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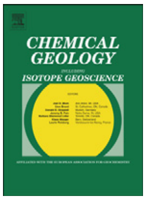

Formation of high-Al komatiites from the Mesoarchean Quebra Osso Group, Minas Gerais, Brazil: Trace elements, HSE systematics and Os isotopic signatures

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ABSTRACT

We report highly siderophile element data combined with Re–Os isotopes and major and trace elements of the ca. 2.7–3.0 Ga komatiites from the Quebra Osso Group, Minas Gerais, Brazil. These komatiites resemble the rare high Al-type, characterized by high Al_2O_3/TiO_2 ratios (26.7–59.8). These geochemical similarities are shared with the 3.33 Ga Commondale and 3.26 Ga Weltevreden komatiites from the eastern Kaapvaal Craton pointing to a similar origin of these suites. While anhydrous melting in an unusually hot mantle was inferred for the Weltevreden komatiites, the Commondale komatiites were suggested to have formed by hydrous, multi-stage melting. Significant depletion in LREE is coupled with subchondritic Re/Os, unradiogenic to radiogenic $^{187}Os/^{188}Os$ and fractionated HSE, with enrichments in Ru, Pt, and Pd over Os and Ir. The combination of these signatures suggests minor late-stage crustal influence. Potential late-stage alteration overprint, assimilation of ambient mantle material during magma ascent and complex phase relationships of HSE-hosting phases make it difficult to estimate the composition of the source of the Quebra Osso komatiites and to place constraints on the nature of the late Archean mantle. However, the Quebra Osso komatiites are unlikely to have formed in a single-stage plume setting or in a supra-subduction zone setting. Instead we suggest a multi-stage melting history of the komatiite source to explain the origin of their peculiar geochemical characteristics, as has been suggested for other high-Al_2O_3/TiO_2 komatiite suites.

1. Introduction

Since their recognition as ultramafic lavas generated by high degrees of mantle melting (Viljoen and Viljoen, 1969; Arndt et al., 1977), komatiites have been extensively studied to understand Archean mantle dynamics and thermal state (e.g., Herzberg et al., 2010). Because they are considered to have formed by degrees of partial melting of 30% and above, they are thought to record geochemical signatures of their source region within the mantle (Sun and Nesbitt, 1977; Herzberg, 1992), and hence allow estimates of early Earth's mantle composition.

The mechanisms by which komatiites form are still debated, as the effusive nature of these ultramafic volcanics requires mantle temperatures in excess of 2000 °C (e.g. Nesbitt and Sun, 1976; Arndt, 1977; Nisbet et al., 1993). Depending on their source mineralogy, different types of komatiite are found that can be broadly classified into Al-enriched, Al-undepleted, and Al-depleted komatiites (Nesbitt et al., 1979; Jahn and Gruau, 1981; Jahn et al., 1982; Arndt, 2008; Robin-Popieul et al., 2012).

A komatiite origin as plumes similar to modern day intraplate volcanism has been suggested (Campbell et al., 1989; Herzberg, 1995), either by melting in hydrous mantle plumes (Inoue et al., 2000; Asahara and Ohtani, 2001) or fractional crystallization of parental ultramafic high-degree partial melts (Shimizu et al., 2005). The Al-depleted komatiites have significant amounts of garnet present during melting, while formation of Al-undepleted and Al-enriched komatiites occurs by multi-stage melting of a refractory garnet-poor residuum and trapped melts in a hotter mantle (Arndt, 1977; Herzberg, 1995; Wilson, 2003; Robin-Popieul et al., 2012), re-melting of a garnet-enriched mantle (Gruau et al., 1990; Ohtani, 1990), or wet melting in subduction zones (e.g., Parman et al., 1997, 2004). The most Al-enriched komatiites described so far, from the 3.33 Ga Commondale Greenstone inlier, South Africa, have been suggested to have been formed by hydrous

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melting of a previously depleted mantle source at shallower depth, potentially in a mantle wedge (Wilson, 2003; Wilson et al., 2003; Barr et al., 2009). This formation mechanism would make these anomalous komatiites the Archean relatives of modern day boninites (e.g. Cameron et al., 1979), and suggests that subduction-driven mantle dynamics similar to modern day mechanism were operational in the late Archean (e.g. Wyman and Kerrich, 2009), in contrast to models centering on plume-only vertical tectonics (e.g. Bédard, 2006; Debaille et al., 2013). Alternatively, Al-enriched komatiites such as the Commondale suite can be explained by fractional melting of approximately 40% of an ascending, cooler mantle source after the exhaustion of garnet (Robin-Popieul et al., 2012).

