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Platinum-group element geochemistry of komatiite-derived 3.1 Ga ultramafic–mafic rocks and chromitites from the Nuggihalli greenstone belt, Western Dharwar craton (India)

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ABSTRACT

The 3.1 Ga Nuggihalli greenstone belt in the Western Dharwar craton (southern India) comprises a sill-like layered ultramafic–mafic igneous complex with associated metasedimentary and metavolcanic (komatiitic to komatiitic basalt) schists that are enclosed by the tonalite–trondhjemite granodiorite suite of rocks (TTG). The sill-like layered complex is represented by a succession of chromitite-bearing serpentinite (after dunite) and peridotite, anorthosite, pyroxenite, and gabbro hosting magnetite bands. Extensive bulk-rock trace element and platinum-group element (PGE) geochemical study of the plutonic sill-like layered complex and the metavolcanic schists, suggest immobility of most trace elements (except La and Cu) and the PGEs, despite greenschist facies metamorphism and hydrothermal alteration experienced by the rocks. Their immobile nature is understood from good correlation of the trace elements and PGE with MgO and Cr. Other than chromitites and serpentinites all plutonic rocks show PPGE (Pd, Pt, Rh) enriched primitive-mantle normalized PGE patterns ($Pd/Ir_N = 3.9–81.1$) that are suggestive of fractionation of IPGEs (Ir, Os, Ru) by the early crystallizing chromite mineral, and the incompatible nature of PPGEs in the same. The chromitites show high PGE abundances ($\sum PGE = 96–296$ ppb), especially IPGEs ($\sum IPGE = 63–223$ ppb), due to the presence of inclusions of IPGE-bearing minerals. In the primitive-mantle normalized PGE plot the chromitites show an IPGE enriched pattern. The PPGE enriched pattern ($Pd/Ir_N = 7.7–26$) of the komatiitic to komatiitic basalt schists in a primitive-mantle normalized PGE plot indicates retention of IPGEs in the mantle or IPGE-bearing alloy saturation in the melt, while incompatible behavior of the PPGEs implies the sulfide undersaturated nature of the mantle source.

The PGE pattern of the metavolcanic schists resembles the pattern of early Archean (3.5 Ga) Barberton komatiites ($Pd/Ir_N^{Barberton} = 1–40.7$; $Pd/Ir_N^{Nuggihalli} = 6.3–21.3$), which corroborates our previous results based on REE study, and also resembles the pattern of komatiites from the 2.9 Ga Sandstone greenstone belt in the Youanmi Terrane of Western Australia ($Pd/Ir_N^{Sandstone} = 6$). The metavolcanic schists exhibit the typical PGE depleted character observed in early Archean komatiites ($\sum PGE_{schist} = 0.4–27.2$ ppb; $\sum PGE_{Barberton} = 15.0–20.8$ ppb; $\sum PGE_{Youanmi\ Terrane,\ Western\ Australia} = 4.2–7.0$ ppb) which is explained to be a result of progressive mixing of late veneer matter in the Earth's mantle with time. Pt fractionation in the Nuggihalli metavolcanic schists and in early or late Archean komatiites indicates Pt alloy dispersal in the lower mantle during crystallization of the primary magma ocean and a consequent formation of Pt-enriched and Pt-depleted isolated upper mantle domains that did not homogenize and mix away by 2.7 Ga.

In the plutonic layered sequence, pyroxenite represents a change from sulfide-undersaturation to sulfide-saturation. The pyroxenite represents a break in trend from the negative correlation of Pt and Pd with MgO displayed by the serpentinites and peridotites due to incompatible behavior of the PPGEs during lava differentiation, to the positive pattern displayed by the gabbro and metavolcanic schists due to attainment of sulfide saturation. Sulfide-saturation was probably triggered by fractional crystallization of olivine, chromite and pyroxenes. Chondrite-normalized REE patterns and a plot of incompatible elements negate the role of crustal contamination of the parental komatiitic magma. In addition, the absence of ambient sulfidic sediments rules out assimilation of crustal sulfur in the Nuggihalli rocks. The immiscible sulfides segregated from the Al-

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depleted komatiitic parental magma concentrating the PGEs during crystallization of the pyroxenes that accumulated to form pyroxenite.

