Genesis and geotectonic setting of podiform chromitites from the Zhob Valley Ophiolite, Pakistan: Inferences from chromite composition

Zhob valley ophiolite comprises Khanozai, Muslim Bagh, and Zhob chromitite occurrences located in Pakistan. These occurrences occur in massive, disseminated and nodular which exhibit both magmatic and deformingal texture. The Muslim Bagh and Khanozai chromitites are classified into high-Cr chromitite (Cr#=0.66–0.85) while Zhob chromitite falls into high-Al chromitite (Cr#=0.53–0.58) composition. The calculated values of Al$_2$O$_3$ (wt%) and TiO$_2$ (wt%) for parental melts of high-Cr chromitites show similarities with boninitic melts, whereas those of the high-Al ones exhibit MORB melt affinity. Minor and trace element contents (Ti, V, Ni, Zn, and Ga (ppm)) are higher in high-Al chromitites than high-Cr chromitites and contrasting geochemical behavior of these elements with Cr# might be due to magma fractionation. MORB normalized major and trace element patterns of high-Cr chromitite show similar patterns with boninitic while high-Al chromitite differs from boninite. Field and textural investigations, major and trace element geochemistry, and the presence of hydrous silicate inclusions, indicate that high-Cr chromitite were generated in equilibrium with boninitic melt, possibly in supra subduction zone. In contrast, high-Al chromitite crystallized from MORB-like melt during reaction with depleted mantle and probably originated in a back arc basin tectonic environment.

Introduction

The origin and nature of geotectonic setting of podiform chromitites is still not fully understood. The chromite composition is largely dependent on the nature and degree of partial melting of the mantle source. Therefore, the chromite composition can be helpful to determine the parental magma composition (Rollinson, 2008) and the geodynamic environment (Dick and Bullen, 1984; Arai et al., 2006; Cai et al., 2012; Ghosh et al., 2014). For instance, high-Cr and high-Al chromitites are considered to be crystallized from boninitic magmas and mid oceanic ridge basalt (MORB) like tholeiitic melts, respectively (Maurel and Maurel, 1982; Melcher et al., 1997; Kamenskaya et al., 2001; Arai et al., 2011; Zaccarini et al., 2011). Furthermore, supra-subduction zone and back-arc basin are the two most important geodynamic environment which influence the geochemical compositions of podiform chromitites (Roberts, 1988; Nicolas, 1989; Arai and Yurimoto, 1994; Zhou and Robinson, 1997; Ballhaus, 1998; Uysal et al., 2007a, b). Chromite is also a useful petrogenetic indicator to determine the composition of the primary mantle source.

The recent development of the techniques regarding the in situ analysis, like Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS), enable us to analyze a complete suite of minor and trace elements (Sc, Ti, V, Mn, Co, Ni, Zn, and Ga). Variations in the absolute concentrations of these minor and trace elements in chromian spinel are helpful to determine the composition of parental melt of chromitites and their geotectonic setting (Pagé and Barnes, 2009; Pagé et al., 2012; Colas et al., 2014; González-Jiménez et al., 2015). These elements are very sensitive to temperature and oxygen fugacity conditions prevailing during mantle melting (González-Jiménez et al., 2015; Kapsiotis et al., 2018).

In this study, we present petrographic description of chromitites and the first major (Cr, Al, Fe, Mg) and minor-trace element (Sc, Ti, V, Mn, Co, Ni, Zn, and Ga) concentrations in chromitites from the Zhob valley ophiolite. We purpose to determine the genesis of Zhob valley chromitite deposits including their parental melt composition and tectonic environment.

