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Re–Os isotope systematics and HSE abundances of the 3.5 Ga Schapenburg komatiites, South Africa: Hydrous melting or prolonged survival of primordial heterogeneities in the mantle?

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ABSTRACT

We report Re–Os isotope and highly siderophile element (HSE) abundance data for komatiites from the Schapenburg Greenstone Remnant (SGR), South Africa, an equivalent to the lowermost formations of the Onverwacht Group in the Barberton Greenstone Belt (BGB). The Re–Os isotopic data for 13 whole-rock samples define a regression line with an age of 3549 ± 99 Ma, consistent with the ~3.5 Ga age of the Onverwacht Group. The immobility of Os during alteration and the correct Re–Os age provide evidence that the initial $\gamma^{187}Os = +3.7 \pm 0.3$ derived from the regression reflects a time-integrated suprachondritic $^{187}Re/^{188}Os$ in the source of the SGR komatiites. The HSE abundances in the emplaced SGR komatiite lavas are 2× to 3× lower than those in other well-studied komatiites. Compared to the Primitive Upper Mantle (PUM) estimate, the calculated mantle source of the SGR komatiites was moderately depleted in HSE and was characterized by a fractionated HSE pattern. The enrichment in ^{187}Os, HSE depletion, and fractionated HSE pattern in the SGR komatiite source could be the result of fluid transport of radiogenic Os from the subducting slab, incorporation in the overlying mantle, and hydrous melting of the modified mantle to produce the komatiites. This would imply that plate tectonic processes operated as early as 3.5 Ga and that at least some komatiites formed via wet melting in island arc settings at relatively shallow depths and temperatures not exceeding 1400 °C. An alternative model would include dry melting of a chemically distinct, majorite-enriched mantle domain formed very early in Earth's history as a result of an initial stratification of the mantle during crystallization of a magma ocean. Preferential partitioning of Re into the majorite-rich domain would have resulted in its acquiring suprachondritic Re/Os. In order to grow the radiogenic Os isotopic composition, the majorite-rich domain would have to have remained isolated from the rest of the mantle for a billion years. If this model is correct, the data would require a deep plume origin for the SGR komatiites at temperatures ~300 °C higher than the ambient mantle temperatures. Both models have their shortcomings in reconciling the available geochemical and petrologic data for the SGR komatiites. Because BGB komatiites are geochemically closer to island arc tholeiites and boninites than the SGR komatiites, it will be especially important to determine the Re–Os isotope and HSE systematics of the BGB komatiites and of typical boninites.

1. Introduction

Although most models of komatiite origin involve hot melting of dry peridotite in mantle plumes (e.g., Campbell et al., 1989; Herzberg, 1992; Herzberg, 1995), some authors have suggested derivation of at least some komatiites by hydrous melting in island arc settings (e.g., Allègre, 1982; Grove et al., 1999; Parman et al., 2001, 2004). Distinguishing between the two mechanisms of komatiite origin has important bearing on our understanding of the thermal regime of the early Earth and its subsequent evolution. Dry melting implies formation of komatiites in mantle plumes, with mantle temperatures that were ~300 °C hotter during the period of dominant komatiite generation (Archean) than present-day mantle temperatures (Nisbet et al., 1993). Hydrous melting, as would occur in association with a subduction zone, might instead imply the activity of plate tectonic processes during the first billion years of Earth history, with mantle temperatures comparable to or only slightly higher than modern (Grove and Parman, 2004).

Here, we study komatiites from the Schapenburg Greenstone Remnant (SGR) in the Kaapvaal Craton, South Africa, which has been proposed to be equivalent to the lowermost formations of the 3.5 Ga

