood basalts in Brazil and Namibia, and the submarine Rio Grande Rise and Walvis Ridge oceanic plateaus in the South Atlantic (e.g. Renne et al., 1996; Rohde et al., 2013b; Hoernle et al., 2015; O'Connor and Jokat, 2015; Homrighausen et al., 2019). A chain of volcanic ridges and seamounts ("Guyot Province") further links the Walvis Ridge with the Gough and the (volcanically active) Tristan da Cunha Island groups (Figure 1). Accordingly, the entire magmatism is commonly attributed to the Tristan-Gough hotspot, whose initial "plume head" stage is believed to have created the Paraná-Etendeka flood basalts contemporaneous with continental breakup between Africa and South America. The Rio Grande Rise and Walvis Ridge were subsequently formed largely through plume-ridge interaction while the plume was located close to the young Mid-Atlantic Ridge. After several ridge jumps split the Rio Grande from the Walvis Ridge, continuing volcanism above the presumed plume tail formed the Guyot Province on the African Plate. This classic example of the plume head / plume tail hotspot model is supported by a systematic age progression along the hotspot track (Homrighausen et al., 2019; O'Connor and Jokat, 2015; Rohde et al., 2013b) initiated with Paraná and Etendeka volcanism at 135-129 Ma (Renne et al., 1996).

Although the Tristan-Gough hotspot system represents one of the few examples that exhibits a clear spatial and temporal link between a presumed mantle plume head and tail, the evolution from initial LIP to hotspot track volcanism is poorly constrained and even the involvement of a mantle plume in the initial Etendeka flood basalt magmas is disputed. A number of studies have suggested a largely passive role for the plume i.e. merely facilitating melting of subcontinental lithospheric mantle (SCLM) by conductive heating (Erlank et al., 1984). In contrast, Ewart et al. (2004a) explained the geochemical composition of the Etendeka melts as a mixture of the modern Tristan da Cunha ocean island source, subducted material, and asthenosphere with a crustal contaminant. Hoernle et al. (2015) argued that the large range in chemical composition of both flood basalt provinces could largely be explained by plume melts with a Gough-type composition assimilating continental lithosphere (upper and lower crust and lithospheric mantle). Isotopically enriched lavas with elevated $\delta^{74}\text{Pb}$ but low $\delta^{84}\text{Pb}$ ratios have been recognized in southern Etendeka (Ewart et al., 1998; Gibson et al., 2000; Owen-Smith et al., 2017; Thompson et al., 2001), but their origin and relationship to the main phase of the plateau has remained unclear thus far.

This study presents new major and trace element and Sr-Nd-Hf-Pb (double spike) isotope data from mafic Etendeka flood basalts and feeder dikes sampled at a variety of locations in northwestern Namibia to evaluate their compositional relationship to the marine parts of the Tristan-Gough hotspot track. Although Thompson et al., (2007) have published Hf isotope data for dikes near Spitzkoppe, this study is the first to present Hf isotope data for Etendeka lavas, as well as for dikes. We show that the contemporaneously-erupted low- and high-Ti basalts are derived from two spatially distinct plume components derived from the lower mantle, suggesting that the initial (plume head) stage of the Tristan-Gough plume is likely to have been spatially zoned in geochemical composition.

2. Geological background and previous research

Although the heavily eroded Etendeka volcanic succession in NW Namibia only comprises ~6 % of the present-day combined Paraná-Etendeka large igneous province (Miller, 2008), the remaining lavas and intrusions are well-exposed and have been the subject of detailed studies (Erlank et al., 1984; Ewart et al., 1998; Ewart et al., 2004a; Gibson et al., 2000; Marsh et al., 2001; Milner et al., 1995; Owen-Smith et al., 2017; Stroncik et al., 2017; Thompson et al., 2001). Further south, where uplift and erosion has been more extensive, a dense network of feeder dikes is exposed (Figure 1), including the Henties Bay – Outjo dike swarm (Keiding et al., 2013), and the Horingbaai coastal dikes (Thompson et al., 2001). According to these studies, the Etendeka igneous rocks can be divided into high- and low-TiO₂ groups (Erlank et al., 1984). North of a transition zone between Möwe and Terrance Bay (Figure 1), where both types are present, the lavas are predominantly mafic and have high TiO₂ contents (> 2.2 wt.% TiO₂). South of the Möwe and Terrace Bay transition zone, all lavas, ranging from mafic to highly evolved compositions, have low-TiO₂ contents (< 2.2 wt.% TiO₂; Bellieni et al., 1984; Ewart et al., 2004b; Marsh et al., 2001). This division was further constrained using additional commonly-analyzed incompatible elements, such as Zr, Y and Sr (Marsh et al., 2001). Several previous studies have recognized variable extents of crustal contamination in the Etendeka magma suites, in particular in the low-Ti successions (Erlank et al., 1984; Ewart et al., 1998).

Based on their geochemistry, the mafic rocks of the Etendeka province were grouped by Marsh et al. (2001) into five extrusive basaltic and at least three intrusive units (e.g. doleritic dikes, sills and plugs). Equivalent units are recognized in the Paraná (Marsh et al., 2001). Only one high-Ti magma type (*Khumib*) has been defined in the Etendeka, which is exclusively confined to and dominates northern Etendeka (north of the transition zone). The low-Ti units of southern Etendeka can be largely distinguished by their different Zr/Y ratios. The low-Ti *Tafelberg* type, ranging from tholeiitic basalts to andesites, is the most common and voluminous and occurs throughout the southern Etendeka province.

The low-Ti *Tafelkop basalt* type, characterized by low Ti and Zr and high Ti/Zr, is believed to contain the highest proportion of plume-derived material in its magma source (Ewart et al., 2004a; Ewart et al., 1998). The Tafelkop basalts occur near the base of the volcanic succession in central southern Etendeka and there is compelling geochemical evidence that they are related to the nearby Doros intrusive complex (Marsh et al., 2001; Owen-Smith et al., 2017). Magmas with Tafelberg, Khumib and other compositions also form dikes and intrusions. For some intrusive units, however, an assignment to erupted equivalents is unclear. This includes the *Horingbaai dolerites*, with only slightly enriched incompatible-element compositions similar to enriched mid-ocean-ridge basalt (E-MORB), which are therefore widely believed to reflect an asthenospheric contribution to the Etendeka magmatism (Erlank et al., 1984; Ewart et al., 2004a). Modeling of the parental liquid composition for some picritic Horingbaai dikes, however, yielded a komatiitic composition produced by a mantle with a potential temperature of 1520 - 1680°C (Jennings et al., 2019 and references therein). By comparing different modeling approaches, Thompson et al. (2001) concluded that the Horingbaai magmas were generated within a mantle plume bringing up hot mantle from depth.