Regional Geological Setting

The rocks of the Zhob valley ophiolite belt and surrounding area
can broadly be divided into three geologic zones (Fig. 1a, b). In the south, the Calcareous zone is tectonically the lowermost zone of the Indian continental plate margin. This zone contains sedimentary formations that range in age from Early Triassic to Paleocene. These successions are dominantly composed of limestone followed by shale with some sandstone and conglomerate that are deposited in pelagic to shallow marine environments (Hunting Survey Corporation (HSC), 1960). The Calcareous zone is thrust over by the Suture zone; lying between the Indian Plate and Afghan Block (Gansser, 1979) and consisting of the Muslim Bagh ophiolite and Bagh complex. The detailed descriptions of Muslim Bagh ophiolite and Bagh complex are given in their respective sections below. The third geological zone is the Flysch zone which lies to the north of the Suture zone (Fig. 1b). The stratigraphy of the Flysch zone, revised by Kasi et al. (2012), comprises limestone at the basal part which is succeeded by thick flysch sediments composed of cyclic successions of shale, siltstone and sandstone with locally minor conglomerates. These units are largely deltaic and fluvial in nature and range from Eocene to Pleistocene in age.

**Geology of Zhob Valley Ophiolite**

Pakistan contains an extended belt of ophiolites in the Bela-Zhob valley-Waziristan zone from south to north. Bela ophiolite is the largest ophiolite in Pakistan which begins from Bela town (near Arabian Sea coast) up to Khuzdar city while the Zhob valley ophiolite belt extends from northeast of Quetta up to Zhob town, followed by the Waziristan ophiolite further north. The Bela-Zhob valley-Waziristan ophiolite belt demarcates a suture zone between the Indian continental plate and the Afghan Block in northwestern Pakistan (Sengor, 1987). The Zhob valley ophiolitic belt consists of the Khanozai, Muslim Bagh and Zhob ophiolitic bodies (Fig. 1b). Among these bodies, the Khanozai ophiolite comprises both mantle peridotite and crustal mafic-ultramafic cumulates which are underlain by mélangé (Fig. 1c; Popal et al., 2018; Ulhaq, 2018). The mantle peridotite covers about two third of the area of the Khanozai ophiolite. The Muslim Bagh ophiolite is well-developed and the largest body in the Zhob valley ophiolite. This ophiolite was described by Vredenburg (1901) and Bilgrami (1964) as intrusive complex, but it was identified by Rossman et al. (1971) as ophiolite
complex. It contains a nearly complete ophiolitic succession (Penrose, 1972), with a less developed crustal section overlying a thick residual mantle section (Fig. 1d). The crustal portion is composed of ultramafic to mafic cumulate rocks which gradually grades into mafic cumulate or gabbros and poorly developed sheeted dykes at the top (Kakar et al., 2014). The mantle section consists of harzburgite, dunite and lherzolite (Mahmood et al., 1995). These rocks are partially to completely serpentinized (30 to 100%) and intensively sheared (Mahmood et al., 1995). The swarms of 3 to 15 m thick mafic dyke cross cut the mantle section of this body (Kakar et al., 2015).

Ahmad (1974), Otsuki et al. (1989) and Sawada et al. (1992) proposed a mid-oceanic ridge tectonic setting for the Muslim Bagh ophiolite. But Hoshino and Anwar (1989), Siddiqui et al. (1996) and Kakar et al. (2014) disagreed and suggested that the Muslim Bagh ophiolite developed in a back arc basin or supra-subduction setting. Furthermore, the Zhob ophiolite consists of three detached bodies around Zhob town namely Naweoba, Omzha, and Ali Khanzai Blocks. Triassic-Jurassic rocks of the Calcareous zone surround all the three bodies (HSC, 1960). The Omzha Block contains mostly two elongated but parallel peridotite bodies. They are up to 3 km in length and 300 m in width, and diorite covers the margin of these bodies. The Ali Khanzai Block consists of peridotite and volcanic rocks (HSC, 1960 named it as Bahlolzai). Further, the Naweoba Block contains a thick unit of volcanic rocks with some gabbroic rocks. It also contains serpentinized peridotite which is largely composed of harzburgite and dunite (Ayoub, 2014; Fig. 1e).

