Lithos 312–313 (2018) 343–357

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Anatomy of a chromitite dyke in the mantle/crust transition zone of the Oman ophiolite

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ARTICLE INFO

Article history:
Received 22 January 2018
Accepted 9 May 2018
Available online xxxx

Keywords:
Chromite
Nodular chromitite dyke
Oman ophiolite
Mantle-crust transition zone

ABSTRACT

The igneous and mechanical processes controlling the formation of nodular chromite ore have been investigated through the study of a chromitite dyke emplaced in the uppermost part of the 330 m-thick dunitic mantle/crust transition zone that developed at the top of a mantle diapir in the Maqsad area of the Oman ophiolite. The dyke is parallel to the paleo-ridge axis, has a vertical extent of about 30 m and an average thickness of 2 m. It presents spectacular variations in ore texture, offering a unique opportunity to identify the zones of nodule nucleation in the upper parts of the dyke, growth in the intermediate parts and accumulation at the bottom.

Nodules grew by progressive accretion of euhedral chromite grains, 100–200 μm in size, around a nucleus made essentially of olivine and plagioclase embedded in skeletal chromite. At a critical size of 2 to 3 cm, the nodules, still poorly consolidated, sunk, accumulated and compacted at the bottom of the dyke. The interstitial silicate matrix between the nodules is essentially troctolitic (high Mg (Fo~92) and high Ni (NiO ~0.35 wt%) olivine and calcic (An_{83} to An_{85}) plagioclase with minor pargasite). At about mid-height, the dyke broadens significantly, reaching a width of 12 m, the center of this bulge being filled with smaller-sized nodules embedded in an anorthositic matrix. This feature is interpreted to represent a magma pocket where the melt and nodule nuclei accumulated before complete crystallization and cooling of the system. The alteration of the silicate matrix is less intense in this bulge than in the rest of the dyke.

Silicate inclusions within chromite grains indicate that the parental melt of the chromite was hybrid between two endmembers: a common MORB-like melt and a silica-rich hydrous fluid or a water-rich trondhjemitic melt, possibly produced by low degree melting of hydrothermally altered gabbro and/or serpentinized peridotite from the country rocks. The Ti content in the chromite (average ~0.5 wt% TiO_2) from the dyke is significantly higher than that of chromites emplaced at deeper levels in the mantle/crust dunitic transition zone (DTZ) and in the harzburgitic mantle from the Maqsad area. This points to the progressive evolution of the MORB component (product of decompression melting in the diapir) during its ascent from the mantle diapir to the base of the crust. Fractional crystallization occurred in a context of buffering of compatible element concentrations (Mg, Cr, Ni) around elevated, "primitive" values through exchanges between the percolating melt and the host harzburgite and dunite.

The chemical composition of both chromite and silicates is constant (i.e. evenly scattered) from the bottom to the top of the dyke and does not mimic the evolution in the ore texture nor in the size and abundance of the nodules. This implies that the parental melt composition remained globally unchanged during the formation of the ore body arguing for open system conditions during nodule formation and accumulation. The only significant evolution is observed in the central bulge where the chromite Ti content is higher (average ~0.7 wt% TiO_2 with spikes reaching several percent) confirming that this magma pocket was filled with more evolved melt.

No bottom to top evolution in the XCr of chromite is observed within the dyke but individual nodules show a well-developed zoning in XCr ratio from their nucleus (XCr ~58) to their margins (XCr ~48). An increase in the TiO_2 content of chromite toward the nodules' edges is not systematic and, when present, is quite moderate. In the largest nodules, inclusions of hydrated silicates are preferentially distributed in a circle, midway between the nodule's nucleus and its edge. This garland of inclusions coincides with a positive peak in the XCr profile, while the TiO_2 profile is not affected. This implies that the zoning in XCr cannot be assigned to fractional crystallization alone. It is tentatively explained by a scenario where the nodules crossed a gradient in the proportion of

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https://doi.org/10.1016/j.lithos.2018.05.012
0024-4937/

the MORB vs. more reducing hydrous melt during their growth. The gradient could have been maintained by a density contrast between a buoyant hydrous silica-rich melt and denser MORB.

1. Introduction

Chromite ore bodies are common features in the mantle section and in the mantle/crust transition zone of ophiolites. They are currently named "pods" in reference to their irregular, elongated shape (Fisher, 1929). Cassard et al. (1981) have shown that the podiform structure results from plastic deformation at high temperature, low stress conditions typical of asthenospheric flow and alignment parallel to the foliation and lineation of their host mantle peridotite. In such "concordant pods", the primary igneous textures have been erased to some extent due to the overprint of solid state deformation complicating attempts to understand the ore genesis.

Fortunately, in some situations, chromite ore bodies escaped deformation and transposition (the "discordant pods" of Cassard et al. (1981), a somewhat misleading term as the podiform structure is assigned to deformation by these authors). Non deformed chromite ore bodies are more common at high structural levels in ophiolites. In the mantle/crust dunitic transition zone (DTZ), elevated chromite concentrations occur in schlieren, in layers interstratified with ultramafic cumulates, and in dyke-like structures, i.e. vertical bodies having sharp boundaries with their host dunite (e.g. Augé, 1987; Ceuleneer and Nicolas, 1985; Leblanc and Ceuleneer, 1991; Rahgoshay et al., 1981). Occurrences of chromitites within the gabbroic crust and up to the base of the sheeted dyke complex have been reported but are uncommon (Arai et al., 2004; Augé, 1987).

