Mesoproterozoic and Paleoproterozoic subcontinental lithospheric mantle domains beneath southern Patagonia: Isotopic evidence for its connection to Africa and Antarctica

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ABSTRACT

New isotopic studies on mantle xenoliths from Santa Cruz Province, southern Patagonia, Argentina, reveal that at least three discrete subcontinental lithospheric mantle (SCLM) domains—the Deseado Massif, Tres Lagos, and Pali Aike—form the southernmost part of South America. Re-Os systematics yield early Paleoproterozoic (up to 2.5 Ga) SCLM formation ages (rhenium depletion ages, \( T_{\text{RD}} \)) for Pali Aike spinel peridotites, while samples from the Deseado Massif and Tres Lagos indicate a younger SCLM origin with Neoproterozoic to Mesoproterozoic (0.9–1.3 Ga) and Mesoproterozoic to late Paleoproterozoic (1.3–1.9 Ga) \( T_{\text{RD}} \) ages, respectively. Hf-Sr-Nd isotopic compositions indicate metasomatic overprinting of the majority of the samples, which, however, has not affected the Os isotopic system. Based on similar formation ages, the geological evolution of the Deseado Massif is most likely connected to the evolution of the Namaqua-Natal belt of South Africa. \( T_{\text{RD}} \) ages from SCLM domains underneath Tres Lagos and Pali Aike indicate a common origin with crustal sections from Shackleton Range, Antarctica, positioning the southern tip of South America closer to west Antarctica in the reconstructed Rodinia supercontinent than previously assumed.

INTRODUCTION

The origin of the Patagonian continental terrane is highly debated. Whether Patagonia is a uniform part of the southernmost South American continental plate or an assemblage of fragments with different mantle roots is a matter of controversy (Stern et al., 1999; Pankhurst et al., 2003; Ramos, 2008; Schilling et al., 2008; Wang et al., 2008). As a result of the rarity of southern Patagonian crustal basement outcrops, which can provide precise evidence on the timing of crustal formation, Patagonia’s geological evolution has remained enigmatic.

The formation of ancient continental terranes is related to the formation of their underlying subcontinental lithospheric mantle (SCLM) roots, as continental crust is formed by the extraction of melt of a mantle section that has experienced variable degrees of partial melting. This residual depleted lithospheric mantle coevally forms the root of the overlying continental crust (e.g., Griffin et al., 1999a, and references therein; Pearson, 1999). This relationship permits us to use the determined timing of lithospheric mantle formation as a proxy for the timing of the genesis of continental terranes. Hence, mantle xenoliths brought to the surface by magmas can provide detailed information on SCLM sections. The Re-Os isotopic system is, compared to other isotopic systems, less sensitive to mantle metasomatism, providing reliable information on the timing of melt extraction events leading to the formation of the SCLM and its overlying crust (Walker et al., 1989; Carlson, 2005). We have used the Re-Os isotopic system on carefully selected mantle xenoliths to determine the timing of the stabilization of SCLM domains beneath southern Patagonia. In addition, Hf-Nd-Sr isotopic data obtained from leached clinopyroxene (cpx) separates of those samples analyzed for Os isotopic composition are presented to provide better insight into the origin and complex history of South Patagonia.

GEOLOGICAL SETTING

Patagonia, in southern South America, is geographically defined as the region south of Río Colorado and east of the Andean Cordillera. The only basement outcrop in southern Patagonia is the Deseado Massif which covers 60,000 km² (Fig. 1). Pankhurst et al. (2003) presented Mesoproterozoic (1.3–1.6 Ga) Sm-Nd mantle separation ages from Deseado Massif granites, amphibolites, and schists. The basement south of the Deseado Massif is covered by sedimentary sequences >7 km thick, reflecting several episodes of basin formation of Triassic to Cretaceous age. The Late Jurassic breakup of Gondwana resulted in voluminous rhyolitic volcanism in southern Patagonia (Bruhn et al., 1978; Kay et al., 1989). Since then, subsidence and sedimentation have dominated the area, forming the Magellan Basin (Wang et al., 2008). Phanerozoic rhenium depletion ages (\( T_{\text{RD}} \)) obtained by Wang et al. (2008) have led them to interpret the basement beneath Pali Aike (Fig. 1) to be a young accretionary lithosphere that was either part of the Deseado Massif or a separate part that accreted to the Deseado Massif during the Paleozoic.

