

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl


Conversion of low-pressure chromitites to ultrahigh-pressure chromitites by deep recycling: A good inference



Shoji Arai

Department of Earth Sciences, Kanazawa University, Kanazawa 920-1192, Japan

ARTICLE INFO

Article history:

Received 6 June 2013

Accepted 2 August 2013

Available online 28 August 2013

Editor: B. Marty

Keywords:

podiform chromitites
 low-pressure cumulates
 UHP minerals
 mantle convection
 deep recycling

ABSTRACT

Podiform chromitites have been interpreted as a peridotite/melt reaction product within the upper mantle (= low-P chromitites). Some of them, however, contain ultrahigh-pressure (UHP) minerals such as diamond and coesite (= UHP chromitites). The UHP chromitites can be produced by deep recycling of low-P chromitites via mantle convection. Carbon-rich UHP minerals were changed from fluidal C species (e.g., CO₂) metasomatically entrapped during the travel of chromitites within the mantle. Lamellae of coesite and other silicates observed in UHP chromite were possibly originated from globular inclusions of hydrous minerals and pyroxenes, which are common in low-P chromitites. Platinum-group element (PGE) sulfides, which commonly characterize the low-P chromitites, were converted to PGE metals or alloys by heating on their decompression during mantle convection. Peculiar igneous textures, e.g., nodular textures, characteristic of low-P chromitites can be preserved even after compression and subsequent decompression during recycling because of possible absence of reactions between olivine and chromite or their high-P polymorphs. The UHP chromitites can thus be an indicator of mantle convection; UHP minerals in chromitite may support the two-layer convection model.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

There has been a consensus that podiform chromitites are formed through reaction between mantle peridotite (especially harzburgite) and melt, with subsequent magma/melt mixing at an uppermost mantle level (e.g., Arai and Yurimoto, 1994; Zhou et al., 1994; Arai, 1997). The podiform chromitites serve as a good indicator of peridotite–melt reaction in the upper mantle (e.g., Arai, 1997). However, ultrahigh-pressure (UHP) minerals including diamond have been recently found from two Tibetan ophiolites as well as from Ray-Iz massif, the Polar Urals (e.g., Robinson et al., 2004; Yang et al., 2007, 2011; Yamamoto et al., 2009; Xu et al., 2009), and this strongly requires us to revisit the origin(s) of podiform chromitites. Origin of UHP chromitites has been recently proposed but not been discussed in great detail (e.g., Robinson et al., 2004; Ruskov et al., 2010). The important point is that, as far as we know, the UHP podiform chromitites are basically similar in petrography and mineral chemistry to “ordinary” podiform chromitites. The UHP chromitite mainly comprises chromite (chromian spinel) and olivine, and some of them show nodular textures (e.g., Zhou et al., 1996; Yamamoto et al., 2009), which characterize igneous low-P chromitites (e.g., Nicolas, 1989). Arai

(2010) proposed a possibility of deep recycling origin for the UHP chromitites. Here I would like to discuss the origin of the UHP podiform chromitites in more detail and more extensively based on mineralogical characteristics, although the discussion below may be speculative at present. This work will promote re-examination and more systematic descriptions of UHP chromitites and related peridotites.

2. Low-pressure magmatic origin of podiform chromitites: some lines of evidence

The podiform chromitites, enveloped by dunite (e.g., Cassard et al., 1981), are commonly found within mantle peridotites, mainly harzburgite (e.g., Arai, 1997) in ophiolites or mantle-derived peridotite complexes (Fig. 1a). They form a kind of cumulates filling melt conduits within the residual mantle peridotite (e.g., Cassard et al., 1981; Lago et al., 1982). Origin of the podiform chromitites with dunite envelope can be explained by harzburgite–melt reaction and subsequent melt mixing (e.g., Noller and Carter, 1986; Arai and Yurimoto, 1994; Zhou et al., 1994): the dunite envelope is essentially similar to a replacive dunite (Quick, 1981; Kelemen et al., 1990; Arai and Yurimoto, 1994). This process includes incongruent decomposition of orthopyroxene, and is effective at low-P conditions (cf. Kushiro, 1969).

E-mail address: ultrasa@kenroku.kanazawa-u.ac.jp.

