

## Article

# Genetic Link between Podiform Chromitites in the Mantle and Stratiform Chromitites in the Crust: A Hypothesis

Shoji Arai Kanazawa University, Kanazawa 920-1192, Japan; [ultrasa@staff.kanazawa-u.ac.jp](mailto:ultrasa@staff.kanazawa-u.ac.jp)

**Abstract:** No genetic link between the two main types of chromitite, stratiform and podiform chromitites, has ever been discussed. These two types of chromitite have very different geological contexts; the stratiform one is a member of layered intrusions, representing fossil magma chambers, in the crust, and the podiform one forms pod-like bodies, representing fossil magma conduits, in the upper mantle. Chromite grains contain peculiar polymineralic inclusions derived from Na-bearing hydrous melts, whose features are so similar between the two types that they may form in a similar fashion. The origin of the chromite-hosted inclusions in chromitites has been controversial but left unclear. The chromite-hosted inclusions also characterize the products of the peridotite–melt reaction or melt-assisted partial melting, such as dunites, troctolites and even mantle harzburgites. I propose a common origin for the inclusion-bearing chromites, i.e., a reaction between the mantle peridotite and magma. Some of the chromite grains in the stratiform chromitite originally formed in the mantle through the peridotite–magma reaction, possibly as loose-packed young podiform chromitites, and were subsequently disintegrated and transported to a crustal magma chamber as suspended grains. It is noted, however, that the podiform chromitites left in the mantle beneath the layered intrusions are different from most of the podiform chromitites now exposed in the ophiolites.



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**Keywords:** chromite-hosted inclusions; peridotite–melt reaction; stratiform chromitite; podiform chromitite; genetic link

## 1. Introduction

We have a consensus that chromitites (chromite-rich rocks) can be divided into two main types, stratiform chromitites in the crust and podiform chromitites in the mantle [1]. The former chromitites occur as laterally continuous layers together with ultramafic or mafic cumulative rocks within layered intrusions (=fossil magma chambers) in the crust [2]. In contrast, the latter form pod-like bodies closely associated with dunite within the mantle peridotite (harzburgite) [3,4], as one of the mantle peridotite–magma reaction products [5–7]. Those two types of chromitite are quite different in many aspects with each other, and have been studied by different scientist communities. As far as I know, no paper has aimed to discuss the genetic linkages between them. I attempt for the first time to link together the generations of the crustal stratiform chromitite and the mantle podiform chromitite in this article. Note that this work aims not to present detailed petrological and chemical data for individual rocks or complexes, which are available from the literature or will be published elsewhere, but to propose a model for the genetic linkage between the two types of chromitites. This work will promote further discussion on the origin and generation of chromitites.

## 2. Stratiform Chromitites vs. Podiform Chromitites: Their Differences and Similarities

The stratiform chromitites are typically a member of the Archean to Proterozoic layered intrusions [8,9] or sill-like ultramafic–mafic intrusions in Archean greenstone belts [10]. They are associated with peridotites, pyroxenites, gabbros and anorthosites,

and show various sediment-like structures, indicating their accumulation origin from magmas that filled a crustal magma reservoir. Irvine [11] proposed that the chromite-oversaturated magmas responsible for precipitation of the stratiform chromitites were produced by mixing of a silica-rich magma with a main mafic magma. The silica-rich magma is a partial melt of wall crustal rocks [12,13] or a differentiate of a primitive magma in the reservoir [11]. Recently, Latypov et al. [14] argued for the importance of a pressure reduction for production of the chromite-oversaturated magma that precipitate the stratiform chromitite (see Schulte et al. [2] for more details about stratiform chromitite).

