We used high-resolution X-ray computed tomography (HRXCT) combined with scanning electron microscopy (SEM) to obtain 3D and 2D images of multiphase solid inclusions within chromite from the Samail ophiolite to investigate post-entrapment modification of the inclusions. Results indicate that the parental melt of the chromitite was supersaturated in chromian spinel. Chromite continued to crystallize on the inner wall of the host chromite after the melt was trapped. Rapid growth caused crystallization of high-Cr# chromite lining around inclusions. The necking-down of originally large melt inclusions probably produced various assemblages of daughter minerals among the inclusions. We report two observations that are consistent with rapid growth of the host chromite: the 3D distribution of inclusions in host chromite and the host chromite showing skeletal morphology. High-temperature homogenization experiment was conducted to obtain the parental melt composition of the inclusions. We found that the homogenized glass does not represent the parental melt trapped in the host chromite because of the remaining of high-Cr# chromite lining and possible residual phases in the experiments.

Keywords: Chromitite, Melt inclusion, High-Cr# chromite lining, Samail ophiolite, Oman Drilling Project

INTRODUCTION

Melt inclusions have the potential to provide important information on the primary melt that have crystallized host minerals, including the chemical composition of the melt and the pressure and temperature conditions of the entrapment (Roedder, 1979; Frezzotti, 2001; Danyushevsky et al., 2002). After the melt inclusions are captured, they can be regarded as closed or isolated systems, together with the host minerals. Upon cooling, the melt inclusions will turn into multiphase solid inclusions (MSIs), which can be regarded as time capsules that store the information regarding the physical and chemical evolution of the system since the time of entrapment. In addition, by examining the compositions of multiple melt inclusions, it may be possible to deduce the liquid line of descent of the trapped magmas (Cannatelli et al., 2016).

Multiphase solid inclusions in chromite (chromium-rich spinel) are common and have been reported from podiform chromitite (Schiano et al., 1997; Borisova et al., 2012; Akmaz et al., 2014; Rollinson and Adetunji, 2015; Khedr and Arai, 2016; Rollinson et al., 2018; Rosspéeb, et al., 2019), stratiform chromitite (Li et al., 2005; Spandler et al., 2005; Vukmanovic et al., 2013), abyssal peridotite (Matsukage and Arai, 1998; Tamura et al.,...
2014), and other environments. In those studies, pargasite, enstatite, and aspidolite (the Na analogue of phlogopite) are found to be the most common daughter minerals. Many studies have suggested that these daughter minerals formed by the peritectic reaction between trapped melt and host chromite (Li et al., 2005; Spandler et al., 2007; Tamura et al., 2014; Khedr and Arai, 2016). Recently, high-Cr# [atomic Cr/(Cr + Al)] chromite has been observed as the lining of inclusions within high-Al, low-Cr# chromite, and has been proposed to have originated as early crystallizing microcrystals (Borisova et al., 2012).

These high-Cr# chromite lining, however, cannot be explained by the host chromite-melt reactions, and consequently its origin remains controversial. Most studies of MSIs in chromites have focused on the composition of the daughter minerals, and the genesis and the evolution of the inclusions are poorly understood. In this study, we use high-resolution X-ray computed tomography (HRXCT) (Créon et al., 2018; Richard et al., 2019) and scanning electron microscopy (SEM) to investigate the origin of MSIs in chromites from the Samail ophiolite in Oman.

GEOLOGICAL BACKGROUND AND SAMPLES

The crust-mantle transition zone (MTZ) is the boundary between the mantle and crustal sections in oceanic lithosphere. In the Samail ophiolite, the MTZ is composed mainly of dunite with gabbroic lenses and ranges in thickness from several meters to several hundred meters (Ceuleneer and Nicolas, 1985; Boudier and Nicolas, 1995; Jousselin and Nicolas, 2000; Abily and Ceuleneer, 2013). The MTZ is located beneath lower-crustal gabbros (with minor ultramafic lenses or layers) and above residual mantle harzburgites (with ~ 5–15%, tabular dunites; Boudier and Coleman, 1981). Podiform chromitites in the Samail ophiolite occur both in the MTZ and in the mantle section. In the MTZ, they commonly have a disseminated banded structure, but in the mantle section exhibit podiform or massive structures (Ahmed and Arai, 2002; Rollinson, 2008; Arai and Miura, 2016). Moreover, the composition of chromitite is variable. In general, the chromitites in the MTZ have lower Cr# than those in the mantle section (Rollinson, 2008; Borisova et al., 2012).