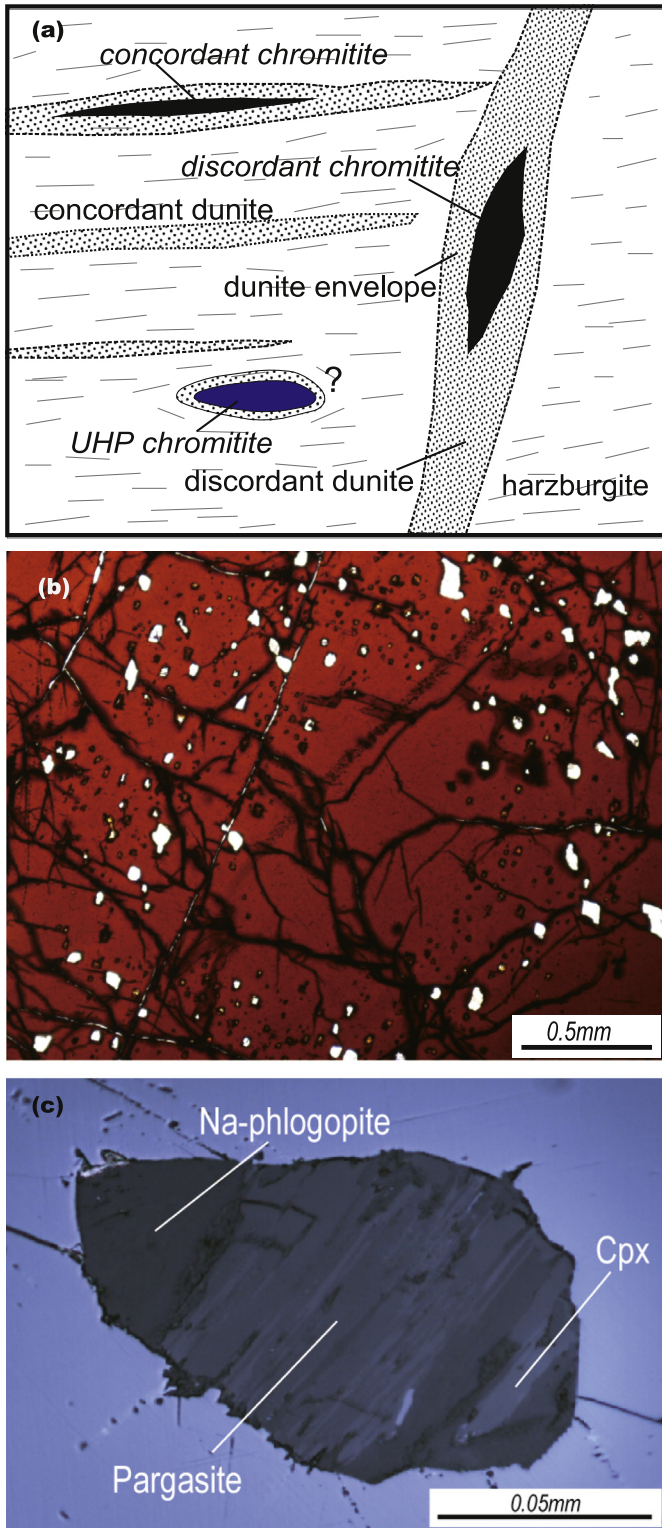


Fig. 1. Geological and petrographical characteristics of podiform chromitites. (a) Idealized modes of occurrence of podiform chromitites on outcrop. Chromitites always, enveloped by dunites, vary in attitude to the surrounding harzburgite, concordant to discordant. UHP chromitites may be concordant to foliation of harzburgite. (b) Photomicrograph of primary inclusions concentrically arranged in chromite of a discordant chromitite from Wadi Hilti, northern Oman ophiolite. Plane-polarized light. (c) Close-up of one of inclusions composed of pargasite, Na-phlogopite and diopside clinopyroxene. Note the predominance of pargasite. Reflected light.

Chromite in chromitites sometimes contains minute inclusions of Na-rich pargasite, Na-phlogopite and pyroxenes (e.g., Augé, 1987; Lorand and Ceuleneer, 1989; Borisova et al., 2012) (Fig. 1b, c). Their globular shape (Fig. 1b, c) indicates their initial entrapment as melt by spinel (e.g., Borisova et al., 2012). They sometimes show concentric distribution within spinel grains, indicating their primary nature (Roedder, 1984) (Fig. 1b). Pargasite, one of the main constituents of the inclusions (Fig. 1c), shows a low-P (< ca. 3 GPa) stability field (e.g., Niida and Green, 1999; Frost, 2006). The presence of low-P hydrous minerals in the primary inclusions in spinel (Fig. 1b, c) indicates a shallow upper mantle origin for concerned chromitites (e.g., Borisova et al., 2012), which is consistent with the above inference.

Typical low-P chromitites may be represented by so-called discordant chromitites, which are relatively young and, if flattened, can become so-called concordant chromitites together with surrounding peridotites via mantle flow beneath a spreading center (Cassard et al., 1981; Lago et al., 1982). Cassard et al. (1981) concluded that peculiar igneous textures, e.g., nodular, anti-nodular and orbicular, were only found in the discordant chromitites, but got unclear via deformation (cf. Nicolas, 1989). The minute mineral inclusions possibly disappeared with the progress of deformation too (Cassard et al., 1981). The situation is, however, not so simple with concordant and discordant chromitites (Ahmed and Arai, 2002) from the northern Oman ophiolite; the two types are essentially different in terms of chemical and petrographical characteristics (Miura et al., 2012). That is, the concordant chromitite is not simply a deformed equivalent to the discordant one (Ahmed and Arai, 2002; Miura et al., 2012).

3. Characteristic of UHP chromitites

The geological context of UHP chromitites has not been described in great detail and is not clearly known, but, as far as we know from the literature, they show features on the outcrop similar to those of ordinary low-P chromitites. The chromitites from Luobusa, Tibet (e.g., Zhou et al., 1996; Xu et al., 2011), some of which show UHP features (e.g., Robinson et al., 2004; Yang et al., 2007; Yamamoto et al., 2009; Xu et al., 2009), seem to share the same geological features to those of low-P origin, e.g., those from Oman ophiolite (e.g., Miura et al., 2012) (Fig. 1a). UHP chromitites are enveloped by dunite, within harzburgitic mantle peridotite (e.g., Zhou et al., 1996, 2005; Yamamoto et al., 2009). A concordant attitude to surround harzburgite is expected for UHP chromitites but not clearly shown (cf. Zhou et al., 1996) (Fig. 1a).

Diamond and other UHP minerals have been found as inclusions in chromite in podiform chromitites from Tibetan ophiolites (e.g., Robinson et al., 2004; Yang et al., 2007, 2011; Yamamoto et al., 2009; Dobrzhinetskaya et al., 2009; Xu et al., 2009) (Table 1). They include native elements (e.g., diamond), alloys (e.g., PGE and Ni-Fe-Cr-C), Fe-silicides, carbide (moissanite), oxides (e.g., Si-rich rutile) and nitrides (TiN and c-BN) (Table 1). In addition, even the former presence of much higher-P minerals was suggested, although they had been broken down. Yamamoto et al. (2009) suggested a precursor UHP CF(calcium ferrite)-type chromite that is decomposed to low-P chromite containing silicate exsolutions. Yang et al. (2007) considered the precursor stishovite for the blade-shaped coesite. Robinson et al. (2004) suggested the presence of ringwoodite as a precursor of now altered Mg-Fe silicate with an octahedral shape.