Zhob Valley Chromitites

Chromitite deposits occur in the mantle portion of the Zhob valley ophiolite which is largely composed of highly serpentinized harzburgite and dunite. Chromitite bodies form lenses, pods and banded structures (Fig. 2a, b, c). At many places, these structures do not show any apparent directional relationship with the boundaries of intrusive while at some places chromitite layers are parallel with and have same to dip with host rocks (Bilgrami, 1963, 1969). Pods reach up to 4 m in thickness while lenses of chromite are found up to 25 cm. The pods and lenses are surrounded by dunite envelopes which are highly serpentinized. Dunite envelopes make sharp to slightly gradual contact with harzburgite. Chromitites form alternate layers with dunite of varied thickness. Chromitites form massive to semi-massive, nodular, disseminated, and layered or banded textures. Massive chromitite and semi massive chromitite contains aggregates of medium to coarse, subhedral to anhedral grains of chromite (Fig. 2d, e). Furthermore, nodular chromitite is observed at some locations (Fig. 2f) which is massive in nature and has anhedral grain shape. The nodules reach in size up to 10 mm and are embedded in serpentinized matrix. Disseminated chromitite is

Figure 2. Photographs of Zhob valley chromitites, (a) Chromitite pods with massive textures and sharp contacts with dunite envelopes, (b) chromitites lenses in dunite envelope, (c) banded chromitites, (d) massive texture in Zhob Valley chromitites, (e) chromitites with semi-massive texture, (f) chromitites with nodular textures, (g) disseminated texture in chromitites, (h) layered structure in Zhob valley chromitites. The coin is 27.5 mm in diameter.
made up of fine grained subhedral chromite grains (Fig. 2g). Layering in the Zhob valley chromitite is also observed locally in which chromites usually form disseminated texture (Fig. 2h).

**Petrography**

Lherzolite forms thin layers at the base of the ophiolitic sequence. The layers are less serpentinitized and show porphyroclastic to mylonitic textures. Modal composition of lherzolite is olivine (70%), clinopyroxene (14%), orthopyroxene (14%) and spinel (2%) (Kakar et al., 2013). Harzburgite shows serpentinitization, is generally medium to coarse grained, granoblastic and hypidiomorphic textures. It contains orthopyroxene (25–35%), serpentine (56–60%, mostly after olivine), olivine (5–10%) and chrome spinel (3–6%) (Siddiqui et al., 1996). Dunite is the most important rock type of the mantle section and it is highly serpentinitized across all bodies. It shows granoblastic texture and in some samples the relict core of olivine is surrounded by a serpentinitized mesh. Dunite is composed of olivine (15–20%), serpentine (65–70%), diopside (3–5%) and spinel (2–3%) (Siddiqui et al., 1996). Serpentinites in the Muslim Bagh body of the Zhob valley ophiolite contain 90% serpentinite with minor opaque oxides and olivine. It is massive and greenish in color (Mahmood et al., 1995).

The investigated chromitites from Zhob valley ophiolite are massive–semi massive, disseminated, banded, and nodular in texture. Massive–semi massive chromite grains are surrounded by alteration product such as serpentine (Fig. 3a, b). Also, massive chromitites show brecciated textures in which grains are fragmented in small pieces (Fig. 3c). However, disseminated chromitites contain largely subhedral grains embedded in serpentinitized matrix (Fig. 3d).

Chromite is largely unaltered, at the same time a few grains show alteration (Fig. 3e). The ferritchromite alteration occurs along fractures and boundaries of some chromite grains, the development of ferritchromite is not limited to fractures and grain margin, and covers up to 75 vol% of chromite grain. The formation of ferritchromite yields spongy textures in chromite grains (Fig. 3e).

