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Crystallization of Podiform Chromitites from Silicate Magmas and the Formation of Nodular Textures

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Abstract: Podiform chromite deposits consist of numerous individual accumulations of chromite in the mantle sequences of ophiolites, suggesting formation in separate, mini-magma conduits in the upper mantle. They may show unique nodular and orbicular textures. Simple mixing of two distinct magmas, invoked for chromite deposits in layered intrusions, is inadequate to explain the formation of podiform chromite deposits. More likely, melt/rock interaction triggers the precipitation of chromite by addition of newly-formed droplets of melt to the main body of magma passing through a conduit, a process similar to that of magma mingling but involving a turbulent, moving magma so that newly-formed melt droplets behave like snowballs. These droplets concentrate chromite to form an outer shell and, while the magma is moving upwards, less dense silicate melts are squeezed out of the droplets as the shell collapses to form a nodule. Upon cooling, both orbicular and nodular textures are preserved in the chromitite.

1. Introduction

It has been suggested that a multistage melting and magma mixing in the upper mantle might have played an important role in the production of podiform chromitites (Paktunc, 1990) and, based on experimental studies, Ballhaus (1998) has recently suggested that magma mixing in a melt conduit can explain the origin of certain textures in these deposits. This model involves magma mixing, in a manner similar to that argued for large stratiform intrusions (Irvine, 1977). However, podiform chromite deposits consist of numerous individual accumulations of chromite for which simple mixing of two distinct magmas is difficult to envisage. In addition, the podiform bodies in places display unique nodular and orbicular textures that are not observed in stratiform chromitites. We therefore believe that the process of formation of podiform chromitites may be different from that suggested for stratiform occurrences.

Below, we argue that melt/rock interaction initially triggers chromite precipitation in the upper mantle, and propose that nodular and orbicular textures are produced when melt droplets extracted from the wall rock mix with the main body of magma. Once formed, the nodules may be deformed, abraded or aligned by later movement of the semi-solid mass.

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2. Formation of Podiform Chromitites

Thayer (1960, 1964) classified podiform chromitites as characteristic of alpine ultramafic complexes. These complexes are now almost universally recognised as the ultramafic portions of ophiolite suites or subcontinental mantle. Podiform orebodies are very different from the stratiform ones that occur within layered igneous intrusions. The pods are generally irregular in shape, with a limited lateral extent. Tabular, rod-like and sack-like bodies occur and the deposits have been described as concordant, discordant and subconcordant (Cassard et al., 1981) depending upon the relationship between structures in the ore and those in the host rock. The ore very often exhibits nodular or orbicular textures and generally show the results of high temperature deformation such as pull-apart textures and strong mineral lineation. These features are unique to podiform chromitites (Thayer, 1964).

It is generally agreed that podiform chromitites form by precipitation of chromite from basaltic or boninitic magmas in the upper mantle, but an unresolved fundamental question is how large volumes of massive chromitite can be concentrated from silicate magmas that contain relatively small amounts of chromium (600-1200 ppm). For stratiform chromitite deposits within layered intrusions (e.g., Stillwater and Muskox), mixing of a primitive Mg-rich melt lying on the olivine-chromite cotectic with more evolved Al-rich tholeiitic melt in the orthopyroxene stability field produces a hybrid melt that lies in the chromite stability field

(Irvine, 1977). Repeated injection of primitive melts into large evolving magma chambers is confirmed by the lithologies and mineral chemistries of the layered rocks containing the chromite seams. In layered intrusions, magma mixing generates relatively continuous layers of chromitite in large magma chambers.