SAMPLES AND RESULTS

Sample Description

From a large number (>200) of mantle xenoliths collected at different sites throughout Santa Cruz Province, 11 anhydrous spinel...
lherzolites and 13 anhydrous spinel harzburgites were chosen and studied in detail (see the GSA Data Repository1 for selection criteria). Host rocks are Pliocene and Quaternary alkali basalts, basanites, and pyroclastics (D’Orazio et al., 2000) that erupted in the back-arc region of the Andean subduction zone (Stern et al., 1990).

Sample localities are Don Camilo (DC) and Gobernador Gregores (DUB) within the Deseado Massif; Tres Lagos (TL); and Potrok Aike (POKA), El Ruído (ELRU), and Salsas (SA) from within the Pali Aike volcanic field (Fig. 1).

Bulk-rock major element analyses show that samples from Pali Aike (POKA, SA, ELRU) and Tres Lagos have mean Al2O3 contents and Mg# [Mg/(Mg + FeT)] of 1.46 wt% and 0.91, respectively, and are generally more depleted than mantle xenoliths found in the Deseado Massif with mean Al2O3 contents and Mg# of 2.08 wt% and 0.90, respectively. Bulk-rock rare earth element (REE) compositions reveal elevated light REE (LREE) in the majority of Pali Aike samples (ELRU and SA). All POKA samples exhibit a hump in middle REE (MREE) suggesting melt percolation processes. Except for sample TL143, Tres Lagos samples have slightly elevated LREE compositions. Deseado Massif samples exhibit roughly flat REE patterns with a minor increase in LREE in DC and a minor MREE and stronger LREE enrichment in DUB samples (Table DR2 and Fig. DR2 in the Data Repository).

**Sulfide Petrography**

The modal abundances of sulfides in the studied mantle xenoliths are generally low and do not correlate with fertility indices (e.g., bulk rock Al2O3). Sulfides occur either interstitially or as spherical inclusions and trails preferentially in olivine and orthopyroxene (Table DR4). Primary enclosed sulfides with diameters ranging from 30 to 150 µm are multiphase grains formed mainly of monosulfide solid solution, pentlandite, and chalcopyrite, with rare Pt- and/or Ir-rich microphases (Figs. DR3a–DR3f). Interstitial sulfides are commonly irregularly shaped and can be found in melt pools, around spongy cpx, and as up to 10 µm elongated or round sulfide droplets in intergranular propagating fresh host basalt glass consisting mainly of Ni monosulfide solid solution, pyrrhotite, or pentlandite, as well as sulfide alteration products (Figs. DR3g–DR3i).

**Re-Os Concentrations and Os-Hf-Nd-Sr Isotopic Systematics**

Bulk-rock osmium concentrations vary from 0.5 to 3.3 ppb while rhenium contents are generally low, between 0.002 ppb and 0.105 ppb. Initial 187Os/188Os ratios, calculated back to time of eruption (4 Ma), are subchondritic, ranging from 0.1114 to 0.1266, except in one sample from the Deseado Massif (DC08) exhibiting a suprachondritic Os isotopic ratio of 0.1327 (Fig. 2). Osmium isotopic ratios do not correlate with either 187Re/188Os or bulk-rock Al2O3 (Figs. 2A and 2B). In samples from the Deseado Massif (DUB and DC), 187Os/188Os ratios lead to TMA ages between 0.5 and 1.3 Ga. Except for sample TL142 (0.6 Ga), samples from Tres Lagos yield older TMA ages ranging from 1.3 to 1.9 Ga. The largest variation in calculated TMA ages can be found in the Pali Aike sample suite, with Neo- to early Paleoproterozoic TMA ages (0.7–2.5 Ga). Hf isotopic analyses from Deseado Massif cpx separates yield εHf ranging from +5.8 to +23.0. One sample (DC18) yields a model age (TMA) of 1.2 Ga, consistent with Mesoproterozoic TReo ages determined from Os isotopic analyses for Deseado Massif samples. εHf values from Tres Lagos samples lie between +15.2 and +52.0. Sample TL142 yields a calculated TMA age of 1.8 Ga. Samples from Pali Aike show a broad range in εHf values from −17.1 to +23.0. Sample ELRU3, with εHf of +23.0, yields a TMA age of 2.7 Ga, slightly older than the oldest Pali Aike TReo ages (2.4–2.5 Ga). Laser ablation analyses of cpx reveal no metasomatic addition of Hf or Lu to samples DC18, TL142, or ELRU3 (Table DR3). Hence, calculated TMA ages can be considered reliable. Hf isotopic ratios from the remaining South Patagonian peridotites yield unrealistic future or impossibly old TMA ages and suggest a resetting of the Lu-Hf system, also evidenced by enriched cpx trace element concentrations (Table DR3).

