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Re–Os isotope and highly siderophile element systematics of the Paraná continental flood basalts (Brazil)

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ABSTRACT

Basalts of the Paraná continental flood basalt (PCFB) province erupted through dominantly Proterozoic continental crust during the Cretaceous. In order to examine the mantle source(s) of this major flood basalt province, we studied Os, Sr, Nd, and Pb isotope systematics, and highly siderophile element (HSE) abundances in tholeiitic basalts that were carefully chosen to show the minimal effects of crustal contamination. These basalts define a precise Re–Os isochron with an age of 131.6 ± 2.3 Ma and an initial ^{187}Os/^{188}Os of 0.1295 ± 0.0018 (γ^{187}Os = +2.7 ± 1.4). This initial Os isotopic composition is considerably more radiogenic than estimates of the contemporary Depleted Mantle (DM). The fact that the Re–Os data define a well constrained isochron with an age similar to ^{40}Ar/^{39}Ar age determinations, despite generally low Os concentrations, is consistent with closed-system behavior for the HSE. Neodymium, Sr, and Pb isotopic data suggest that the mantle source of the basalts had been variably hybridized by melts derived from enriched mantle components. To account for the combined Os, Nd, Sr, and Pb isotopic characteristics of these rocks, we propose that the primary melts formed from metasomatized asthenospheric mantle (represented by arc-mantle peridotite) that underwent mixing with two enriched components, EM-I and EM-II. The different enriched components are reflected in minor isotopic differences between basalts from southern and northern portions of the province.

The Tristan da Cunha hotspot has been previously suggested to be the cause of the Parana continental flood basalt magmatism. However, present-day Tristan da Cunha lavas have much higher ^{187}Os/^{188}Os isotopic compositions than the source of the PCFB. These data, together with other isotopic and elemental data, preclude making a definitive linkage between the Tristan plume and the PCFB.

1. Introduction

Large igneous provinces are among the most massive, short-lived igneous events on Earth, producing vast volumes of lavas and intrusive rocks during magmatic periods that may last only a few million years or less (Coffin and Eldholm, 1994). Continental flood basalts (CFB), a manifestation of one type of large igneous provinces, are thought by some to form as a result of impingement of a rising mantle plume head on sub-continental lithospheric mantle (SCLM, e.g., Coffin and Eldholm, 1994). In such cases, it has been argued that the degree of partial melting, and the proportion of mantle plume material versus SCLM material contributing to parental melts, depends on the proximity of the site of melting to the plume head. White and Mckenzie (1989) postulated that magma is generated by decompression melting in plumes, and variations in melt production rates primarily reflect both the extension and/or thickness of the overlying lithosphere (tectonic control), and the temperature of the plume (thermal control). Additionally, the origin of geochemical signatures of CFB can be explained by mixing of various mantle-derived melts with continental crust (e.g., Campbell and Griffiths, 1990). Gibson et al. (1995) and Thompson et al. (2001) suggested that upwelling mafic–ultramafic melts, generated during pre-climactic and climactic stages of plume impact, can carry heat upwards by advection and cause substantial melting of both SCLM and upper

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crust. Collectively, such studies suggest that, despite relatively simple conceptual models for their formation, the genesis of CFB may be complex, involving contributions from diverse sources.

Numerous prior studies have attempted to identify mantle and crustal contributions to CFB (e.g., Allègre et al., 1999; Ellam et al., 1992; Marques et al., 1999; Merle et al., 2011; Puchtel et al., 1995; Qi and Zhou, 2008). Some CFB are characterized by Sr, Nd, and Pb isotopic signatures that are outside the normal range of compositions defined for mantle plume sources, as recorded in ocean-island basalts (OIB), and only rarely do CFB have isotopic compositions that can be linked to other possible contributors, such as SCLM (e.g., Ellam et al., 1992). For example, detailed geochemical and isotopic studies of Mesozoic Gondwana CFB, such as the Central Atlantic Magmatic Province (CAMP), Karoo, Ferrar and Paraná, indicate derivation from heterogeneous source regions, but with overall characteristics typified by low-$^{143}Nd/^{144}Nd$, high-$^{87}Sr/^{86}Sr$, and high-$^{207}Pb/^{206}Pb$, at a given $^{206}Pb/^{204}Pb$, relative to ambient convecting upper mantle (e.g., Merle et al., 2011; Molzahn et al., 1996). As noted by Carlson (1991), the origins of the enriched isotopic compositions commonly observed in CFB are not well constrained, as the isotopic contrasts between some possible sources, such as ancient SCLM and certain enriched plume sources, are not sufficient to discriminate and assign respective proportions.

Basalts of the Paraná continental flood basalt (PCFB) province were emplaced in the early Cretaceous on a large intracratonic Paleozoic sedimentary basin (Paraná Basin) that began subsiding in the Early Paleozoic. The crystalline basement probably formed by accretion of different geotectonic domains comprising Archean and Paleoproterozoic cratonic terrains, as well as Neoproterozoic mobile belts related to the Pan-African and Brasiliano orogenies that were responsible for the assemblage of West Gondwana (Holz et al., 2006).

Previous geological, geochemical, and isotopic studies (e.g., Bellieni et al., 1984; Marques et al., 1999; Peate et al., 1992) have led to the division of the PCFB into two main regions (Fig. 1). The southern PCFB province is characterized by the occurrence of tholeiitic basalts with TiO_2 ($\leq 2\%$), and relatively low concentrations of incompatible lithophile trace elements, such as P, Ba, Sr, Zr, Hf, Ta, and Y, as well as the light rare earth elements (LREE) (Fig. 2). The northern PCFB province is characterized by the occurrence of tholeiitic basalts with higher concentrations of TiO_2 ($TiO_2 > 2\%$) and incompatible lithophile trace elements (Fig. 2). The goal of this study is to further characterize the mantle source(s) involved in the genesis of the PCFB using the Re–Os isotope system, coupled with Nd, Sr, and Pb isotopic data, as an additional means to discriminate between different types of mantle sources involved in the formation of these basalts.

Osmium may be diagnostic in such applications, particularly in identifying the involvement of SCLM, because the initial $^{187}Os/^{188}Os$ ratios present in ancient SCLM (cratonic xenoliths) are, on average, considerably lower than those in ambient convecting upper mantle and OIB sources. If the SCLM is divided into 'on-craton' and 'off-craton' compositions, on-cratonic SCLM is typified by very un-radiogenic Os isotope compositions, with frequency distributions that are strongly negative (e.g., mean $\gamma^{187}Os = -10.3$; Pearson and Nowell, 2002). On the other hand, according to Pearson and Nowell (2002), off-cratonic xenoliths are not characterized by such low Os isotopic compositions, many of which are within the range of chondritic meteorites, and overlap with the estimates for contemporary Primitive Mantle (PM) (e.g., mean $\gamma^{187}Os = -1.5$).

Previous applications of Os isotopes to CFB as a genetic tool have commonly failed (e.g., Allègre et al., 1999; Qi and Zhou, 2008). This is because flood basalt magmas normally contain very low Os abundances that are easily overprinted by highly radiogenic Os from the continental crust (Asmerom and Walker, 1998). In such systems, Os isotopes are very sensitive tracers of basalt melt–crust interaction, but not of source provenance. In addition, the high Re/Os ratios typical of basalts can make precise determination of initial $^{187}Os/^{188}Os$ problematic in all but relatively young basaltic systems.