The fact that a variety of primitive and more evolved magmas have passed through the upper mantle sections of many chromitite-bearing ophiolites (e.g., Robinson et al., 1983; Edwards, 1995; Zhou et al., 1996), raises the possibility of magma mixing similar to that invoked for layered intrusions (Paktunc, 1990; Ballhaus, 1998). However, any given podiform chromitite ore field is composed of numerous individual bodies of relatively small size, in which the chromite generally shows an overall uniform chemistry. The magma mixing model would require that each pod formed in an individual conduit, which had hosted the passage and mixing of batches of different magmas, and that this process had been exactly duplicated in a number of conduits at the same time. This seems an unlikely scenario and indeed, Edwards (1995) has shown that if two distinct magmas follow the same physical pathway, the earlier melt generally leaves a crystalline product in the conduit, precluding mixing of the two. One way out of the problem has been to argue that the chromitites originally formed by magma mixing in a large chamber at the crust-mantle boundary and were later either gravitationally or tectonically incorporated into the upper mantle (Dickey, 1975; Greenbaum, 1977). However, structural and geochemical studies do not support the notion that podiform chromite deposits were originally formed in a crustal magma chamber (e.g., Cassard et al., 1981; Lago et al., 1982).

Concentration of even a single pod of chromitites must necessarily take place from a large volume of mafic magma. Unlike the case of stratiform deposits where the crystallization products of the magma are visible as the layered cumulates, a magmatic host is not present in podiform ore bodies. This implies continual flow and extraction of magmas from the mantle leaving a host of highly residual peridotites surrounding the earliest chromite crystallization products. A simple magma mixing model is therefore clearly inadequate to explain the formation of podiform chromitites.

On the other hand, during a single, continuous magmatic event where the conduit remains open, there is ample opportunity for modification of the magma composition through melt reaction with the conduit wall rock. Reaction between a basaltic melt and harzburgitic mantle forms dunite (Quick, 1981; Keleman et al., 1992), which may occur as veins, dykes or pods. In the Luobusa ophiolite, southern Tibet, dunite dykes contain 'stringers' of chromite (Fig. 1) which have almost identical chemistry to the chromite in massive ores in the same massif. The dunite dykes are also compositionally and mineralogically similar to the dunites enveloping the more massive podiform chromitites. Such features have been used to support a model of melt/rock interaction for the formation of the podiform chromitites (Arai and Yurimoto, 1994; Zhou et al., 1994, 1996; Arai, 1997), during which pyroxene in the host peridotite reacted and dissolved, thereby raising the silica content of the melt and moving it into the chromite stability field.

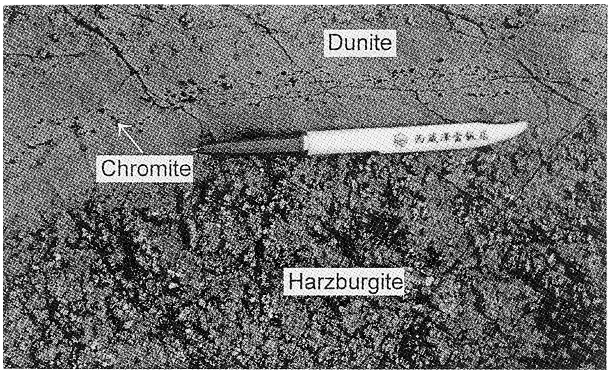

Fig. 1 A dunite dyke crosscutting harzburgite in the Luobusa ophiolite, Tibet. A chromite stringer in the middle of the dyke marks the passage of magma through the harzburgite.

3. New Interpretation for the Origin of Orbicular and Nodular Textures

The origin of nodular textures has long been a matter of debate. Previous models for formation of nodules include aggregation of free-formed chromite grains prior to settling, pelletization resulting from chromite crystals rolling down pre-formed silicate banks, snowballing in a turbulent zone of magma segregation, solidification of globules of a hypothetical chrome-rich immiscible liquid, or abrasion of pieces of solidified chromite ore during flowage (Greenbaum, 1977). Leblanc et al. (1981) interpreted orbicular chromite as a concentration of small concretions, with successive layers of chromite and olivine, formed in a magma flowing rapidly enough to maintain them in suspension.

Podiform chromitites typically exhibit a variety of textures including massive, banded, disseminated, nodular, and orbicular (Fig. 2). Most orebodies display several of these textural types (Thayer, 1969; Leblanc, 1987).