Robinson et al. (2004) referred to a possibility of a xenocrystal origin for UHP minerals; they were accidentally trapped as xenocrysts by chromite in magmatic formation of podiform chromitites in the upper mantle. Yamamoto et al. (2009), however, found exsolution of coesite and pyroxenes in chromite from

Table 1
Ultrahigh-pressure and other unusual minerals found in podiform chromitites from Luobusa, Tibet.

native elements
C (diamond, graphite), Si, Ti, Fe, Cr, Ta etc
alloys
Ni–Fe–Cr–C alloys, Fe–Ti–Si alloys, Cr–Fe, PGE alloys (Os–Ir, Os–Ir–Ru, Pt–Fe), W–Ta, Ni–Mn–Co
Fe-silicides
Fe ₃ Si ₇ , Fe _{0.59} Si _{0.37} Ti _{0.04} etc.
carbide
moissanite (SiC)
oxides
Si-rich rutile, TiO ₂ II, wüstite (sometimes Mn-rich), coesite, corundum
nitrides
TiN, c-BN
CF-type chromite[*], stishovite^{**}, ringwoodite^{***}

Data source: Bai et al. (2000), Robinson et al. (2004), Yang et al. (2007), Xu et al. (2009), Dobrzynetskiy et al. (2009), and Yamamoto et al. (2009). Modified from Arai (2010).

^{*} Precursor of chromite with diposide exsolution lamellae (Yamamoto et al., 2009).

^{**} Possible pseudomorph now consisting of blade-like coesite crystal (Yang et al., 2007).

^{***} Possible pseudomorph now composed of altered Mg–Fe silicate suggesting an octahedral shape (Robinson et al., 2004).

some Luobusa chromitites, suggesting a UHP formation of chromitite and precluding the possibility of xenocrystal origin for the UHP minerals.

To be interesting, the nodular texture has been preserved in some of the Luobusa chromitites (Zhou et al., 1996; Yamamoto et al., 2009), which are seemingly concordant to the surrounding peridotite (although not referred to clearly in the literature). According to the descriptions of the Luobusa chromitites, their chromites are completely free from the minute primary inclusions of hydrous and other minerals (e.g., Zhou et al., 1996; Yamamoto et al., 2009; Miura et al., 2012), of which presence is one of the characteristics of discordant chromitites (Cassard et al., 1981) (Fig. 1).

Platinum-group minerals (PGMs) are only PGE-bearing alloys in the Luobusa and Dongqiao chromitites (Bai et al., 2000; Shi et al., 2007); this is in contrast to predominance (or common presence) of laurite and other PGE sulfides and arsenides in ordinary podiform chromitites (e.g., Ahmed and Arai, 2002, 2003). Bulk-rock IPGE (Ir-group PGE)/PPGE (Pt-group PGE) ratio is relatively high in the Luobusa chromitites (Zhou et al., 1996; Bai et al., 2000) as discussed below.

4. Discussion: Possible conversion of low-pressure chromitites to UHP chromitites through mantle recycling

4.1. Possibility of direct UHP magmatic formation of chromitite

One possibility of UHP origin is their direct magmatic formation at UHP condition (cf. Ruskov et al., 2010). The primary magmatic UHP chromitite with associated rocks, if any, is strictly required to be converted to the set of chromitite + dunite envelope + harzburgite host (Fig. 1a), when decompressed. It is, however, difficult to picture the decompression-induced conversion of the UHP primary chromitite–dunite (ringwoodite rock?) pair to exactly the same thing, by coincidence, commonly formed by low-P magmatism. On the other hand, it is much easier to recycle the low-P chromitite–dunite–harzburgite set (Fig. 1a) through the mantle, because the basic structure and texture of chromitite and associated

peridotites can be restored when reappearing at the upper mantle after recycling as discussed below.

4.2. Recycling origin of UHP chromitite

Deep recycling of low-P magmatic chromitites formed at the upper mantle well explains several key features of the UHP chromitites as discussed below in detail. The depth for recycling is a matter of debate; subducted slab may be stagnated as megathrust around the transition zone and further subsided down to the core–mantle boundary (e.g., Ringwood, 1975, 1991). The megathrust is expected to contain chromitite pods, because the low-P igneous chromitite is one of the members of oceanic lithosphere (Arai and Matsukage, 1998; Abe, 2011). Some of subducted materials, on the other hand, have been known to be recycled only through the upper mantle without further sinking (e.g., Morishita et al., 2003).

The recycling of chromitite does not mean recycling of a whole crust–mantle slice that will reappear as a “recycled ophiolite”, if any. Any of crustal sequences of ophiolites of which mantle section contain UHP chromitites are not representative of recycled materials. Mantle rocks, which contain recycled materials, have been partially melted to form magmatic crustal rocks in ophiolites or oceanic lithosphere. Constituents of subducted lithosphere are possibly disintegrated during sinking, and may be mixed individually with ambient mantle peridotite to various extents (e.g., Allègre and Turcotte, 1986). This is consistent with the findings of crustal zircons from podiform chromitites (Savelieva et al., 2006, 2007; Yamamoto et al., 2013), which suggests disintegration and partial digestion of subducted crustal materials. These examples suggest that zircons as relics of recycled crustal materials were restored in the mantle and participated in magmatic formation of podiform chromitites at the shallow mantle (Yamamoto et al., 2013). It is noteworthy that this is not at all the case for the UHP chromitites, which have been formed together with surrounding peridotites in the upper mantle and recycled together as a rock suite (chromitite + peridotites) within the mantle. They reappeared as the chromitites (+ surrounding peridotites) that have experienced UHP condition to show UHP mineral features, still preserving basic textural features established at low pressures. The density of the bulk rock suite (chromitite + peridotites) can be low enough, depending on their proportions, to be recycled. Depending on the melting condition, some of the mantle rocks, e.g., very old peridotites recovered from a current mid-ocean ridge (Gakkel ridge) (Liu et al., 2008), did not participate in partial melting beneath a spreading ridge. The UHP chromitites and surrounding peridotites could survive magmatism beneath a ridge, and can be incorporated in newly formed residual and cumulative rocks of the upper mantle.

4.3. Diamond genesis

Very minute diamond inclusions in PGM (Os–Ir alloy) totally included by chromite in a Luobusa chromitite (Yang et al., 2007) can be formed by reduction of CO₂ fluids obtained during the travel of low-P chromitites in the mantle due to the downward decrease of f_{O_2} in the mantle (e.g., Ballhaus, 1995; Frost and McCammon, 2008) (Fig. 2). Inclusions of fluidal carbon species are so common in minerals from mantle-derived peridotites (e.g., Roedder, 1965). Diamonds, if any, can be oxidized easily during upwelling of recycled chromitites, but can survive modification especially when encapsulated in PGM that are further included by chromite (e.g., Yang et al., 2007).