The studied samples were collected from three localities: (1) a banded chromite mine in massive dunite within the MTZ of the Samail massif (UTM: 0596794, 2556987), (2) chromite veins, from ICDP Oman Drilling Project (OmanDP) Hole CM2B in the MTZ, in Wadi Zeeb of the Wadi Tayin massif [Core 18 (Section 1, Interval 89–94 cm)], and (3) a podiform chromite mine in the western part of the Fizh massif (mantle section) (UTM: 0393300, 2689455) (Fig. 1). The banded chromitite ores show a disseminated structure and consist mainly of irregular mosaics of subhedral olivine (0.3–0.5 mm) and chromite (0.3–0.5 mm), in which variations in the proportions of chromite and olivine define the banded texture (Figs. 2a and 2b). The chromite ores are relatively fresh (less than 5% serpentine), although serpentine, native copper, copper carbonate, and copper oxide minerals are present within fractures in the dunite wall rocks. In the chromitite veins from drill cores in Hole CM2B, subhedral chromites are 0.4–0.6 mm, and the dunite host rock is totally altered to serpentinite (Fig. 2c). The podiform chromitite samples are massive ores, with more than 90% of the chromite arranged as irregular aggregates of variable grain size (Fig. 2d).

ANALYTICAL METHODS

The major element compositions of the chromite and other MSI minerals were analyzed by an electron microprobe analyzer (EPMA) with wavelength dispersive spectrometer (JEOL JXA-8600) at Niigata University. Analyses used a beam diameter of 1 μm, a probe current of 13 nA and an accelerating voltage of 15 kV. Quantitative analysis of compositions and acquisition of backscattered electron images of MSIs were conducted using a JEOL...
HRXCT and SEM studies of inclusions in Oman podiform chromitite

RESULTS

Characteristics of multiphase solid inclusions

MSIs are rare in the podiform chromitite samples, whereas they are common in the banded chromitite samples (Fig. 3a) and in the chromitite veins from the OmanDP cores. The host chromite in the banded chromitite shows a skeletal morphology (Fig. 3b). MSIs in the chromites are round with the size varying from 1 to 200 µm in diameter. Primary MSIs are randomly distributed in the chromites, whereas a few secondary MSIs occur along cracks in the chromites. Only crack-free primary MSIs were used in this study. Primary inclusions vary in shape from negative crystal shapes and spherical to irregular morphologies. In rare cases, necking-down of MSIs was observed (Fig. 4). MSIs in the banded chromitite samples from Oman ophiolite have also been described in detail by Rospabé et al. (2019).

Daughter minerals are those minerals that crystallized from the trapped, initially homogeneous melt/fluid within the inclusion (Roedder, 1984). In the banded chromitite samples from the MTZ, various types of daughter minerals were found, including silicate minerals, sulfides and chromites with a higher Cr# than that of the host chromite. The silicate MSIs, ranging from 5 to 200 µm in diameter, consist of pargasite, aspidolite, diopside [Mg# = Mg/(Mg + Fe2+) = 0.78–0.99, Wo = 100 × Ca/(Ca + Mg + Fe2+) = 45–51], enstatite (Mg# = 0.90–0.92), forsterite (Fo = 93–94), albite (An = 14–38), titanite and apatite. High-Cr# chromite (Cr# > 0.6) exists as the lining of inclusions (Figs. 5b–5d). Compositions of the host chromite grains and the chromite linings are presented in Table 1 and Supplementary Table S1 (available online from https://doi.org/10.2465/jmps.191008). Examples of SEM-EDS intensity profiles across the host chromite, high-Cr# chromite and daughter minerals are given in the Supplementary Figures S1–S3 (available online from https://doi.org/10.2465/jmps.191008).