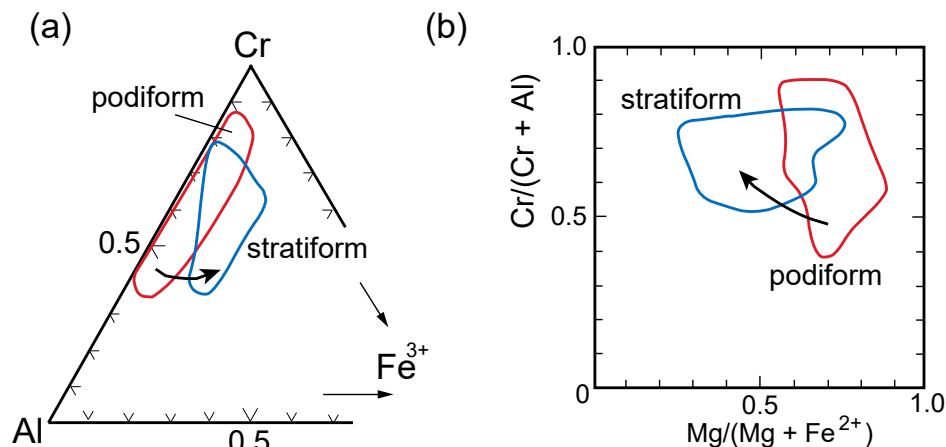
The podiform chromitites are typically a member of the ophiolites, especially of their mantle section or Moho transition zone. They are enveloped by dunite [4] within harzburgites [7,15]. Some chromitite pods are concordant, and others are discordant, to the foliation of the surrounding harzburgite [4,16]. The chromitite pods possibly formed as cumulates, filling magma conduits, in the upper mantle harzburgite [17]. The chromite-oversaturated magma basically forms through mixing of a relatively silica-rich magma with a primitive magma in the conduit [5,18]. The silica-rich magma is one of the products of the reaction between the wall harzburgite and a primitive olivine-oversaturated magma moving upward in the conduit. The dunite envelope is another product of the reaction that is essentially the breakdown of orthopyroxene (=to olivine and a silica-oversaturated melt) combined with olivine precipitation. Barren dunites are left as dike-like bodies if the collection of Cr by melt only occurs in the mantle peridotite [18]. The dunites with or without chromite concentrations thus represent trails of the magmas that were channeled upward in the mantle, and ultimately supplied to the crust (see Arai and Miura [18] for more details about podiform chromitite).

Chromite compositions are similar but slightly different between the podiform and stratiform chromitites [19,20] (Figure 1). The Cr# (= Cr/(Cr + Al) atomic ratio) of chromite is not so different; 0.4 to 0.9 for the podiform chromitite, and 0.5 to 0.8 for the stratiform one. The Fe contents are different between the two types; the Mg# (= Mg/(Mg + Fe<sup>2+</sup>) atomic ratio) is lower on average in the stratiform chromitites than in the podiform ones (Figure 1). Chromites show a very low and limited range of the Fe<sup>3+</sup> ratio (Fe<sup>3+</sup>/(Cr + Al + Fe<sup>3+</sup>) atomic ratio; <0.1) for the podiform chromitites. The Fe<sup>3+</sup> ratio (<0.3) of chromite is negatively correlated with the Cr# in the stratiform chromitites (Figure 1). The podiform and the stratiform chromitites are different in PGE (platinum-group elements) and PGM (platinum-group minerals) content. Most of the podiform chromitites show enrichment in IPGE (iridium-group PGE; Os, Ir and Ru) relative to PPGE (palladium-group PGE; Rh, Pt and Pd), while the stratiform chromitites are enriched in PPGE relative to IPGE [21,22]. The PPGE enrichment is prominent in chromitites from higher stratigraphic levels, especially in the silicate-rich matrix [23,24]. However, their chromite grains show some similarities to each other: chromite grains in podiform chromitites are characterized by inclusions of IPGM (iridium-group PGM), especially laurite [25], and some of stratiform chromitites contain laurite-bearing chromite [24,26].

The two types of chromitite that we can observe now are different in age [20,27]. The podiform chromitites mostly show the Late Proterozoic to Phanerozoic ages, and are very rarely of the Archean to Early Proterozoic [20,27–29]. In contrast, the stratiform chromitites, especially large-scale ones, are of the Archean to Proterozoic ages [27]. Therefore, most of the currently exposed podiform chromitites do not have direct genetic connections with most of the stratiform chromitites.

Various kinds of magma are involved in formation of ophiolites [30], although the subduction-related arc-type and/or MORB (mid-ocean ridge basalt)-like magmas are mainly responsible for production of major ophiolites [30,31]. The most common podiform chromitite that contains high-Cr# (0.7–0.9) chromites was in equilibrium with arc magmas, especially the boninitic ones [32–34]. Others, which contain moderate-Cr# (~0.5) chromite, were possibly formed in relation to the activity of MORB or MORB-like magmas [16,35–37]. The layered intrusions are characterized by their large sizes, sometimes forming the main part of LIPs (large igneous provinces) [38]. Stratiform chromitite is also characterized by

its large volume as compared with the podiform one [2,27]. The chemistry of the magma involved in formation of the layered intrusions (i.e., the stratiform chromitite) varies from picritic to boninitic [39].