Sr and Nd isotopic compositions in the Deseado Massif mantle xenoliths yield variable 87Sr/86Sr ratios ranging from 0.70278 to 0.70588 and 143Nd/144Nd ratios between 0.51223 and 0.51328 (present-day εNd of −7.9 to +11.2). Samples from Tres Lagos show Sr and Nd isotopic ratios between 0.70225 and 0.70320 and 0.51283 and 0.51321 (εNd of +3.2 to +11.2), respectively. Sr and Nd isotopic compositions in Pali Aike cpx range from 0.70282 to 0.70769 and 0.51209 to 0.51318 (εNd of −10.7 to +10.6), respectively, and correlate well with each other as well as with Hf isotopes (Figs. 3A–3C). Sr and Nd isotopic results combined with cpx trace element analyses reveal a cryptic metasomatic overprint of the majority of our studied samples.

**DISCUSSION**

**SCLM Formation Ages**

A scatter in Os isotopic ratios and the absence of a correlation thereof with melt depletion indices (e.g., bulk rock Al2O3) within a sample suite is often interpreted to indicate metasomatic overprint (i.e., Pearson et al., 1995; Brandon et al., 1996; Handler et al., 2005). However, our samples do not show significant variations in their highly siderophile element abundances (i.e., enrichment in the palladium group of the platinum-group elements, Ir-Ru fractionation; Fig. DR1) as is typical for many metasomatized
Figure 3. Isotopic ratios of clinopyroxene separates. A: $^{143}\text{Nd}$/${^{144}\text{Nd}}$ versus $^{87}\text{Sr}$/${^{86}\text{Sr}}$, showing a well-defined negative correlation. B: $\varepsilon_{\text{Hf}}$ versus $\delta^{18} \text{O}$. C: $\varepsilon_{\text{Nd}}$ versus $^{87}\text{Sr}$/${^{86}\text{Sr}}$ of the three subcontinental lithospheric mantle domains. BSE—bulk silicate earth. Fields in A for depleted mantle (DMMa and DMMb), prevalent mantle (PREMA), high $\mu$ (HIMU), and enriched mantle I and II (EM-I and EM-II) are from Zindler and Hart (1986). Mid-oceanic-ridge basalt (MORB) and ocean island basalt (OIB) fields in B and C are from Nowell et al. (1998, and references therein). Symbols and other abbreviations are as in Figure 1.

Figure 4. Histogram of calculated rhenium depletion ages ($T_{\text{rd}}$), comprising all 24 Patagonian spinel peridotites, using primitive mantle values from Meisel et al. (1996). $^{187}\text{Os}$/${^{188}\text{Os}} = 0.1296$. U-Pb zircon data from exposed basement rocks of the Natal belt and Mesoproterozoic ages from Dronning Maud Land in East Antarctica suggest a continental crust formation between 1.2 and 1.0 Ga (McCourt et al., 2006; Jacobs et al., 1996). These ages are similar to our determined $T_{\text{rd}}$ ages of up to 1.3 Ga for the Deseado Massif mantle xenoliths, as well as to Mesoproterozoic ages (1.1–1.0 Ga) obtained for basement rocks from Cape Meredith Complex, West Falkland–Malvinas (Thomas et al., 2000, and references therein). We suggest that the Patagonian SCLM fragment represented by Deseado Massif mantle xenoliths was accreted together with other microcontinents during the formation of Rodinia and stayed contiguous to South Africa and West Antarctica until the Mesozoic breakup of Gondwana.

Tres Lagos and Pali Aike

$T_{\text{rd}}$ ages of the Tres Lagos samples are distinctly older than Deseado Massif ages, indicating a different origin. Ntaflos et al. (2007) proposed that the SCLM beneath Tres Lagos represents an isolated old Proterozoic lithospheric mantle fragment, based on the depleted nature and low pressure-temperature conditions of the mantle xenoliths. Our data support this model and further reveal distinct isotopic and trace element compositional differences between Tres Lagos and other Patagonian mantle xenoliths.

Previous studies suggest a Mesoproterozoic to early Paleozoic (Stern et al., 1999; Schilling et al., 2008) or even younger (Wang et al., 2008) formation of the SCLM beneath Pali Aike. However, our Re-Os data clearly show that the SCLM beneath Pali Aike was formed at least as long ago as early Paleoproterozoic times.