In addition to the mafic units, several geochemically distinct latite and quartz latite units (which were used for correlations with rhyolite units in the Paraná; Milner et al., 1995) overlie the main basaltic lava sequences and contain minor amounts of interbedded basaltic lavas (Ewart et al., 2004b). Since both high- and low-Ti mafic and silicic units are intercalated in the north and the transition zone, and only low-Ti mafic and silicic units are present in southern Etendeka (Marsh et al., 2001), the spatial differences in composition suggest a fundamental petrogenetic or structural difference between both areas. The marked provinciality of the magma types appear to hamper a stratigraphic correlation of the igneous sequences in Etendeka (Marsh et al., 2001). Correlations between adjacent portions of Etendeka and Paraná, however, have been more successful than between north and south Etendeka (Erlank et al., 1984; Milner et al., 1995; Marsh et al., 2001; Ewart et al., 2004a, Ewart et al., 2004b).

Whereas Tafelberg (mainly in southern Etendeka) and Khumib (exclusively in northern Etendeka) lava flows are intercalated in northern and transitional Etendeka, the Tafelkop and Horingbaai magma types are restricted to southern Etendeka. Radiometric age determinations of the different low-Ti mafic igneous (extrusive and intrusive) units presented in numerous studies yield largely overlapping ages between 135 and 125 million years (see compilation in Appendix A). Although no radiometric ages are available from mafic high-Ti basaltic lavas, a quartz latite with clear high-Ti affinities from southern Angola (Ewart et al., 2004b) was dated at 132 ± 0.4 Ma (Renne et al., 1996), providing a minimum age for the underlying intercalated low- and high-Ti basaltic lavas. The southern Etendeka igneous units were emplaced on/intruded into Neoproterozoic basement rocks, as well as metasedimentary and igneous rocks of Damara orogenic belt (Neoproterozoic; Miller, 2008). The northern Etendeka units were emplaced on a Paleoproterozoic basement as well as metasedimentary and igneous rocks of Kaoko orogenic Belt (Neoproterozoic; Miller, 2008 and references therein). In conclusion, high- and low-Ti basaltic (as well as silicic) igneous units appear to have formed contemporaneously, despite the spatial variations in geochemistry with high-Ti (Kumib) basalts restricted to northern and transitional Etendeka, whereas only low-Ti mafic igneous rocks (lavas, dikes and intrusions) outcrop in southern Etendeka.

After emplacement of the Etendeka flood basalts (135-129 Ma; Renne et al., 1996), the mantle plume interacted with the incipient Mid Atlantic Ridge, forming the aseismic Walvis Ridge on the African Plate and the Sao Paulo Plateau and Rio Grande Rise on the South American Plate between ~120 and 60 Ma (Homrighausen et al., 2019; O'Connor and Jokat, 2015; Rohde et al., 2013b). After the Rio Grande Rise was separated from Walvis Ridge by ridge jumps (O'Connor and Jokat, 2015), the hotspot was located beneath the African Plate and bifurcated to form a double chain of seamounts and ridges, Tristan subtrack and Gough subtrack (Hoernle et al., 2015; Rohde et al., 2013a). All lavas have Enriched Mantle (EM I) type composition, but compared to the Gough subtrack, the Tristan subtrack lavas are characterized by systematically lower $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$ ratio. This isotopic zonation can

be traced from the active islands to the old DSDP Sites 525, 527 and 528, located at the southwestern end of Walvis Ridge (Figure 1) with an age of ~70 Ma (Homrighausen et al., 2019; O'Connor and Jokar, 2015; Rohde et al., 2013b). North of these drill sites, lavas with almost exclusively Gough composition have been dredged from the Walvis Ridge plateau basement (Hoernle et al., 2015; Homrighausen et al., 2019), suggesting that Gough is the dominant composition in the Etendeka and Paraná flood basalts (Hoernle et al., 2015).

In recent years it has been shown that most hotspots that are believed to be associated with deep-seated mantle plumes are generated within or near seismically detected large low-shear-velocity provinces (LLSVPs), such as Tristan-Gough, Discovery, Shona Segments at the western and Mozambique Ridge at the eastern margin of the African LLSVP (Torsvik et al., 2006).

3. Samples and analytical methods

All our samples are described in Appendix C and the analytical procedures in Appendix D.

4. Results

4.1. Major and trace elements

Major and trace element data are given in Appendix B. Overall the rocks are well-preserved with loss on ignition (LOI) values of 0.14-2.78 wt.% for all but four samples with LOI of 3.9-7.4 wt.% (NAM50, NAM51, NAM56 and NAM60C), which are thus excluded from further consideration. Accordingly, most samples show reasonably good correlations between mobile and immobile element enrichment, such as K vs. Th ($r = 0.86$), K vs. Hf ($r = 0.90$) and K vs. Zr ($r = 0.85$).

The analyzed rocks show a wide compositional range on the total alkali-silica (TAS) diagram (Figure 2a).

The SiO₂ content ranges from 43 to 76 wt.% with a gap between 56 and 63 wt.% (Bunsen-Daly gap),

dividing the samples into mafic ($\text{MgO} = 1.3\text{-}20.8 \text{ wt.}\%$) and silicic ($\text{MgO} = 0.06\text{-}3.36 \text{ wt.}\%$) suites (Milner et al., 1995).

As noted by Marsh et al. (2001) and Ewart et al. (2004b), relatively high Ti, Zr and Sr are found in mafic and silicic Etendeka igneous rocks north of Terrace Bay (Figure 1), whereas comparatively low Ti, Zr and Sr contents dominate the Etendeka rocks south of the bay. This geographic division is confirmed by our new data. Accordingly, samples with $\text{TiO}_2 > 2.2 \text{ wt.}\%$ and $\text{Sr} > 450 \text{ ppm}$ are henceforth labeled as “high-Ti” rocks and samples with lower Ti and Sr contents as “low-Ti” rocks (Figure 2b; Marsh et al., 2001). The high-Ti rocks have MgO ranging from 2.7-13.8 wt% and the low-Ti rocks from 0.3-20.8 wt%. Using the nomenclature of Marsh et al. (2001), all our high-Ti rocks from northern Etendeka would classify as “Khumib-type” (Appendix B).