Nodular chromitites consist of spherical or ovoid masses of chromite in a matrix of dunite (Fig. 2). Individual chromite nodules are as much as a few centimetres in size and, in many cases, ovoid varieties exhibit a crude alignment. Orbicular textures are also common, for example, in the podiform chromitites of the Troodos ophiolite (Malpas and Robinson, 1987). These

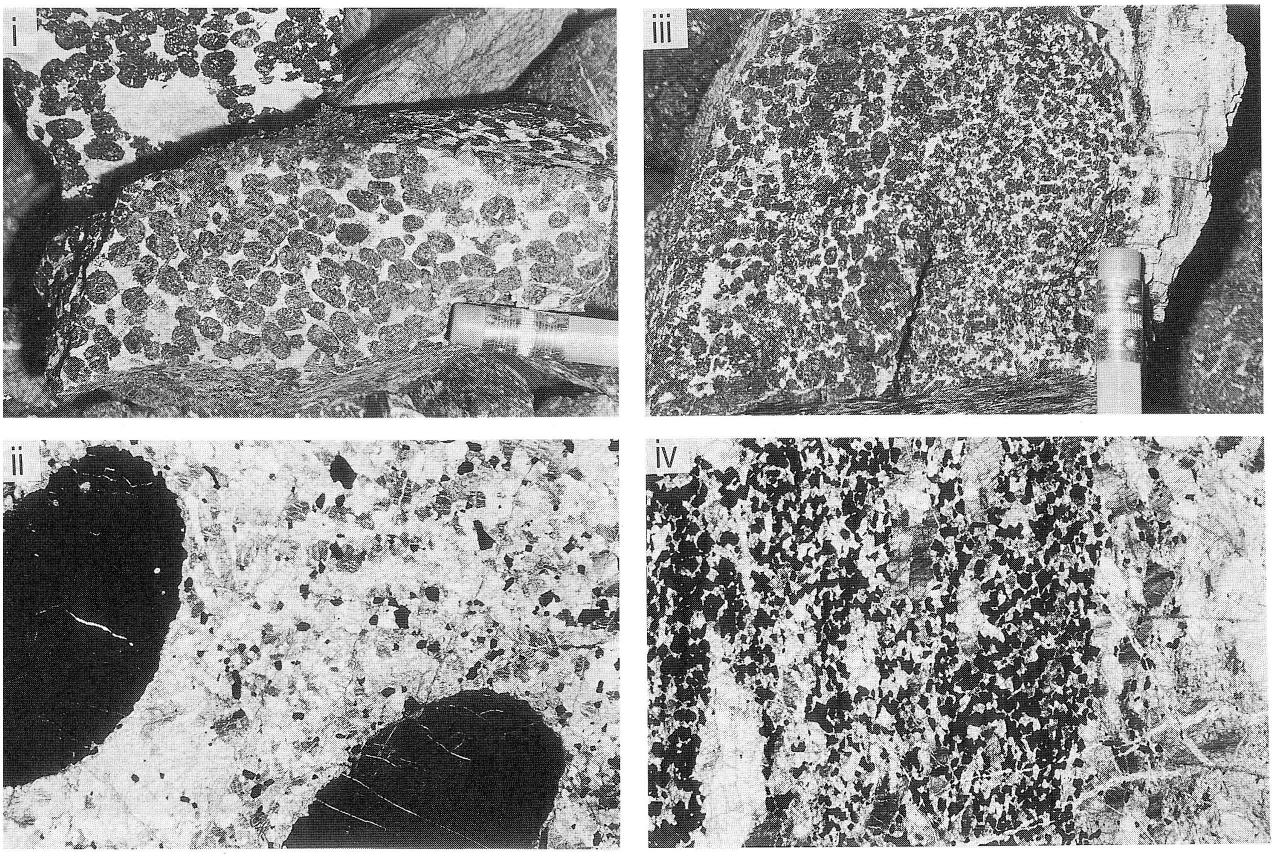

Fig. 2 Textures of podiform chromitites; i) Nodular texture of chromitite; ii) Microphoto of the nodular texture: note the euhedral fine-grained chromite in the dunite matrix; iii) Transition from nodular to massive chromites; and iv) Microphoto of layered chromitite and dunite. Microphotos of ii) and iv) were taken under the polarized light with lengths of 26 mm.

