Continental material in the shallow oceanic mantle—How does it get there?

Cornelia Class Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA
Anton P. le Roex Department of Geological Sciences, University of Cape Town, Rondebosch 7701, South Africa

ABSTRACT

Unusual compositions of some oceanic basalts have been attributed to their sources containing continental lithosphere detached during the breakup of Gondwana. However, the processes of how such continental lithospheric material is detached and transported into the ocean basin have not been constrained. Here we identify Walvis Ridge, where it has been argued that Deep Sea Drilling Project (DSDP) Site 525A contains continental material, as a unique location to constrain these processes. Absolute plate motion (relative to the Tristan mantle plume) and relative plate motion (between Africa and South America) of the African plate are oblique to one another, such that tectonic detachment versus hotspot-related thermal erosion should sample spatially separated continental units of different age. We present isotopic compositions of xenoliths representing the neo-Proterozoic lithosphere at the inferred site for tectonic detachment during continental breakup and show that this process does not explain the Walvis Ridge DSDP Site 525A mantle source. Rather, thermal erosion of ancient cratonic mantle by the Tristan mantle plume is indicated. A convective return flow is required to transport the eroded subcontinental lithospheric mantle to the site of plume activity some ~50 m.y. later and provides constraints on the direction and velocity of mantle flow in the upper mantle.

Keywords: mantle plume, lithosphere, recycling, craton, geodynamics.

INTRODUCTION

Some oceanic basalts have unusual isotopic signatures different from spatially related mantle plumes but typical for ancient continental lithospheric mantle (e.g., Hawkesworth et al., 1986; Shirey et al., 1987; Mahoney et al., 1991) or ancient lower continental crust (Kamenetsky et al., 2001). These unusual compositions have been suggested to indicate lithospheric material detached during continental breakup and transported into the shallow oceanic mantle. As possible detachment processes, thermal erosion by a plume and tectonic detachment due to rifting have been suggested but not distinguished in individual cases (e.g., Milner and le Roex, 1996), and the transport path of such material has not been constrained. The strongest case for subcontinental lithospheric mantle (SCLM) in the source of oceanic basalts has been made for Walvis Ridge Deep Sea Drilling Project (DSDP) Site 525A (Hawkesworth et al., 1986; Carlson et al., 1996; Milner and le Roex, 1996; Peate et al., 1999). Here we show that Walvis Ridge provides a unique geological setting to constrain for the first time both the detachment process and the transport path of continental material into the shallow oceanic mantle, also allowing an estimate to be made of the direction and velocity of mantle flow in the upper mantle beneath this region.

GEOLOGICAL SETTING AND PREVIOUS WORK

Walvis Ridge is an aseismic ridge of age-progressive volcanism in the South Atlantic formed by the activity of the Tristan mantle plume since the breakup of Gondwana (Fig. 1). The Tristan plume initially formed the vast Paraná-Etendeka flood basalt province, then, following continental breakup, the Rio Grande Rise and Walvis Ridge, and finally the islands of the Tristan da Cunha group, Gough, and related seamounts. Samples from Tristan da Cunha, Inaccessible, and Gough islands form a tight cluster in isotope space (Fig. 2, open circles, diamonds, and squares) that overlaps with Walvis Ridge DSDP Sites 527 and 528 basalt compositions (open triangles). In contrast, samples from Walvis Ridge DSDP Site 525A (Fig. 2, black circles in black field) do not overlap with any other oceanic basalt compositions from the Tristan plume track. Instead, DSDP Site 525A basalts are indistinguishable from Urubici-Khumib–type flood basalts (Fig. 2, black diamonds and triangles in gray field) (Milner and le Roex, 1996; Peate et al., 1999), which have a restricted spatial extent (Fig. 1; region highlighted in gray within the northern Etendeka flood basalt province shows their occurrence on the African side) and are thought to reflect the composition of ancient SCLM (Peate et al., 1999). This similarity in composition led to the suggestion that the source of Walvis Ridge DSDP Site 525A basalts contains dispersed pieces of delaminated SCLM (Hawkesworth et al., 1986; Milner and le Roex, 1996). Strong support for this hypothesis comes from SCLM-derived Cretaceous potassic rocks from Alto Paranaiba in southern Brazil that overlap in Sr-Nd-Pb isotopic composition (Fig. 2, white crosses in gray field) with Walvis Ridge DSDP Site 525A basalts (Carlson et al., 1996). Os isotope data for kimberlites and lamproites from Alto Paranaiba point to a peridotitic source in the