Plots of MgO versus other major oxides are shown in Figure 3. MgO vs. SiO_2 shows an inverse hyperbolic (concave-up) array. Rocks with $\text{MgO} > 10\text{-}12 \text{ wt.}\%$ have apparently accumulated olivine consistent with petrographic examinations (Appendix C). For the low-Ti lavas, CaO, Al_2O_3 , FeO and TiO_2 initially increase with decreasing MgO and then decrease, reflecting fractionation of plagioclase (in samples with $\text{MgO} < 8 \text{ wt.}\%$), Fe-Ti oxides ($\text{MgO} < 5 \text{ wt.}\%$) and apatite ($\text{MgO} < 2.5 \text{ wt.}\%$). The high-Ti lavas form parallel trends to the low-Ti rocks on the MgO vs TiO_2 and P_2O_5 diagrams but are shifted to higher values (Figure 3). The high-Ti samples with $\text{MgO} > 10 \text{ wt.}\%$ have significantly lower Al_2O_3 and slightly lower CaO and slightly higher SiO_2 and FeO. The overall constant CaO values with decreasing MgO, but marked increase in Al_2O_3 , Sr and Eu (not shown) of the high-Ti lavas point to primarily clinopyroxene rather than plagioclase fractionation, in contrast to the low-Ti rocks for which the data indicate both plagioclase and clinopyroxene fractionation. With the exception of the sample with the lowest MgO, there is no evidence for significant Fe-Ti oxide or apatite fractionation in the high-Ti samples. According to the division scheme of Marsh et al. (2001), most of our low-Ti samples from southern Etendeka would

classify as Tafelberg-type except for samples with distinct lower Zr/Y ratios consistent with a Horingbaai composition (See the Appendix B for overview).

On the Nb/Yb vs. Th/Yb diagram (Figure 4a), our samples plot both within or above the mid-ocean-ridge basalt – ocean-island basalt (MORB-OIB) array. In addition, the data form a crude positive correlation on a diagram of Pb/Ce vs. Th/Nb (Figure 4b), indicating variable extents of continental crustal contamination. We have therefore divided the samples into a minimally (Pb/Ce $\leq$ 0.13, Th/Nb $<$ 0.22; filled symbols) and a more strongly crustally-contaminated group (open symbols; Figure 4), based on the range of these ratios observed in the lavas from the submarine hotspot track, which did not pass through continental crust.

The high-Ti samples show uniform patterns on incompatible multi-element diagrams with moderate depletions of U, Nb, Ta and Pb compared to the neighboring elements of similar incompatibility (Figure 5a). The high-Ti samples also have high ratios of large ion lithophile elements (LILE) and light rare earth element (LREE) versus high field strength elements (HFSE) (e.g. high Ba/Nb, K/Nb, La/Nb) and high Ba/Th and Ba/La, as is typical for incompatible-element patterns of EM I-type lavas (Willbold and Stracke, 2006), such as those from the Gough track. Moreover, the multi-element patterns of the high-Ti group samples are nearly identical to and plot within the relatively narrow range of the Gough Track lavas. Like the Gough-Track lavas, the high-Ti group samples possess enrichment of the more incompatible over less incompatible elements but display steeper HREE patterns. Compared to the high-Ti rocks, the low-Ti rocks show less depletion of the HFSE Nb and Ta and relative enrichment of Pb (Figure 5b). In addition, the low-Ti lavas are characterized by relatively flat heavy rare earth element patterns, similar to enriched mid-ocean-ridge basalt (E-MORB) (Figure 5). These low-Ti group samples, considered to be strongly contaminated by continental crust (see section 6.1), have generally higher concentrations of all incompatible elements and more pronounced negative Nb and Ta and positive Pb anomalies (Figure 5c).

4.2. Isotopes

The high-Ti group rocks display relatively unradiogenic initial Sr, Nd Hf and $^{206}\text{Pb}/^{204}\text{Pb}$ isotope ratios and plot consistently within the Gough compositional field of the marine hotspot track in all isotope systems (Figure 6-8). The low-Ti samples reveal more complex chemistry: Those low-Ti samples, considered to be less affected by crustal contamination, have more radiogenic initial $^{143}\text{Nd}/^{144}\text{Nd}$, $^{176}\text{Hf}/^{177}\text{Hf}$, and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios (15.55-15.68) but less radiogenic $^{208}\text{Pb}/^{204}\text{Pb}$ ratios at a given $^{206}\text{Pb}/^{204}\text{Pb}$ (Figure 6-8) than the high-Ti group samples. The composition of our low-Ti samples largely overlaps with the isotope ratios for the Horingbaai dikes (and the Doros intrusion). Low-Ti lavas that show evidence for crustal contamination, however, yield variable to very radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$, radiogenic $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$, and unradiogenic $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios.

5. Discussion

5.1. Crustal Contamination

In contrast to magmas that traverse young (<200 Ma), depleted, mafic oceanic crust or have enriched incompatible-element compositions, magmas passing through old (Proterozoic), thick, felsic and incompatible-element-enriched continental lithosphere, especially those with relatively depleted initial compositions, are highly sensitive to crustal contamination during their ascent. The lithospheric mantle beneath continents is in many cases additionally enriched, due to the past passage of melts and fluids through it. In general, continental crust is highly enriched in Th and Pb relative to Nb and Ta. The respective enrichment/depletion of these elements in some of our samples indicate variable contamination by local crustal lithologies. On the Nb/Yb vs. Th/Yb discrimination diagram (Figure 4) after Pearce (2008), only a few of our samples plot within the MORB-OIB array. Most samples plot well above the array, near the average composition of the Nosib and Swakop metasedimentary groups (McDermott and Hawkesworth, 1990), a major constituent of the (upper crustal) orogenic Damara and Kaoko belts,

underlying most of the Etendeka igneous units (Miller, 2008). Although they vary widely in composition, most Damara granites have less radiogenic Pb (average $^{206}\text{Pb}/^{204}\text{Pb} = 18.03$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.63$ and $^{208}\text{Pb}/^{204}\text{Pb} = 37.84$, age-corrected to 132Ma; Jung et al., 2015; Paul et al., 2014; Stammeier et al., 2015) than our contaminated samples. Therefore, we use the average composition of Nosib and Swakop group metasedimentary rocks to evaluate (and quantify) potential crustal contamination.