Anhydrous-hydrous silicates, and sulfide minerals occur in chromitite samples as inclusions and matrix in chromite grains. Olivine is the most frequent silicate phase that occurs as matrix among chromite grains as well as inclusions (Fig. 3f). Olivine is typically altered into serpentine minerals in the matrix, which is subhedral in shape and 40 µm in size. Hydrous silicates are amphibole and chlorite. Chlorite is found in the matrix of chromitite (Fig. 3g) while amphibole occurs in chromite grains as inclusions (Fig. 3f, h). These are largely anhedral to subhedral in shape and range in size up to 20 µm. Occasionally minute sulfide grains occur between chromite grains in the matrix (Fig. 3i).

**Analytical Methods**

Petrographic analysis of host rocks and chromitites were carried out with transmitted and reflected light microscopy. Micro X-ray fluorescence (micro-XRF) was used to analyze the microstructure as well as phase composition. Polished blocks of representative samples were used for the analysis. The X-ray fluorescence analysis was conducted with the Bruker M4 Tornado X-ray apparatus at the Institute of Geoscience at Aarhus University, Denmark. The source used was a single rhodium target X-ray tube. For all samples the following criteria were the same. The spot size used was 20 µm and the distance between measured points was 25 µm. Two spectrometers were running at a range of 40 keV/130 kcps. The X-ray tube was running at 50 kV electron voltage and the current was set to 600 µA. All analysis was carried out in vacuum.

The major element composition of chromites and silicate inclusions was analyzed using a JEOL JXA-8600 superprobe at the Department of Geoscience, Aarhus University, Denmark. The method for quantitative analysis was EDS (energy dispersive X-ray spectroscopy) with an acceleration voltage set to 15 keV and a current beam of 10 nA. The beam diameter was 5 µm with a counting time of 20 seconds. For the calibration of the microprobe natural mineral standards, including quartz, sanidine, apatite, jadeite, corundum, hematite, rutile, chrome, or oxides (NiO, MgO) were used. The analysis quality was monitored with two in-house standards; clinopyroxene BBI and labradorite (Oslo plagioclase). These standards were measured intermittently and compared with the known chemical composition to check the quality of the analysis. They contain all the major elements measured and the relative reproducibility was better than 1%.

The minor and trace element concentrations of chromite were analyzed by LA-ICP-MS at the Aarhus Geochemistry and Isotope Research (AGIR) platform, Department of Geoscience at Aarhus University. The instrument consists of a 193 nm ArF Excimer laser from Resonetics attached to an Agilent 7900 ICPMS. The analysis was carried out with single spot ablations which had a spot size of 80 µm. The ablation rate was 8 Hz at an energy of 80 mJ/cm². Helium was used as the carrier gas, which then was mixed with Ar before it entered the ICP. The measurements included 15 seconds of background and 25 seconds of ablation. The NIST 610 reference standards was used as the external calibration standards, and Fe-values determined by electron microprobe/stoichiometry were used as internal standards. The data processing and quantification was done in Iolite software (Paton, 2011) and follows the procedure outlined in Heinrich et al. (2003).