Highly siderophile elements (HSE: Os, Ir, Ru, Rh, Pt, Pd, Au, Re), including the long-lived Re–Os isotope system, partition into metal and sulfide minerals over silicates and display a wide range in compatibility during partial mantle melting (e.g. Barnes et al., 1985; Morgan, 1986; O'Neill et al., 1995), making them particularly useful to constrain fractionation of mantle melts and composition of their sources. The HSE have been studied in komatiites to understand formation and development of mantle reservoirs in the early Earth (Brügmann et al., 1987; Puchtel et al., 1999, 2004a, 2004b, 2007, 2009a, 2009b, 2014; Puchtel and Humayun, 2000, 2005; Lesher et al., 2001; Walker and Stone, 2001; Walker and Nisbet, 2002; Gangopadhyay and Walker, 2003; Gangopadhyay et al., 2005, 2006; Maier et al., 2009; Connolly et al., 2011), as well as its accretionary history reflected by their mantle sources (Maier et al., 2009; Touboul et al., 2012).

In this study, we present comprehensive major and trace element as well as HSE and ^{187}Os isotope data for a suite of Al-enriched komatiites from the Quebra Osso Group, Rio das Velhas Greenstone Belt, Minas Gerais, Brazil, that share similar geochemical characteristics with the Weltevreden and Commondale komatiites, in order to further constrain the formation mechanisms of high-Al komatiites and to improve understanding of late Archean mantle dynamics.

2. Geology and samples

The Quebra Osso Group forms the lowermost portion of the Meso- to Neoarchean supracrustal Rio das Velhas Supergroup with a thickness of 600 to 800 m, below the Nova Lima and Maquiné Groups (Schorscher, 1976, 1978, 1979, 1992; Schobbenhaus et al., 1981; Inda et al., 1984). The Quebra Osso meta-ultramafic volcanic rocks are komatiites metamorphosed under greenschist to lowermost amphibolite facies conditions, interlayered with rare Algoma-type BIFs, metacherts and tuffs. These metakomatiites occur as pillow lavas, sills, and pyroclastics derived from volatile-rich magmas in the Santa Barbara greenstone belt in the easternmost part of the Quadrilatero Ferrifero mining region at the southern end of the Sao Francisco Craton in Minas Gerais, Brazil, about 80 km east of the city of Belo Horizonte. Thickness of magma flows does not exceed 1.5 m. While the komatiites are intercalated with chemical carbonaceous sediments (Schrank et al., 1990), there are no marker horizons to establish a clear stratigraphic sequence within the komatiite succession.

They are in tectonic contact with Archean tonalite–trondhjemite–granodiorite (TTG) gneisses, migmatites and metagranitoids of the Santa Barbara Complex (Dorr, 1969; Herz, 1970, 1978; Baltazar and Zucchetti, 2007). According to Schorscher (1992), the evolution of the Rio das Velhas Supergroup began possibly by rifting of sialic TTG-type crust, triggering komatiitic volcanism.

Magmatism of the Quebra Osso Group occurred subaquatically. Mafic material, with subordinate ultramafic and intermediate compositions, interlayered with volcanoclastics, clastic sediments, and limestone. The Quebra Osso komatiites derived from degrees of melting of 40–50% in the deep upper mantle (>200 km depth; Schorscher, 1992). Throughout the overlying Nova Lima Group towards the Maquiné Group forming the top portion of the Rio das Velhas Supergroup, terrestrial clastic sedimentation of conglomerates and orthoquartzites occurs, indicating increasing influence of continental erosion. Later stages of metamorphism to upper greenschist facies conditions occurred isochemically (Schorscher, 1976), with the exception of hydration reactions during serpentinization.