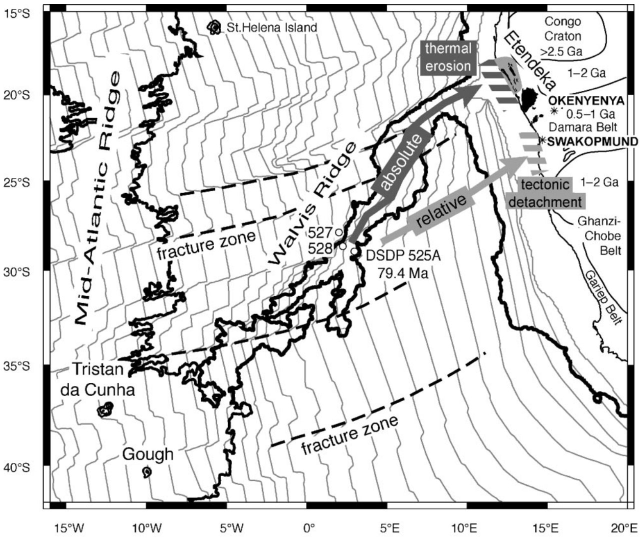

Figure 1. Map of South Atlantic in vicinity of Walvis Ridge showing location of Deep Sea Drilling Project (DSDP) Sites 525–528 and extent of Etendeka flood basalt province and major crustal units on African continent. Sites of possible detachment of continental material are identified by relative plate motion between Africa and South America (light gray area for tectonic detachment), or absolute motion of Africa relative to Tristan mantle plume (dark gray area and extent of Etendeka flood basalts in black for thermal erosion). Generic mapping tool map (Smith and Sandwell, 1997) showing ocean floor in 5 m.y. age intervals and 4000 m isobath. A few fracture zones are highlighted by dashed lines.

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*E-mails: class@ldeo.columbia.edu; aleroex@geology.uct.ac.za.

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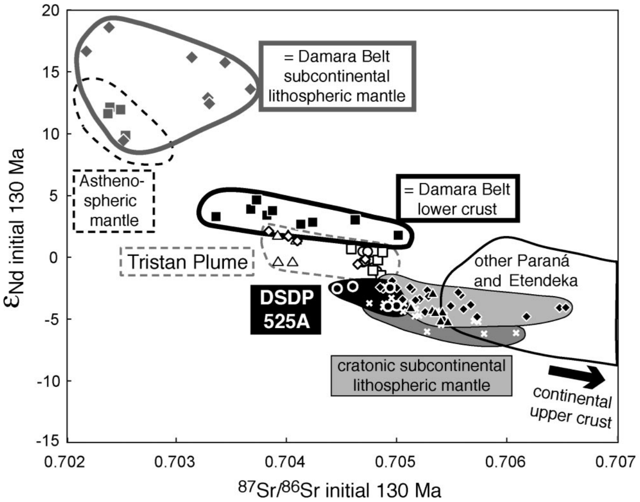

Figure 2. **$^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ (as ε_{Nd}) of Walvis Ridge Deep Sea Drilling Project (DSDP) Site 525A (black circles in black field) relative to Damara Belt subcontinental lithospheric mantle (gray squares and diamonds), Damara Belt lower crust (black squares), and cratonic subcontinental lithospheric mantle (gray fields with white crosses—Alto Paranaiba potassic alkaline rocks; black diamonds—Paraná Urubici; black triangles—Etendeka Khumib). Asthenospheric mantle, Tristan plume (DSDP Sites 527 and 528—open triangles, Inaccessible—open diamonds, Tristan da Cunha—open circles, Gough—open squares), other Paraná and Etendeka (open field), and arrow to continental upper crust are shown for comparison. Initial values allow comparison of samples of different ages. $\varepsilon_{Nd\ initial}$ is from DePaolo and Wasserburg (1976). Data sources: Richardson et al. (1982); le Roex (1985); le Roex et al. (1990); Cliff et al. (1991); Carlson et al. (1996); le Roex and Lanyon (1998); Peate et al. (1999); Ewart et al. (2004, and references therein).**