**Results**

**Major Element Geochemistry of Chromite**

The composition of fresh chromite grains from the Zhob valley chromitite deposits of all three bodies are given in Table 1. Chromite in these bodies shows a wide range of composition. The range of major element concentration (wt%) in the chromite from the Zhob body is: Cr₂O₃ (39.8–44.9), Al₂O₃ (21.3–23.7), FeO (11.00–13.20), MgO (12.34–17.70) and TiO₂ (0.1–0.3). In the Muslim Bagh chromite the values are as wt%: Cr₂O₃ (49.4–60.6), Al₂O₃ (9.4–17.3), FeO (10.40–17.50), MgO (10.30–15.60) and TiO₂ (0.01–0.2). The chromite from the Khanozai chromitite contains Cr₂O₃ (52.7–55.2), Al₂O₃ (9.4–12.9), FeO (11.90–16.30), MgO (10.30–15.20) and TiO₂ (0.08–0.4) (wt%). Generally, Muslim Bagh and Khanozai chromites have similar composition while the Zhob chromite shows higher Al₂O₃ and MgO values, but lower Cr₂O₃ compared to the others (Fig. 4). Nevertheless, nearly all data from all the three chromitite ore deposits fall into the podiform chromitites region on the TiO₂ vs Cr₂O₃ diagram (Fig. 5a). The Al₂O₃ and Cr₂O₃ show a negative correlation (Fig. 5b) in the Zhob
Figure 3. Photomicrographs, micro-XRF, and BSE images showing petrographic characteristics, a) and b) massive-semi massive chromite grains are surrounded by serpentine, c) chromitites with brecciated texture, d) disseminated texture with subhedral to anhedral grains, e) ferrarian alterations of chromitites, f) olivine and amphibole inclusions in chromite grain, g) chlorite in matrix h) amphibole inclusions in chromite and chlorite in interstitial matrix and i) sulfide grains. Ol=Olivine, Srp=serpentine, Chr=chromite, Amp=Amphibole, Sul=Sulfide. Note that (b) and (h) are micro-XRF images.
Table 1. Representative chromite compositions (wt%) of chromitites from the Zhob valley ophiolite and calculated melt compositions. Cr# = Cr/(Cr+Al), Mg# = Mg/(Mg+Fe2+), Fe2+/2 = Fe3+/3/(Mg+Fe2+)

| Locations | Muslim Bhagh |
|-----------|---------------|
| Sample No | B43 | B43a | B44 | B45cb | B48 | B49 | B54 | B63 | B64 | B65 | B69 |
| Type      | High-Cr | High-Cr | High-Cr | High-Cr | High-Cr | High-Cr | High-Cr | High-Cr | High-Cr | High-Cr | High-Cr |
| SiO2      | 1.30    | 1.30   | 0.10   | 0.20   | 0.50   | 0.40   | 0.00   | 0.20   | 0.10   | 0.80   | 0.40   |
| TiO2      | 0.19    | 0.10   | 0.14   | 0.08   | 0.19   | 0.20   | 0.10   | 0.06   | 0.01   | 0.20   | 0.10   |
| Al2O3     | 10.20   | 10.58  | 11.80  | 11.90  | 17.10  | 16.20  | 9.00   | 7.20   | 9.40   | 12.20  | 17.30  |
| Cr2O3     | 56.50   | 59.58  | 52.70  | 52.90  | 51.20  | 52.10  | 60.00  | 60.60  | 58.10  | 49.40  | 50.80  |
| Fe2O3     | 2.60    | 0.30   | 6.40   | 6.70   | 3.20   | 3.60   | 3.70   | 5.70   | 4.90   | 7.50   | 4.40   |
| FeO       | 15.30   | 14.80  | 14.80  | 14.70  | 12.60  | 12.90  | 13.20  | 10.40  | 10.40  | 17.50  | 10.90  |
| MnO       | 0.23    | 0.60   | 3.00   | 3.90   | 0.18   | 0.50   | 0.60   | 2.70   | 1.90   | 0.29   | 0.60   |
| MgO       | 13.20   | 11.87  | 10.60  | 10.30  | 15.10  | 14.90  | 12.50  | 13.30  | 13.60  | 11.10  | 15.60  |
| NiO       | 0.10    | 0.10   | 0.20   | 0.20   | 0.21   | 0.10   | 0.40   | 0.20   | 0.10   | 0.10   | 0.00   |
| TotalΣ   | 99.82   | 99.24  | 99.74  | 100.88 | 100.28 | 100.90 | 99.50  | 100.36 | 98.51  | 99.09  | 100.10 |