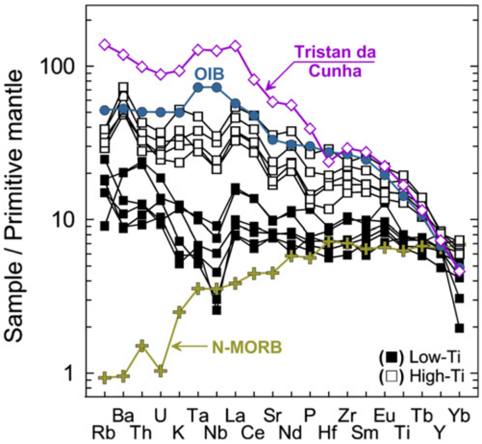

Fig. 2. Primitive mantle-normalized (Mcdonough and Sun, 1995) lithophile trace element distribution patterns for low-Ti and high-Ti tholeiites. In contrast to the PCFB basalts, the trace element pattern of the OIBs (in particular Tristan da Cunha volcanic rocks) shows a distinctive Nb–Ta positive anomaly.

Data sources: OIB and N-MORB—Sun and McDonough (1989), Tristan da Cunha is based on data from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/).

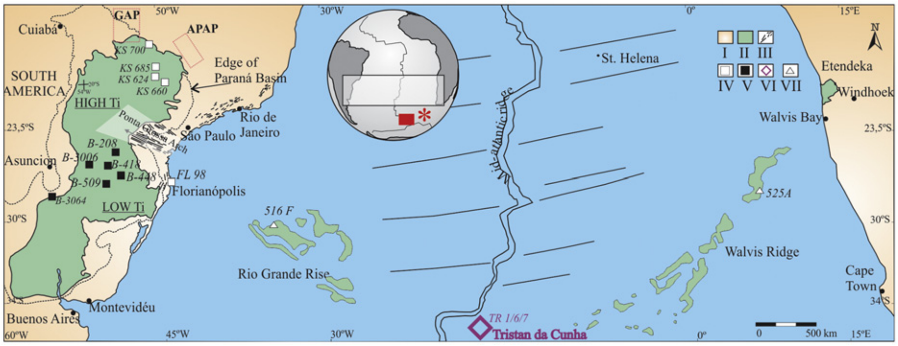

Fig. 1. Generalized geological map of the area studied. (I) crystalline basement, (II) PCFB, (III) dikes occurrence, (IV) high-Ti basalts, (V) low-Ti basalts, (VI) Tristan da Cunha samples, (VII) Rio Grande Rise (516F) and Walvis Ridge (525A) locations. Red asterisk in the inset represents the 40–50°S segment of the South Atlantic ridge (48.5–49.2°S segment corresponding to the DUPAL anomaly, Enriched-MORB (E-MORB), Escrig et al., 2005).

Data sources: Piccirillo and Melfi (1988), Stewart et al. (1996), Richardson et al. (1984), Weaver et al. (1983), Marques et al. (1999).

For this study, the Re–Os isotopic system was examined in the PCFB because prior Nd, Sr, and Pb isotopic work on these basalts has revealed little to no crustal contamination for at least some of the basalts (Marques et al., 1999; Rocha-Júnior, 2011). Also, the PCFB system is only ~132 Ma old and the Re/Os ratios for these basalts are relatively low, so age corrections for the radioactive decay of ^{187}Re are sufficiently minor to allow relatively accurate projections to initial ^{187}Os/^{188}Os ratios.

2. Analytical methods

Samples were ground to fine powders using an agate mortar and pestle. Strontium, Nd, and Pb isotopic analyses were performed at the Centro de Pesquisas Geocronológicas, Instituto de Geociências, Universidade de São Paulo via thermal ionization mass-spectrometry (TIMS). Strontium and Nd isotopic compositions were determined following the analytical procedures described by Kawashita (1972) and Sato et al. (1995). The Sr isotopic ratios were normalized to ^{86}Sr/^{88}Sr$=0.1194$ and replicate analyses of ^{87}Sr/^{86}Sr for the NBS-987 standard gave a mean value of 0.71028 ± 0.00006 (2σ); the total analytical blank for Sr was < 6.4 ng. The Nd isotopic compositions were normalized to ^{146}Nd/^{144}Nd$=0.72190$. Multiple analyses of ^{143}Nd/^{144}Nd for the La Jolla and BCR-1 standards gave mean values of 0.511847 ± 0.00005 (2σ) and 0.512662 ± 0.00005 (2σ), respectively; total analytical blanks were < 0.03 ng for both Nd and Sm. The analytical procedures employed for sample preparation and Pb chemical separation followed those reported by Babinski et al. (1999) and Marques et al. (1999). The mass fractionation correction was 0.11% per a.m.u. for ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb, and 0.07% per a.m.u. for ^{208}Pb/^{204}Pb; the average total analytical blank measured during the analytical campaign was < 100 pg, which is negligible in comparison to the quantities of Pb separated from the PCFB rocks, typically less than 0.2%.

The Re–Os isotopic and HSE concentration data were obtained at the *Isotope Geochemistry Laboratory* (*IGL*), Department of Geology, University of Maryland College Park, following the protocols described in detail in Puchtel et al. (2009a, 2009b). Approximately 1.5 g of whole-rock sample powder, 6 mL of purged, double-distilled conc. HNO_3, 4 mL of double-distilled conc. HCl, and appropriate amounts of mixed ^{185}Re–^{190}Os and HSE (^{99}Ru, ^{105}Pd, ^{191}Ir, ^{194}Pt) spikes were sealed in double, internally-cleaned, chilled 25 mL Pyrex^{TM} borosilicate Carius Tubes (CTs) and heated to 270 °C for 96 h. Osmium was extracted from the acid solution by CCl_4 solvent extraction (Cohen and Waters, 1996), then back-extracted into HBr, followed by purification via microdistillation (Birck et al., 1997). Ruthenium, Pd, Re, Ir, and Pt were separated and purified using anion exchange chromatography. Average total analytical blanks during the analytical campaign were (in pg): Ru 1.1 ± 0.5 ($\pm 2\sigma_{mean}$, $N=5$), Pd 6 ± 2, Re 0.43 ± 0.17, Os 0.19 ± 0.05, Ir 0.45 ± 0.23, and Pt 11 ± 5. The total analytical blank for Re constituted less than 0.1%, for Os – less than 0.4%, for Ir – less than 1.3%, for Ru – less than 0.8%, and for Pt and Pd – less than 0.2%, of the total element analyzed.

Osmium isotopic measurements were accomplished via negative thermal ionization mass-spectrometry (Creaser et al., 1991). All samples were analyzed using a secondary electron multiplier detector of a *ThermoElectron Triton* mass spectrometer at the *IGL*. The measured isotopic ratios were corrected for mass fractionation using ^{192}Os/^{188}Os$=3.083$. The internal precision of measured ^{187}Os/^{188}Os in all samples was better than 0.05% relative. The ^{187}Os/^{188}Os in 300 pg loads of the in-house Johnson–Matthey Os standard reference material measured during the analytical campaign averaged 0.11377 ± 20 ($\pm 2\sigma_{stdev}$, $N=13$). This value characterizes the external precision of the isotopic analysis (0.2%). We used this value to calculate the true uncertainty on the measured ^{187}Os/^{188}Os ratio for each individual sample. The ^{187}Os/^{188}Os ratio measured in each sample was also corrected for the instrumental bias relative to the average ^{187}Os/^{188}Os$=0.11378$ measured in the Johnson–Matthey Os standard reference material on the Faraday cups of the *IGL Triton*, which is our accepted value for this standard.