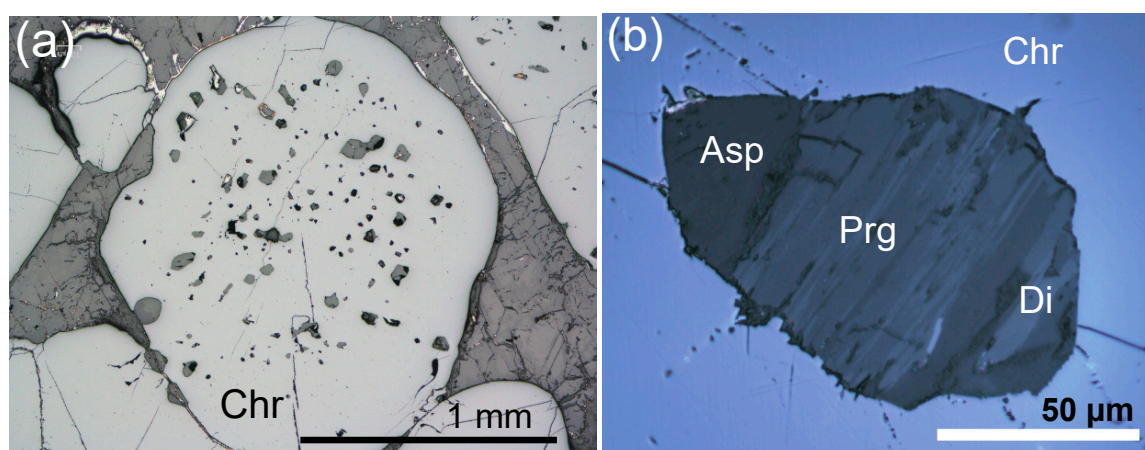
**Figure 1.** Chemical characteristics of chromites in stratiform and podiform chromitites. (a) The trivalent cation (Cr-Al-Fe<sup>3+</sup>) ratios in an atom. (b) Relations between Mg/(Mg + Fe<sup>2+</sup>) and Cr/(Cr + Al) in an atom. Data compilation by Arai and Miura [18] and Arai and Ahmed [20]. Arrows indicate possible modification of the chromite compositions during solidification of magmas in the crustal magma chamber in the model discussed below. See the text for more details.

### 3. Chromite-Hosted Polyminerale Inclusions: A Remarkable Similarity between the Two Types of Chromitite

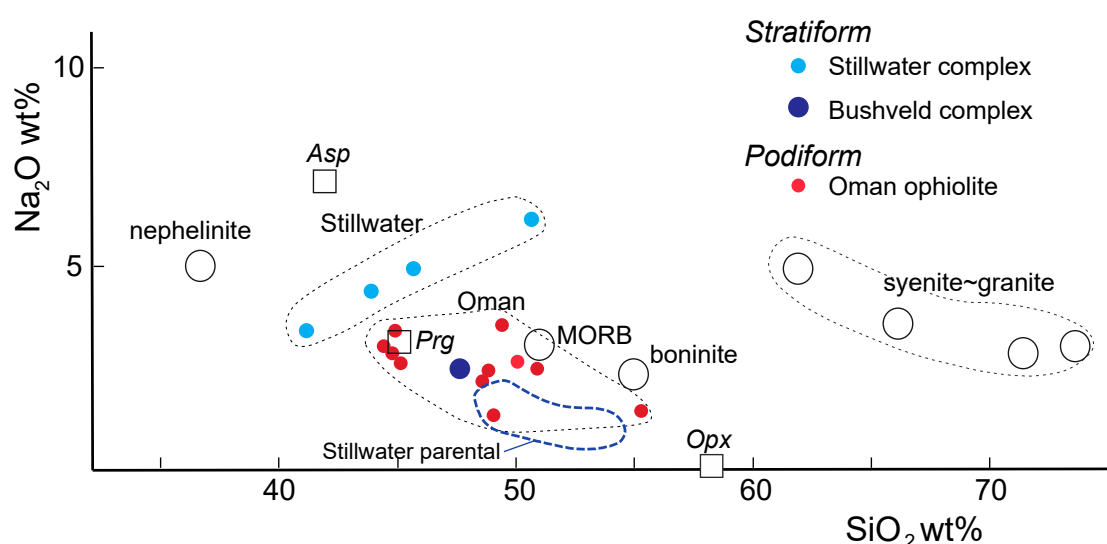
Among various solid inclusions in chromite from chromitites [40–42], the polyminerale inclusions characterized by hydrous, Na-rich minerals are noteworthy. They occur in various types of chromitites and are similar in mineral assemblage and chemistry (Figure 2) [43]. The inclusions are globular in shape and typically 100 microns across or less, and show even or concentric distributions in individual chromite grains (Figure 2). The chromite-hosted inclusions of this type are very common in podiform chromitites from ophiolites [16,44–48]. The chromitite pod found from the Pacific Ocean also contains chromite with abundant solid inclusions of this type [35,49]. They also have been reported from layered intrusions [12,43], including the two famous large chromitite-producing layered intrusions, the Bushveld and Stillwater complexes [13,50–52]. The mineral assemblage of this type of inclusions is varied but the main minerals are pyroxenes (enstatite and diopside), micas (aspidolite and phlogopite) and amphiboles (mainly pargasite), some of which are Na-rich and hydrous (Figure 2). The aspidolite (=Na analogue of phlogopite) especially characterizes the chromite-hosted inclusions [18]; it is very common as an inclusion mineral in chromite but has not been found both in the silicate matrix of chromitites and in surrounding peridotites [53].