The simple recycling of low-P chromitites that we know is, however, possibly difficult to produce coarse euhedral diamonds enclosed by chromite in UHP chromitites (e.g., Xu et al., 2009;

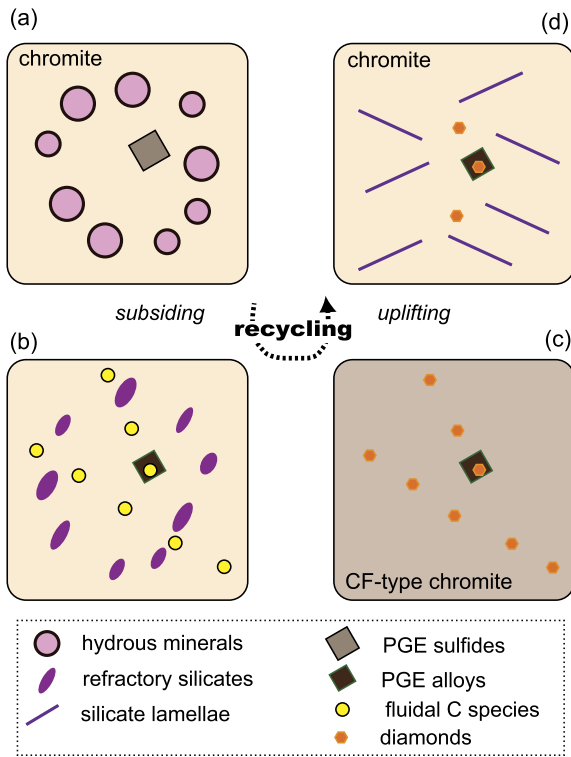


Fig. 2. Possible change of petrographical characteristics of chromite from a low-P chromitite to a UHP chromitite via deep recycling. Low-P igneous chromite with silicate inclusions (a) can be converted to low-P metamorphic chromite with silicate lamellae in UHP chromitites (d) through high-P chromite (b) and a Ca-ferrite (CF) type UHP polymorph of chromite (c) (Yamamoto et al., 2009). Diamond and other C-bearing UHP minerals can be formed by modification of fluidal C species trapped by chromite. Diamonds more easily survive upon decompression when encapsulated by PGE alloys (Yang et al., 2007). Low-P PGE sulfides can be decomposed to PGE alloys and S-rich fluids during deep recycling. See text for details.

Yang et al., 2011). Some unknown diamond-producing process, such as metasomatic addition of an appreciable amount of C-rich fluid (or melt) to chromite may be indispensable.

4.4. Fate of silicate mineral inclusions in chromite

The primary low-P silicate inclusions in chromite in chromitites mainly comprise Na-rich pargasite, pyroxenes and Na-phlogopite (e.g., Augé, 1987; Borisova et al., 2012). The hydrous minerals will be partially melted or broken down when compressed and/or heated during recycling although there have been no experimental results on such Na-rich systems. Depending on P–T path of recycling, they may be ultimately broken down or partially melted to expel fluid/melt outside and leave pyroxenes, especially diopside, (or their high-P polymorphs) (cf. Hollaway, 1973) because the bulk silicate inclusions in spinel are possibly rich in pargasite components (e.g., Augé, 1987; Borisova et al., 2012) (Fig. 1c). The residual pyroxene components will be dissolved in chromite (or in its high-P polymorph(s)), and will reappear as pyroxene lamellae exsolved in chromite (Yamamoto et al., 2009) when decompressed en route to the surface (Fig. 2). Silicate exsolutions in chromite from UHP chromitites (Yamamoto et al., 2009) are thus representative of refractory silicate components ultimately derived from the globular inclusions of hydrous and other silicate minerals, which initially formed magmatically at the uppermost mantle (Fig. 1). This is consistent with our careful observation that chromite grains in UHP chromitites are totally free from the primary globular inclusions of hydrous and other silicates (Miura et al., 2012).

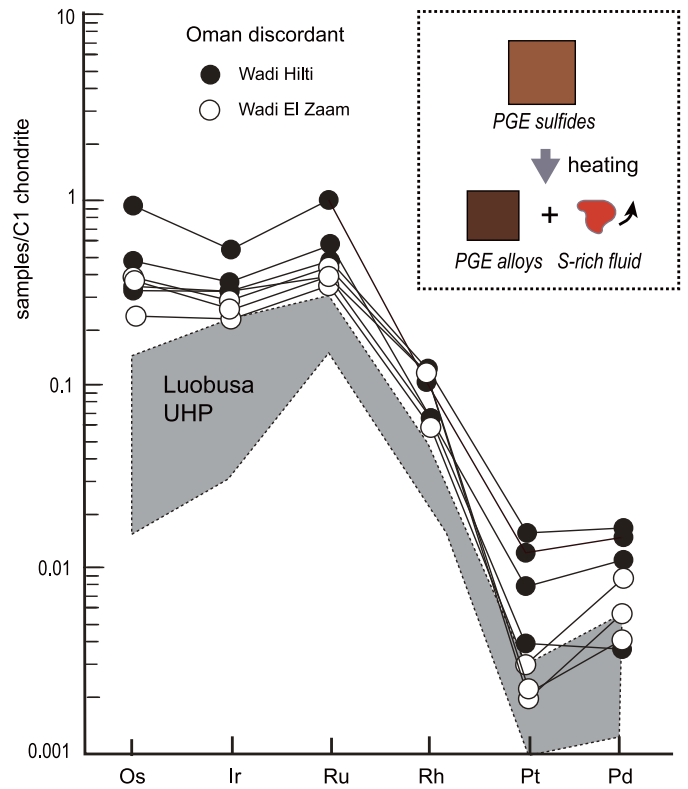


Fig. 3. Chondrite-normalized PGE distribution patterns of the Luobusa UHP chromitites from Tibet in comparison with those for discordant chromitites from the northern Oman ophiolite. Note the relatively low PGE contents, high IPGE/PPGE ratio and no Ir trough on the pattern for the Luobusa UHP chromitites (Zhou et al., 1996) in contrast to the low-P Oman discordant chromitites (Ahmed and Arai, 2002; Ahmed, unpublished). All platinum-group minerals are PGE-bearing alloys for the Luobusa chromitites (Bai et al., 2000), but PGE sulfides and arsenides are predominant in the Oman discordant chromitite (Ahmed and Arai, 2002, 2003). PGE sulfides can be converted to PGE alloys and S-rich fluids, which are mobile and high in PPGE/IPGE ratio (Andrews and Brenan, 2002). See text for discussion.