The measurements of Ru, Pd, Re, Ir, and Pt were performed at the *IGL* via inductively coupled plasma mass-spectrometry (ICP-MS) using a *Nu Plasma* instrument with a triple electron multiplier configuration in a static mode. Isotopic mass fractionation was monitored and corrected for by interspersal of samples with standards. The accuracy of the data was assessed by comparing the results for the reference materials UB-N and GP-13 (Puchtel et al., 2007, 2008) with the results from other laboratories. Concentrations of all HSE and Os isotopic compositions obtained at the *IGL* are in good agreement with the other labs. Diluted spiked aliquots of iron meteorites were run during each analytical session as secondary standards. The results from these runs agreed within 0.5% for Re and Ir, and within 2% for Ru, Pt, and Pd, with fractionation-corrected values obtained from measurements of undiluted iron meteorite solutions using Faraday cups of the same instrument with a signal of > 100 mV for the minor isotopes. We therefore cite $\pm 2\%$ as uncertainty on the concentrations of Ru, Pt, and Pd, $\pm 0.5\%$ on Re and Ir, and $\pm 0.2\%$ on the concentrations of Os in the whole-rock samples.

All regression calculations were performed using ISOPLOT 3.17 (Ludwig, 2008). The uncertainties on the concentrations and isotopic ratios used for the regression calculations are those stated above. The initial γ^{187}Os value was calculated as the percent deviation of the isotopic composition at the time defined by the isochron, relative to the chondritic reference (Shirey and Walker, 1998) at that time. The average chondritic Os isotopic composition at the time defined by the isochron was calculated using the ^{187}Re decay constant $\lambda = 1.666 \times 10^{-11}$ yr^{-1}, an early Solar System initial ^{187}Os/^{188}Os$=0.09531$, and ^{187}Re/^{188}Os$=0.40186$ (Shirey and Walker, 1998; Smoliar et al., 1996).

3. Results

3.1. Lithophile element isotopic systems

The calculated initial ^{87}Sr/^{86}Sr, ^{143}Nd/^{144}Nd, ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb isotopic ratios obtained in this study (Table 1) are consistent with those reported previously (Marques et al., 1999; Piccirillo and Melfi, 1988). The low-Ti and high-Ti basalts from the PCFB show moderate variations in Sr and Nd isotopic compositions (for low-Ti rocks: ^{87}Sr/^{86}Sr$_i$: 0.70461–0.70578, initial ε_{Nd} values vary from $+2.7$ to -0.2; for high-Ti rocks: ^{87}Sr/^{86}Sr$_i$: 0.70453–0.70586, initial ε_{Nd} values range from -1.7 to -4.4). The initial Pb isotopic ratios vary according to the different rock types of the PCFB (Table 1). The low-Ti basalts show small variation in initial Pb isotopic compositions, with initial ^{206}Pb/^{204}Pb$_i$ ratios varying from 18.10 to 18.30, ^{207}Pb/^{204}Pb$_i$ from 15.60 to 15.63 and ^{208}Pb/^{204}Pb$_i$ from 38.20 to 38.45. In comparison, the high-Ti basalts have less radiogenic Pb, with initial ^{206}Pb/^{204}Pb$_i$ ratios varying from 17.65 to 17.76, ^{207}Pb/^{204}Pb$_i$ from 15.50 to 15.54 and ^{208}Pb/^{204}Pb$_i$ from 37.95 to 38.09.

3.2. Os isotopic composition and HSE abundances

Osmium isotope and HSE concentration data for the 19 basalt samples (including replicate digestions) analyzed in this study are provided in Tables 2 and 3. Rhenium and Os concentrations vary between 0.55 and 1.1 and 0.033 and 0.13 ng/g, respectively. These Re and Os concentrations overlap with those reported for other CFB, such as Deccan and Emeishan (Allègre et al., 1999; Qi and

Table 1
Sr–Nd–Pb isotopic data for PCFB and Tristan da Cunha basalts.

Sample	^{87}Sr/^{86}Sr	^{143}Nd/^{144}Nd	ε^{143}Nd$_i$[a]	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb
Low Ti PCFB						
B-208	0.70608 ± 1[b]	0.51264 ± 3[b]	+0.7	18.328 ± 6[b]	15.635 ± 7[b]	38.732 ± 24[b]
B-448	0.70496 ± 1[b]	0.51274 ± 8[b]	+2.1	18.413 ± 6[b]	15.617 ± 7[b]	38.528 ± 23[b]
B-3064	0.70522 ± 1[b]	0.51278 ± 2[b]	+2.7	18.379 ± 6[b]	15.613 ± 7[b]	38.501 ± 24[b]
B-3006	0.70565 ± 1[b]			18.442 ± 6[b]	15.625 ± 7[b]	38.548 ± 24[b]
B-418	0.70504 ± 3[b]			18.387 ± 6[b]	15.609 ± 7[b]	38.520 ± 24[b]
B-509	0.70564 ± 1[b]	0.51261 ± 2[b]	−0.2	18.367 ± 8[b]	15.636 ± 8[b]	38.716 ± 26[b]
High Ti PCFB						
KS-624	0.706018 ± 72	0.512382 ± 8	−4.1	17.889 ± 1	15.546 ± 1	38.369 ± 3
KS-660	0.706159 ± 50	0.512385 ± 11	−4.0	17.887 ± 4	15.513 ± 4	38.260 ± 9
KS-685	0.705801 ± 41	0.512379 ± 10	−4.1	17.907 ± 4	15.537 ± 3	38.341 ± 8
KS-700	0.705650 ± 95	0.512359 ± 10	−4.4	17.882 ± 3	15.532 ± 2	38.326 ± 7
FL-98	0.704704 ± 77	0.512500 ± 8	−1.7	17.909 ± 2	15.536 ± 1	38.307 ± 3
Tristan da Cunha basalts						
TR-7	0.70507[c]	0.512528[c]	−2.1	18.541[c]	15.533[c]	39.002[c]
TR-6	0.70501[c]	0.512567[c]	−1.4	18.534[c]	15.546[c]	39.049[c]
TR-1	0.70505[c]	0.512534[c]	−2.0	18.534[c]	15.546[c]	39.049[c]

[a] Calculated for the age of 131.6 Ma (PCFB) and 1 Ma (Tristan da Cunha).

[b] These isotopic compositions were determined by Piccirillo and Melfi (1988), Marques et al. (1989, 1999).

[c] Sr–Nd–Pb isotopic data for Tristan da Cunha are from White and Hoffman (1982) and Newsom et al. (1986).

Table 2
Re–Os isotopic data for PCFB and Tristan da Cunha basalts.