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Onverwacht Group in the Barberton Greenstone Belt, BGB (Viljoen and Viljoen, 1969a). The Schapenburg komatiites belong to the so-called Barberton-type (as opposed to the Munro-type) komatiites, and are characterized by depletions in Al, Y, Sc, and the heavy rare earth elements (HREE; including Yb and Lu), relative to elements with similar incompatibility during mantle melting, as compared to primitive mantle estimates. These are elements commonly hosted by garnet, so it has been proposed that garnet was a residual phase during melting in deep mantle plumes that produced Al-depleted komatiites (Sun and Nesbitt, 1978). This hypothesis received support from experimental studies that demonstrated that majorite garnet (pyrope-pyroxene, high-P solid solution) is a likely liquidus phase during mantle melting at depths >450 km (Ohtani et al., 1986; Ito and Takahashi, 1987; Kato et al., 1988). Uncertainty has remained as to whether fractionation of majorite garnet at the time of mantle melting controlled the composition of Al-depleted komatiites (Ohtani, 1984, 1990), or whether the source regions of Barberton-type komatiites were characterized by majorite enrichment originally caused by fractionation in, and subsequent solidification of, a primordial terrestrial magma ocean (Gruau and Jahn, 1983; Ohtani et al., 1989).

One way to test this hypothesis, using the Lu–Hf isotope system, was proposed by Gruau et al. (1990) and, more recently, by Blichert-Toft et al. (2004). ^{176}Lu decays to ^{176}Hf with a half-life of ~36 Ga. Since Lu partitions more strongly into majorite garnet than Hf (Green, 1994), a cumulate from a magma ocean that is enriched in majorite garnet would likely have a suprachondritic Lu/Hf ratio and, given sufficient time, would develop a suprachondritic ^{176}Hf/^{177}Hf isotopic composition. As a result, Al-depleted komatiites derived from sources with long-term enrichments in majorite garnet should have positive ε^{176}Hf values. In contrast, Al-depleted komatiites produced via melting of previously unmelted mantle that involved majorite fractionation only at the time of melting, would likely have chondritic ε^{176}Hf values. Blichert-Toft et al. (2004) reported an average ε^{176}Hf value of $+5.4\pm0.7$ for five samples from Carl's Flow of the SGR. This average initial isotopic composition is substantially higher than the model depleted mantle reservoir (DM) value of $+0.5$ at 3.5 Ga (Blichert-Toft and Albarède, 1997), so Blichert-Toft et al. (2004) interpreted it to indicate that the mantle source was enriched in majorite for a substantial period of time prior to melting. They speculated that this was a result of accumulation of majorite during the solidification of a magma ocean. For this study, Blichert-Toft et al. (2004) used a $\lambda^{176}\text{Lu}=1.93\times10^{-11}$ year^{-1} to calculate the ε^{176}Hf values. If the data are re-calculated using an alternative λ of 1.87×10^{-11} year^{-1} (Scherer et al., 2001; Söderlund et al., 2004), a similar, although slightly lower, average initial ε^{176}Hf value of $+4.4\pm0.6$ is obtained. This value nonetheless remains consistent with the Blichert-Toft et al. (2004) interpretation.

It has also conversely been proposed that komatiites in general, and those from the BGB in particular, formed in a subduction zone environment (Parman et al., 2001, 2004). Parman et al. (1997) estimated on the basis of microprobe studies of igneous pyroxenes from BGB komatiites that these lavas might have contained as much as 4% to 6% H_2O upon emplacement. Further, Gaetani and Grove (1998) showed that garnet joins the mantle residual assemblage at a lower pressure under hydrous conditions, being a stable aluminous phase at as low as 1.6–2.0 GPa and 1260–1290 °C. This observation is consistent with the Al-depleted nature of the BGB komatiites. Consequently, Grove et al. (1999) concluded that magmas parental to the BGB komatiites were derived via hydrous melting at depths of ~60 km and temperatures of ~1400 °C.

The SGR komatiites, being equivalents of the BGB komatiites, are, therefore, important potential recorders of planetary processes that may include either primordial silicate differentiation of the Earth, or early plate tectonic processes. As a means of further interrogating these rocks, we examine their Re–Os isotope systematics and highly siderophile element (HSE: Re, Os, Ir, Ru, Pt, and Pd) abundances. These are important elements to extend to these issues. Due to the contrasting behaviour of the HSE during differentiation of the silicate Earth (e.g., Righter et al., 2000), studies of HSE abundances and the Pt–Re–Os isotope systematics have proven useful for mapping spatial and temporal chemical variations in the mantle caused by generation and recycling of oceanic lithosphere (e.g., Walker et al., 1991; Hauri and Hart, 1993), mantle melting and extraction of continental crust (Walker et al., 1989), material transport in subduction zones (Brandon et al., 1996, 1999a; Alves et al., 1999; Woodland et al., 2002; Widom et al., 2003; Chesley et al., 2004), and possible core–mantle exchange (e.g., Walker et al., 1995; Brandon et al., 1999b; Puchtel and Humayun, 2000; Puchtel et al., 2005). Thus, the HSE may provide information with direct bearing on the questions related to the origin of the SGR komatiites.