4.5. Platinum-group elements (PGE) and platinum-group minerals (PGM)

The UHP Luobusa chromitites are characterized by relatively low PGE levels as well as a high IPGE/PPGE ratio (Zhou et al., 1996) (Fig. 3). As stated above, the absence of PGE sulfides (and arsenides) is one of the characteristics of the Luobusa chromitites; only alloys have been found as PGM in them (Bai et al., 2000). These characteristics can be explained by heating of originally low-P chromitites in recycling. Primary igneous PGE sulfides in low-P chromitites are expected to be decomposed to PGE alloys and melts (or fluids), which are S-rich and possibly show a low IPGE/PPGE ratio (e.g., Andrews and Brenan, 2002; Peregoedova et al., 2004). Loss of these fluidal phase(s) outside, which possibly occurs, can give rise to lowering of total PGE levels as well as an increase of IPGE/PPGE ratio of the bulk chromitite. This process leaves only PGE alloys as PGM, which is characteristic of the Luobusa UHP chromitites (Zhou et al., 1996; Bai et al., 2000) (Fig. 3).

There is a small but clear difference in PGE distribution pattern between the Luobusa UHP chromitites (Zhou et al., 1996) and some discordant chromitites from Oman and other ophiolites (Fig. 3). The latter show a clear trough at Ir, which is absent in the former (Fig. 3). This is possibly due to a preference of Ir relative to other PGE for alloys in equilibrium with S-rich melt (Andrews and Brenan, 2002). If we assume decomposition of a PGE sulfide into an alloy + S-rich melt during recycling, the PGE alloy is expected to show an abundance of Ir relative to other PGE (Andrews and

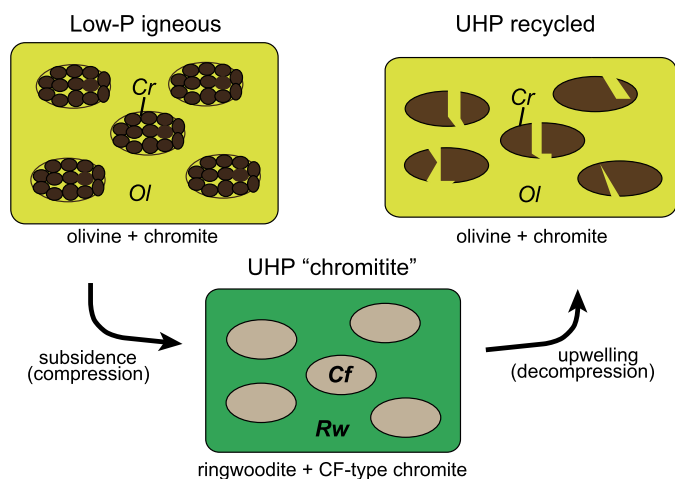


Fig. 4. Possible preservation of an orbicular texture of low-P chromitites during deep recycling down to the transition zone mantle. Olivine and chromite are converted to ringwoodite (e.g., Ita and Stixrude, 1992) and Ca-ferrite type chromite (e.g., Chen et al., 2003; Yamamoto et al., 2009), respectively, when compressed, and reverted to olivine and chromite in UHP chromitites when decompressed. The orbicular texture is possibly preserved through this recycling; chromite grains are loosely packed with interstitial silicates (mainly olivine) in the low-P chromitite, but may be closely packed (possibly single-grained) in UHP ones. Cr, chromite. Ol, olivine. Rw, ringwoodite. Cf, Ca-ferrite type chromite.

Brenan, 2002). The loss of S-rich melt thus produces the Ir trough in PGE distribution pattern for the bulk chromitite (Fig. 3).

4.6. Preservation of igneous textures of chromitites

If deep recycling occurred, the primary igneous textures may have been destroyed through possibly strong physical and chemical modification. Cassard et al. (1981) argued that the peculiar igneous textures, such as nodular, anti-nodular and orbicular textures, are destroyed even during conversion of discordant chromitites to concordant ones, i.e., during transportation of the discordant chromitites off the spreading center, beneath which they were formed in magmatic processes. The process of textural conversion from the discordant chromitite to the concordant one is, however, difficult to observe in the field, especially in the Oman ophiolite, despite the conclusion of Cassard et al. (1981) and Nicolas (1989).

The initial igneous textures have been basically preserved even during deep recycling down to the transition zone mantle, if any, because of the possible absence of reactions between olivine (and its high-P polymorphs) and chromite (and its high-P polymorph) (Fig. 4). For example, chromitites can be converted to a mixture of ringwoodite (or wadsleyite) (e.g., Ringwood, 1991) and CF (calcium ferrite) type chromite (e.g., Chen et al., 2003) with compression, and the ringwoodite–chromite rocks (cf. Robinson et al., 2004) will revert to ordinary chromitites on decompression (Fig. 4). The enveloping dunite may be more ductile than chromitites and easily deformed, and is expected to act as a lubricant to prevent enclosed chromitites from strong deformation during mantle convection, if any. The nodular textures of some UHP chromitites from Luobusa (Zhou et al., 1996; Yamamoto et al., 2009) have been basically preserved from the initial magmatic ones (Fig. 4).

Behavior of chromitites brought to the lower mantle is further unclear. If UHP chromite (or its UHP decomposed equivalents) will not be reacted or solved with ferroperricline and Mg-perovskite, decomposed from ringwoodite (e.g., Wood, 2000; Stachel et al., 2005), some of the primary igneous textures can be preserved when reappearing near the surface. Ferroperricline, however, does contain appreciable amount of Cr (cf. Odake et al., 2008), and we need UHP phase relations in appropriate systems, such as $\text{Mg}_2\text{SiO}_4\text{--MgCr}_2\text{O}_4\text{--SiO}_2$.

