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The structure of and origin of nodular chromite from the Troodos ophiolite, Cyprus, revealed using high-resolution X-ray computed tomography and electron backscatter diffraction

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ABSTRACT

Nodular chromite is a characteristic feature of ophiolitic podiform chromitite and there has been much debate about how it forms. Nodular chromite from the Troodos ophiolite in Cyprus is unusual in that it contains skeletal crystals enclosed within the centres of the nodules and interstitial to them. 3D imaging and electron backscatter diffraction have shown that the skeletal crystals within the nodules are single crystals that are surrounded by a rim of polycrystalline chromite. 3D analysis reveals that the skeletal crystals are partially or completely formed cage or hopper structures elongated along the <111> axis. The rim is composed of a patchwork of chromite grains that are truncated on the outer edge of the rim. The skeletal crystals formed first from a magma supersaturated in chromite and silicate minerals crystallised from melt trapped between the chromite skeletal crystal blades as they grew. The formation of skeletal crystals was followed by a crystallisation event which formed a silicate-poor rim of chromite grains around the skeletal crystals. These crystals show a weak preferred orientation related to the orientation of the core skeletal crystal implying that they formed by nucleation and growth on this core, and did not form by random mechanical aggregation. Patches of equilibrium adcumulate textures within the rim attest to in situ development of such textures. The nodules were subsequently exposed to chromite under-saturated magma resulting in dissolution, recorded by truncated grain boundaries in the rim and a smooth outer surface to the nodule. None of these stages of formation require a turbulent magma. Lastly the nodules impinged on each other causing local deformation at points of contact.

1. Introduction

Fossilised oceanic crust or ophiolite complexes often contain podiform chromitite. These are bodies of massive high-chromium chromite that are commonly economically viable orebodies, as in Kazakhstan (e.g. Melcher et al., 1997). Podiform chromitites are located within mantle harzburgite surrounded by a lens of dunite and are often found in the transition zone between the mantle and overlying crustal dunite, as well as in the dunite itself (González-Jiménez et al., 2014; Pagé and Barnes, 2009; Prichard and Neary, 1982; Roberts and Neary, 1993; Thayer, 1964; Uysal et al., 2005). Much of a typical podiform chromitite is composed of massive granular chromite, but the pods are also often made up of stacks of discontinuous layers of chromitite. Nodular and orbicular chromite are common components of podiform chromitite in many ophiolites of all ages and have been described by many authors (Fig. 1), e.g. from California (Rynearson and Smith, 1940), Cuba (Thayer, 1964), Oman (Brown, 1980), Pakistan (Ahmed, 1982), Turkey (Paktunc, 1990), northern China (Huang et al., 2004) and southern Tibet (Xu et al., 2011).

The origin of nodular chromite is controversial as is the origin of podiform chromitite. Nodular and orbicular chromite, although not the major forms of chromite in podiform chromitite, provide important clues to the mode of formation of this style of deposit. In this contribution, we provide new microtextural information on a rare variety of nodular chromite associated with skeletal chromite that provides a unique insight into the contentious question of how chromite nodules crystallise.

Nodular chromite is restricted to ophiolitic chromitite and is absent from stratiform chromitite in layered intrusions (Matveev and Ballhaus, 2002), such as the Bushveld complex in South Africa, (e.g. Irvine, 1977; Jackson, 1969; Naldrett et al., 2009). The restriction of the occurrence of nodular chromite to ophiolite complexes indicates a formation mechanism that is unique to an oceanic setting.

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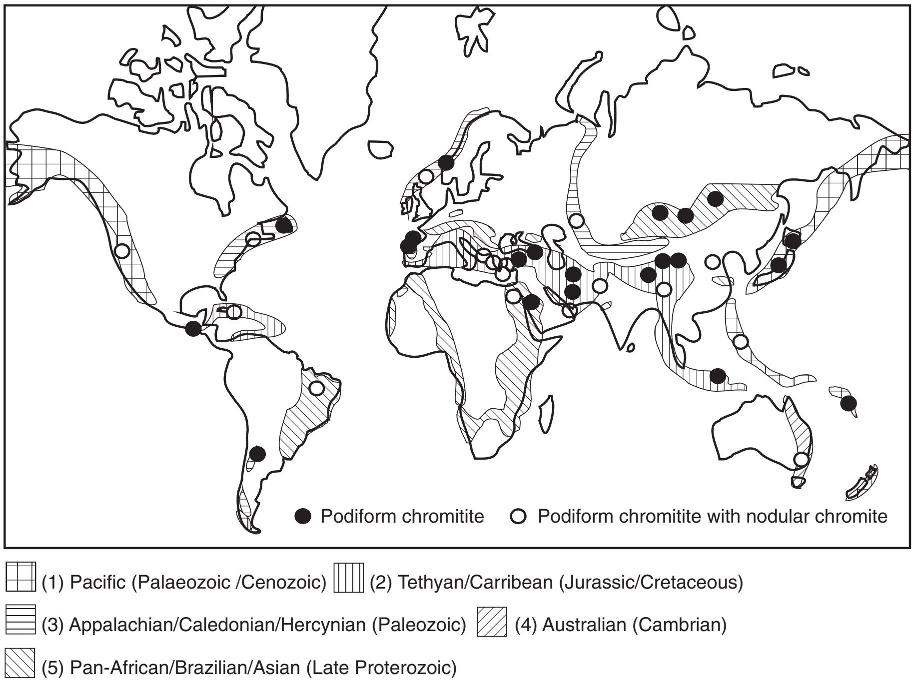

