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Coexistence of compositionally heterogeneous chromitites in the Antalya–Isparta ophiolitic suite, SW Turkey: A record of sequential magmatic processes in the sub-arc lithospheric mantle

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ABSTRACT

The Antalya–Isparta region in southwestern Turkey is well known for its large ophiolitic peridotite exposures, which host various chromite orebodies. These are small-sized, massive to disseminated in texture chromitites occurring in the form of lenses or veinlets, and commonly surrounded by dunite envelopes of variable thickness. Chromitite seams from the Antalya mantle suite are both high- and intermediate-Cr varieties (Cr# = 0.56–0.83), whereas chromitites in the Isparta mantle sequence are exclusively Cr-rich (Cr# = 0.75–0.85). *In situ* minor and trace element abundances obtained by LA-ICP-MS analyses of unaltered Cr-spinel from the Cr-rich chromitites are comparable to those reported in Cr-spinel of chromitites from typical fore-arc peridotite complexes. However, minor and trace element concentrations in Cr-spinel from intermediate chromitites are dissimilar to those acquired from Cr-spinels of chromitites from well-known back-arc basin-derived ultramafic massifs. Calculation of parental magma compositions indicates that both types of chromitites share a common parentage with progressively fractionating arc-related melts. The studied chromitites are characterized by a systematic enrichment in IPGE [Os, Ir, and Ru (41–317 ppb)] with respect to PPGE [Rh, Pt, and Pd (3–49 ppb)], resulting in negatively-sloping chondrite-normalized PGE patterns that are less fractionated in intermediate chromitites. Their noble mineral assemblage is vastly dominated by tiny (≥10 μm) euhedral laurite crystals, followed by subsidiary irarsite and trivial amounts of Os–Ir alloy grains. PGM grains are not encountered in the intermediate chromitites, potentially due to crystallization resulting from PGE-poor melt. Laurite is Os-poor and exhibits a narrow range of Os-for-Ru substitution [Ru/(Ru + Os) = 0.75–0.99]. However, the concomitance of laurite and millerite in the Cr-rich chromitites of the mutual Antalya–Isparta mantle suite is in favour of their precipitation from an Os-depleted melt, characterized by local and rapid variations of fS_2 prior to or coevally with Cr-spinel crystallization. Moreover, the presence of amphibole inclusions in Cr-spinel indicates that the melt-triggered chromitite genesis potentially involved a hydrous component. Overall, data suggest that investigated orebodies were produced by a successively fractionating arc-derived melt that generated compositionally distinct chromitites at two different pseudo-stratigraphic levels within the Antalya–Isparta arc-type mantle suite.
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1. Introduction

Ophiolitic chromitites have been repeatedly reported from remnants of the sub-oceanic lithospheric mantle, which is currently exposed on the continental margin as the mantle suite of obducted ophiolite nappes (e.g., Ahmed and Arai, 2003; Dönmez et al., 2014; Nicolas, 1989; Uysal et al., 2005; Zhou et al., 1996, 1998). Their multi-stage structural evolution, (Kapsiotis, 2014; Li et al., 2002; Nicolas, 1989) combined with the broad compositional range of the chromitite-making spinel grains (Dick and Bullen, 1984; Kamenetsky et al., 2001; Rollinson and Adetunji, 2015) is supportive of their igneous origin by uprising and reactive mafic/ultramafic melts (Arai and Yurimoto, 1994; González-Jiménez et al., 2011a; Uysal et al., 2007a; Zhou et al., 1996, 2005) in a mantle domain that is strongly affected by flow-induced strain (Ghosh et al., 2013).