In some MSIs, some silicate or sulfide minerals occur with the high-Cr# lining (Fig. 5b). Most sulfides are pentlandite and Fe-Ni-Cu sulfides. In the chromitite vein samples from the OmanDP cores, the MSIs consist of pargasite, aspidolite, enstatite, apatite, albite, diopside, tremolite, spinel (Cr# = 0.21), calcite, and pentlandite. A
high–Cr# chromite lining surrounding MSI is also observed in these samples. Rare MSIs in the podiform chromitite samples from the mantle section consist of minerals similar to those in the chromitite vein, and the high–Cr# chromite lining also occurs (Fig. 5g). In addition, growth striations of chromite occur in the banded chromitite sample (Figs. 6a and 6b); whereas several high–Cr# chromite microcrystals are developed along the walls of the MSI in the OmanDP sample (Figs. 6c and 6d). Moreover, the percentage of MSIs was obtained by counting the number of MSIs containing individual daughter minerals (including high–Cr# chromite lining) for each sample (Fig. 7). The results show that the percentage of MSIs containing high–Cr# chromite lining is 67, 27, and 7%, for OmanDP samples, banded samples and podiform samples, respectively.

3D images of MSIs

The banded chromitite samples were scanned using HRXCT. Given the high density contrast between chromite and MSIs, we attempted to capture the exterior shape of the MSIs within chromite. Figure 8 shows the spatial distribution and the precise surface expression of MSIs. Most MSIs show negative crystal morphology (Fig. 8). A central MSI has a size of 80 µm or more, whereas the others are <30 µm in size and are distributed around the large MSI in the center. In addition, there is a single sharp protrusion from the surface of the central MSI (Fig. 9).

Compositions of the host chromite and high–Cr# chromite lining

Major element compositions of the studied chromite (host and the lining) show a limited compositional range (Table 1 and Table S1). The host chromite from the banded chromitite samples shows Cr# values ranging from 0.52 to 0.56 and Mg# from 0.58 to 0.70. Fe3+#/[(Cr + Al + Fe3+) ranges from 0.05 to 0.08. The chromite linings around the MSIs from the banded chromitites show Cr# from 0.62 to 0.65, which is higher than
Figure 5. Backscattered electron images of daughter minerals in chromite. (a) and (e) from the OmanDP sample. (b), (c), and (d) from banded chromitite. (f) and (g) from podiform chromitite. (a) and (f) A needle-shaped aspidolite cross-cuts diopside and host chromite, showing that aspidolite growth must have occurred before diopside crystallization and growth of the host chromite lining. (b) A sulfide crystal on the inner wall of host chromite. The area of the high-Cr# chromite lining is 32% of that of the entire inclusion. (c) and (d) Aspidolite and high-Cr# chromite on the inner wall of host chromite. The areas of high-Cr# chromite linings are 40 and 46% of that of the entire inclusion, respectively. (e) Low-Cr# spinels on the wall and interior of an inclusion. (g) A small grain of high-Cr# chromite on the wall of the inclusion.

Table 1. Major-element oxide compositions of chromite grains in representative samples