Crustal rocks of similar age close to the position of southernmost Patagonia in Gondwana occur only at Shackleton Range, a composite terrane located at the northwestern edge of the East Antarctica (e.g., Dalziel et al., 2000; König and Jokat, 2006). U-Pb zircon data from exposed basement rocks of the Natal belt and Mesoproterozoic ages from Dronning Maud Land in East Antarctica suggest a continental crust formation between 1.2 and 1.0 Ga (McCourt et al., 2006; Jacobs et al., 1996). These ages are similar to our determined $T_{\text{rd}}$ ages of up to 1.3 Ga for the Deseado Massif mantle xenoliths, as well as to Mesoproterozoic ages (1.1–1.0 Ga) obtained for basement rocks from Cape Meredith Complex, West Falkland–Malvinas (Thomas et al., 2000, and references therein). We suggest that the Patagonian SCLM fragment represented by Deseado Massif mantle xenoliths was accreted together with other microcontinents during the formation of Rodinia and stayed contiguous to South Africa and West Antarctica until the Mesozoic breakup of Gondwana.

SCLM Domains

Deseado Massif

The determined SCLM formation ages for DC and DUB mantle xenoliths match that of the Mesoproterozoic basement interpreted by Pankhurst et al. (2003), as well as Mesoproterozoic ages from Cerro Redondo and Estancia Lote 17 (Schilling et al., 2008). Rodinia and Gondwana reconstructions have placed the Deseado Massif close to South Africa and West Antarctica (e.g., Dalziel et al., 2000; König and Jokat, 2006). U-Pb zircon data from exposed basement rocks of the Natal belt and Mesoproterozoic ages from Dronning Maud Land in East Antarctica suggest a continental crust formation between 1.2 and 1.0 Ga (McCourt et al., 2006; Jacobs et al., 1996). These ages are similar to our determined $T_{\text{rd}}$ ages of up to 1.3 Ga for the Deseado Massif mantle xenoliths, as well as to Mesoproterozoic ages (1.1–1.0 Ga) obtained for basement rocks from Cape Meredith Complex, West Falkland–Malvinas (Thomas et al., 2000, and references therein). We suggest that the Patagonian SCLM fragment represented by Deseado Massif mantle xenoliths was accreted together with other microcontinents during the formation of Rodinia and stayed contiguous to South Africa and West Antarctica until the Mesozoic breakup of Gondwana.

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Antarctic craton. U-Pb data from orthogneisses from the northern belt of Shackleton Range suggest granite emplacement at 2.3 Ga (Brommer et al., 1999), indicating the existence of early Paleoproterozoic crust. U-Pb data from magmatic zircons in gneisses from the Shackleton Range’s Southern Terrane document an additional slightly younger Paleoproterozoic (1.9 Ga) magmatic period in this region (Will et al., 2009). These ages match our determined T_{RD} ages from Pali Aike (2.5 Ga) and Tres Lagos (1.9 Ga) and hence suggest a common geological origin.

**CONCLUSIONS**

The Mesoproterozoic evolution of the SCLM beneath the Deseado Massif, southern Patagonia, is most likely connected to the formation of the Namaqua-Natal belt and hence was formed during the assembly of Rodinia. Osmium isotopic results show that, contrary to previous studies suggesting Mesoproterozoic to Paleozoic formation (Stern et al., 1999; Wang et al., 2008; Schilling et al., 2008), the SCLM beneath Pali Aike in southernmost South Patagonia was formed as early as the early Paleoproterozoic. We suggest that the SCLM underneath the southernmost part of Patagonia and southwest of the Deseado Massif is represented by late Archean to early Paleoproterozoic and mid-Paleoproterozoic fragments whose origin is connected to the geological evolution of Shackleton Range, Antarctica. These SCLM fragments accreted to the Deseado Massif probably during the formation of supercontinent Rodinia before drifting off together with the rest of South Patagonia during Gondwana breakup.

**ACKNOWLEDGMENTS**

This work was financed by Austrian Science Fund grant P 23575-N19 (Principal Investigator: Th. Nataša). We gratefully acknowledge W. Wegner (University of Vienna) for Sr and Nd isotope analyses; V. Erban (Czech Geological Survey) for Os isotope analyses; and J. Duríšová (Czech Academy of Sciences) for inductively coupled plasma-mass spectrometry analyses of highly siderophile elements. We thank W.L. Griffin, J. Bédard, and two anonymous reviewers for their constructive comments to improve this manuscript. The editorial handling and suggestions by J.B. Murphy are greatly appreciated.

**REFERENCES CITED**

Alard, O., Griffin, W.L., Lorand, J.-P., Jackson, S.E., Alén, J.M., and O’Reilly, S.Y., 2000, Non-chondritic distribution of the highly siderophile elements: We thank W.L. Griffin, J. Bédard, and two anonymous reviewers for their constructive comments to improve this manuscript. The editorial handling and suggestions by J.B. Murphy are greatly appreciated.
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Geology 2015;43:39-42
doi: 10.1130/G36344.1