Ratios of elements with similar partition coefficients to Nb, Ta and Pb, for example, (Th, La)/(Nb,Ta) and (Pb, Nd)/Ce, which are distinct between intraplate volcanism and continental crust, can also be used to evaluate the extent of crustal contamination. Lavas that have ratios of these elements within the range of Gough-type lavas from the submarine hotspot track ($\text{Th}/\text{Nb} < 0.22$ and $\text{Pb}/\text{Ce} \leq 0.13$; Figure 4) are considered to be not or only minimally affected by crustal contamination and are shown with filled symbols in all diagrams. Consistent with this interpretation, contaminated lavas show isotopic ratios (e.g. high $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{207}\text{Pb}/^{204}\text{Pb}$) that trend toward local upper crustal lithologies, like the Nosib and Swakop group metasedimentary rocks (Figure 6-8). Simple (bulk) mixing model calculations indicate that the isotopic composition of contaminated lavas can be explained by the addition of ~10% of these metasedimentary rocks to an initial Gough or Doros-type magma composition, respectively (Figure 6-8). Other studies have also identified upper crustal lithologies as apparent contaminants for Etendeka lavas. For example, a positive correlation of Pb/Ce and $^{206}\text{Pb}/^{204}\text{Pb}$ in Tafelberg and Horingbaai basalts was interpreted to indicate their contamination by the upper crust rather than lower crust or SCLM, which possess relatively low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of < 18 (Thompson et al., 2001; Ewart et al., 2004a). The low-Ti samples, especially the picrites, have very low concentrations of incompatible elements due to dilution of incompatible elements through olivine accumulation, making their Sr, Nd, Pb and Hf isotope ratios especially sensitive to even very small amounts of crustal contamination. Since assimilation of continental crust can drastically change the geochemical composition of mantle-derived magmas, the

contaminated low-Ti group samples (with open symbols in all diagrams) are not considered in the discussion of potential mantle source compositions below.

5.2. Source composition of the low-Ti basalts

Only three of our low-Ti lavas plot within/near the mantle array in [Figure 4a](#) and are therefore considered to be minimally contaminated by continental crustal. These samples have N-MORB and E-MORB-type trace element compositions, similar to the Doros and Horingbaai magma-types (Owen-Smith et al., 2017; Thompson et al., 2001; [Figure 5](#)). A slight effect of continental contamination, however, cannot be ruled out for NAM59 (elevated $^{87}\text{Sr}/^{86}\text{Sr}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$), but is considered to be insignificant compared to all other low-Ti samples. In comparison with the Gough composition, the minimally-contaminated low-Ti lavas have slightly higher $^{143}\text{Nd}/^{144}\text{Nd}$ and lower $^{208}\text{Pb}/^{204}\text{Pb}$ for a given $^{206}\text{Pb}/^{204}\text{Pb}$, but similar to higher $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$. The low-Ti lavas in Paraná have similar composition (Peate et al., 1999), but the $^{208}\text{Pb}/^{204}\text{Pb}$ is not as low as in our Etendeka low-Ti lavas.

Previously, the isotopic composition of the low-Ti Etendeka lavas was explained to represent a mixture of 1) Tristan plume component with MORB mantle and upper crust (Ewart et al., 1998) or 2) depleted mantle peridotite, lower crust and upper crust (Thompson et al., 2001; Thompson et al., 2007). No mixtures of Gough- or Tristan-type plume mantle, however, with depleted upper (MORB-source) mantle and/or local continental crust (e.g. metasediments, felsic granite (Stammeier et al., 2015) and mafic basement (Jung et al., 2015)) can produce the combined uranogenic and thorogenic Pb isotopic systematics of the Horingbaai dikes and low-Ti samples ([Figure 7](#)). If the Gough endmember mixed with depleted MORB-source mantle, then the $^{207}\text{Pb}/^{204}\text{Pb}$ isotope ratios of the resulting magma would also have to be lower than the Gough composition - not just the $^{208}\text{Pb}/^{204}\text{Pb}$ isotope ratios (Hoernle et al., 2015). Mixing of a (hypothetically already present) Tristan plume component with depleted upper mantle $\pm$ crust also cannot explain the composition of the minimally contaminated low-Ti samples.

276 Therefore, a different magma source having low $^{87}\text{Sr}/^{86}\text{Sr}$, intermediate to high $^{143}\text{Nd}/^{144}\text{Nd}$ and high
277 $^{207}\text{Pb}/^{204}\text{Pb}$ but low $^{208}\text{Pb}/^{204}\text{Pb}$ relative to $^{206}\text{Pb}/^{204}\text{Pb}$ is required to explain the composition of the low-Ti
278 lavas and dikes. The high $^{207}\text{Pb}/^{204}\text{Pb}$ yet low $^{208}\text{Pb}/^{204}\text{Pb}$ relative to $^{206}\text{Pb}/^{204}\text{Pb}$ precludes the low-Ti
279 basalts from being derived from an upper mantle Atlantic (or Indian) MORB-type source.

280 Such a low-Ti end member is found in the Doros intrusion (130Ma; Owen-Smith et al., 2017) and related
281 Tafelkop lava flows (Ewart et al., 1998; Gibson et al., 2000), which are believed to originate from the
282 Doros igneous center (Marsh et al., 2001), and the Horingbaai dikes (131-132Ma; Thompson et al., 2001).
283 The isotopic composition of the Horingbaai dikes could be derived through two component mixing of a
284 depleted normal (N)-MORB type component (with $^{206}\text{Pb}/^{204}\text{Pb} \sim 17.7$, $^{207}\text{Pb}/^{204}\text{Pb} \sim 15.43$, $^{208}\text{Pb}/^{204}\text{Pb} \sim$
285 37.5 , $^{143}\text{Nd}/^{144}\text{Nd} \sim 0.5130$ and $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.7040$ at 132 Ma) and an upper continental crustal (Damara
286 belt meta-sediment) component. Such two-component mixing, however, does not work for a
287 combination of the Doros and Tafelkopf rocks, which require mixing of at least 3 components. Modeling
288 of the parental liquid composition for picritic Horingbaai dikes, however, yielded a potential
289 temperature of 1520-1680°C (Jennings et al., 2019 and references therein), confirming that the
290 Horingbaai magmas were generated within a hot mantle plume from the lower mantle (Thompson et al.,
291 2001).

292 For Doros/Tafelkop rocks, a predominantly plume derivation was already proposed (Ewart et al., 1998;
293 Gibson et al., 2000; Milner and le Roex, 1996; Owen-Smith et al., 2017). Ewart et al. (2004a) calculated a
294 plume contribution between 25 and 75% for these magmas (although still using the Tristan component,
295 which does not work in all isotope systems and did not exist then, instead of the Gough composition as a
296 mixing endmember). Further support for a lower mantle origin of the low-Ti source comes from high
297 $^3\text{He}/^4\text{He}$ isotope ratios reported from low-Ti dikes (Stroncik et al., 2017). The isotopic composition of 11
298 southern Etendeka low-Ti rocks for which He isotopes were generated are shown in [Figures 6-8](#) as stars.