Sample	^{187}Re/^{188}Os	^{187}Os/^{188}Os	γ^{187}Os$_i$*	T$_{MA}$ (Ma)
Low Ti PCFB				
B-208	31.0	0.19794 ± 12	+3.0	139
B-448	89.4	0.32701 ± 69	+3.7	135
B-3064	29.1	0.19355 ± 12	+2.7	139
B-3006	31.1	0.19749 ± 11	+2.5	138
Replicate	28.5	0.19229 ± 12	+2.9	139
B-418	87.5	0.32042 ± 27	+1.8	133
Replicate	79.5	0.30288 ± 13	+1.9	133
B-509	28.6	0.19385 ± 13	+3.8	142
Replicate	52.5	0.24715 ± 13	+4.7	138
High Ti PCFB				
KS-624	62.6	0.26766 ± 67	+3.3	136
Replicate	77.9	0.29884 ± 15	+1.3	133
KS-660	41.3	0.22189 ± 33	+4.1	139
Replicate	43.8	0.22422 ± 12	+1.5	134
KS-685	47.9	0.23805 ± 60	+5.3	140
Replicate	65.5	0.26950 ± 15	−0.4	131
KS-700	29.7	0.19437 ± 39	+2.4	138
replicate	27.9	0.18934 ± 10	+1.5	136
FL-98	42.1	0.21979 ± 55	+1.0	133
Replicate	41.2	0.21892 ± 10	+1.9	135
Tristan da Cunha basalts				
TR-7	224	0.1633 ± 3	+26	9.7
TR-6	724	0.2401 ± 7	+80	9.4
TR-1	288	0.1508 ± 6	+15	5.0

γ^{187}Os and Model age (T_{MA}) were calculated as per Shirey and Walker (1998).

* Calculated for the age of 131.6 Ma (PCFB) and 1 Ma (Tristan da Cunha).

Table 3
HSE abundance data (ng/g) for PCFB and Tristan da Cunha basalts.

Sample	Magma-type	Os	Ir	Ru	Pt	Pd	Re
Low Ti PCFB							
B-208	Esmeralda	0.0864	0.0318	0.222	3.37	9.65	0.551
B-448	Esmeralda	0.0334	0.0231	0.178	4.70	8.77	0.604
B-3064	Esmeralda	0.125	0.0713	0.229	6.76	9.87	0.752
B-3006	Esmeralda	0.0881	0.0560	0.239	5.73	8.50	0.563
Replicate		0.0973	0.0607	0.247	6.23	8.13	0.570
B-418	Esmeralda	0.0364	0.0239	0.194	5.49	7.25	0.645
Replicate		0.0401	0.0206	0.186	5.23	7.14	0.647
B-509	Esmeralda	0.100	0.0417	0.165	5.06	11.4	0.589
Replicate		0.0558	0.0243	0.158	5.32	11.8	0.598
High Ti PCFB							
KS-624	Paranapanema	0.0850					1.08
Replicate		0.0671	0.114	0.0963	4.15	1.73	1.06
KS-660	Paranapanema	0.113					0.957
Replicate		0.107	0.191	0.139	4.51	3.77	0.963
KS-685	Paranapanema	0.0751					0.737
Replicate		0.0549	0.0885	0.0813	4.01	2.87	0.733
KS-700	Pitanga	0.101					0.619
Replicate		0.105	0.201	0.106	8.95	7.79	0.605
FL-98	Urubici	0.0970					0.838
Replicate		0.0935	0.0867	0.154	3.75	8.84	0.790
Tristan da Cunha basalts							
TR-7	NMNH110020	0.010	0.024	0.082	0.701	0.501	0.483
TR-6	NMNH110019	0.003	0.039	0.007	0.067	0.101	0.476
TR-1	NMNH110014	0.010	0.003	0.008	0.037	0.036	0.571

Zhou, 2008). Rhenium concentrations in the PCFB are generally higher than those in most OIB (Hauri and Hart, 1997; Ireland et al., 2011; Jackson and Shirey, 2011), but are similar to those in MORB (e.g., Escrig et al., 2005; Gannoun et al., 2007). All samples are strongly depleted in Os, Ir, and Ru compared to Pt, Pd, and Re, and chondrite-normalized patterns are similar to those reported for Emeishan CFB (Qi and Zhou, 2008) as well as oceanic basalts (e.g., Dale et al., 2008) (Fig. 3).

The ^{187}Re/^{188}Os ratios measured in the PCFB range from ~30 to 90. On a plot of ^{187}Re/^{188}Os versus ^{187}Os/^{188}Os, the Re–Os data for 11 samples (data for the eight samples for which the analyses were replicated were averaged for each sample and treated as single data points) of both high- and low-Ti basalts form a linear trend with a slope that corresponds to a Model 3 ISOPLOT age of 131.6 ± 2.3 Ma and an initial ^{187}Os/^{188}Os = 0.1295 ± 0.0018 (γ^{187}Os = +2.7 ± 1.4) (Fig. 4). The scatter of the data about the regression line exceeds that resulting from the analytical uncertainty, as indicated by the MSWD = 4.5, which is higher than the maximum expected value of ~2 calculated for the given degree of freedom using the protocol of Wendt and Carl (1991). This might be due to some Re mobility in these samples after lava emplacement and/or some Os isotopic heterogeneity in the source(s) of the lavas. However, both mobility and heterogeneity were very limited, since the regression age is consistent, within uncertainty, with the accepted emplacement age of the lavas. For instance, ^{40}Ar/^{39}Ar ages and paleomagnetic studies indicate that the main magmatic activity occurred within a short time interval between 133 and 132 Ma (Renne et al., 1992; Turner et al., 1994). Most recently, Thiede and Vasconcelos (2010)

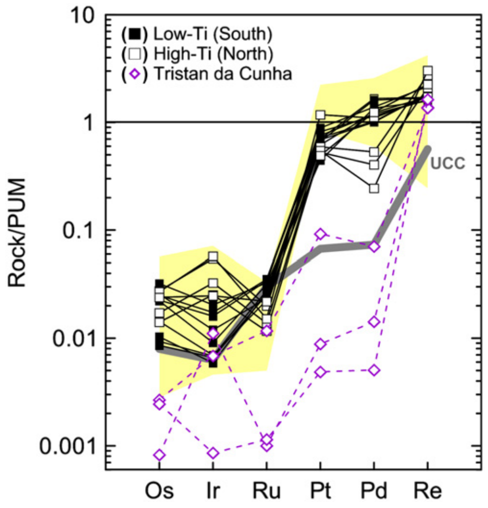

Fig. 3. Highly siderophile element abundances in the PCFB and Tristan da Cunha basalts normalized to the primitive mantle values of Walker (2009). Upper Continental Crust (UCC) composition (from Peucker-Ehrenbrink and Jahn, 2001) is shown for comparison. Yellow shaded band represents the range of compositions reported for Emeishan basalts from Qi and Zhou (2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

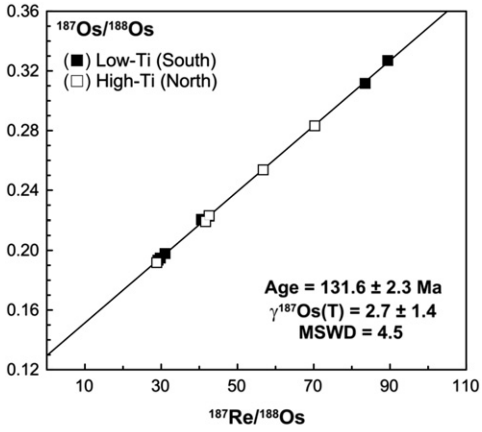

Fig. 4. Re–Os isochron diagram for the PCFB. Analytical uncertainties are smaller than the size of the symbols.

placed PCFB extrusion at 134.6 ± 0.6 Ma, concluding that the duration of the PCFB volcanism was < 1.2 Ma.

For the regression age of 131.6 Ma, the initial γ_{Os} values calculated for individual samples range only from +1.5 to +4.3. The average initial $^{187}Os/^{188}Os$ calculated for all individual samples for the age of 131.6 Ma is 0.1295 ± 0.0006 ($\gamma^{187}Os = +2.7 \pm 0.5$) and represents our best estimate of the initial $^{187}Os/^{188}Os$ in the lavas. These data indicate remarkably little variation in initial $^{187}Os/^{188}Os$ within the suite.