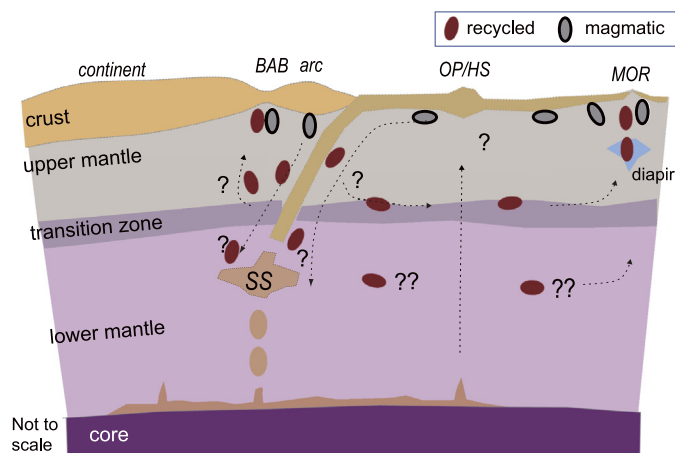


Fig. 5. An illustration for deep recycling of low-P igneous podiform chromitite to form UHP chromitites. Low-P igneous chromitites are possibly converted to UHP chromitites by subsidence via mantle convection. The UHP chromitites appear at a mid-oceanic ridge (MOR) as a part of mantle diapir, of which partial melt can newly produce low-P chromitites via conventional interaction with pre-existing harzburgite (Arai and Yurimoto, 1994). Both the UHP and low-P igneous chromitites can coexist beneath the MOR. Note that sub-arc chromitites can also be recycled through dragging by subducting slab/mantle convection. The recycled chromitite can also appear at the backarc spreading center. BAB, backarc basin. OP/HS, oceanic plateau/hotspot. SS, stagnant slab.

5. Conclusions and further implications

The recycling origin seems to be a very good model at present, explaining some key features of UHP chromitites, although other possibilities cannot be excluded. No other good models have been available from the literature.

The recycled UHP chromitites can coexist with young low-P chromitites at a spreading center because the upper mantle beneath the spreading center can be the very place in that the low-P chromitite forms via peridotite/melt interaction (e.g., Arai and Yurimoto, 1994) and the deep recycled (UHP) chromitites appears via upwelling mantle flow (Fig. 5). This is in accordance with Shi et al. (2007) who reported two types of chromitites in terms of Os isotopic ratio (of model Re–Os isotopic age) from the Luobusa and Dongqiao ophiolites, Tibet, both of which contain UHP chromitites (e.g., Yang et al., 2011). One is possibly of magmatic origin, co-genetic with the ophiolite, and the other could be of deep recycled origin, although Shi et al. (2007) did not refer to the type of their chromitites, UHP or low-P ones. Podiform chromitites should be re-examined in terms of origin in more systematic ways; some of them are possibly deep recycled materials within the mantle. If ringwoodite was included in UHP chromitites as Robinson et al. (2004) suggested (Table 1), the UHP chromitites were originated from the mantle transition zone (e.g., Ringwood, 1991; Ita and Stixrude, 1992; Agee, 1998; Stachel et al., 2005). This seems to support the two-layer mantle convection model (e.g., Courtillot et al., 2003) instead of the whole-mantle convection model (e.g., Maruyama et al., 2007) (Fig. 5). There has been no evidence for that the UHP chromitite has traveled through the lower mantle although the possibility cannot be denied. “Megalith” (stagnant slab materials) may contain former low-P chromitites, which were formed at the Moho transition zone or uppermost mantle, and are possibly mixed with harzburgite (Ringwood, 1991). We should note that the presence of Fe-rich alloys (e.g., Robinson et al., 2004; Xu et al., 2009) in the UHP chromitites does not directly indicate their origin from the core–mantle boundary, because the Fe-rich alloys can exist even in the upper mantle peridotites (e.g., Ishimaru et al., 2009).

Some of the UHP minerals such as diamond and moissanite in chromitites are C-bearing (cf. Robinson et al., 2004), and the UHP chromitites play an important role in global C cycle. Age determination and analysis of P–T trajectory of the UHP chromitites (cf. Yamamoto et al., 2009) are potentially important for our understanding of mantle dynamics; the UHP podiform chromitite can be an indicator of mantle dynamics (Fig. 4). The UHP chromitites can be present beneath the mid-ocean ridge, and available through ultra-deep mantle drilling on the ocean floor. They can be one of important targets for the coming MoHole project.

Acknowledgements

I thank Y. Tatsumi, P.T. Robinson, S. Yamamoto, A.H. Ahmed, S.K. Mondal and M. Miura for their discussions. A.H. Ahmed kindly provided me with unpublished data on some of bulk PGE contents of Oman chromitites. M. Miura helped me to prepare some of the figures. I am grateful to P.T. Robinson and an anonymous reviewer for their critical comments, which greatly helped me in revision.