As can be seen on the Pb/Ce vs. Th/Nb diagram (Figure 4b), seven of these samples (filled stars) plot within the field that indicates minimal crustal assimilation. Of these seven samples, three (one associated with Brandberg and two associated with the Doros intrusive complex) have $^3\text{He}/^4\text{He}$ ratios higher than $12 R_A$ (normalized to atmospheric helium; filled large stars in Figure 6-8), indicating a deep, lower-mantle source. These rocks plot consistently within the Doros/Horingbaai compositional fields in all isotope systems. The $\delta^{18}\text{O}$ values of olivine phenocrysts from these three high $^3\text{He}/^4\text{He}$ samples range from 5.30-5.71‰, overlapping with or extending to slightly higher values than olivines from mantle peridotites (5.0-5.4‰, Eiler et al., 1997), indicating a small amount of assimilation (<5% to raise $\delta^{18}\text{O}$ from 5.2 to 5.7‰) of the adjacent Neoproterozoic Damara Supergroup schist (mean $\delta^{18}\text{O} = 14.75\text{‰}$, $n=12$, $SD = 0.48$; Jung et al., 2001). The three samples with highest $^3\text{He}/^4\text{He}$ plot within the field for Atlantic MORB on the thorogenic Pb isotope diagram but above the MORB field on the uranogenic Pb isotope diagram, and thus clearly are not derived from depleted upper mantle. We conclude that the Doros/Horingbaai end member, as characterized by sample KT-10-3 (Stroncik et al., 2017) with low $^{206}\text{Pb}/^{204}\text{Pb}$ (~17.74), $^{208}\text{Pb}/^{204}\text{Pb}$ (~37.50) and $^{87}\text{Sr}/^{86}\text{Sr}$ (~0.704), high $^{207}\text{Pb}/^{204}\text{Pb}$ (~15.58), $^{143}\text{Nd}/^{144}\text{Nd}$ (~0.5127) and $^3\text{He}/^4\text{He}$ (~20.3 R_A), and mantle-like $\delta^{18}\text{O}$ olivine (5.3‰), stems from the lowermost mantle and was transported to the base of the lithosphere by a mantle plume. Accordingly, we use this endmember for our mixing calculations shown in Figure 6-8.

The isotopic characteristics of Tafelkop lavas (having transitional composition between low- and high-Ti) and low-Ti lavas in Paraná require both the Gough and Doros end members, as well as various amounts of crustal contamination (Figure 7b). Accordingly, all low-Ti samples (including the contaminated samples) lie within triangular mixing fields that are spanned by the Doros end member, the Gough composition and the (local) Damara upper crust.

In summary, the geochemical composition of the (minimally contaminated) low-Ti rocks in southern Etendeka can be best explained by derivation from plume material derived from the lower mantle (high $^3\text{He}/^4\text{He}$ and high temperatures) with an isotopic composition similar to the Doros/Horingbaai rocks. Picritic magmas from this relatively incompatible-element depleted source, in part due to dilution as a result of olivine accumulation, experienced various extents of contamination while passing through the continental lithosphere in southern Namibia (Thompson et al., 2007). The isotopic composition of all of our (contaminated) low-Ti samples is variably offset towards crustal compositions hampering identification of their original isotopic composition. Stroncik et al. (2017) also report low-Ti dikes with low $^3\text{He}/^4\text{He}$ composition that have $\delta^{18}\text{O}$ values of 5.74-6.70‰, showing clear evidence of crustal contamination despite their low Pb/Ce and Th/Nb. Applying a simple mixing model, ~15% of adjacent Neoproterozoic Damara Supergroup schist (Jung et al., 2001) is needed to increase the $\delta^{18}\text{O}$ from 5.2‰ to 6.7‰ (Stroncik et al., 2017), consistent with our calculation of crustal contamination based on Sr, Nd and Pb isotope ratios (Figure 6-8). In conclusion, the composition of the low-Ti samples can be explained by mixing of a Doros-type end member, possibly with some minor Gough-type end member contribution (source of high-Ti basalts) (Figure 8), plus variable amounts of subsequent continental crustal contamination.

5.3. Source composition of the high-Ti basalts

High-Ti basalts are exclusively found in Northern Etendeka (e.g. Marsh et. al. 2001; this study). Since the high-Ti basalts have high concentrations of incompatible elements, they are less vulnerable to crustal contamination and we see no evidence of significant contamination. Instead the rocks show very similar trace element and isotopic compositions to the Gough-type lavas erupted on oceanic crust (Figure 5-8). Before it was known that the Tristan composition didn't appear until ~70 Ma ago, resulting in a zoned hotspot track, it was proposed that the high-Ti basalts represent a mixture of a Tristan-type composition,

344 MORB and recycled subducted sediment (Ewart et al., 2004a). The high-Ti lavas, however, display higher
345 $^{207}\text{Pb}/^{204}\text{Pb}$, yet lower $^{208}\text{Pb}/^{204}\text{Pb}$ than the Tristan composition, and thus it is not possible to explain the
346 high-Ti magma source composition by mixing of the Tristan component with a depleted MORB-source
347 component and sediments (Figure 7). Instead, the high-Ti samples have very restricted trace element
348 compositions (Figure 5), overlapping the narrow field for the marine Gough lavas on multi-element and
349 on Sr-Nd-Pb-Hf isotope diagrams (Figure 6-8). Therefore, we believe that the high-Ti lavas reflect the
350 composition of their mantle plume source having a Gough-type composition. A predominant derivation
351 of the high-Ti Etendeka magmas by the Tristan-Gough plume was already recognized by Ewart et al.
352 (2004a), but these authors still assumed a Tristan-type endmember for their mixing calculations. Our
353 new data confirm Hoernle et al. (2015), who found no evidence for compositional Tristan-type lavas
354 erupted in either the Etendeka or Paraná large igneous provinces.

355 Compared to the trace element pattern of the marine part of the hotspot track, the high-Ti lavas show
356 slightly steeper primitive-mantle normalized HREE patterns (Figure 5a), indicative of a greater role of
357 residual garnet in the magma source (which fractionates the HREE) and thus deep melting starting at
358 ≥ 70 -80 km. This is consistent with melting of plume material beneath thick continental lithosphere in
359 contrast to the Walvis Ridge, which formed through plume-ridge interaction, and the Guyot province
360 magmas that formed beneath young and comparably much thinner oceanic lithosphere. Plume melting
361 beneath Walvis and the Guyot province could thus continue to much shallower depths with increasing
362 dilution of the garnet signal by mixing with melts that formed at the upper end of the melting column
363 (spinel stability zone). Finally, the nearly flat HREE patterns of the low-Ti, compared to steep slope of the
364 high-Ti, basalts points to shallower melting (under thinner Neoproterozoic Damara Belt lithosphere
365 compared to Paleoproterozoic lithosphere beneath NW Namibia) to form the low-Ti basalts.