| Cations (structural formula on the basis of 4 oxygen) |
|-----------|
| Si         | 0.04    |
| Ti         | 0.00    |
| Al         | 0.38    |
| Cr         | 1.44    |
| Fe2+       | 0.06    |
| Fe3+       | 0.41    |
| Mn         | 0.00    |
| Mg         | 0.63    |
| Ni         | 0.00    |
| Cr#        | 0.79    |
| Mg#        | 0.60    |
| Fe2+/2     | 0.39    |
| Al2O3-melt | 11.06   |
| TiO2-melt  | 0.29    |
| SiO2       | 0.10    |
| TiO2       | 0.14    |
| Al2O3      | 12.80   |
| Cr2O3      | 52.70   |
| Fe2O3      | 5.00    |
| FeO        | 15.60   |
| MnO        | 2.00    |
| MgO        | 10.70   |
| NiO        | 0.20    |
| TotalΣ    | 99.24   |

| Locations | Khanaozai | Zhob |
|-----------|-----------|------|
| Sample No | KO30      | KO30a|
| Type      | High-Cr   | High-Cr|
| SiO2      | 0.10      | 0.10  |
| TiO2      | 0.14      | 0.08  |
| Al2O3     | 12.80     | 12.90 |
| Cr2O3     | 52.70     | 52.90 |
| Fe2O3     | 5.00      | 4.90  |
| FeO       | 15.60     | 16.30 |
| MnO       | 2.00      | 2.00  |
| MgO       | 10.70     | 10.30 |
| NiO       | 0.20      | 0.20  |
| TotalΣ   | 99.24     | 99.68 |

| Cations (structural formula on the basis of 4 oxygen) |
|-----------|
| Si         | 0.00    |
| Ti         | 0.00    |
| Al         | 0.49    |
| Cr         | 1.36    |
| Fe2+       | 0.12    |
| Fe3+       | 0.42    |
| Mn         | 0.05    |
| Mg         | 0.52    |
| Ni         | 0.00    |
| Cr#        | 0.73    |
| Mg#        | 0.55    |
| Fe2+/2     | 0.44    |
| Al2O3-melt | 12.25   |
| TiO2-melt  | 0.23    |
valley chromitites which is characteristic for ophiolitic chromitites. On the basis of compositional variation of chromite, the studied chromitites can be classified into two groups as high-Cr (Cr# = Cr/(Cr+Al) > 0.6) and high-Al (Cr# = Cr/(Cr+Al) < 0.6). Muslim Bagh and Kha- nozai chromitites are high-Cr composition which contains high Cr# values ranging from 0.66 to 0.85 and from 0.73 to 0.79, respectively. In contrast, the Zhob chromitite is high-Al character and shows Cr# values from 0.53 to 0.58. Generally, both high-Cr and high-Al chromitites are low in Fe₂O₃ concentrations (approx. 5 wt%) but a few samples from high-Cr chromitites contain higher Fe₂O₃ contents, reaching up to 7.4 wt%.

Profile analyses of chromite are mostly unzoned but a few grains in high-Cr and high-Al chromite show weak and strong zonation, respectively. The zoned chromite grains from high-Al chromitite exhibit an increase from rim to core in Mg# (Fig. 6a). But Cr# and FeO total (wt%) values decrease from rim to core in grains from high-Al chromitite (Fig. 6a). On other hand, values of Cr#, Mg# and FeO total (wt%) are approximately uniform from rim to core in grains from high-Cr chromitites but some grains show slight zonation. In high-Cr chromitites, values of Cr# increase from rim to core while FeO total (wt%) values decrease from rim to core and Mg# values increase partially from rim to core (Fig. 6b).