2. Geological background, samples, and previous geochemical studies

The geology of the SGR is described in detail elsewhere (e.g., Anhaeusser, 1983, 1991), and a brief account of petrological features of the SGR komatiites is given in Lécuyer et al. (1994) and Blichert-Toft et al. (2004). According to these authors, the SGR is a 12×2.5 km sliver of alternating volcanic and sedimentary units located ~25 km southwest of the BGB. It is interpreted to belong to a trail of greenstone fragments within the tonalite-trondhjemitic gneisses surrounding the BGB (Anhaeusser and Robb, 1980), and the greenstone lithologies of the remnants were proposed to be equivalents to the lowermost formations of the Onverwacht Group of the BGB, namely, the Theespruit and Komati (Viljoen and Viljoen, 1969a).

Volcano–sedimentary sequences of the SGR are cyclic in nature. Each cycle consists of komatiitic lavas at the base overlain by komatiitic basalts, which are in turn capped by banded iron formations. All rocks have undergone pervasive alteration and greenschist to amphibolite facies metamorphism, which resulted in a near complete obliteration of all primary mineral assemblages.

The age of the SGB komatiites is constrained indirectly on the basis of the analyses of magmatic zircons from mafic and ultramafic volcanic rocks of the Komati Formation (3482±5 Ma: Armstrong et al., 1990) and magmatic zircons from felsic tuffs and lavas of the underlying Theespruit Formation (3544±2 to 3547±3 Ma: Kröner et al., 1996).

Lécuyer et al. (1994) and Blichert-Toft et al. (2004) studied the lithophile element isotope and geochemical characteristics of the SGR rocks. These authors concluded that the komatiites have preserved most of their primary chemical and isotopic signatures despite metamorphism and alteration. The ratios of incompatible elements $(\text{Gd}/\text{Yb})_N=1.64\pm0.12$, $\text{Al}_2\text{O}_3/\text{TiO}_2=11\pm2$, and $\text{CaO}=1.8\pm0.2$ were reported to be nearly identical to the respective values for BGB komatiites (Gruau et al., 1990; Herzberg, 1992), which represent the type locality for Al-depleted komatiites. Unlike the BGB komatiites, however, which have less-depleted light rare earth element (LREE) patterns ($\text{La}/\text{Sm}_N=0.95\pm0.07$) and $\varepsilon\text{Nd}(T)=+0.9\pm0.4$ (Brévart et al., 1986), the SGR komatiites are somewhat more depleted in LREE with $(\text{La}/\text{Sm})_N=0.91\pm0.06$, and are characterized by uniformly positive initial $\varepsilon\text{Nd}=+2.5\pm0.2$ (Lécuyer et al., 1994). As noted above, study of the Lu–Hf systematics in the SGR komatiites has revealed a high initial ε^{176}Hf in its mantle source indicating that the source evolved with a time-integrated suprachondritic Lu/Hf ratio (Blichert-Toft et al., 2004). The combination of the long-term elevated Lu/Hf in the source and the depletions of the komatiites in Al and HREE allowed these authors to propose a two-stage model for their formation. During the first, very early, stage, garnet accumulated in the source, creating a reservoir with a suprachondritic Lu/Hf. This source then remained isolated and evolved to a high initial ε^{176}Hf. During the second, partial melting stage, garnet was retained in the residue/fractionated from the melt, and the resultant magma was accordingly depleted in Al and HREE.

What can generally be seen in the Schapenburg komatiite sampling locality is a series of differentiated komatiite lava flows that vary in