Fig. 1. Map of the global distribution of Proterozoic and Phanerozoic ophiolite belts modified from Dilek (2003) showing the distribution of ophiolites with podiform chromitite from (Prichard and Brough, 2009) including those that contain nodular chromite of all ages including (1) taken from Rynearson and Smith (1940), Arai and Yurimoto (1994), Morishita et al. (2006), (2) Economou-Eliopoulos (1996), Tarkian et al. (1991), Paktunc (1990), Brown (1980), Ahmed (1982), Zhou et al. (1996), Proenza et al. (1999), (3) Pagé and Barnes (2009), Prichard and Neary (1982), Melcher et al. (1997), (4) Golding (1975), (5) Ahmed et al. (2001), Huang et al. (2004).

Nodules of chromite range from 2 to 30 mm in size and are approximately spherical or ovoid in shape. They can however have flat surfaces giving the nodules distinctive cubic shapes with rounded corners (Ceuleneer and Nicolas, 1985). The nodules usually have fairly smooth outer surfaces and are mostly composed of chromite. They are commonly associated with euhedral chromite grains, as first described by Thayer (1969). Nodules generally occur in groups, often in layers and may be in contact with each other (Ahmed, 1982) sometimes appearing to have collided with each other causing deformation of the nodules (e.g. Paktunc, 1990; Prichard and Neary, 1982). Nodular ore types are typically restricted to the peripheries of the ore bodies or to smallish ore bodies, usually they occur in close proximity to the dunite halo (Ballhaus pers. comm.).

Chromite in some cases forms rims around cores of silicates producing orbicular chromite or chromite anti-nodules (Brown, 1980). Multiple thin shells of alternating chromite and olivine form more complex orbicular chromite (Ahmed, 1982; Dickey, 1975; Greenbaum, 1977; Huang et al., 2004; Melcher et al., 1997; Thayer, 1969; Zhou et al., 2001).

There is no agreement on how these nodules form or even whether the nodules crystallised inwards towards the core or grew from the centre outwards. Nodules have been reported to lack chemical zoning (Ahmed, 1982; Greenbaum, 1977). Other researchers report chemical differences towards the rim including Cr decrease and Ti increase (Leblanc and Ceuleneer, 1992).

In rare cases the nodules can have skeletal chromite in their cores. Examples include the samples from the Troodos ophiolite complex presented in this study and by Greenbaum (1977). Skeletal chromite has also been reported from the Vourinos ophiolite complex in Greece (Christiansen and Olesen, 1990) and the Zunhua ophiolite in northern China (Huang et al., 2004). Skeletal chromite has also been described from komatiites (e.g. Godel et al., 2013) from spinifex-textured flow tops and coarse grained olivine cumulates and also within massive sulphide ores at the contact with overlying komatiite flows (Dowling et al., 2004; Groves et al., 1977). However, these skeletal grains lack the distinctive association with nodules reported here. Skeletal chromite has been interpreted as the result of rapid crystal growth from chromite-supersaturated magma (Godel et al., 2013). This is also the process suggested by Greenbaum (1977) for the formation of the nodules associated with skeletal forms from Cyprus.

1.1. Hypotheses for the origin of nodular and orbicular chromite

There have been many mechanisms suggested for the growth of nodular and orbicular chromite. The main theories include:

(1) Growth from suspended aggregates of chromite accumulating concentrically in fast flowing magma (Huang et al., 2004) with aggregation, and coalescence or clustering of free-formed chromite grains prior to settling (Ahmed, 1982; Lago et al., 1982; Lorand and Ceuleneer, 1989; Thayer, 1969) and similarly snowballing in a turbulent flow as suggested by Dickey (1975).
(2) Separation from already consolidated chromite ore and abrasion during rock flowage (van der Kaaden, 1970).
(3) Collection of chromite from silicate magma during magma mingling by its attachment to a water-rich fluid that forms an envelope around the chromite producing spherical aggregates (Ballhaus, 1998; Matveev and Ballhaus, 2002).
(4) Formation in turbulent picritic magma flow accompanied by a water-rich fluid (Moghadam et al., 2009).
(5) Solidification of globules from a (hypothetical) chromite-rich immiscible liquid (Pavlov et al., 1977).
(6) Association with silica-rich droplets arising from wall-rock reaction causing chromite crystallisation around the droplet and their 'collapse' to form chromite nodules (Zhou et al., 2001). This builds on the ideas of magma processes in oceanic mantle developed by Kelemen (1995).

1.2. Sample locations

This paper presents results of a study of a suite of samples from the Troodos Ophiolite. The Troodos Mountains in Cyprus host the classic ophiolite sequence exposed on Mt Olympus: mantle harzburgite is