| Location            | Banded chromitite | Chromite vein in OmanDP core | Podiform chromitite |
|---------------------|-------------------|-------------------------------|---------------------|
|                     | Host chromite     | Chromite lining               | Host chromite       | Chromite lining | Host chromite     | Chromite lining |
| MgO                 | 0.04              | 0.01                          | 0.06                | 0.12           | 0.00              | 0.03              | 0.00              | 0.03             | 0.00              | 0.05              | 0.06              |
| SiO₂                | 0.47              | 0.47                          | 0.47                | 0.47           | 0.47              | 0.47              | 0.47              | 0.47             | 0.47              | 0.47              | 0.47              |
| Fe₂O₃               | 24.82             | 24.82                         | 24.82               | 24.82          | 24.82             | 24.82             | 24.82             | 24.82            | 24.82             | 24.82             | 24.82             |
| Al₂O₃               | 42.32             | 42.32                         | 42.32               | 42.32          | 42.32             | 42.32             | 42.32             | 42.32            | 42.32             | 42.32             | 42.32             |
| Cr₂O₃               | 17.16             | 17.16                         | 17.16               | 17.16          | 17.16             | 17.16             | 17.16             | 17.16            | 17.16             | 17.16             | 17.16             |
| MnO                 | 15.76             | 15.76                         | 15.76               | 15.76          | 15.76             | 15.76             | 15.76             | 15.76            | 15.76             | 15.76             | 15.76             |
| MgO                 | 2.00              | 2.00                          | 2.00                | 2.00           | 2.00              | 2.00              | 2.00              | 2.00             | 2.00              | 2.00              | 2.00              |
| CaO                 | 0.01              | 0.04                          | 0.04                | 0.04           | 0.04              | 0.04              | 0.04              | 0.04             | 0.04              | 0.04              | 0.04              |
| NiO                 | 0.28              | 0.08                          | 0.08                | 0.08           | 0.08              | 0.08              | 0.08              | 0.08             | 0.08              | 0.08              | 0.08              |
| Total               | 101.02            | 101.70                        | 99.33               | 100.87         | 100.81            | 99.61             | 101.18            | 99.73            | 101.10            | 99.73             | 101.10            |
| FeO                 | 5.38              | 4.58                          | 6.29                | 5.83           | 3.39              | 5.17              | 2.64              | 2.59             | 1.72              | 2.43              | 2.15              |
| MgO                 | 12.33             | 14.64                         | 15.22               | 15.00          | 11.92             | 11.27             | 17.58             | 18.83            | 14.52             | 13.06             | 16.40             | 14.15             |
| FeO                 | 0.31              | 0.37                          | 0.40                | 0.39           | 0.30              | 0.29              | 0.48              | 0.51             | 0.39              | 0.34              | 0.45              | 0.38              |
| CaO                 | 0.12              | 0.10                          | 0.15                | 0.14           | 0.08              | 0.12              | 0.06              | 0.07             | 0.06              | 0.10              | 0.07              | 0.04              |
| MgO                 | 0.53              | 0.55                          | 0.65                | 0.63           | 0.54              | 0.55              | 0.79              | 0.79             | 0.72              | 0.72              | 0.82              | 0.79              |
| MgO                 | 0.70              | 0.64                          | 0.60                | 0.61           | 0.70              | 0.71              | 0.52              | 0.48             | 0.61              | 0.65              | 0.54              | 0.62              |
| CaO                 | 0.44              | 0.42                          | 0.32                | 0.34           | 0.45              | 0.42              | 0.20              | 0.20             | 0.27              | 0.27              | 0.17              | 0.20              |
| MgO                 | 0.50              | 0.53                          | 0.61                | 0.59           | 0.52              | 0.52              | 0.77              | 0.76             | 0.70              | 0.68              | 0.79              | 0.78              |
| MgO                 | 0.06              | 0.05                          | 0.08                | 0.07           | 0.04              | 0.06              | 0.03              | 0.04             | 0.03              | 0.05              | 0.03              | 0.02              |

Mg# = atomic Mg/(Mg + Fe²⁺). Cr# = atomic Cr/(Cr + Al). FeO, total Fe as FeO.
YCr, YAℓ, and YFe are the atomic ratios of Cr, Al, and Fe³⁺, respectively, to trivalent cations (Cr + Al + Fe³⁺).
Figure 6. Backscattered electron images of two types of chromite crystal growth on the inner walls of host chromite grains. The voids within inclusions may have been bubbles or holes created during polishing. (a) Chromite within a banded sample. (b) Dislocation growth striations of chromite on inclusion walls. (c) Chromite within an OmanDP sample. (d) Chromite grains show 2D nucleation growth, and several high-Cr# chromite microcrystals are present on the inclusion walls.

Figure 7. Percentage of the number of inclusions containing individual daughter minerals and high-Cr# chromite lining to the total number of inclusions studied for individual samples. (a) OmanDP samples. (b) Banded samples. (c) Podiform samples. (d) Percentage of the number of inclusions containing high-Cr# chromite lining to the total number of inclusions with various sizes in banded samples. n, denotes the number of inclusions in each size range.
the host chromites, and Fe$^{3+}$# from 0.06 to 0.08, nearly equivalent to the host values. In the host chromites in the veins from OmanDP samples, values ranges of Cr# and Mg# are 0.49–0.57 and 0.62–0.71, respectively, with Fe$^{3+}$# varying from 0.04 to 0.06. The chromite linings from the Oman DP samples have higher Cr# (0.58–0.79), lower Mg# (0.48–0.68) and Fe$^{3+}$# (0.01–0.05) values. The host chromite in the podiform chromitites have Cr# values (all are 0.72), which are higher than those of the host chromite in other chromitite samples, and Mg# and Fe$^{3+}$# values of 0.61–6.67 and 0.03–0.05, respectively. The Cr# and Mg# values of chromite linings in the podiform chromitites are 0.79–0.82 and 0.54–0.79, respectively. Values of Fe$^{3+}$# range from 0.01 to 0.11. Overall, the chromite linings generally have higher Cr# values than those of their host chromite grains (Fig. 10).