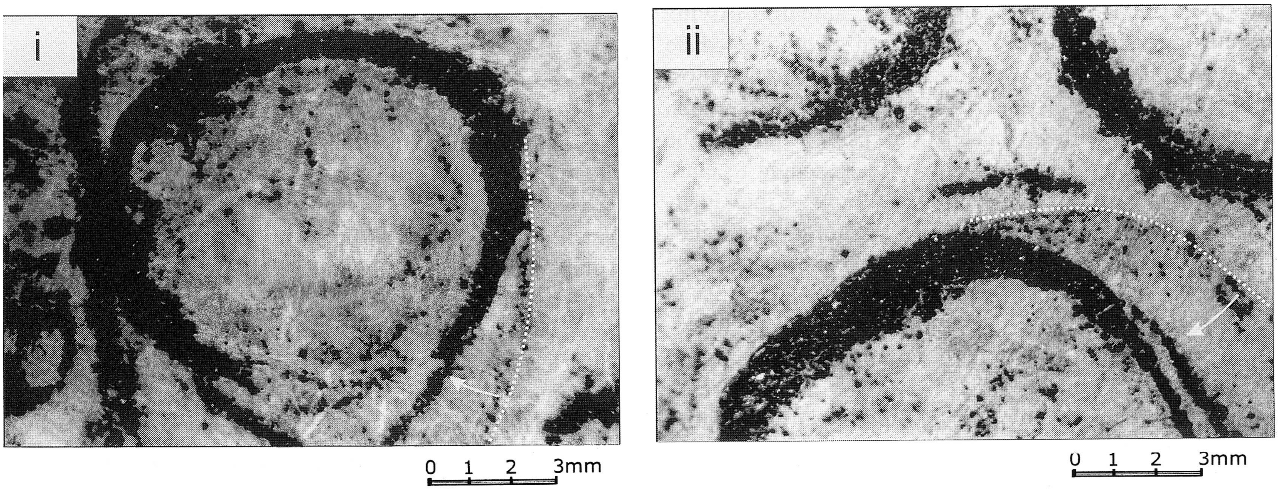

Fig. 3 i) and ii) Orbicular (ring-shaped) chromitites set in dunite with disseminated chromite (black). Thin chromite rings form shells at an early stage of the development of nodular texture. Note that the shifting of the shells can be traced as the shells are condensing. Dotted lines mark the previous shells of chromite, and arrows show the direction of collapse.

textures comprise enigmatic, ring-shaped masses of chromite with ellipsoidal or irregularly rounded cores of dunite, enclosed by shells of massive chromite (Fig. 3). The orbicules are set in a dunite matrix, and both contain chemically similar euhedral chromite grains. The dunite cores and matrix are mineralogically identical

(Brown, 1980). The orbicular textures are, in places, gradational to nodular textures as the dunite cores become smaller and the chromite shells thicker. This transition suggests that both textures may have formed by the same process.

We have identified a particular example of orbicular chromitite that may have implications for the origin of these textures (Fig. 3). In this example, the collapse of orbicules can be seen as traces of chromite outlining the 'ghost' of the original shell configuration, suggesting that such collapse took place in a turbulent magma. Each chromite orbicule likely formed from an individual droplet of melt either newly introduced to or immiscible in a large magma body. The formation mechanism is demonstrated in a melt experiment (Ballhaus, 1998), which suggested the development of nodular and orbicular textures by mingling of primitive and more evolved silicate melts in magma conduits. In this model, injection of new melt into an existing melt body would form numerous droplets that disperse to crystallize as chromite nodules. However, although this mechanism fits with the magma mixing model proposed for stratiform chromitites in layered intrusions, nodular and orbicular textures are not reported in stratiform chromitites. This anomaly needs further explanation.