SCLM of Late Archean to mid-Proterozoic age (Carlson et al., 1996). Although there is some consensus that ancient SCLM might form the source of Walvis DSDP Site 525A basalts, neither the actual process of how SCLM might get detached during continental breakup nor the transport mechanism of such detached SCLM into the source of oceanic basalts has yet been constrained.

DISTINGUISHING DETACHMENT PROCESSES

Two major processes of detachment of continental material are distinguished. (1) Stretching and/or shearing-off fragments of the continental lithosphere during continental breakup, is here called tectonic detachment. Both SCLM and continental crust, lower and upper, could be tectonically detached. (2) Thermal erosion of the base of the SCLM by a mantle plume leads to the introduction of pieces of SCLM into the convecting asthenospheric mantle. Walvis Ridge provides a unique geological setting to distinguish between these alternatives, in that the site of thermal erosion of SCLM by the Tristan plume differs from the likely site of tectonic detachment (Fig. 1, dark and light gray shaded areas, respectively). This difference in location results from the absolute plate motion of the African plate (relative to the Tristan mantle plume) being oblique to the relative plate motion between South America and Africa (e.g., Duncan, 1981).

Tectonically detached material is assumed to reside at shallow depth and to get transported into an opening ocean basin in the direction of relative plate motion, for which small roll-like circulation cells or trapping of material in fracture zones have been suggested as possible processes (Bonatti and Crane, 1982; Rabinowicz et al., 1984). Figure 1 shows the age of the oceanic crust in 5 m.y. intervals (Smith and Sandwell, 1997). Kinks in the seafloor age give the location and direction of fracture zones, which generally reflect the direction of relative plate motion (Fig. 1, some highlighted by dashed lines). The light gray arrow follows the direction of fracture zones between Walvis Ridge Site 525A and the African continent and defines the location for tectonic detachment (Fig. 1, light gray shaded area).

The site of thermal erosion of SCLM by the Tristan plume is constrained by the location of the Tristan plume at the time of continental breakup. The direction of Walvis Ridge documents directly the motion of the African plate over the Tristan mantle plume. If the Tristan plume was stationary since the opening of the South Atlantic, the associated plume track records the absolute plate motion of the African plate (Fig. 1, dark gray arrow labeled absolute). The location of possible thermal erosion of the SCLM by the Tristan mantle plume is given then by the intersection of Walvis Ridge with the African continent (Fig. 1, dark gray shaded area) and the extent of the Etendeka flood basalt province (Fig. 1, in black).

The location of possible tectonic detachment is represented by the 0.5–1 Ga Damara Belt (Miller, 1983) (Fig. 1). In contrast, the location of possible thermal erosion by the Tristan plume is farther north and involves sampling of the SCLM of the Archean Congo craton (Cahan et al., 1983), although Proterozoic crustal units and part of the Damara Belt might be involved as well. Lower crustal units overlying the mantle component of the Congo craton are unlikely to be thermally eroded by a plume as this would require thermal erosion of the full extent of the thick underlying Archean SCLM prior to lower crust mobilization.

RESULTS

Here we present isotopic compositions of SCLM and the lower crust of the Damara Belt (Table 1) samples, which, based on their location, allow testing of a possible role for tectonically detached Gondwana fragments in the source of Walvis Ridge DSDP Site 525A basalts.