In summary, we propose that the high-Ti basalts in Northern Etendeka were derived from the same (Gough) plume component as found in the Walvis Ridge and Gough subtrack lavas. The absence of any evidence for a Tristan composition implies that this component was not present in the early plume (head) stage. The Gough component has also been shown to be the dominant component of the northern Discovery hotspot track (Schwindrofska et al., 2016) and the Shona hotspot (Hoernle et al., 2016) in the South Atlantic. At both of these hotspots, the Gough-type composition is associated with high $^3\text{He}/^4\text{He}$ at the southern Mid-Atlantic Ridge segments that interact with these hotspots, pointing to a lower mantle origin of this source material (Sarda et al., 2000).

5.4. A possible model for the Etendeka flood basalt lavas

As shown above, our study confirms that the Gough-type EMI component of the Tristan-Gough hotspot track was already present in the initial Etendeka plume head stage, sampled by the high-Ti lavas of northern Namibia. The high-Ti lavas with Gough-like incompatible element and isotopic composition are located exclusively in northern Etendeka (NW Namibia) adjacent to the intersection with the offshore hotspot track (Walvis Ridge). Additional high-Ti lava compositions occur at the Bero volcanic complex (SW Angola) (Marsh and Swart, 2016) and in the Urubici magma type (Paraná, South America) (Peate et al., 1999), which were spatially connected before the break-up of Gondwana. Thus, the Gough component appears to have been widespread in the plume head and apparently dominated the entire northern portion of the plume head (Figure 9a).

In contrast, the low-Ti lavas are primarily located in southern Etendeka (western central Namibia) and were derived from a different (Doros-type) source. This component was primarily present in the southern part of the early plume (head) stage and is not found in the marine (plume tail) part of the hotspot. In addition, effusive Doros-type lavas (Tafelkop type) have only been found at the base of the (southern) Etendeka lava succession so far (Gibson et al., 2000; Miller, 2008), although they seem to have once covered a far greater area than their present extension (Owen-Smith et al., 2017). It is not

clear why the low-Ti (Doros) source material was only present in the initial plume-head stage and not thereafter but three options are possible: 1) This component may have been completely exhausted in the plume source during formation of the Etendeka flood basalts; 2) the base of the plume stem (in the lower mantle) may have migrated to a different location where different material was entrained (Hoernle et al., 2015); or 3) only plume heads may be able to carry dense deep mantle material (carrying the Doros signal?) to the surface whereas the plume tail does not (Jones et al., 2019). In any case, we note that plume zonation can vary with time as is evident by the sudden appearance of the Tristan plume component on the northern side of the plume and hotspot track at ~70 Ma. Since entrainment of ambient mantle material into a plume head is improbable based on fluid dynamic considerations (Lohmann et al., 2009), it is unlikely that the plume head entrained this material during ascent through the lower or mid mantle. Instead, the low-Ti source material might represent another (intrinsic) lithology of the African LLSVP. An isotopically similar composition was recently found in the submarine Mozambique Ridge lavas (Figure 7- 8), a north-south trending oceanic plateau located south of Africa up to 2500 km away from southern Etendeka (Jacques et al., 2019). However, the Mozambique Ridge was emplaced at the same time (ca. 135-125 Ma) (Jacques, 2019 and references therein) and is believed to have also formed by a deep mantle plume rooted at the (southern) edge of the African LLSVP (Jacques et al., 2019).

Considering hotspot volcanism around the southern tip of Africa and along the southern margin of the African LLSVP, four distinct enriched mantle components have been identified thus far. These components are all characterized by low $^{206}\text{Pb}/^{204}\text{Pb}$, but are variably enriched in $^{207}\text{Pb}/^{204}\text{Pb}$ and/or $^{208}\text{Pb}/^{204}\text{Pb}$ ratios, as well as more radiogenic Sr and less radiogenic Nd and Hf isotope ratios than MORB. They include: 1) the Gough (high-Ti) component, the dominant component in the northern Etendeka and Paraná LIPs, and in the Tristan-Gough, northern Discovery and Shona hotspot tracks, 2) the Tristan component, that is only found along the northern subtrack of Tristan-Gough hotspot trail since ~70 Ma,

3) the southern Discovery component (identified in lavas of the zoned Discovery hotspot track located south of the Tristan-Gough hotspot track, Schwindrofska et al., 2016), and 4) the Doros/Horingbaai or Mozambique (low-Ti) component found in southern Etendeka and the Mozambique Ridge. High $^3\text{He}/^4\text{He}$ ratios were reported from lavas from the Gough (northern Discovery and Shona; Sarda et al., 2000) and the Doros (Stroncik et al., 2017) components, pointing to a lower mantle origin for at least these two components. Considering the common geochemical characteristics of these four spatially and temporally related enriched components, they could very well represent different derivatives of a once genetically related source (for example, ancient subducted lithospheric material with different ages or parent/daughter fractionation at different times subsequent to their formation/subduction; Geldmacher et al., 2008).

From a global perspective, geochemically enriched (e.g. high-Ti) and relatively depleted (e.g. low-Ti) source components have been described in several oceanic LIPs, such as the Karoo LIP (Cox et al., 1965), the Manihiki Plateau (Golowin et al., 2018; Golowin et al., 2017), the Caribbean LIP (Dürkefälden et al., 2019a; Dürkefälden et al., 2019b) and the Shatsky Rise (Sano et al., 2012). Although different sources may be sampled at different times in the evolution of a LIP, as is the case with the Ontong Java Plateau and the Caribbean LIPs, the enriched (high-Ti) and depleted (low-Ti) lavas appear to have been at least in part erupted contemporaneously during the Etendeka, Manihiki and Shatsky LIP events.