4. Discussion

4.1. The role of crustal and ancient SCLM contamination

The limited range in calculated initial Os isotopic compositions for individual samples is in contrast to typically much wider ranges of initial Os isotope compositions reported for basalts from other CFB suites, such as Karoo, Deccan, and Emeishan (e.g., Allègre et al., 1999; Ellam et al., 1992; Qi and Zhou, 2008). Nevertheless, calculated initial Os isotopic compositions for the PCFB do show some variation outside of analytical uncertainties. If they were derived from a source with a homogeneous Os isotopic composition, the limited variations in calculated initial $^{187}Os/^{188}Os$ could reflect minor open-system behavior for individual rocks, or minor, but variable extents of assimilation of continental crust, SCLM, or both. Significant assimilation of continental crust, or ancient SCLM, however, would likely result in samples from the same source falling on mixing lines trending towards either an Os-poor, high-$^{187}Os/^{188}Os$ crustal component, or a SCLM component that is Os-rich and characterized by subchondritic $^{187}Os/^{188}Os$ ratio. Such trends are not observed. There is also no correlation between calculated initial $^{187}Os/^{188}Os$ ratio and 1/Os (Fig. 5), $^{87}Sr/^{86}Sr$ (Fig. 6a) or $^{143}Nd/^{144}Nd$ (Fig. 6b) in either the low-Ti or high-Ti basalts. Although the high-TiO_2 basalts have slightly lower average initial $\gamma^{187}Os$ values of $+2.2 \pm 0.5$ compared to the low-TiO_2 basalts (average initial $\gamma^{187}Os = +3.0 \pm 0.8$), there is no statistically significant difference between the two groups. Thus, the small variations in initial $^{187}Os/^{188}Os$ ratios appear to be inconsistent with appreciable crustal or ancient lithospheric mantle contamination, and we conclude that the initial Os isotopic composition derived from the group isochron reflects the composition of the mantle source of the PCFB that was generally homogeneous with respect to Os isotopes.

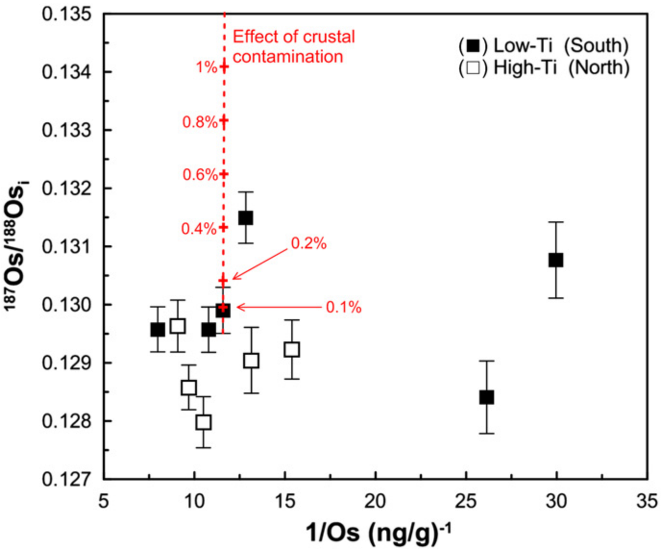

Fig. 5. Initial $^{187}Os/^{188}Os$ for individual samples calculated for the eruption age of 131.6 Ma plotted against 1/Os concentration. A lack of co-variation suggests minimal assimilation of either radiogenic ancient crust or unradiogenic SCLM. Binary mixing between PCFB basalt with highest MgO content ($^{187}Os/^{188}Os_i = 0.1295$, [Os] = 0.086 ng/g) and continental crust ($^{187}Os/^{188}Os = 1.4$, [Os] = 0.031 ng/g) from the Peucker-Ehrenbrink and Jahn (2001) is shown with the dashed line (increments of mixing (%) are shown as crosses).

4.2. The role of Tristan da Cunha mantle plume

The PCFB has commonly been genetically linked to the Tristan da Cunha hotspot, presently located at ~4000 km to the east in the Atlantic Ocean (e.g., Gibson et al., 1995; Richards et al., 1989; White and Mckenzie, 1989). There has been little prior Os isotopic work done on Tristan rocks. In order to compare the mantle sources of Tristan rocks and PCFB, we report new Re–Os isotopic, and HSE data for three Tristan basalts (Tables 2 and 3). Osmium, Ir, and Ru concentrations among the three basalts are highly variable (Fig. 3), whereas there is much less variation in the concentrations of Pt, Pd, and Re. Overall, HSE abundances are within the range of OIB worldwide, although Os concentrations are at the low end of the