The composition of Damara Belt SCLM is constrained by the composition of mantle xenoliths discovered in two Cretaceous nephelinite plugs (ca. 76 Ma) ~17 km east of Swakopmund (Fig. 1). The xenoliths are 1.5–5 cm small lherzolites and harzburgites with no signs of modal metasomatism (Whitehead et al., 2002). Equilibration temperatures of ~840 °C to 1235 °C and pressures of 1.4–2.0 GPa place the xenoliths within the SCLM (Whitehead et al., 2002). Clinopyroxene mineral separates of spinel lherzolite xenoliths give initial ε_{Nd} = 9.9–12.1 and $^{87}Sr/^{86}Sr$ = 0.70237–0.70253 (Fig. 2, gray squares; initial isotopic compositions are calculated for the time of continental breakup, ca. 130 Ma). Mantle and crustal xenoliths have also been described from an alnöite diatreme (Baumgartner et al., 2000) emplaced in the Mesozoic Okenyenya igneous complex (Fig. 1), which is related to the activity of the early Tristan mantle plume (Milner and le Roex, 1996). Mantle xenoliths from Okenyenya are 1.5–12 cm and include both metasomatized and unmetasomatized varieties (Baumgartner et al., 2000; Class and le Roex, 2004). Equilibration temperatures of ~950 °C to 1050 °C and pressures of 1.8–1.9 GPa place the xenoliths within the SCLM (Baumgartner et al., 2000). Modally metasomatized xenoliths are not included here as they have compositions consistent with modal metasomatism by the Tristan mantle plume (Class and le Roex, 2004), whereas cryptically metasomatized xenoliths are included as their origin is more equivocal and might reflect the variable composition of the Damara Belt SCLM prior to the arrival of the Tristan plume. Clinopyroxene mineral separates of lherzolite xenoliths from Okenyenya give initial ε_{Nd} = 9.4–18.6 and $^{87}Sr/^{86}Sr$ = 0.70217–0.70366, overlapping the compositions measured from Swakopmund and indicating a common composition of the depleted SCLM at these two locations. Lower-crustal xenoliths from Okenyenya include granulites and amphibolites and show a range in initial ε_{Nd} = 1.8–4.6 and $^{87}Sr/^{86}Sr$ = 0.70335–0.705 (Fig. 2, black squares).

TABLE 1. ISOTOPIC COMPOSITION OF DAMARA BELT SUBCONTINENTAL LITHOSPHERIC MANTLE AND LOWER CRUST

Sample	Rock Type	Rb (ppm)	Sr (ppm)	^{87}Sr/^{86}Sr measured $\pm 2\sigma \times 10^6$	^{87}Sr/^{86}Sr initial 130 Ma	Sm (ppm)	Nd (ppm)	^{143}Nd/^{144}Nd measured $\pm 2\sigma \times 10^6$	ε_{ND} initial 130 Ma
Swakopmund clinopyroxene from mineral concentrate									
SMXN concentrate	cpx	0.21	15	0.702561 ± 7	0.702528	0.58	1.29	0.513240 ± 7	9.86
Swakopmund mantle xenoliths–clinopyroxene separates									
SMXN 61	spinel lherzolite	0.18	40	0.702416 ± 7	0.702390	1.49	3.32	0.513321 ± 12	12.07
SMXN 80	spinel lherzolite	0.19	35	0.702390 ± 8	0.702366	1.28	2.64	0.513315 ± 11	11.59
SMXN 81	spinel lherzolite	0.20	32	0.702516 ± 13	0.702485	1.27	2.51	0.513341 ± 9	11.91
Okenyenya mantle xenoliths–clinopyroxene separates									
OKYX 98-57	spinel lherzolite	0.21	57	0.703675 ± 5	0.703655	1.09	2.30	0.513415 ± 27	13.66
OKYX 98-60	spinel lherzolite	0.04	16	0.703134 ± 7	0.703119	1.02	1.76	0.513600 ± 10	16.24
			28	0.703448 ± 11	0.703433	1.16	2.13	0.513557 ± 11	15.73
OKYX 98-63	spinel lherzolite	0.23	35	0.703305 ± 10	0.703277	1.26	2.49	0.513393 ± 7	12.90
OKYX 98-64	spinel lherzolite	0.05	63	0.702509 ± 7	0.702505	1.26	3.60	0.513135 ± 8	9.44
OKYX 98-76	spinel lherzolite	0.24	19	0.703398 ± 8	0.703291	1.07	2.07	0.513375 ± 12	12.44
SRN 9	spinel lherzolite	0.11	19	0.702200 ± 5	0.702168	1.25	2.41	0.513595 ± 17	16.71
			23	0.702413 ± 7	0.702380	1.32	2.63	0.513683 ± 6	18.60
Okenyenya lower-crustal xenoliths									
SRN 116	Granulite	2.21	609	0.705024 ± 8	0.705005	0.41	3.03	0.512632 ± 8	1.78
SRN 117	Clinopyroxenite	23.58	738	0.704292 ± 7	0.704122	7.51	40.6	0.512703 ± 8	2.68
SRN 118	Amphibolite	13.59	319	0.704040 ± 6	0.703813	5.03	21.4	0.512766 ± 12	3.40
SRN 120	Amphibolite	55.06	481	0.703965 ± 7	0.703353	4.02	18.0	0.512755 ± 8	3.29
SRN 122	amph-cpx granulite	7.04	694	0.704283 ± 8	0.704229	1.83	6.75	0.512756 ± 11	2.84
SRN 128	amph-cpx granulite	3.26	732	0.704639 ± 8	0.704615	1.53	6.73	0.512743 ± 10	3.03
OKYX 98-52	Amphibolite	2.84	161	0.703761 ± 7	0.703667	3.29	12.7	0.512804 ± 7	3.90
OKYX 98-53	Amphibolite	16.85	994	0.703811 ± 10	0.703720	9.73	56.4	0.512797 ± 5	4.63
OKYX 98-54	Amphibolite	11.35	593	0.703967 ± 14	0.703865	4.81	24.5	0.512765 ± 7	3.77