When erupted contemporaneously, spatial compositional differences could reflect either 1) spatially separated source material (zonation) in the plume head (Figure 9a), or 2) heterogeneity on a relatively small scale in the plume head and differences in the melting properties of the different components/lithologies (Figure 9b). In a heterogeneous upwelling column of mantle containing different lithologies, fertile components (e.g. garnet pyroxenite) will begin melting first, controlling the melt composition formed at greater depths (Dasgupta et al., 2007). Thus, on thick lithosphere (e.g. Paleo-

Proterozoic lithosphere beneath northern Etendeka), erupted melts will have primarily enriched high-Ti Gough-type composition, whereas beneath thinner lithosphere (e.g. Damara mobile belt, which probably represented a region of thinned and weakened lithosphere; Ritter et al., 2003), less-fertile lithologies (e.g. Doros/Horingbaai garnet peridotitic matrix) will mainly melt at shallow depth, thereby diluting the early melts from fertile Gough-type material. The lower HREE fractionation (less steep HREE patterns on a multi-element diagram) of the Doros/Horingbaai magmas, compared to the high-Ti Gough magmas (Figure 5), is consistent with higher degrees of melting at shallower depth to form the low-Ti melts. It is, however, difficult to reconstruct the thickness of the lithosphere at the time of the Etendeka event, because it is difficult to assess the effects of thermal erosion of the lithospheric mantle by the Tristan-Gough plume head. We note that, consistent with this model, the Mozambique Ridge formed on or directly adjacent to the southwest Indian spreading center and thus melting was able to continue to very shallow depths, certainly shallower than anywhere in the Etendeka volcanic province. Nevertheless, if the plume head had been heterogeneous on a small scale and Gough melts dominated beneath thick lithosphere and Doros/Horingbaai melts beneath thinner lithosphere, why have only high-Ti Gough-like and no low-Ti Doros-like lavas been found on the Walvis Ridge thus far, since the Walvis Ridge also formed by plume-ridge interaction and thus under similarly thin lithosphere as the Mozambique Ridge? This can be explained more easily, if the plume head was spatially zoned and tapped two distinct source reservoirs at the time of Etendeka/Paraná volcanism (Figure 9a).

6. Conclusion

The high-Ti samples, which only occur in Northern Etendeka, display enriched incompatible-element and isotopic compositions, similar to the Gough composition of the marine Tristan-Gough hotspot track. The low-Ti samples, primarily found in southern Etendeka, have lower abundances of incompatible elements and were thus more easily contaminated during passage through enriched felsic continental crust.

Minimally contaminated low-Ti samples have an isotopic composition which cannot be explained by mixing of a Gough component with depleted MORB source asthenosphere or SCLM composition. They therefore point to the presence of an additional plume component in the early plume head stage.

We propose that the high-Ti lavas in Northern Etendeka, which formed directly adjacent to the Walvis Ridge and have a similar Gough-type composition, and the lavas of the adjacent Angola and Paraná regions were derived from the northern portion of the starting plume head. The low-Ti lava source represents a composition not found thus far in the marine hotspot track. The recognition of high $^3\text{He}/^4\text{He}$ in some low-Ti dikes (Stroncik et al., 2017) indicates that this component was also derived from the lower mantle and primarily constituted the southern portion of the plume head. This is the first time that clear spatial geochemical zonation has been found in a continuous flood basalt sequence, suggesting a zoned plume head.

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Figures

Figure 1: (a) Map of the Etendeka large igneous province outcrops in northwest Namibia, including sampling sites for this study. Transition zone lavas (purple) separate high-Ti lavas (pink) in northern Etendeka from low-Ti volcanism (green) in southern Etendeka after Marsh et al. (2001). The ranges of dikes are denoted with dashed lines. The range of Henties Bay – Outjo dike swarm and the boundary between Congo Craton and Damara Belt are based on Raab et al. (2002). Sample sites of high and low $^3\text{He}/^4\text{He}$ rocks taken from Stroncik et al. (2017). (b) Inset shows location of sampling area along the SW African (Namibian) coast and relationship to the submarine Walvis Ridge and Tristan and Gough hotspot sub-tracks in the South Atlantic. Maps generated by GeoMapApp (<http://www.geomapapp.org>).

Figure 2: (a) Sampled mafic and silicic igneous rocks of the Etendeka LIP plotted on the total alkali vs. silica diagram (TAS) of Le Maitre et al. (1989). Dashed line dividing alkaline and subalkaline rocks after MacDonald and Katsura (1964). Open symbols denote samples with Th/Nb > 0.22 and Pb/Ce > 0.13,

indicating significant crustal contamination of the magmas (see chapter 5.1 and figure 4b). (b) Following the division of Marsh et al. (2001), the samples are grouped by their TiO_2 content: low-Ti < 2.2 wt.% TiO_2 and high-Ti > 2.2 wt.% TiO_2 . Low-Ti and high-Ti lavas can also be distinguished by their low (<450 ppm) high Sr concentrations (>450 ppm), respectively. The Gough composition is represented by DSDP site 525A lavas on the Walvis Ridge (Hoernle et al., 2015).

Figure 3: MgO content versus major oxides (in wt.%). Olivine (ol) accumulation is apparent for lavas with >10wt.% MgO. The low-Ti lavas crystallized clinopyroxene (cpx) and plagioclase (plg) at MgO < 8wt%,

Fe-Ti oxides at MgO < 5wt% and apatite at MgO < 2.2 wt%. High-Ti samples show similar trends to low-Ti samples, but the mafic (MgO > 7wt.%) high-Ti samples contain less CaO (c) and Al₂O₃ (e), but generally higher FeOt (b) and significantly higher TiO₂ (d), and P₂O₅ (f) than low-Ti lavas. The high-Ti lavas show fractionation of olivine ± clinopyroxene (MgO > 8wt%), clinopyroxene and plagioclase (MgO < 8wt%), but no evidence for significant Fe-Ti oxide or apatite fractionation. Two low-Ti samples with high P₂O₅ have accumulated apatite.

Figure 4: (a) Nb/Yb vs Th/Yb (Pearce, 2008). The “mantle” array comprises data from normal mid ocean ridge basalts (N-MORB), enriched MORB (E-MORB) and oceanic island basalts (OIB). Melts formed in

514 subduction zones and those that have been contaminated by continental crust generally have higher
515 Th/Yb contents at a given Nb/Yb and plot above the mantle array. (b) Pb/Ce vs Th/Nb. The dashed line
516 shows the highest Th/Nb ratio for Gough-type samples. Samples with Th/Nb < 0.22 and Pb/Ce < 0.13 are
517 considered to reflect only minimal continental crustal contamination, because Gough-type samples,
518 erupted on oceanic crust, extend to these values. Samples with higher values are likely to have
519 experienced some continental crustal contamination (see section 5.1). Gough compositional field
520 comprises samples from the present Gough Island, Gough seamount subtrack, as well as the Walvis
521 Ridge (Rohde et al., 2013a; Hoernle et al., 2015; Homrighausen et al., 2019). The Nosib and Swakop
522 metasedimentary groups and their average composition (McDermott and Hawkesworth, 1990) are
523 shown to assess upper crustal contamination. Doros (Owen-Smith et al., 2017; Stroncik et al., 2017) and
524 Horingbaai (Thompson et al., 2001) composition are also shown.