References

- Abe, N., 2011. Petrology of podiform chromitite from the ocean floor at the 15°20'N FZ in the MAR, Site 1271, ODP Leg 209. *J. Mineral. Petrol. Sci.* 106, 97–102.
- Agee, C.B., 1998. Phase transformation and seismic structure in the upper mantle and transition zone. *Rev. Mineral.* 37, 165–203.
- Ahmed, A.H., Arai, S., 2002. Unexpectedly high-PGE chromitite from the deeper mantle section of the northern Oman ophiolite and its tectonic implications. *Contrib. Mineral. Petrol.* 143, 263–278.
- Ahmed, A.H., Arai, S., 2003. Platinum-group minerals in podiform chromitites of the Oman ophiolite. *Can. Mineral.* 41, 597–616.
- Allègre, C.J., Turcotte, D.L., 1986. Implications of a two-component marble-cake mantle. *Nature* 323, 123–127.
- Andrews, D.R.A., Brenan, J.M., 2002. The solubility of ruthenium in sulfide liquid: implications for platinum group mineral stability and sulfide melt–silicate melt partitioning. *Chem. Geol.* 192, 163–181.
- Arai, S., 1997. Control of wall-rock composition on the formation of podiform chromitites as a result of magma/peridotite interaction. *Resour. Geol.* 47, 177–187.
- Arai, S., 2010. Possible recycled origin for ultrahigh-pressure chromitites in ophiolites. *J. Petrol. Mineral. Sci.* 105, 280–285.
- Arai, S., Matsukage, K., 1998. Petrology of a chromitite micropod from Hess Deep, equatorial Pacific: A comparison between the abyssal and alpine-type podiform chromitites. *Lithos* 43, 1–14.
- Arai, S., Yurimoto, H., 1994. Podiform chromitites of the Tari-Misaka ultramafic complex, southwestern Japan, as mantle–melt interaction products. *Econ. Geol.* 89, 1279–1288.
- Augé, T., 1987. Chromite deposits in the northern Oman ophiolite: Mineralogical constraints. *Miner. Depos.* 22, 1–10.
- Bai, W., Robinson, P.T., Fang, Q., Yang, J., Yan, B., Zhang, Z., Zhou, M.-F., Malpas, J., 2000. The PGE and base-metal alloys in the podiform chromitites of the Luobasa ophiolite, southern Tibet. *Can. Mineral.* 38, 585–598.
- Ballhaus, C., 1995. Is the upper mantle metal-saturated? *Earth Planet. Sci. Lett.* 132, 75–86.
- Borisova, A., Ceuleneer, G., Kamenetsky, V., Arai, S., Bějina, F., Bindeman, I., Polvé, M., de Parseval, P., Aigouy, T., Pokrovski, G., 2012. A new view on the petrogenesis of the Oman ophiolite chromitites from microanalyses of chromite-hosted inclusions. *J. Petrol.* 53, 2411–2440.
- Cassard, D., Nicolas, A., Rabinovitch, M., Moutte, J., Leblanc, M., Prinzhofer, A., 1981. Structural classification of chromite pods in southern New Caledonia. *Econ. Geol.* 76, 805–831.
- Chen, M., Shu, J., Mao, H.-K., Xie, X., Hemley, R.J., 2003. Natural occurrence and synthesis of two new postspinel polymorphs of chromite. *Proc. Natl. Acad. Sci. USA* 100, 14651–14654.
- Courtillot, V., Davaille, A., Besse, J., Stock, J., 2003. Three distinct types of hotspots in the Earth's mantle. *Earth Planet. Sci. Lett.* 205, 295–308.
- Dobrzhinetskaya, L., Wirth, R., Yang, J.-S., Hutcheon, I., Weber, P., Green, H.W., 2009. High pressure highly reduced nitrides and oxides from chromite of a Tibetan ophiolite. *Proc. Natl. Acad. Sci. USA* 106, 19233–19238.
- Frost, D.J., 2006. The stability of hydrous mantle phases. *Rev. Mineral. Geochem.* 62, 243–271.
- Frost, D.J., McCammon, C.A., 2008. The redox state of Earth's mantle. *Annu. Rev. Earth Planet. Sci.* 36, 389–420.
- Hollaway, J.R., 1973. The system pargasite–H₂O–CO₂: a model for melting of a hydrous mineral with a mixed-volatile fluid – I. Experimental results to 8 kbar. *Geochim. Cosmochim. Acta* 37, 651–666.
- Ishimaru, S., Arai, S., Shukuno, H., 2009. Metal-saturated peridotite in the mantle wedge inferred from metal-bearing peridotite xenoliths from Avacha volcano, Kamchatka. *Earth Planet. Sci. Lett.* 284, 352–360.
- Ita, J., Stixrude, L., 1992. Petrology, elasticity, and composition of the mantle transition zone. *J. Geophys. Res.* 97, 6849–6866.
- Kelemen, P.B., Joyce, D.B., Webster, J.D., Holloway, J.R., 1990. Reaction between ultramafic rock and fractionating basaltic magma II. Experimental investigation of reaction between olivine tholeiite and harzburgite at 1150–1050 °C and 5 kb. *J. Petrol.* 31, 99–134.
- Kushiro, I., 1969. The system forsterite–diopsidesilica with and without water at high pressures. *Am. J. Sci.* 267–A, 269–294.
- Lago, B.L., Rabinowicz, M., Nicolas, A., 1982. Podiform chromitite ore bodies: a genetic model. *J. Petrol.* 23, 103–125.
- Liu, C.-Z., Snow, J.E., Hellebrand, E., Brüggemann, G., von der Handt, A., Büchl, A., Hofmann, A.W., 2008. Ancient, highly heterogeneous mantle beneath Gakkel ridge, Arctic Ocean. *Nature* 452, 311–315.
- Lorand, J.P., Ceuleneer, G., 1989. Silicate and base-metal sulfide inclusions in chromites from the Maqсад area (Oman ophiolite, Gulf of Oman): A model for entrapment. *Lithos* 22, 173–190.
- Maruyama, S., Santosh, M., Zhao, D., 2007. Superplume, supercontinent, and post-perovskite: Mantle dynamics and anti-plate tectonics on the core–mantle boundary. *Gondwana Res.* 11, 7–37.
- Miura, M., Arai, S., Ahmed, A.H., Mizukami, M., Okuno, M., Yamamoto, S., 2012. Podiform chromitite classification revisited: a comparison of discordant and concordant chromitite pods from Wadi Hilti, northern Oman ophiolite. *J. Asian Earth Sci.* 59, 52–61.
- Morishita, T., Arai, S., Gervilla, F., Green, D.H., 2003. Closed-system geochemical recycling of crustal materials in alpine-type peridotite. *Geochim. Cosmochim. Acta* 67, 303–310.
- Nicolas, A., 1989. Structures of Ophiolites and Dynamics of Oceanic Lithosphere. Kluwer Academic Publishers, Dordrecht.
- Niida, K., Green, D.H., 1999. Stability and chemical composition of pargasitic amphibole in MORB pyrolyte under upper mantle conditions. *Contrib. Mineral. Petrol.* 135, 18–40.
- Noller, J.S., Carter, B., 1986. The origin of various types of chromite schlieren in the Trinity Peridotite, Klamath Mountains, California. In: Carter, B., Chowdhury, M.K.R., Jankovic, S., Marakushev, A.A., Morten, L., Onikhimovsky, V.V., Raade, G., Rocci, G., Augustithis, S.S. (Eds.), *Metallogeny of Basic and Ultrabasic Rocks (Regional Presentations)*. Theophrastus, Athens, pp. 151–178.
- Odake, S., Fukura, S., Arakawa, M., Ohta, A., Harte, B., Kagi, H., 2008. Divalent chromium in ferropericase inclusions in lower-mantle diamonds revealed by micro-XANES measurements. *J. Mineral. Petrol. Sci.* 103, 350–353.
- Peregoedova, A., Barnes, S.-J., Baker, D.R., 2004. The formation of Pt–Ir alloys and Cu–Pd-rich sulfide melts by partial desulfurization of Fe–Ni–Cu sulfides: results of experiments and implications for natural systems. *Chem. Geol.* 208, 247–264.
- Quick, J.E., 1981. The origin and significance of large, tabular dunite bodies in the Trinity peridotite, northern California. *Contrib. Mineral. Petrol.* 78, 413–422.
- Ringwood, A.E., 1975. *Composition and Petrology of Earth's Upper Mantle*. McGraw-Hill, London.
- Ringwood, A.E., 1991. Phase transformations and their bearing on the constitution and dynamics of the mantle. *Geochim. Cosmochim. Acta* 55, 2083–2110.
- Robinson, P.T., Bai, W.-J., Malpas, J., Yang, J.-S., Zhou, M.F., Fang, Q.-S., Hu, X.-F., Cameron, S., Staudigel, H., 2004. Ultra-high pressure minerals in the Luobasa Ophiolite, Tibet, and their tectonic implications. In: Malpas, J., Fletcher, C.J.N., Ali, J.R., Aitchison, J.C. (Eds.), *Aspects of the Tectonic Evolution of China*. J. Geol. Soc. Special Publication 226, 247–271.
- Roedder, E., 1965. Liquid CO₂ inclusions in olivine-bearing nodules and phenocrysts from basalts. *Am. Mineral.* 50, 1746–1782.
- Roedder, E., 1984. *Fluid Inclusions*. Rev. Mineral., vol. 12. Mineralogical Society of America, Washington, DC.
- Ruskov, T., Spirov, I., Georgieva, M., Yamamoto, S., Green, H.W., McCammon, C.A., Dobrzhinetskaya, L.F., 2010. Mossbauer spectroscopy studies of the valence state of iron in chromite from the Luobasa massif of Tibet: implications for a highly reduced deep mantle. *J. Metamorph. Geol.* 28, 551–560.
- Savelieva, G.N., Suslov, P.V., Larionov, A.N., Berezhnaya, N.G., 2006. Age of zircons from chromitites in the residual ophiolitic rocks as a reflection of upper mantle magmatic events. *Dokl. Earth Sci.* 411A, 1401–1406.
- Savelieva, G.N., Suslov, P.V., Larionov, A.N., 2007. Vendian tectono-magmatic events in mantle ophiolitic complexes of the Polar Urals: U–Pb dating of zircon from chromitite. *Geotectonics* 41, 105–133.
- Shi, R., Alard, O., Zhi, X., O'Reilly, S.Y., Pearson, N.J., Griffin, W.L., Zhang, M., Chen, X., 2007. Multiple events in the Neo-Tethyan oceanic upper mantle: Evidence from Ru–Os–Ir alloys in the Luobasa and Dongqiao ophiolitic podiform chromitites, Tibet. *Earth Planet. Sci. Lett.* 261, 33–48.
- Stachel, T., Brey, G.P., Harris, J.W., 2005. Inclusions in sublithospheric diamonds: Glimpses of deep earth. *Elements* 1, 73–78.