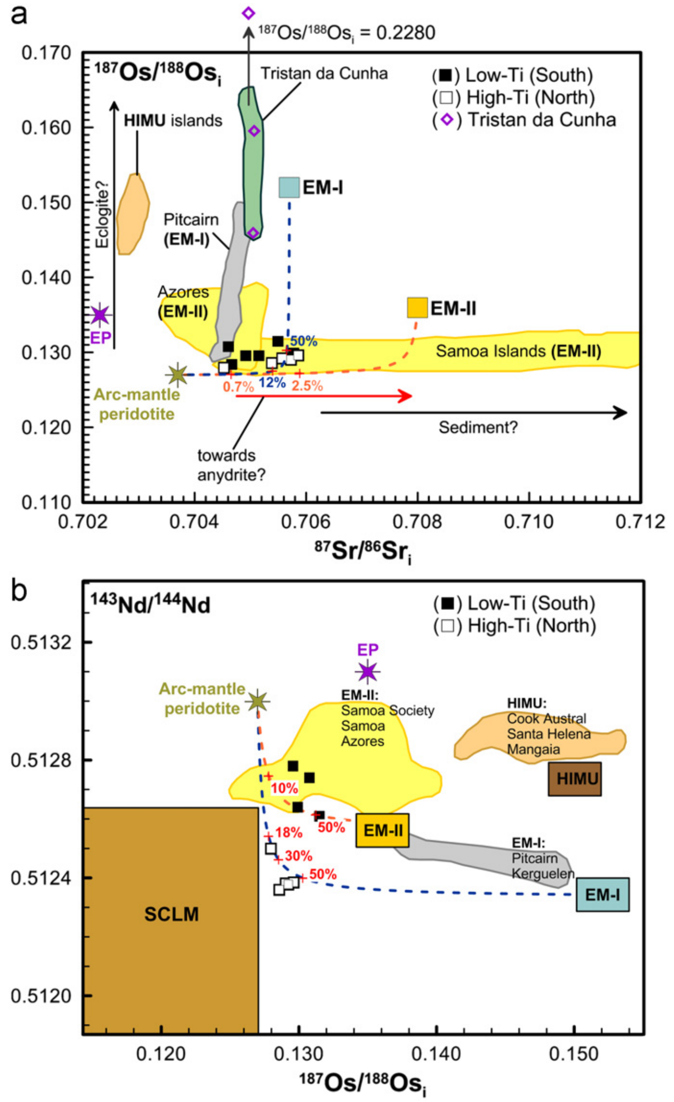

Fig. 6. (a) Initial $^{187}Os/^{188}Os$ (at 131.6 Ma) plotted against initial $^{87}Sr/^{86}Sr$. Modeling assumes two-component mixing between sublithospheric mantle (represented by arc-mantle peridotite, $^{187}Os/^{188}Os=0.127$, $[Os]=0.45$ ng/g, $^{87}Sr/^{86}Sr=0.7037$, $[Sr]=12$ μg/g) and two enriched components. Model (1) is EM-I (blue curve; $^{187}Os/^{188}Os=0.152$, $[Os]=0.068$ ng/g; $^{87}Sr/^{86}Sr=0.7057$, $[Sr]=495$ μg/g). Model (2) is EM-II (orange curve; $^{187}Os/^{188}Os=0.136$, $[Os]=0.40$ ng/g, $^{87}Sr/^{86}Sr=0.7080$, $[Sr]=484$ μg/g). (b) Initial ε_{Nd} plotted against initial $^{187}Os/^{188}Os$ (at 131.6 Ma). Modeling assumes two-component mixing between depleted mantle-derived melts (represented by arc-mantle peridotite, $^{187}Os/^{188}Os=0.127$, $[Os]=0.3$ ng/g, $\varepsilon_{Nd}=+11$, $[Nd]=2.9$ μg/g) and two enriched components. Model (1) is EM-I (blue curve; $^{187}Os/^{188}Os=0.152$, $[Os]=0.068$ ng/g, $\varepsilon_{Nd}=-5.75$, $[Nd]=30.6$ μg/g). Model (2) is EM-II (orange curve; $^{187}Os/^{188}Os=0.136$, $[Os]=0.293$ ng/g, $\varepsilon_{Nd}=-1.5$, $[Nd]=41.4$ μg/g). The parameters for the Enriched Plume (EP), EM-I, EM-II, and HIMU are from Jackson and Shirey (2011), Shirey and Walker (1998), Walker et al. (2002) and Zindler and Hart (1986). The parameters for the arc-mantle peridotite are from Handler et al. (2005), Hart et al. (1997) and Tatsumoto et al. (1992). Increments of mixing (%) are shown as crosses. Uncertainties are smaller than the size of the symbols representing the data points. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

range. The initial $^{187}Os/^{188}Os$ ratios of the three basalts, calculated for 1 Ma, vary from 0.146 to 0.228 (initial $\gamma^{187}Os$ values range from +15 to +80). All three samples are considerably more radiogenic than the modern projection of the PCFB source. These suprachondritic isotopic compositions could reflect direct contamination of lavas, as they passed through the oceanic crust. The two basalts with the lowest $^{187}Os/^{188}Os$ also have the highest Os concentrations, providing limited support to this contention. On the other hand, the oceanic crust through which the Tristan lavas were erupted, is <20 Ma, and unlikely to have generated sufficient ^{187}Os to have significantly contributed to these heterogeneities. More likely, the radiogenic initial Os isotopic compositions of the Tristan da Cunha basalts dominantly reflect a substantial, variable ancient recycled component in the source, such as recycled oceanic crust and/or pelagic sediments, as is common in other OIB sources (e.g., Hauri and Hart, 1997; Reisberg et al., 1993; Zindler and Hart, 1986).

Although presently limited, the suprachondritic Os isotopic data weigh against the conclusions of Gibson et al. (2005) and Peate et al. (1999) that the present-day Tristan da Cunha plume contains a delaminated ancient SCLM component that has undergone deep mantle recycling. It is, however, not possible to preclude the involvement of pyroxenite veins derived from recently metasomatized SCLM, which would have much higher $\gamma^{187}Os$ values.

We conclude that, although additional work on Tristan lavas will be necessary to rule out contributions to the PCFB from the Tristan plume, the Os isotopic data currently provide no evidence for a direct linkage. This conclusion is consistent with studies carried out by Ernesto et al. (2002), Marques et al. (1999) and Peate and Hawkesworth (1996) that all noted substantial compositional and isotopic (Sr–Nd–Pb) differences between PCFB tholeiites and the modern Tristan da Cunha volcanic rocks.

4.3. Nature of the mantle source of PCFB magmatism

In order to compare the isotopic compositions of the PCFB source with modern OIB and other possible mantle components, the initial $^{143}Nd/^{144}Nd$ ratio for the source of the low-Ti and high-Ti basalts was projected to the present, assuming evolution with a $^{147}Sm/^{144}Nd$ of 0.1967 that is consistent with the Chondritic Uniform Reservoir (CHUR) of DePaolo and Wasserburg (1976). This projected ratio is 0.512871 ($\varepsilon_{Nd}(T=0)=+4.5$) for the low-Ti basalts, and is 0.512471 ($\varepsilon_{Nd}(T=0)=-3.3$) for the high-Ti basalts. The average initial $^{87}Sr/^{86}Sr$ ratio for the source of the low-Ti and high-Ti basalts, when projected to the present, assuming evolution with a $^{87}Rb/^{86}Sr$ of 0.0827 that is consistent with an Undifferentiated Reservoir (UR) of DePaolo and Wasserburg (1979 and references therein), is 0.70482 for the low-Ti basalts, and is 0.70516 for the high-Ti basalts. To calculate the modern $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ ratios for the source of the low-Ti and high-Ti basalts of the PCFB, we assume the U/Th and U/Pb of the Depleted Mid-Ocean Ridge Basalt Mantle (DMM) reservoir (the $^{238}U/^{204}Pb=10.95$, $^{235}U/^{204}Pb=0.08$ and $^{232}Th/^{204}Pb=27.93$; Hofmann, 2003). Initial $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ ratios for the low-Ti basalts, when projected to the present, are 18.321, 15.615 and 38.379, respectively. For the high-Ti basalts, the initial $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ ratios, when projected to the present, are 17.878, 15.513 and 38.137, respectively. Note that the low-Ti basalts have higher Pb initial ratios ($^{206}Pb/^{204}Pb=18.092$–18.300) than the high-Ti basalts ($^{206}Pb/^{204}Pb=17.649$–17.763). These different initial isotopic compositions could not have been produced from mantle with identical long-term U/Pb ratios. In noting this, Marques et al. (1999) suggested that the distinct enrichments in these incompatible trace elements is the result of the involvement of fluids and/or small volume melts related to metasomatic processes.

The initial $^{187}Os/^{188}Os$ ratio for the PCFB source, when projected to the present, assuming evolution with an average chondritic $^{187}Re/^{188}Os$ of 0.40186 (Shirey and Walker, 1998), is 0.13038 ($\gamma^{187}Os=+2.7$). This is nearly 2% higher than maximum estimates for the DMM based on extrapolations from data for ophiolites (Walker et al., 2002), and nearly 5% higher than estimates for the DMM based on the data for abyssal peridotites (Harvey et al., 2006; Liu et al., 2008; Snow and Reisberg, 1995) (Fig. 7). The projected isotopic composition overlaps with the Os isotopic compositions of some plume derived basalts, such as