1. Introduction

The platinum-group elements (PGEs: Os, Ir, Ru, Rh, Pt and Pd) have been used as geochemical tracers to study the different igneous processes operating in the Earth like magmatic fractionation, mantle melting and melt–rock interactions, and also to understand the nature and evolution of the source mantle (e.g., Maier et al., 2009; Puchtel et al., 2009, 2014; Lorand et al., 2013). Their chalcophile nature makes them useful for studying the sulfide-saturation history of the melt (e.g., Hamlyn and Keays, 1986), thus PGEs are effective tools in lithogeochemical exploration for Ni–Cu-sulfide deposits (e.g., Fiorentini et al., 2010). In the present study we have utilized whole-rock PGE geochemistry of sill-like chromitite- and magnetite-bearing ultramafic–mafic rocks and metavolcanic (komatiitic to komatiitic basalt) schists from the Archean Nuggihalli greenstone belt (3.1 Ga; Mukherjee et al., 2012) to understand the sulfide-saturation history of the parental melt. The sill-like ultramafic–mafic rocks and associated metavolcanics in Archean greenstone belts are genetically related to high-Mg magmas like komatiites, high-Mg siliceous magmas or boninites (e.g., Rollinson, 1997; Mondal et al., 2006; Prendergast, 2008; Mukherjee et al., 2012). Geochemical study of the platinum-group of elements in high-Mg magmas like komatiites is essential to understand the PGE character of the mantle source, as komatiites are high-degree partial melts and sulfide-undersaturated (Maier et al., 2003; Puchtel et al., 2009, 2014). In addition, study of PGEs in Archean high-Mg magma derived rocks is critical to understand the evolution of the Archean mantle.

In the Archean, PGE mineralization is associated with both major chromite and Ni–Cu-sulfide deposits that occur within the greenstone belts (e.g., Lesher and Keays, 2002). Common examples of PGE mineralization associated with chromite deposits include the Jamestown igneous complex (Barberton greenstone belt, South Africa; DeWit and Tredoux, 1987), the Nuasahi ultramafic–mafic complex (Singhbhum craton, eastern India; Mondal and Zhou, 2010), the Bird River sill (Bird River greenstone belt; Peck et al., 2002) and the Lac des Iles intrusive complex in the Superior craton, Canada (Wabigoon sub-province; Hinchey et al., 2005). Those associated with Ni–Cu-sulfide deposits are more common in the volcanic rocks of the greenstone belt e.g., komatiites from the Abitibi greenstone belt (Superior craton, Canada; Puchtel et al., 2004), the Agnew-Wiluna greenstone belt and the Kalgoorlie Terrane (Yilgarn craton, Western Australia; Keays et al., 1981; Fiorentini et al., 2007, 2012; Barnes et al., 2012, 2013).

In India, significant PGE mineralization ($PGE_{total} \approx$ 258–24,100 ppb) has solely been reported from the Nuasahi ultramafic–mafic complex (Mondal and Baidya, 1997; Mondal and Zhou, 2010), where the mineralized zone is located within a shear zone masked by the breccia that separates a lower chromiferous ultramafic unit from an upper gabbro unit.

Detailed PGE geochemical study has not been conducted so far in the Nuggihalli greenstone belt. Our present work therefore focuses on detailed geochemical study of platinum-group elements of the plutonic ultramafic–mafic igneous complex, and the associated metavolcanic schist rocks in the Nuggihalli greenstone belt. We have addressed the whole-rock major and trace element study of these rocks in our previous work (Mukherjee et al., 2012) to understand about the nature of the parental melt and magmatic fractional crystallization history of the rocks in the greenstone belt. In this study a larger number of samples has been analyzed for major and trace elements to augment our earlier findings.