Although various models have been proposed to explain chromitite genesis, the mechanism under which they are formed is still heavily debated. However, the general assumption that orthopyroxene in a harzburgite-dominant mantle suite can represent a substantial donor of Cr in the magma, which is produced after prolonged interaction between mantle harzburgite and multiple injections of exotic melts, seems very probable (Arai, 1997). This scenario can effectively explain the origin of dunite envelopes that commonly surround chromitites as a result of protracted removal of pyroxene from the mantle (Zhou

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et al., 2005). Additional controversy regarding chromitite derivation relates to the coexistence of high-Cr and high-Al chromitites within the ultramafic sequence of an individual ophiolite massif. Currently, the most supported scenarios regarding concomitance of chromitites with variable compositions in close proximity involve either discrepancies in their geotectonic setting (e.g., Akmaz et al., 2014; González-Jimenéz et al., 2011b) or formation at distinct mantle levels from a progressively fractionating basaltic melt (e.g., Graham et al., 1996; Kapsiotis, 2013; Zaccarini et al., 2011).

Regardless of their provenance, chromitites are commonly regarded as potential targets for noble elements. In particular, ophiolitic chromitites display enrichment in the so-called platinum-group elements (PGE), especially when compared with their host peridotites (Ahmed and Arai, 2003; Economou-Eliopoulos, 1996; Garuti et al., 1999; Kiseleva et al., 2014; Melcher et al., 1997; Prichard et al., 1996). Several mineralogical studies have proven that PGE are not carried in solid solution within chromitite-composing spinel grains, as proposed by Capobianco et al. (1994) and Righter et al. (2004); instead, they tend to form discrete mineral species known as platinum-group minerals (PGM; Augé, 1985; Garuti and Zaccarini, 1997; Uysal et al., 2005, 2007a, 2009a; González-Jiménez et al., 2009; Kapsiotis et al., 2011). The most common type of PGM assemblage in mantle-hosted ophiolitic chromitites encompasses members of the laurite-erlichmanite series and Os–Ir alloys (Kapsiotis et al., 2009; Uysal et al., 2009a, 2015). However, the systematic lack of alloys from the noble mineral paragenesis of ophiolitic chromitites is unusual and believed to be indicative of the relative status of physicochemical conditions (fS_2 and T) prevailing in the melt from which chromitite was generated (Augé and Johan, 1988; Garuti et al., 1999; Nakagawa and Franco, 1997; Zaccarini et al., 2008).

This study discusses the chemical variability of a set of chromitites located in the Antalya–Isparta ophiolite occurrences. Major and trace- to minor-element abundances in the chromitite-making spinel are examined to discuss the coexistence of two different compositional types of chromitites, particularly in the Antalya mantle suite. Additionally, this study attempts to provide insight into the geotectonic regime in which the investigated chromitites were produced. Special emphasis is placed on the composition of the noble mineral assemblage hosted in examined chromitites to determine the metallogenic factors controlling PGE mineralization throughout the mutual Antalya–Isparta ophiolite complex.

2. General geological framework

The intense convergence between the Laurasia and Gondwana mega-plates resulted in the development of the collisional Alpine mountainous belt, which extends from central Europe throughout the Balkan Peninsula to the eastern Mediterranean region and into the Himalayas (Dilek et al., 2007). In Turkey, orogeny was generated as a result of a vigorous collision between the Anatolide, Tauride, and Arabian platforms during the Jurassic and the Cretaceous (Şengör and Yılmaz, 1981). The boundaries of these micro-continents mark pre-existing suture zones stemming from separate oceanic basin closure incidents (Dilek and Moores, 1990) in the western branch of the so-called Neotethyan Ocean. Several ophiolite outcrops are distributed along these suture zones in a nearly W–E-oriented belt, representing remnants of the Neotethyan oceanic lithosphere that was obducted onto the continental margins (Robertson, 2002).