The differences in compositions are apparent in backscattered electron images, in which the high-Cr# chromite linings are brighter than the host (Figs. 5b–5d).

High-temperature experiments

The glass obtained by the 1200 °C heating experiment was first observed using SEM. About half of the glass appears homogeneous, but the other half contain fine-grained spot-like solid phases (Fig. 11 and Figs. S2 and S3). These phases were too small to be analyzed. Only homogeneous glasses with diameters greater than 20 µm without the spot-like solid phases were analyzed using EPMA. The result shows a limited compositional range of major elements (Table 2), with SiO$_2$ (51–56 wt%).

Figure 8. (a) 3D HRXCT image showing the distributions of inclusions in the banded chromitite. Four clusters of inclusions are contained in the four individual chromite grains. (b)–(d) Three different orientations of an inclusions cluster, comprising a large inclusion surrounded by smaller inclusions. The diameters of the yellowish and greenish inclusions are ~100 and ~80 µm, respectively. Inclusions <30 µm in diameter are shown in blue.

Figure 9. The 3D HRXCT image of an inclusion. An angular protrusion of extending into the host chromite crystal is visible at the top.

Figure 10. Major-element compositions of host chromite grains (open symbols) and chromite linings (closed symbols) for the three sample localities.
CaO (8–13 wt%), MgO (1.7–3.3 wt%), and FeO (3–7 wt%). Variations in major-element composition across the host chromite grains and the glass in the banded chromite sample were assessed using SEM–EDS (Fig. 11 and Figs. S2 and S3). These profiles indicate the presence of compositionally homogeneous cores in the glass, although a 2–3 µm–thick boundary zone occurs between the host and the glass, where anomalous enrichment of Fe and depletion of Al occur.

In Figure 12, the glass compositions obtained in our experiments are compared with some previous results of similar heating experiments at 1050–1400 °C (Schiano et al., 1997) and at 1300 °C (Borisova et al., 2012), which were obtained using Oman samples. The compositions of the daughter minerals (Tables S2–S4; available online from https://doi.org/10.2465/jmps.191008) and the chromite host are also plotted in the same diagram. The compositions of the homogenized melt in our experiments are higher in SiO2 and Al2O3 contents and lower in MgO and FeO contents than the Borisova et al. (2012) results; whereas, the Schiano et al. (1997) results straddle between the two (Fig. 12). The difference may have resulted from the lower temperature in our experiment than previous studies. At lower temperatures melting of daughter minerals may not have been thorough. In fact, the high-Cr# chromite lining remained after the high-temperature experiments at 1200 °C (Fig. S3), meaning that the glass compositions do not represent those of the parental melt primarily trapped in the host chromite but those of evolved melts after the entrapment. According to Schiano et al. (1997) experiment, even at higher temperature such as 1325 and 1360 °C, chromite dissolution does not appear to have occurred. Obviously much higher temperature is required to obtain true primary parental melt compositions.

**DISCUSSIONS**

**Entrapment of primary inclusions in chromite**

The specific mechanism by which crystals trap inclusions remains poorly understood. Processes that prevent smooth crystal growth can cause entrapment of primary inclusions (Roedder, 1979, 1984). Prichard et al. (2018) suggested that silicate melt may be trapped by the necking-down of concave cavities within ‘hopper-shaped’ chromite crystals as they grew. Moreover, in chromite–supersaturated magmas, chromite showed early rapid skeletal crystal growth that developed into hopper crystals while melt was trapped within the crystal (Prichard et al., 2015). Based on 3D images of the inclusions studied here (Fig. 8), we envisage a similar model for the mechanism by which melt inclusions are trapped by a growing chromite (Fig. 13).

**Evolution of primary melt after the entrapment**

After entrapment, various physical and chemical changes may occur within the melt inclusions (Roedder, 1984). Numerous experiments have shown the evolution of inclusion shape from irregular to more regular during heat-
ing (Bodnar and Samson, 2003; Esposito et al., 2012). Regular shapes (i.e., negative crystal form) would represent most stable form because of the lower surface energy (Van den Kerkhof and Hein, 2001). Here we discuss the most important changes that probably took place in the melt inclusions, i.e., the chromite overgrowths on the inner walls and the necking-down of the melt inclusions after the entrapment.