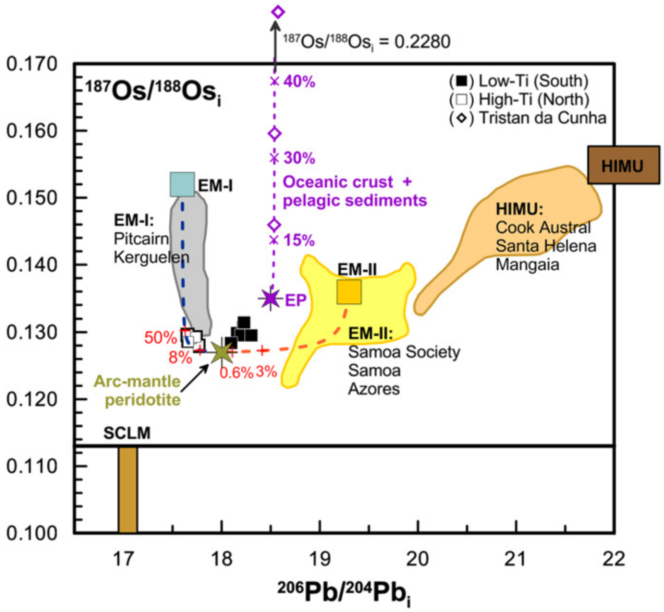

Fig. 7. Plot of initial $^{187}Os/^{188}Os$ (at 131.6 Ma) versus $^{206}Pb/^{204}Pb_m$. Parameters for EM-I, EM-II, HIMU, and SCLM are from Zindler and Hart (1986) and Shirey and Walker (1998). The parameters for the arc-mantle peridotite are from Handler et al. (2005), Hart et al. (1997) and Tatsumoto et al. (1992). Purple dashed line denotes binary mixing. Mixing curves are similar to those presented in Hauri et al. (1996), Shirey and Walker (1998), Widom (1997). Tristan da Cunha modeling assumes two-component mixing between Enriched Plume (EP) component ($^{187}Os/^{188}Os=0.135$, $[Os]=3.3$ ng/g, $^{206}Pb/^{204}Pb=18.50$, $[Pb]=30$ ng/g) and 2.0-Ga recycled crust plus 1.7% 2.0-Ga pelagic sediment ($^{187}Os/^{188}Os=1.74$, $[Os]=0.102$ ng/g, $^{206}Pb/^{204}Pb=18.54$, $[Pb]=807$ ng/g). PCFB modeling assumes two-component mixing between sublithospheric mantle (represented by arc-mantle peridotite; $^{187}Os/^{188}Os=0.127$, $[Os]=0.45$ ng/g, $^{206}Pb/^{204}Pb=18.00$, $[Pb]=0.2$ μg/g) and two enriched components. Model (1) is EM-I (blue curve; $^{187}Os/^{188}Os=0.152$, $[Os]=0.068$ ng/g, $^{206}Pb/^{204}Pb=17.60$, $[Pb]=2.8$ μg/g). Model (2) is EM-II (orange curve; $^{187}Os/^{188}Os=0.136$, $[Os]=0.40$ ng/g, $^{206}Pb/^{204}Pb=19.30$, $[Pb]=3.0$ μg/g). Increments of mixing (%) are shown as crosses. Uncertainties are smaller than the size of the symbols representing the data points. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Hawaiian Kea trend lavas (e.g., Bryce et al., 2005; Ireland et al., 2011).

Of greatest importance regarding these data, there is no Os isotopic evidence for the significant involvement of ancient SCLM in the source of the PCFB, which would most likely be characterized by $\gamma^{187}Os \ll 0$. Osmium–Nd isotope trends between DMM and SCLM, that have been used in prior studies to argue for contributions of ancient SCLM to the genesis of other flood basalts (e.g., Ellam et al., 1992; Horan et al., 1995; Merle et al., 2011; Molzahn et al., 1996), are lacking in the data for the Paraná basalts (Fig. 6b). Consequently, we conclude that there is no evidence that would suggest that ancient SCLM was a major source component for the PCFB.

In contrast to ancient SCLM, it remains possible that relative young SCLM was involved in the generation of the PCFB. Carlson et al. (2007) reported data for spinel-peridotites from the Goiás Alkaline Province (GAP), located on the northeastern margin of the Paraná Basin, revealing the existence of shallow SCLM with Re–Os isotopic compositions ($\gamma^{187}Os$ calculated for 85 Ma ranging from -5.1 to $+2.2$) similar to the modern DMM. They interpreted this to imply recent derivation of this lithospheric mantle from the convecting mantle. The study concluded that at least some of the lithospheric mantle in this area may have been created during the Mesoproterozoic assembly of the Brasiliano mobile belt basement.

Given that the average initial $\gamma^{187}Os$ value for the basalts of the PCFB overlaps with the compositions of fertile SCLM xenoliths from the GAP, the results provide permissive evidence for the involvement of newly-formed SCLM, and leads to the question of whether or not the SCLM sampled by the GAP extends under the PCFB. Yet, as previously noted, the crystalline basement of the Paraná Basin probably formed as a cratonic nucleous, such as the Paranapanema continental lithospheric fragment (remaining of the Rodinia break up), to which accreted mobile belts during the Neoproterozoic (Mantovani and Brito-Neves, 2005). Hence, the geotectonic framework of the basement underlying the PCFB is characterized by several cratonic blocks and intervening mobile belts that form a complex framework of lineaments and crustal discontinuities (Holz et al., 2006). We conclude that it seems unlikely that a relatively uniform Os isotopic composition, as recorded by the range of basalts of the PCFB, could be generated from such diverse SCLM, let alone record a component that, at best, comprises a small proportion of the overall underlying lithospheric mantle.

Osmium isotopes, combined with other radiogenic isotope systems, can provide some additional possibilities for the origin of the PCFB. For example, although the Os isotopic composition of the PCFB overlaps with that of the Kea-trend lavas from Hawaii, the Nd isotopic compositions of the Paraná basalts obtained in this study ($\varepsilon_{Nd}=+2.7$ to -4.4) are much lower than those of the Hawaiian lavas ($\sim+6.5$ to $+7.5$, Bryce et al., 2005). $^{87}Sr/^{86}Sr$ ratios in the Paraná (0.7045–0.7059) are also considerably higher than in the Hawaiian lavas (~0.7034–0.7037, Bryce et al., 2005). These data indicate that the PCFB were not derived from a source that was similar to that of the Kea-trend volcanoes, nor, as will be shown below, of any pure mantle end-member component.

Exclusive melting of either ancient SCLM or mantle end-member components (e.g., Zindler and Hart, 1986) cannot satisfactorily explain the overall chemical and isotopic features of the PCFB (Fig. 7). Further, the lack of a compositional continuum between the low-Ti and high-Ti basalt groups requires the participation of at least two distinct, enriched mantle components in the genesis of the PCFB province (Marques et al., 1999). As noted above, although initial $^{187}Os/^{188}Os$ ratios are essentially identical for all PCFB examined, the low-Ti basalts have substantially higher Nd and Pb initial isotopic ratios ($\varepsilon_{Nd}=-0.2$ to $+2.7$, $^{206}Pb/^{204}Pb=18.092$–18.300) than the high-Ti basalts ($\varepsilon_{Nd}=-4.4$ to -1.6, $^{206}Pb/^{204}Pb=17.649$–17.763), whereas the Sr isotopic compositions overlap between the two compositional groups. Note that the low-Ti basalts are located in the southern portion of the basin, while the high-Ti basalts are in the northern portion. The southern portion of the basin consists of an assemblage of Neoproterozoic mobile belts formed by the collision among the São Francisco, Rio de la Plata, Luiz Alves, and Kalahari cratons, while the northern portion developed on a mosaic of mobile belts and is associated with the collision of the Amazonas and São Francisco cratons (Holz et al., 2006 and references therein).

In order to characterize the mantle sources involved in PCFB genesis and account for the chemical and isotopic observations, the involvement of asthenospheric mantle and two enriched mantle sources (EM-I and EM-II) are required. We envision an asthenospheric component that is similar to the DMM, but that was also enriched by fluids and/or magmas related to the Neoproterozoic subduction processes. This sub-lithospheric mantle region may have been frozen and coupled to the base of the Paranapanema Craton. This component dominates the Os isotopic composition of the resulting melts. The two enriched mantle components dominate Nd, Pb, and possibly Sr isotopic compositions. We propose that one enriched component is delaminated lower continental crust, and the other enriched component is recycled upper continental crust. According to Willbold and Stracke (2010), the entire isotopic and chemical range of enriched mantle sources sampled by OIBs were generated by a single geodynamic process, the recycling of upper and lower continental crust, plus oceanic lithosphere at destructive plate margins. They proposed that during continental break-up, delamination and foundering of the lower continental crust into the shallow asthenosphere may be an important means for lower continental crust recycling.