Note: For isotope analyses clinopyroxenes were leached hot with 2.5N HCl for 20 min. and cold with 5% HF for 10 min. Sr, Nd, and Sm by isotope dilution, Rb by laser inductively coupled plasma–mass spectrometry (ICP-MS) in clinopyroxenes. Whole-rock trace elements of lower crustal xenoliths by solution ICP-MS. For isotope analyses, whole-rock powders were leached hot with 6N HCl for 1 hr. Sr and Nd isotope ratios were normalized to ^{86}Sr/^{88}Sr = 0.1194 and ^{146}Nd/^{144}Nd = 0.7219. Nd isotope analyses were made using NdO^+. Values are corrected based on replicate analyses of National Bureau of Standards NBS 987 (^{87}Sr/^{86}Sr = 0.710255 ± 18, 2σ external reproducibility, n = 10), and the La Jolla Standard (^{143}Nd/^{144}Nd = 0.511869 ± 23, n = 14). The sample ratios are corrected to a value of ^{87}Sr/^{86}Sr = 0.710230 for NBS 987 and ^{143}Nd/^{144}Nd = 0.511860 for La Jolla.

DISCUSSION

No Role for Tectonic Detachment

Tectonic detachment during continental breakup would only be indicated if the isotopic composition of the Damara Belt SCLM or lower crust showed similarities to the Walvis Ridge DSDP Site 525A geochemical signature. Figure 2 shows clearly that the ^{143}Nd/^{144}Nd (as ε_{Nd}) and ^{87}Sr/^{86}Sr isotopic composition of DSDP Site 525A samples (black circles in black field) are significantly more enriched than the compositions of the SCLM and lower crust of the Damara Belt. Consequently, to the extent that these samples reflect the composition of the SCLM and lower crust of the Damara Belt, it is evident that tectonic detachment through stretching or shearing-off of fragments of continental lithosphere can be excluded as a viable process giving rise to the mantle heterogeneity sampled by Walvis Ridge DSDP Site 525A basalts.