The polyminerale inclusions are probably of primary origin because of their concentric or even distribution within the host chromite grains (Figure 2). They have been interpreted as the melts trapped by chromite when crystallizing from magmas based on their globular shapes [12,13,47,52,54].

The chromite-hosted polyminerale inclusions are variable in bulk chemistry; the Na<sub>2</sub>O and SiO<sub>2</sub> contents vary from 1 to 6 wt% and 41 to 55 wt%, respectively, even from the same locality [13,47,52,55] (Figure 3). The origin of the trapped melt has not been well interpreted and we have not reached a consensus on its origin.



**Figure 2.** Polymineralic silicate inclusions in a discordant podiform chromitite chromite in wadi Hilti, the northern Oman ophiolite. See Miura et al. [16] for detailed petrological descriptions of this chromitite pod. Chr, chromite; Asp, aspidolite; Prg, pargasite; Di, diopside clinopyroxene. (a) Photomicrograph of the Hilti chromitite by reflected light. Note the central chromite grain, where inclusions are distributed evenly or concentrically. (b) Back-scattered electron image of an inclusion. Note their hydrous and Na-rich character.

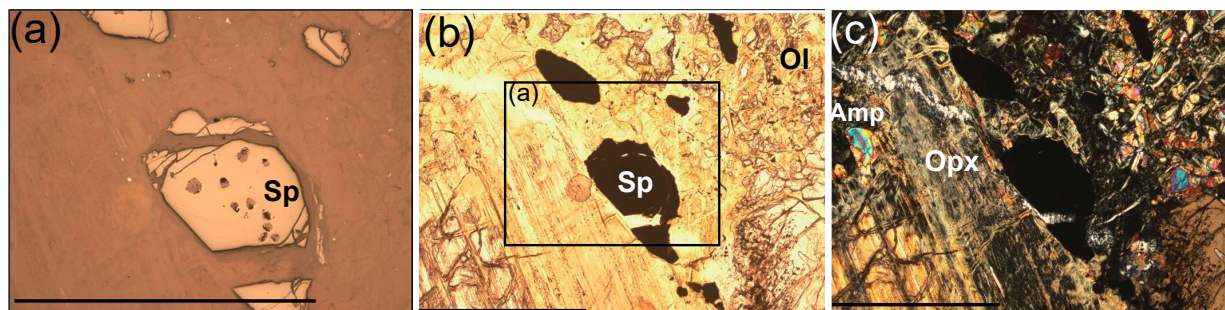


**Figure 3.**  $\text{Na}_2\text{O}$ – $\text{SiO}_2$  relations of the bulk compositions of the chromite-hosted inclusions and some representative magmas. The bulk compositions of the chromite-hosted inclusions in the chromitites were determined by homogenization experiments for the Stillwater layered intrusion [13] and for the Oman ophiolite [47,55]. An averaged composition of inclusions was calculated for the Bushveld layered intrusion [52]. The compositions of a nephelinite [56], an averaged mid-ocean ridge basalt (MORB) [57], an averaged Hawaiian tholeiite (TH) [58], boninites [59] and granites–syenites [60] are shown for comparison. The range for possible parental magmas to the Stillwater complex [61] is also shown.