- Wood, B.J., 2000. Phase transformations and partitioning relations in peridotite under lower mantle conditions. *Earth Planet. Sci. Lett.* 174, 341–354.
- Xu, X., Yang, J., Fang, Z., Bai, W., Ba, D., 2009. Unusual mantle mineral group from chromitite orebody Cr-11 in Luobusa ophiolite of Yarlung-Zangbo Suture Zone, Tibet. *J. Earth Sci.* 20, 284–301.
- Xu, X., Yang, J., Ba, D., Guo, G., Robinson, P.T., Li, J., 2011. Petrogenesis of the Kangjinla peridotite in the Luobusa ophiolite, Southern Tibet. *J. Asian Earth Sci.* 42, 553–568.
- Yamamoto, S., Komiya, T., Hirose, K., Maruyama, S., 2009. Coesite and clinopyroxene exsolution lamellae in chromites: In-situ ultrahigh-pressure evidence from podiform chromites in the Luobusa ophiolite, southern Tibet. *Lithos* 109, 314–322.
- Yamamoto, S., Komiya, T., Yamamoto, H., Kaneko, Y., Terabayashi, M., Katayama, I., Iizuka, T., Maruyama, S., Yang, J., Kon, Y., Hirata, T., 2013. Recycled crustal zircons from podiform chromites in the Luobusa ophiolite, southern Tibet. *Isl. Arc* 22, 89–103.
- Yang, J.-S., Dobrzynetskaia, L., Bai, W.-J., Fang, Q.-S., Robinson, P.T., Zhang, J., Green II, H.W., 2007. Diamond- and coesite-bearing chromites from the Luobusa ophiolite, Tibet. *Geology* 35, 875–878.
- Yang, J., Xu, X., Li, Y., Liu, Z., Li, J., Ba, D., Robinson, P.T., 2011. Diamond discovered from six different ultramafic massifs along the Yarlung Zangbu Suture between the Indian and Eurasian plates. In: *Geol. Soc. Am., Annual Meet. Minneapolis*, pp. 203–204.
- Zhou, M.-F., Robinson, P., Bai, W.-J., 1994. Formation of podiform chromites by melt/rock interaction in the upper mantle. *Miner. Depos.* 29, 98–101.
- Zhou, M.-F., Robinson, P.T., Malpas, J., Li, Z., 1996. Podiform chromites in the Luobusa ophiolite (southern Tibet); Implications for melt–rock interaction and chromite segregation in the upper mantle. *J. Petrol.* 37, 3–21.
- Zhou, M.-F., Robinson, P.T., Malpas, J., Edwards, S.J., Qi, L., 2005. REE and PGE geochemical constraints on the formation of dunites in the Luobusa ophiolite, southern Tibet. *J. Petrol.* 46, 615–639.