2. Geological background

The Dharwar craton is divided into an eastern and western component by a 500 km long body of Closepet granite (Fig. 1A). The Western Dharwar craton consists of both early Archean (3.4–3.1 Ga; Table 1) and meso- to late Archean greenstone belts (3.0–2.6 Ga; Table 1; Mukherjee et al., 2012 and references therein). The rocks of the early Archean greenstone belts are also known as the Sargur Group (Swami Nath and Ramakrishnan, 1981). The Sargur Group is comprised of conformable units of volcano-sedimentary rocks and sill-like plutonic ultramafic–mafic rocks, all of which are encompassed by the tonalite–trondhjemite-granodiorite suite (TTG; Fig. 1A). The Sargur Group of rocks are deformed and metamorphosed to the low-grade greenschist facies, despite which primary igneous textures are preserved and the protoliths can still be identified. The volcanic rocks are mainly komatiites, komatiitic basalts and tholeiites (Ramakrishnan 2009), which are now represented by tremolite–actinolite–chlorite–hornblende–quartz bearing schists. The metasedimentary rocks are fuchsite-quartzites, banded-iron formations, bedded barites, and kyanite–garnet-bearing quartzites and mica schists (Ramakrishnan, 1981).

The sill-like chromitite-bearing layered ultramafic–mafic rocks are the focus of our study. They occur in the early Archean greenstone belts (Sargur Group) of Nuggihalli–Holenarsipur–Krishnarajpet–Nagamangala in the Western Dharwar craton. The sill-like rocks occur as *en echelon*, lenticular fragments (length ≈ 30–60 km; width ≈ 2–6 km) that occupy nearly a 250 km long N–S zone in the craton (Nijagunappa and Naganna, 1983). The Sargur Group of rocks is stratigraphically followed by the rocks of the meso-to late Archean greenstone belts, known as the Dharwar Supergroup (Fig. 1A), following an unconformity. The TTG suite acts as the basement for the Dharwar Supergroup, which are later intruded by a N–S trending conspicuous body of alkali feldspar-rich granite known as the Closepet granite (2.5 Ga; Taylor et al., 1988). The general stratigraphy of rocks in the Western Dharwar craton is tabulated in Table 1.

The Nuggihalli greenstone belt (length 60 km; width 2 km), which is the area of our study, occurs within the Western Dharwar craton as a linear belt with a NNW–SSE disposition (Fig. 1B). The sill-like ultramafic bodies host chromite deposits whereas the mafic sequence contains magnetite bands, which are all encompassed within the TTG suite. The plutonic ultramafic–mafic rocks and the metavolcanic schists are well exposed in the Tagdur mining district of the Nuggihalli greenstone belt (Fig. 1B). The stratigraphic column of all the rocks exposed in the greenstone belt has been illustrated in Fig. 2. A detailed description of the ultramafic–mafic unit, including the chromitite bodies, is provided in Mukherjee et al. (2010) and Mukherjee et al. (2012). We have recently dated the sill-like plutonic ultramafic–mafic rocks in the greenstone belt at 3150 ± 120 Ma by the whole-rock Sm–Nd isochron method (Mukherjee et al., 2012). The age is found to be similar (within the error limits) to the reported ages of komatiites in the craton.

The rocks in the greenstone belt are metamorphosed (greenschist facies) and rarely primary minerals are preserved. The igneous protolith of the ultramafic–mafic cumulate rocks was inferred from their present altered and metamorphosed mineralogy. The serpentinites represented an altered dunite body, while the presence of metamorphic minerals like chlorite, tremolite, actinolite and talc in the cumulate rocks implied the protolith to be a peridotite and pyroxenite (depending on the modal proportions of the minerals). The anorthosite and gabbro were easy to identify due to predominance of cumulus plagioclase in the former and occurrence of cumulus plagioclase with interstitial chlorite and