We note that the similar chromite-hosted hydrous silicate inclusions have been also found in dunites, troctolites and some harzburgites drilled from the East Pacific Rise and the Mid-Atlantic Ridge [62–64]. Those rocks were produced through reaction between mantle harzburgite and MORB magma [62–64]. The abyssal podiform chromitite has been interpreted as one of the products of the same kind of MORB–harzburgite reaction [35,62,65]. In addition, the chromite-hosted inclusions of the same type were found in mantle harzburgites from the Circum-Izu Massif Serpentine Belt (CIMB), central Japan (Figure 4) [66]. The inclusions are composed of pargasite, phlogopite, aspidolite and pyroxenes. The CIMB harzburgites have frequently suffered from plagioclase impregnation and hydration (formation of amphiboles and phlogopite) [66]. Ishimaru and Arai [67] reported silicic



hydrous melt (glass) inclusions in chromites from metasomatized harzburgite xenoliths from Avacha volcano, Kamchatka. The chromite-hosted melt inclusions from Avacha xenoliths (Figure 2 of [67]) are rich in  $\text{Na}_2\text{O}$  (mostly  $> 3$  wt%) and show some resemblance in chemistry to the other poly-phase silicate inclusions in chromite.



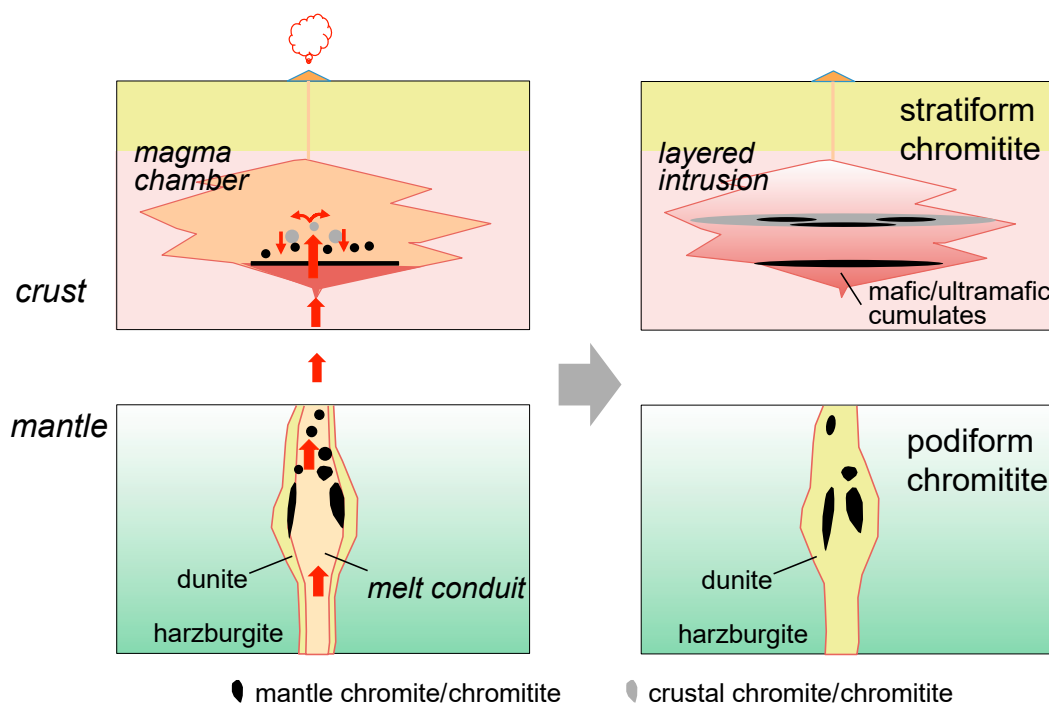
**Figure 4.** Photomicrographs of chromite-hosted silicate inclusions in a metasomatized harzburgite from the Circum-Izu Massif Serpentine Belt (Setogawa, Shizuoka, Japan). (a) Chromite containing globular silicate inclusions. Reflected light. (b) Harzburgite. The position of panel (a) is shown. Plane-polarized light. (c) Crossed polarized light. Sp, chromite; Opx, partially serpentinized orthopyroxene; Ol, serpentinized olivine; Amp, pargasite. Scale bar, 1 mm.

#### 4. Discussion: A Possible Link between the Stratiform and Podiform Chromitites

The chromite grains that are produced by the peridotite–melt reaction (olivine precipitation associated with orthopyroxene breakdown) trap chemically heterogeneous melts, of which chemical variations are due to various melt/rock ratios during the reaction [63,64]. The strong chemical gradient observed in the melt produced by the orthopyroxene–melt reaction [68] may also contribute to the drop-to-drop chemical heterogeneity of the included melt (Figure 3). The enrichment of  $\text{H}_2\text{O}$  and other incompatible components in the inclusions is due to the effect of zone refining during the reaction process [69]. A reaction with hydrated peridotites also possibly contributes to the gain of  $\text{H}_2\text{O}$  and incompatible components for the reacted magma [47].