In some inclusions, the daughter minerals protrude into the host chromite (Figs. 5a, 5f, and 9) or into the high-Cr# chromite lining (Figs. 5b–5d). This phenomenon can be explained as overgrowths of chromite that were precipitated from melt onto the inner wall (Fig. 14), although precipitation of chromite is not easily recognizable (Roedder, 1984). In some particular situations, the overgrown part can be recognized by a compositional gradient. For example, a zone with a gradation in the Fo (forsterite) and NiO contents may be present at the edge of melt inclusions within olivine (Ryabchikov et al., 2009). In our samples, we consider that the high-Cr# chromite lining may represent an overgrowth of the host chromite (Mollo and Hammer, 2017).

Figure 12. Major-element oxide compositions plot for homogenized melts obtained in this study and previous studies, compared with those of daughter minerals of MSIs from banded samples. Total Fe as FeO®. The numbers attached to the plots of Schiano et al. (1997) data indicate the experiment temperature. Dashed lines connect the composition of the major daughter minerals. The composition of homogenized inclusions is expected to fall within its enclosed area. The glass compositions obtained in our experiments are mostly plotted outside of this area. The compositions of Borisova et al. (2012) and Schiano et al. (1997) are partially compatible with the composition ranges of daughter minerals in TiO₂, Al₂O₃, and FeO®, but are lower in MgO and higher in SiO₂. The calculated melt compositions by Rollinson et al. (2018) fall in the enclosed area.
SEM data from the banded chromitite samples show that inclusions >30 µm across rarely have high-Cr# chromite linings (Fig. 7d). The reason for that is still unclear and requires further study.

Roeder et al. (2001) suggested that for chromite in MORB lavas, some of the Cr# zoning was due to variation in growth rate in response to the degree of supercooling and to the rate of transport of Cr to the growing crystals. These authors concluded that the characteristic vermiform and other textures in chromite grains within the lavas were growth textures and not reaction textures. Chromite grains affected by alteration commonly have elevated Fe³⁺ contents. Table 1 reveals that the studied chromite linings have normal Fe³⁺/²⁺ values and that these linings are not likely due to hydrous alteration.

In most oxide minerals, the crystal growth interface is smooth, and the crystal exhibits discontinuous (faceted) growth whereby layer growth is controlled by 2D nucleation and crystal dislocations (Fig. 15) (Frank, 1952; Sunagawa, 2007; Stefanescu, 2015; Vesselinov, 2016). At a low degree of supercooling, the crystal growth is controlled by the dislocation growth mechanism. Thus, the growth striations of chromite on inclusion walls (Fig. 6b) indicate that some melt inclusions reflect a low degree of supercooling (Vesselinov, 2016). In contrast, 2D nucleation growth of the chromite in Figure 6d suggests that trapped melt had much strong driving force for crystallization.

On the basis of the reasoning above, we interpret that the high-Cr# chromite linings reflect rapid growth caused by a high degree of supercooling. After the melt was trapped in the host chromite, chromite continued to precipitate on the inclusion walls. With a smaller driving force for crystal growth, as in the case of larger inclusions, chromite grew slowly on dislocations from layer to layer (Sunagawa, 2007). When crystals grow sufficiently slowly, crystallization was close to equilibrium. In such a case, the
interior lining would have the same composition as the host chromite, in which case the chromite lining will not be visible (Fig. 6a). This equilibrium process corresponds to the growth rate shown by the curve A in Figure 15. With a larger driving force for crystal growth as in the case of smaller inclusions, the chromite lining grew by 2D nucleation (Sunagawa, 2007), corresponding to the curve B in Figure 15. After entrapment, chromite continued growing rapidly on inclusion walls. Such a rapid disequilibrium growth reflects a process of crystallization whereby the growth rate of crystals exceeded the ability of chemical elements to equilibrate between melt and/or the surrounding chromite host through diffusion (Mollo and Hammer, 2017). With rapid growth, it can be assumed that diffusion hardly progresses in solids and diffusion mixing occurs only in liquids. When chromite begins to grow as a thin layer, a diffusive boundary layer will be formed at the interface. Owing to the redistribution of the solute, the Si concentration in the boundary layer becomes higher than in the melt, probably causing the crystallization of aspidolite. During aspidolite crystallization, the concentration of Al in the boundary layer further decreases and becomes lower than in the melt further from the interface. This requires the chromite lining to use more Cr, resulting in high-Cr# (Fig. 16). The disequilibrium crystallization of high-Cr# chromite lining and aspidolite thus will cause unique forms (Figs. 5b–5d).