We prefer a model in which the formation of chromite orbicules in podiform chromitite is a consequence of the melt/rock reaction that initially triggers chromite precipitation. Melt/mantle interaction may have involved incongruent melting of pre-existing pyroxenes. In a sample from the Luobusa ophiolite, southern Tibet, a stringer of euhedral chromite adjacent to fine, anhedral olivine grains occur in a large olivine crystal of the immediate dunite host (Fig. 4-i). Although there is a strong deformation, this large olivine grain probably formed through incongruent melting when magma passed through the host rock. The stringer of chromite is thought to mark the pathway of a melt newly formed by wall-rock interaction, around which the transformation of pyroxenes (clinopyroxene or orthopyroxene) to olivine occurred by incongruent reaction. The passage of this newly-created melt can also be seen in the dunite dyke in Figure 1, where a chromite stringer is composed of euhedral, fine-grained chromite (Fig. 4-ii). The newly formed chromite is chemically and morphologically different from residual chromite in the host peridotites. Chromite with similar origin was also noted in basalts from Mid-Atlantic Ridge (Kamenetsky and Crawford, 1998).

In this case, as a melt/rock reaction proceeds, many individual droplets of modified silicate melt form and are dispersed to mingle with the large body of magma (Fig. 5-i). These droplets are likely to lie in the chromite stability field as the magma in the main body penetrates into the wall rocks and causes breakdown of

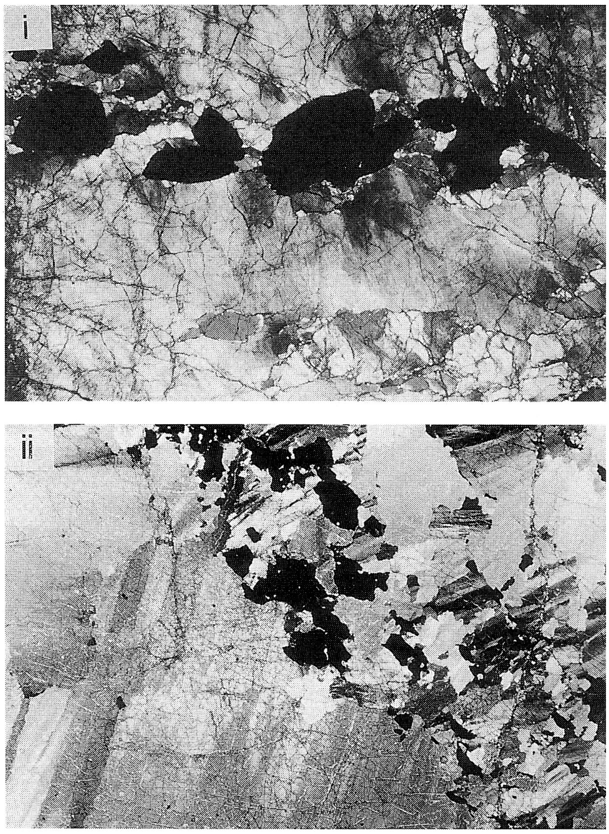

Fig. 4 Silicate rocks adjacent to a chromitite. i) Stringer of euhedral chromite (black) in a larger olivine grain (under polarized light, 3mm across); and ii) Euhedral chromite forming a chain of grains in a dunite vein (under polarized light, 6mm across).

pyroxenes, enriching the newly formed melts in Si and Cr. As a consequence, these begin to crystallize chromite to form an outer shell (Fig. 5-ii). In a turbulent flow they would likely be subject to snowballing while continuing to crystallize chromite, although some melt droplets might disperse and mix with the evolving magma body, before building up a significant carapace. In cases where the orbicules evolve further, the chromite is concentrated when less dense silicate magmas are squeezed out of the droplet to mix with the main magma body, and the shell is condensed (Fig. 5-iii). Eventually, where all of the core disappears in this way, chromite nodules are formed and may undergo gravitational settling to be frozen into a host of dunite (Fig. 5-iv). The different stages of the process are recorded where magmas cool quickly enough, or become stagnant, preventing the collapse of the orbicules and leaving an incomplete nodular or orbicular texture. The model also explains the presence of chromite nodules in a dunitic matrix, which contains disseminated chromite of similar composition (Fig. 2-i and ii).