Moreover, some studies have also raised the possibility that the DMM contains poorly mixed portions of materials that have experienced older depletion events, resulting in, for example, the observation that the Os isotopic composition of the DMM is not very homogeneous. For example, Parkinson et al. (1998) even suggested that subduction zones may be graveyards for ancient depleted mantle material.

For our model, we assume a sub-lithospheric end-member component, represented by the average composition of arc-mantle peridotite xenoliths, similar to that proposed by Handler et al. (2005), Hart et al. (1997) and Tatsumoto et al. (1992). In the model we use the EM-I and EM-II components, whose parameters were taken from Jackson and Shirey (2011), Shirey and Walker (1998) and Zindler and Hart (1986). The trace element and isotopic data used in the model are found in Figs. 6 and 7.

Evidence for the involvement of ancient, delaminated lower continental crust in the source of the high-Ti basalts is both circumstantial and direct. Circumstantial evidence comes from the observation that the $^{187}Os/^{188}Os$ ratios measured in Enriched MORB (E-MORB) from the 48.5°–49.2° S ridge segment (Fig. 1) have previously been interpreted to indicate that delaminated lower continental crust is responsible for the DUPAL signature observed in the South Atlantic and Indian Oceans (Escrig et al., 2005). Thus, there is indirect evidence that ancient, lower continental crust may have been mixed into the mantle underlying the PCFB. More direct evidence comes from model mixing calculations that show that the high-Ti basalt isotopic compositions can largely be generated by mixing between the hypothesized arc-mantle peridotite and EM-I components (Figs. 6 and 7). It has previously been suggested that the EM-I component includes either an ancient, recycled lower continental crustal component (Willbold and Stracke, 2006), or a metasomatized SCLM component (Gibson et al., 2005).

Model mixing calculations between arc-mantle peridotite and EM-I for Nd, Pb, Sr and Os isotopic compositions suggest that EM-I contributions ranging from 10% to 50% can account for the observed high-Ti basalt compositions. Of the isotopic mixing calculations performed for these basalts, only the Sr isotopic compositions cannot be well accounted for by the mixing mode. This could suggest that additional complexities were involved. As was suggested by Arndt et al. (2003) for the Siberian traps, an increase in the Sr isotopic compositions of the PCFB basalts (this study) can potentially be attributed to a limited extent of assimilation of anhydrite-rich, evaporitic sediments (Passa Dois Group), which are found in the sedimentary sequence that underlies the volcanic sequence (Fig. 6a). This suggestion, however, must be treated with caution because all the samples investigated in this work have Sr/Sm less than ~80, representing evolved magmas in which plagioclase fractionation evidently lowered the Sr content.

Although geochemical and Sr–Nd–Pb isotopic signatures of Walvis Ridge (525A) and Rio Grande Rise (516F) basalts (Fig. 1) may be explained by the presence of detached SCLM that remained in the asthenosphere after the break-up of Africa and South America (e.g., Hawkesworth et al., 1986; Peate et al., 1999), there is no evidence for the involvement of ancient SCLM in the PCFB provided by the Os data, although small contributions from it cannot be entirely ruled out.

Our models suggest that mixing 1–50% of an EM-II component with arc-mantle peridotite can account for most of the isotopic systematics of the low-Ti basalts (Figs. 6 and 7). Note that the involvement of the EM-II end-member can account for the more radiogenic Pb in the low-Ti basalts. The EM-II component has been proposed to reflect mantle that has incorporated recycled upper continental crust (Zindler and Hart, 1986) or metasomatized (i.e., fluid/melt infiltration) oceanic lithosphere. Some studies, based on Os isotopic data (i.e., Widom, 1997; Widom and Shirey, 1996), have also suggested the involvement of small amounts of SCLM in EM-II sources, especially if the SCLM was not highly depleted and was recently metasomatized, yet as with the high-Ti basalts, there is no evidence for this, but the possibility cannot be entirely ruled out.

Many characteristics of CFB, such as Karoo, Ferrar, Deccan, and Emeishan, result from processes acting during melt ascent and interaction with the continental lithosphere (e.g., Ellam et al., 1992; Molzahn et al., 1996; Qi and Zhou, 2008; White and Mckenzie, 1989). One of the most intriguing results of the present study is the lack of evidence for the involvement of ancient continental lithosphere in the genesis of the PCFB. In addition, based on the published trace element and isotopic data for the PCFB (e.g., Marques et al., 1999; Peate et al., 1999; Piccirillo and Melfi, 1988), there is evidence for some heterogeneity in the lavas, which is due to either geodynamical processes occurring during Gondwana assemblage or earlier, or to metasomatic reworking of the source. In this context, the absence of substantial Os isotopic heterogeneity provides an important new constraint on the origin of the lavas. Metasomatic inputs to the sources of CFB have been commonly invoked to explain geochemical signatures of the lavas (e.g., Allègre et al., 1999), but the present data show that the Re–Os system was not sensitive to this process, at least in this system, as was also noted previously by Becker et al. (2001).

Another widely accepted hypothesis to explain the genesis of CFB is the mantle plume model, in which the CFB is formed by decompression melting in rising hot plume heads that impinge at the base of the lithosphere while the lithosphere retains its thickness (Campbell and Griffiths, 1990; Richards et al., 1989). The PCFB magmatism has been linked in space and time to a combination of mantle plume upwelling and continental rifting, and has previously been linked to the Tristan da Cunha hotspot via the Rio Grande Rise and Walvis Ridge (e.g., Ewart et al., 1998). This study, however, suggests that the Tristan da Cunha plume model may not be consistent with the PCFB genesis.

5. Concluding remarks

This work presents the first Re–Os data for the PCFB. The ^{187}Re–^{187}Os age for the studied basalts is in agreement with the previous results based on the ^{40}Ar–^{39}Ar plateau method. The average initial $^{187}Os/^{188}Os$ ratio of 0.1295 ± 0.0006 ($\gamma^{187}Os = +2.7 \pm 0.5$) of the source of the basalts is several percent above most estimates for the DMM. The presence of an asthenospheric mantle source in the genesis of the Etendeka CFB has long been known. This has not previously been shown for the Paraná basalts but is highlighted by the new Os data. However, the asthenospheric mantle involved in the generation of the PCFB, was enriched by fluids and/or magmas related to the Neoproterozoic subduction process. The new, combined HSE and lithophile element geochemical data for the PCFB indicate that the high-Ti and low-Ti basalts were derived from magmas that originated from an asthenosphere-like source (similar to arc-mantle peridotite) variably enriched in recycled components, EM-I and EM-II, respectively.

The first Os isotope and HSE abundance data for the island of Tristan da Cunha basalts are also presented. All samples have considerably more radiogenic Os isotopic compositions than the modern projection for the PCFB. These supra-chondritic compositions can reflect variable ancient recycled component in the source (i.e., recycled oceanic crust and/or pelagic sediments). In addition, the Os isotopic data provide no evidence for the participation of Tristan da Cunha plume in the genesis of the PCFB.

Acknowledgments

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