Numerous geological, structural, and petrological data acquired from the study of various ophiolite exposures in Turkey (Fig. 1a, b) document the occurrence of young oceans encompassed in the western realm of Neotethys (e.g., Dilek et al., 2007). In particular, the ophiolite outcrops of southwestern Turkey occur across the western Tauride mountainous region, which is composed of a main carbonate platform surrounded by two allochthonous tectonic units that include relicts of oceanic origin: the Lycian Nappes to the west and the Antalya Complex to the east (Robertson, 2002). More specifically, the Antalya–Isparta complex is composed of four principal tectono-structural units, which include, from bottom to top: 1 — shallow-water platform limestones; 2 — basinal sequences interlayered with volcanic formations; 3 — a chaotic, accretionary lithological formation referred to as sub-ophiolitic mélange; and 4 — a nearly fully-developed ophiolite sequence (Juteau et al., 1977; Dilek et al., 1999; Fig. 1c-e).

The Antalya–Isparta ophiolite complex represents a complete but strongly dismembered and deformed slice of oceanic lithosphere (Juteau et al., 1977; Robertson, 2002). The mantle rocks are comprised of variably depleted spinel harzburgites accompanied by subordinate dunites and lherzolites (Aldanmaz et al., 2009; Caran et al., 2010), as well as pyroxenites in the form of discordant sheets. The contact between the mantle unit and the crustal sequence varies between "transitional" and "tectonic." The western domains of the entire area covered by ophiolite exposures includes minor cumulate rocks, such as layered and isotropic gabbros, as well as a poorly developed sheeted dike complex hosting minor plagiogranite pods. In these regions, the ophiolitic formations are locally accompanied by limited metamorphic sole outcrops (Çelik and Delaloye, 2003). Based on the study of compositional signatures in mantle peridotites, it was deduced that the Antalya–Isparta ophiolitic massif was formed in a mid-ocean ridge (MOR) geotectonic regime that progressively changed to a supra-subduction zone (SSZ) (Aldanmaz et al., 2009; Caran et al., 2010). Although the Antalya–Isparta ophiolite complex is deprived of metamorphic sole, the dating of amphiboles for the mélange-hosted amphibolites yielded ages ranging between 93 and 94 Ma (Çelik et al., 2006).

3. Geological description of the chromitites

Various chromitite occurrences crop out in the mantle suite of the Antalya–Isparta ophiolite exposures. Most occur in close proximity, and are homogeneously distributed within the mantle section at a pseudo-stratigraphic level immediately below the so-called petrological Moho. The size of these chromitite bodies ranges from a few centimetres to a few meters in length. The majority of these chromitites occur as NE-SW-trending lenticular bodies or veinlets exhibiting sharp and rarely transitional contacts to the host dunite. Dunite surrounds the chromitites in the form of envelopes of variable thickness (≥2 m); and unusually, some sizeable chromitites are wrapped in thin dunite halos. More rarely, harzburgite is determined to be the host rock of chromitites. In this case, contact between the orebodies and harzburgite is diffuse and irregular, resulting in asymmetrically outlined chromitite seams. Less frequently, chromitites are cross-cut by thin (≥15 cm) pyroxenite dykes exhibiting sharp boundaries to the orebodies. The investigated chromitites in this study display no discernible characteristics of ductile deformation. The impact of serpentinisation on them can be intense, though only on a local basis. Furthermore, dunites are more severely serpentinised when compared with harzburgites.

The examined chromitites display a relatively wide range of chromitite textures, including, in decreasing order of abundance, massive (>85 vol.%; Fig. 2a, b), semi-massive (50–85 vol.%; Fig. 2c, d), and disseminated (<50 vol.%; Fig. 2e,f). Infrequently, two different textural types are distinguishable in a single chromitite exposure. In all cases of variably-textured outcrops, massive chromitite dominated the inner parts of the orebodies, grading outwardly to semi-massive or disseminated textured chromitite. Semi-massive orebodies exhibit stronger marks of affection by serpentinisation when compared with the remaining chromitite textural types.

4. Sampling and analytical approach

Two polished thick sections were prepared from each sample for the study of micro-textural features of the solid inclusions hosted in the chromitite-making spinel.

The entire surface of each polished thick section was prudently scanned at 250–500× magnification to discover even sub-microscopic

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