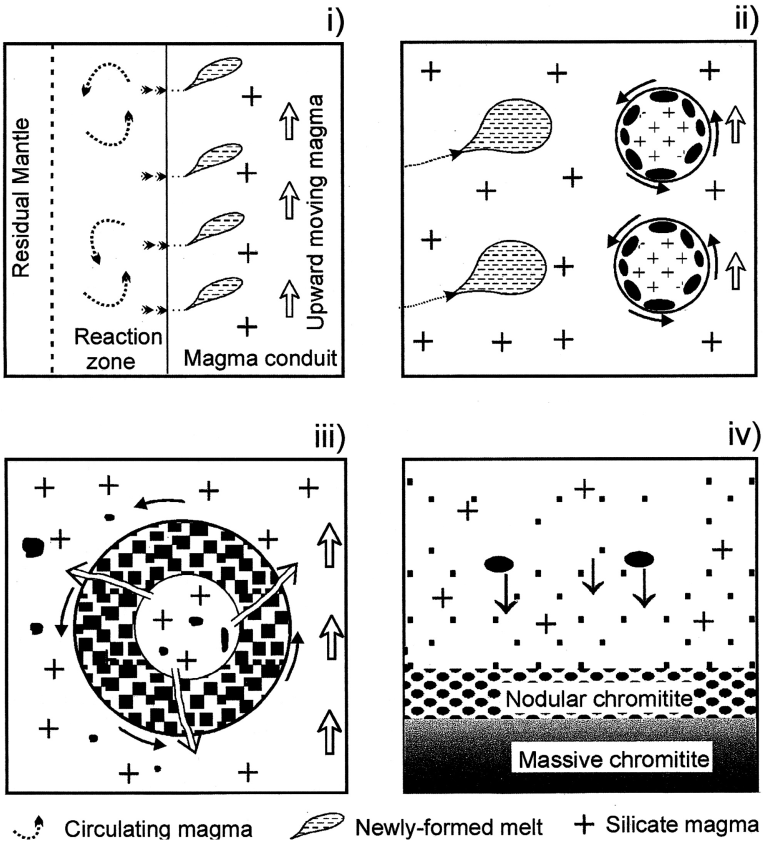

Fig. 5 Model showing the formation of nodular and orbicular texture (not to scale). i) Numerous droplets rich in Si and Cr, formed through melt/rock interaction, reach the main magma body separately; ii) Crystallization of chromite forms a "snowball" with a shell of chromite in a turbulent, moving magma; iii) Snowballing and condensation of chromite shells form nodular textures; and iv) Deposition of nodular ores as the magma cools.

4. Conclusions

Melt/rock interaction provides a mechanism for the continuous supply of Cr and effective segregation of chromite to form a podiform body. This process is different from a simple magma mixing and can also explain the formation of nodular and orbicular textures that are not observed in stratiform chromitites. During their passage through the upper mantle, silicate magmas react with host peridotites to produce new hybrid melts. Incomplete mixing of droplets of these newly-formed melts with the original magma in the melt conduit promotes crystallization of these droplets with a shell of chromite. In a hot, turbulent environment, each droplet concentrates chromite like a rolling "snowball" while the less dense silicate melt is squeezed out of the droplet to mix with the main magma. Condensation and gravitational settling of the nodules and orbicules form a variety of textures including the characteristic nodular "leopard-ore" chromitites. The incomplete nodules with ring textures, seen in some chromitites, might have resulted from particularly rapid cooling of the melt droplets and host magma.

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