Within dykes and discordant pods, the chromite ore commonly adopts a spectacular nodular texture whose origin is enigmatic and still debated. In concordant pods, the ore texture is more generally massive but in some cases it is clear that the massive ore derives from the deformation and sintering of a former nodular ore (e.g. Cassard et al., 1981; Ghosh et al., 2014; Leblanc et al., 1981). Accordingly, nodule formation is likely an important step in the concentration of chromite in many ophiolitic ore bodies whatever their geodynamic setting, their depth of emplacement and their tectonic history (Gonzalez-Jimenez et al., 2014). The nodular texture is typically absent in stratiform chromitites from both ophiolitic and layered intrusions contexts (e.g. Jackson, 1969).

Previous studies of nodular chromite ore worldwide have led to a few well established conclusions. (i) The growth of the nodules proceeds by progressive aggregation of minute (a few tens to a few hundred of micrometers) euhedral to subhedral chromite grains, a process referred to as synneusis (Thayer, 1969; Vance, 1969; Vogt, 1921). (ii) Chromite crystallization is triggered by hybridization between a melt of basaltic composition, sensu *lato*, and exotic melts much richer in silica and water of various possible origins (e.g. Borisova et al., 2012; Gonzalez-Jimenez et al., 2014; Irvine, 1977; Zhou et al, 1994; Matveev and Ballhaus, 2002). (iii) Nodules grow in most cases from a polymineralic nucleus made of an assemblage of skeletal chromite grains and silicates (mostly olivine and plagioclase and their alteration products) (Ceuleneer and Nicolas, 1985; Leblanc and Ceuleneer, 1991; Prichard et al., 2015). (iv) The nodules' size, typically reaching but rarely exceeding 3 cm, is conditioned by dynamic processes, i.e. by parameters related to each other through Stokes law, including the velocity of the magma flow, melt viscosity and the chromite/melt density contrast (Lago et al., 1982).

In spite of an abundant literature devoted to the nodular texture (see Gonzalez-Jimenez et al., 2014 for a recent comprehensive review), a detailed description of the petrological and textural evolution of nodular chromite ore and its silicate matrix within a single un-deformed ore body is, to our knowledge, currently lacking. In order to fill this gap, we resampled a chromitite dyke cropping out in the Oman ophiolite where subtle features inherited from chromite crystallization and nodule formation are perfectly preserved and present a spectacular evolution from the bottom to the top of the ore body (Ceuleneer and Nicolas, 1985; Leblanc et al., 1991).

This detailed study allowed us to address aspects of nodular chromite ore formation that are still poorly constrained and a matter of debate: the nature of the parental melt and of the tectono-igneous setting of their genesis (cf. a recent debate: Rollinson and Adetunji, 2013; Arai and Miura, 2015); the extent of differentiation of this melt during the lifetime of the ore body formation; the potential impact on chromite composition of different degrees of hybridization between silicate melts and aqueous fluids and of related changes in extensive parameters; the evolution of magma dynamics during the growth and accumulation of the nodules in the dyke.

2. Geological context

With an exposure of ~30.000 km^2, the Oman ophiolite is one of the largest fragments of oceanic lithosphere exposed on Earth. It was accreted in the Tethys ocean during Late Cretaceous times, about 95–97 Ma ago (e.g. Glennie et al., 1974; Rioux et al., 2012; Tippit et al., 1981). Early intra-oceanic thrusting occurred soon after (93–95 Ma) in a near ridge environment (Boudier et al., 1985; Hacker et al., 1996; Rioux et al., 2013; Rioux et al., 2016). The thrusting of the ophiolite onto the Arabian plate (the "obduction" *senu stricto*) was completed during Maastrichtian times (~70 Ma ago) (Coleman, 1981; Glennie et al., 1974; Gray et al., 2004). A short-lived northeastward subduction of the Oman continental margin beneath the oceanic lithosphere preceded and made this obduction possible (Searle et al., 1994; Warren et al., 2005). The present exposure of the ophiolite results from the uplift of the Oman Mountains that likely started during the Miocene (Glennie et al., 1974). This part of the Arabian plate has not yet collided with Eurasia, offering unique preservation conditions of the structures inherited from the accretion of the ophiolite.

The tectonic setting during the accretion history of the Oman ophiolite is the subject of a long standing debate and is far from being solved. The ambiguity comes essentially from the occurrence in both crustal and mantle sections of rocks belonging to two contrasted magma series: (1) olivine tholeiites with MORB geochemical affinity and (2) high-Mg andesites ultra-depleted in HFSE and in some other incompatible elements (e.g. Arai et al., 2006; Benoit et al., 1996; Benoit et al., 1999; Clénet et al., 2010; Juteau et al., 1988; Pallister and Knight, 1981; Pearce et al., 1981; Python and Ceuleneer, 2003; Yamasaki et al., 2006). The MORB series is most consistent with a mid-oceanic ridge setting but a mature back-arc basin cannot be excluded. The depleted andesitic series is a priori more consistent with a supra-subduction zone setting but can also be interpreted in the framework of melting induced by near-ridge initiation of intra-oceanic thrusting (e.g., Boudier et al., 1988; Ernewein et al., 1988; Koepke et al., 2009) or as the product of hydrous re-melting of the lithosphere due to the episodic rise of mantle diapirs during accretion (Benoit et al., 1999; Python and Ceuleneer, 2003). The existence of cumulates with andesitic affinity along present-day mid-ocean ridges demonstrates that this process may actually develop in such an environment (Nonnotte et al., 2005).

The Oman ophiolite is not structurally and petrologically homogeneous, which also contributes to the debate concerning its origin. It is best described as a mosaic of blocks accreted from distinct ridge segments. This is attested, among others, by important variations in the strike of the sheeted dyke complex, assumed to correspond to the strike