Thermal Erosion of a Craton

It is well established that Archean SCLM is geochemically enriched (e.g., Hawkesworth et al., 1983) with compositions suitable to account for the Walvis Ridge DSDP Site 525A signature (Carlson et al., 1996; Hawkesworth et al., 1986; Milner and le Roex, 1996; Peate et al., 1999). At the time of continental breakup, the nearest locations of such Archean SCLMs were the cojoined Congo and Rio Apa–Luis Alves cratons, ~400 km north of the possible source region for tectonically detached SCLM or lower crust. Tectonic detachment (as described here) of such material during breakup would require a mechanism to transport the detached SCLM ~1500 km across major transform faults to beneath Walvis Ridge DSDP Site 525A, which seems unlikely. In contrast, the edges of the cratons on the continental margin line up with the Tristan mantle plume track, and thermal erosion of this ancient SCLM material by the upwelling plume seems a feasible mechanism to introduce it into the convecting asthenospheric mantle. However, thermally eroded material is expected to get transported away from the location of the upwelling mantle plume. A mechanism for introducing geochemically anomalous Archean SCLM into the site of melting of DSDP Site 525A basalts ~50 m.y. later is therefore required and provides some constraints on the direction and velocity of mantle flow beneath the Walvis Ridge region between ca. 130 Ma and ca. 80 Ma.

Constraints on Mantle Flow

Flood basalt volcanism is now widely accepted to be caused by the arrival and spreading out of an initial plume head beneath the lithosphere (e.g., Griffiths and Campbell, 1990). Thermally eroded SCLM from the base of the lithosphere above the plume head can be expected to be transported radially away from the center of the plume as continuously hot buoyant material rises through the plume tail. However, the details of such a flow field in the vicinity of a thick Archean SLCM keel are still poorly understood. Assuming a 200–300-km-thick cratonic root (e.g., Fouch et al., 2004), the local flow field along the edge of the cratons would transport delaminated SCLM down to at least this depth and might divert it southward. Following continental breakup, the tail of the Tristan plume had an on-ridge position up to the time of volcanism ca. 80 Ma that formed Walvis Ridge DSDP Site 525A basalts and Rio Grande Rise DSDP Site 516F basalts with similar compositions (Gibson et al., 2005). If SCLM thermally eroded ca. 130 Ma remained stationary relative to the position of the continent, it would have moved ~1500 km away from the Tristan plume between ca. 130 Ma and ca. 80 Ma. To allow sampling of such thermally eroded SCLM by plume activity ca. 80 Ma, a net return flow in the asthenospheric mantle is required, which has to be generally opposite to the direction of plate motion (Fig. 3). The return flow assumed at a depth of 250 km suggests a minimum mantle flow velocity of v = (1500 km + 2 × 250 km)/50 m.y. = 4 cm/yr, whether from erosion of the Congo or the Rio Apa–Luis Alves cratons, and geochemical evidence alone does not allow distinction between these two alternatives.

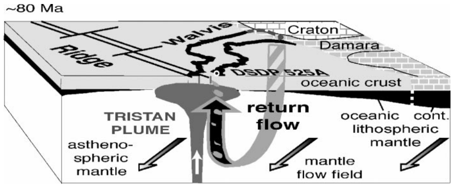

Figure 3. Schematic diagram showing return flow required to transport thermally eroded subcontinental lithospheric material of Congo craton to beneath Deep Sea Drilling Project Site 525A on Walvis Ridge ~50 m.y. later. Arrows illustrate seismically constrained present-day mantle flow field of region from Behn et al. (2004). Not to scale.

Global seismic tomography models show a large-scale, low seismic velocity anomaly in the middle to lower mantle beneath Africa, the so-called African superplume (e.g., Ritsema et al., 1999). Assuming that the African superplume represents a thermal upwelling, its effect on the flow field in the upper mantle has been compared with measured anisotropy in the asthenosphere (Behn et al., 2004) and suggests a direction of flow inconsistent with a return flow from beneath South America, but identical to the direction required for a return flow from beneath Africa. The requirement for the return flow to explain Walvis Ridge DSDP Site 525A volcanism might indicate that the African superplume is a long-lived feature that already affected the mantle flow field at 80–130 Ma. More regionally, the accumulation of oceanic basalts with continental signatures in the South Atlantic and southwestern Indian Ocean might be linked to the existence of the African superplume since the time of Gondwana breakup. Plumes postulated to have existed beneath Gondwana prior to breakup could have thermally eroded the base of the SCLM, with the African superplume providing the driving force that transported such thermally eroded SCLM from beneath Africa in a direction generally opposite to that of plate motion, into the opening South Atlantic and southwestern Indian Ocean.

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