Figure 5: Primitive mantle normalized multi-element diagrams for: (a) high-Ti lavas compared to Gough composition from the submarine Walvis Ridge and Gough hotspot subtrack (Rohde et al., 2013a; Hoernle et al., 2015; Homrighausen et al., 2019), N-MORB and E-MORB (Sun and McDonough, 1989); (b)

minimally-contaminated low-Ti lavas from this study and low-Ti lavas with high $^3\text{He}/^4\text{He}$ ratio from Stroncik et al. (2017) compared with low-Ti Doros intrusion samples (Owen-Smith et al., 2017) and Horingbaai dikes (Thompson et al., 2001), and (c) comparison of clearly crustally-contaminated with minimally-contaminated low-Ti lavas.

Figure 6. Initial (at 132 Ma) Sr and Nd isotopic compositions Etendeka samples from Namibia. The Etendeka and Paraná high-Ti samples plot within the lower part of the Gough field, whereas most of the minimally-contaminated Etendeka low-Ti samples overlap with the Doros and Horingbaai fields or extend toward Damara Belt metasediments. Mixing lines are calculated for mixing endmember compositions represented by 1) enriched high-Ti Gough-type sample NAM21, 2) a depleted low-Ti sample with the highest $^3\text{He}/^4\text{He}$ and the lowest $\delta^{18}\text{O}$ olivine ($\delta^{18}\text{O}=5.3\%$), which lies within the mantle-range (KT-10-3, large black star with white dot at the center; Stroncik et al., 2017), and 3) an upper continental crustal component (average composition of the Nosib and Swakop metasedimentary group samples; McDermott and Hawkesworth, 1990). The extension of the Horingbaai dike field towards more

radiogenic Nd isotope compositions could indicate the involvement of a fourth upper mantle (MORB-type) component or that the plume contains depleted material similar to N-MORB. All samples were age-corrected to 132 Ma, the average age of Etendeka volcanism. The parent/daughter ratios of Etendeka samples and the upper crustal component are derived from their trace element data. Gough-type data were first age-corrected to their initial ratios at time of eruption and then extrapolated to 132 Ma by using the following assumed parent/daughter ratios of their source: U/Pb=0.137, Th/Pb=0.6758, Rb/Sr=0.0204, Sm/Nd=0.3378 (Stracke et al., 2003; Willbold and Stracke, 2006). To project the MORB source to 132 Ma, we used the following parent/daughter ratios: U/Pb=0.1667, Th/Pb=0.4444, Rb/Sr=0.0065, Sm/Nd=0.4114 (Workman and Hart, 2005). References: Gough-type EMI (Rohde et al., 2013a; Hoernle et al., 2015; Homrighausen et al., 2019), Doros intrusion (Owen-Smith et al., 2017; Stroncik et al., 2017), Tafelkop lavas with Th/Nb < 0.22 and Pb/Ce < 0.13 (Ewart et al., 1998; Gibson et al., 2000), Horingbaai dikes (Thompson et al., 2001), Mozambique Ridge (Jacques et al., 2019), Paraná flood basalt (Peate and Hawkesworth, 1996; Peate et al., 1999; Rocha-Júnior et al., 2013; Turner et al., 1999), Damara belt metasediments (McDermott and Hawkesworth, 1990), and Mid-Atlantic Ridge (compilation of Class and Lehnert (2012) in PetDB Expert MORB (Mid-Ocean Ridge Basalt). Interdisciplinary Earth Data Alliance (IEDA). <http://dx.doi.org/10.1594/IEDA/100060>.

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560 Figure 7 Initial (at 132 Ma) (a) $^{206}\text{Pb}/^{204}\text{Pb}$ vs $^{207}\text{Pb}/^{204}\text{Pb}$ and (b) $^{206}\text{Pb}/^{204}\text{Pb}$ vs $^{208}\text{Pb}/^{204}\text{Pb}$ for Etendeka

561 lavas. The composition of the contaminated low-Ti samples can be explained by mixing of Doros-type

562 end member (source of low-Ti basalts) with a possible minor contribution of the Gough-type end

member (source of high-Ti basalts) similar to NAM 21 and an upper crustal component at 132 Ma. Data sources and endmember compositions used for calculating mixing lines in (b) are the same as in Figure 6.

Figure 8: Initial (at 132 Ma) (a) $^{206}Pb/^{204}Pb$ vs ϵNd and (b) ϵHf . The composition of the low-Ti rocks can be explained by mixing of 1) an enriched high-Ti Gough-type composition such as sample NAM21, 2) a depleted low-Ti component represented by sample KT-10-3 (from Stroncik et al., 2017) with high

570 $^3\text{He}/^4\text{He}$ and the lowest $\delta^{18}\text{O}$ olivine (5.3‰), which lies within the mantle-range , and 3) an upper
571 continental crustal component (average composition of the Nosib and Swakop metasedimentary group
572 samples at 132 Ma; McDermott and Hawkesworth, 1990). The extension of the Horingbaai dike field
573 towards more radiogenic Nd isotope compositions could indicate the involvement of a fourth upper
574 mantle (MORB-type) component or that the plume contains depleted material similar to N-MORB. Data
575 sources and endmember compositions used for mixing calculations are the same as in Figure 6. The
576 mixing lines for $^{206}\text{Pb}/^{204}\text{Pb}$ vs ϵHf relationships were calculated with Gough-type end member (NAM21),
577 Doros-type composition (NAM5) and the Damara metamorphic rocks at 132 Ma.

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580 Figure 9: Schematic models of Etendeka volcanism at ~132 Ma illustrating the proposed origin of the
 581 high-Ti northern Etendeka lavas from Gough-type plume material and the low-Ti southern Etendeka
 582 lavas, dikes and intrusives from a Doros/Horingbaai type plume material. (a) Zoned plume head model:
 583 The plume head contains two distinct compositional domains. A high-Ti (Gough-type) domain beneath
 584 northern Etendeka and a low-Ti (Doros-type) domain beneath southern Etendeka. The plume stem,
 585 which subsequently formed the Walvis Ridge (submarine hotspot track), only contains Gough-type
 586 material. (b) Small-scale heterogeneous plume head model: Beneath thick lithosphere, a fertile (Gough-

587 type) component, for example, pyroxenite, melts at greater depth to form high-Ti magmas. Beneath thin
588 lithosphere, a less-fertile lithology (Doros-type), for example peridotite, melts at shallower depth and
589 dilutes the early stage fertile melts. Dashed line in the southernmost part of southern Etendeka
590 indicates inferred distribution of low-Ti lava flows before erosion. At present, only dikes outcrop in this
591 area. Minor low-Ti lava flows also extend into northern Etendeka but are not shown here for clarity.

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