Another possible important morphological change in the melt inclusions may be caused by a necking-down. Necking-down has been reported from fluid inclusions in various systems (Roedder, 1971; Ramboz et al., 1982; Goldstein, 2001). However, necking-down of melt inclusions are rarely reported (Acosta-Vigil et al., 2007). If necking-down occurs to the inclusions before precipitation of daughter minerals, differentiations should not occur among the sub-inclusions and the inclusions should all have the same composition. If, however, daughter minerals begin to precipitate only locally (or heterogeneously) before the necking-down is completed, divergence will occur to the inclusions in terms of daughter minerals, bulk compositions, and therefore, melting temperature (Fig. 17).
Effect of post-entrapment modification on the composition of melt inclusions

As shown in Figure 5, the proportion of each daughter minerals is variable among MSIs. For example, in Figure 5a, the daughter minerals are mainly diopside and aspidolite, whereas in Figure 5b, aspidolite and high-Cr# chromite lining are the daughter minerals. In addition to the different compositions of homogenized glasses and different homogenization temperatures, these results indicate that the heterogeneity in the compositions of the inclusions, may reflect the effect of necking-down as discussed above. It is likely that only those MSIs that did not experience the necking-down can record composition of primary melt. Such inclusions may be located in the center of the host chromite grains and are isolated.

Kamenetsky (1996) considered that post-entrapment modification did not occur to the entrapped melt because of the low Cr content of the melt inclusions. The low Cr content, however, may be the result of a substantial crystallization of chromite on the walls. In contrast, in our study, the presence of high-Cr# chromite lining implies a significant post-entrapment modification. In Figures 5b-5d, the area of the high-Cr# lining ranges from 32 to 46% of that of the entire inclusion. Assuming that the daughter mineral domain represents the composition of the entire melt inclusion (Rollinson et al., 2018), the composition of the entire inclusion, including the high-Cr# chromite lining, must be determined. In such a case, the Cr2O3 content of the primary melt must be higher than those excluding high-Cr# chromite lining.

Figure 12 shows that the composition of the homogenized melts obtained in this study all lie outside the compositional area defined by daughter minerals. This is strange at a first glance, because MSIs are composed of daughter minerals. We propose one possibility to account for this discrepancy, that assumes a production of fractionated melt by incongruent melting of daughter mineral in our heating experiment. For example, incongruent melting of enstatite would produce silica-rich melt and residual olivine. If this is the case, there should be residual phases such as olivine to compensate the compositional discrepancy. It is quite possible that the “spot-like phases” observed in the heated samples may be olivine, but this needs to be confirmed by using higher-resolution microanalysis in the future.

CONCLUSIONS

In this study, we used HRXCT combined with SEM to obtain 3D and 2D images of multiphase solid inclusions within chromite from the Samail ophiolite to investigate post-entrapment modification. As observed in the 3D HRXCT images showing the spatial distributions of inclusions, the rapid growth of skeletal crystals provided interstices to trap melt inclusions. After trapping melt inclusions, the chromite continued to grow on the inner wall of the inclusions. This overgrowth may be recognized as a high-Cr# chromite lining. Many previous studies of the inclusions in chromites have ignored the influence of the formation of lining. The initial Cr content of the melt inclusions should have been much higher than previously estimated, suggesting that the parental melt for the chromitite may have been highly enriched in Cr, being supersaturated in chromite. Moreover, the 3D distribution of inclusions in host chromite with skeletal morphology implies that the formation of inclusions depended on the cooling rate of chromite-forming melt, implying that the parental melt of the chromitite was rapidly cooled in the MTZ.

HRXCT and SEM images, together with high-temperature homogenization experiments, reveals several new findings regarding the origin of MSIs in chromite from the Oman ophiolite:

1. The chromite linings in MSIs are overgrowths of chromite that crystallized from trapped melt, as indicated by the protrusion of some of the daughter minerals into the host chromite or the chromite lining or both.
2. The compositional diversity of small inclusions is probably caused by the effect of necking-down of formerly large inclusions within hopper-shaped, rapidly crystallized chromite grains.
3. The initial Cr content of melt inclusions was probably much higher than previously estimated.
4. Homogenized melt compositions obtained in the high-temperature experiment do not represent those of parental melt because of the remaining of high-Cr# chromite lining and possible presence of residual minerals.

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