Metakomatiite samples were taken from the Abelhas, Francisco III and IV, Joaspe, and Micon localities (Table 1, Fig. 1). Sampled lithotypes consist of massive and spinifex metakomatiite, corresponding to the B_2 and A_2 subdivisions of komatiite flows of Pyke et al. (1973), respectively. Massive metakomatiite shows a fine- to medium-grained granoblastic texture, consisting predominantly of serpentine minerals with minor carbonates, chlorite, and talc. Olivine pseudomorphs replaced by serpentine are ubiquitous. Spinifex metakomatiites possess skeletal serpentinized olivine without preferred orientation embedded in a fine-grained matrix of serpentinized olivine, talc, and carbonates (Fig. 2).

3. Methods

3.1. Major and trace elements

Ca. 1 kg of the samples were crushed in a jaw breaker and milled using an agate mill at the University of Sao Paulo after removal of altered portions. Major elements were analyzed on $Li_2B_4O_7$ glass disks using a PHILIPS PW 2400 X-ray spectrometer at the University of Cologne. Analytical precision was better than 1%. Trace elements were analyzed using an AGILENT 7500cs quadrupole ICP-MS instrument at University of Kiel following the protocols of Garbe-Schönberg (1993). BIR-1 and BHVO-2 were measured as reference materials together with the samples, published in Hoffmann et al. (2014). The analytical precision for most elements was better than 5%.

3.2. Highly siderophile elements

For HSE analysis, approximately 1–1.5 g of sample powder was digested in 2.5 ml 10 M HCl and 5 ml 14 M HNO_3 together with a ^{190}Os–^{185}Re–^{99}Ru–^{106}Pd–^{191}Ir–^{194}Pt spike in an AntonPaar™ High Pressure Asher overnight at 220 °C. Osmium was extracted using the solvent extraction method by Cohen and Waters (1996), followed by microdistillation according to Birck et al. (1997). Samples were loaded in HBr on Pt filaments, covered with $Ba(OH)_2$/NaOH activator solution, and measured in peak-jumping mode on SEM on a Thermo Fisher Triton (N-TIMS) at the University of Vienna. Repeated measurements of 100 pg loads of the DROsS standard solution yielded $^{187}Os/^{188}Os$ of 0.16094 ± 0.00032 ($n = 15$), in excellent agreement with previously reported measurements (Luguet et al., 2008; Nowell et al., 2008).

The remaining aqua regia fraction was processed over anion columns (AG 1-X8, 100–200 mesh; Rehkämper and Halliday, 1997), and measured on a Thermo Fisher Element XR at the Steinmann-Institute, University of Bonn. For Re, Ir, and Pt, a glass cyclonic spray chamber was used with a Micromist glass nebulizer (100 µl/min). Ruthenium and Pd were measured using an ESI Apex HF desolvation system with a Teflon microflow nebulizer (200 µl/min). Measured masses were ^{89}Y, ^{90}Zr, ^{91}Zr, ^{95}Mo, ^{99}Ru, ^{101}Ru, ^{102}Ru, ^{105}Pd, ^{106}Pd, ^{108}Pd, ^{110}Pd, ^{111}Cd, ^{178}Hf, ^{185}Re, ^{187}Re, ^{191}Ir, ^{193}Ir, ^{194}Pt, ^{195}Pt, and ^{196}Pt. In-house multi-element HSE solutions were repeatedly measured to monitor instrument drift and mass bias. For oxide interference correction, standard solutions containing potential interfering elements (Y, Zr, Mo, Hf) were measured at the beginning and end of each day to calculate oxide production. Wash solutions were measured before every sample and used as acid background correction.

Analytical quality was monitored with repeated measurements of reference materials UB-N (lherzolite, SARM-CRPG, $n = 2$) and OKUM (komatiite, OGS, $n = 3$) processed alongside the samples (electronic supplement). All analyses of reference materials reproduce certified values within 2 σ error. Analytical blanks were processed with every batch of samples, and samples were corrected for the respective blank.