The CIMSB (Circum-Izu Massif Serpentine Belt) harzburgite, which contains spinel-hosted inclusions (Figure 4), is possibly a restite produced by melt-assisted partial melting or the peridotite–melt interaction in the uppermost mantle. The close association of plagioclase-bearing harzburgite indicates the derivation of the CIMSB peridotites from the low-pressure ( $<1$  GPa) mantle [66]. The shallowest oceanic mantle just beneath Moho is composed of residual harzburgites after the melt-assisted partial melting or peridotite–melt interaction [70,71]. Dissolution of orthopyroxene is one of the essential processes in such a partial melting or peridotite–melt interaction at low pressures [62,63,72]. The chromian spinel, which includes polymineralic globules (Figure 4), is one of the residual phases after such melting or melt–peridotite interaction processes.

The chromite-hosted melt inclusions from podiform chromitites are most probably produced at the stage of the peridotite–melt reaction, although the exact mechanism for entrapment of the melt by chromite has been left unknown [7]. I propose that the chromite-hosted melt inclusions from stratiform chromitites originally formed in the mantle through the peridotite–melt reaction [35,62–64]. The chromite grains that contain the melt inclusions possibly formed young podiform chromitites along the mantle conduit, and were disintegrated and transported as suspended grains by the subsequently supplied magma up to a lower crustal magma chamber (Figure 5). The chromite-hosted melt inclusions from the Stillwater complex [13] can be hardly explained by mixing of a possible parental magma [61] and granitic melts (Figure 3).



**Figure 5.** Cartoon to indicate a possible linkage of the crustal stratiform chromitite to the mantle podiform chromitite. Young chromitites generated along a magma conduit (=the podiform chromitite) in the mantle were disintegrated by the subsequently supplied magma and transported as suspended chromite grains up to a crustal magma chamber. They were ultimately re-precipitated and contributed to form part of the stratiform chromitite.

The chromite grains of mantle origin contain iridium-group PGM (platinum-group minerals), especially laurite [24,25]. They were precipitated as part of a stratiform chromitite with slight chemical modification (mainly Fe enrichment) during subsequent magmatic differentiation within the magma chamber (Figure 5). The enrichment in palladium-group PGE (platinum-group elements) and palladium-group PGM in the stratiform chromitites is due to fractionation or assimilation during or after emplacement of the involved magma in the crust [23,24]. The peculiar chemistry of the trapped melts was maintained despite the change in chromite chemistry (cf. [73,74]).

This idea is consistent with the conclusions of Eales [75] and Mondal and Mathez [9], in that the magmas supplied to the crustal magma chamber (=the Bushveld complex) were charged with excess chromite grains. This chromite-laden magma was the mixture of primitive magma and chromites disintegrated from the mantle podiform chromitite in this model.

Magmas moving upward in the mantle may react with the surrounding peridotites, irrespective of chemistry and tectonic setting [62,76,77]. Note that the podiform chromitites that are consanguineous with the layered intrusions have not been exposed, and the podiform chromitites now exposed are genetically related to the upsection of small-scale stratiform chromitites (cf. [20,78]). Any magma can form podiform chromitites in the mantle because the peridotite–melt reaction and magma mixing may commonly occur in the mantle [18]. There is possibly high-Cr# podiform chromitite in the mantle through which magmas were supplied to form the layered intrusions [18].

## 5. Conclusions and Implications

The chromite grains that contain polymineralic inclusions (=trapped melt) are common to the podiform and stratiform chromitites and were formed in the mantle through the peridotite–melt reaction. I propose that the chromite grains in the stratiform chromitite, in part, had once experienced a precursor stage as podiform chromitite in the upper mantle.

What I would like to argue for here is some genetic link between the podiform chromitite produced in the mantle and the stratiform one in the crust; some of the chromite grains in the latter are possibly precipitated in the mantle prior to the entrainment by magma to the crust. Many factors for the formation of chromite-oversaturated magmas in the crust have been proposed, such as compression of magmas due to vesiculation [79], an increase in oxygen fugacity [8,80], assimilation of Fe-oxide-rich rocks [81,82] and decompression of magmas [14], reflecting the various geologic and petrologic contexts of the host's layered intrusions.

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