Minor and Trace Element Geochemistry of Chromite

The 174 spots on fresh parts of chromite grains were analysed for minor and trace element concentrations (Sc, Ti, V, Mn, Co, Ni, Cu, Zn, and Ga) in both high-Cr and high-Al chromitites. The average contents are listed in Table 2. Average contents of Ti, V, Ni, Zn and Ga in chromite of high-Cr chromitites (1523, 718, 1002, 551, and 26.2 ppm, respectively) are lower than those in high-Al chromitites (1880, 1158, 1979, 730.5, and 64.3 ppm, respectively) (Fig. 7). Average concentrations of Sc and Mn are higher in chromite (9 and 2264 ppm, respectively) of high-Cr chromitites than those in high-Al chromitites (1523, 718, 1002, 551, and 26.2 ppm, respectively) (Fig. 7). Average concentrations of Sc and Mn are higher in chromite (9 and 2264 ppm, respectively) of high-Cr chromitites than those in high-Al chromitites (1523, 718, 1002, 551, and 26.2 ppm, respectively) (Fig. 7). Average concentrations of Sc and Mn are higher in chromite (9 and 2264 ppm, respectively) of high-Cr chromitites than those in high-Al chromitites (1523, 718, 1002, 551, and 26.2 ppm, respectively) (Fig. 7). Average concentrations of Sc and Mn are higher in chromite (9 and 2264 ppm, respectively) of high-Cr chromitites than those in high-Al chromitites (1523, 718, 1002, 551, and 26.2 ppm, respectively) (Fig. 7).

Silicate Inclusions

Olivine and amphibole are the primary silicate inclusions found in fresh grains of chromite. In both types of chromitites, the chemical
composition of these inclusions are almost similar (Table 3). Olivine is the most common inclusions that contains up to 0.80 wt% NiO and 0.5 wt% MnO which is represented by high Fo content (average Mg# = 0.97, Table 3), showing forsterite composition. Amphibole contains high Mg# ranges from 0.92 to 0.96 and Si contents ranges from 6.53 to 7.25 which classify amphibole as magnesio-hornblende. Major ele-

Figure 6. Profile analysis of chromite grains from Zhob valley chromitites; (a) high-Al and (b) high-Cr chromite.
| Type       | B43-1 | B43-2 | B43-3 | B43-4 | B43-5 | B43-6 | B43-7 | B43-8 | B43-9 | B43-10 | B43a-1 | B43a-2 | B43a-3 | B43a-4 | B43a-5 | B43a-6 | B43a-7 | B43a-8 | B43a-9 | B43a-10 | B43a-11 | B43a-12 | B43a-13 | B43a-14 | B43a-15 | B43a-16 | B43a-17 | B43a-18 | B43a-19 | B43a-20 | B43a-21 | B43a-22 | ST DEV | Average | 8.01 | 1755 | 575 | 2218 | 354 | 1136.3 | 2.12 | 589.3 | 30.26 |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Element    | Sc    | Ti    | V     | Mn    | Co    | Ni    | Cu    | Zn    | Ga    | Sc    | Ti    | V     | Mn    | Co    | Ni    | Cu    | Zn    | Ga    | Sc    | Ti    | V     | Mn    | Co    | Ni    | Cu    | Zn    | Ga    | Sc    | Ti    | V     | Mn    | Co    | Ni    | Cu    | Zn    | Ga    | ST DEV |
| Muslim Bagh|       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       | Average |
| B43-1      | 7.52  | 1752  | 569   | 2161  | 342   | 1177  | 1.49  | 578   | 30.20 | 8.87  | 1726  | 558   | 2391  | 367   | 962   | 2.87  | 636   | 28.70 | 8.99  | 1745  | 563   | 2401  | 369   | 988   | 4.80  | 620   | 28.60 | 7.83  | 1743  | 572   | 2250  | 359   | 1112  | 2.00  | 574   | 29.10 | 8.58  | 1780  | 578   | 2397  | 373   | 1024  | 2.33  | 613   | 31.00 | 7.59  | 1743  | 575   | 2183  | 350   | 1168  | 1.54  | 589   | 30.30 | 7.90  | 1741  | 583   | 2226  | 352   | 1190  | 1.21  | 583   | 30.90 | 7.99  | 1789  | 577   | 2065  | 335   | 1285  | 1.53  | 569   | 31.08 | 8.71  | 1804  | 588   | 2350  | 375   | 1032  | 1.27  | 585   | 31.90 | 9.00  | 1762  | 580   | 2437  | 371   | 973   | 0.54  | 617   | 31.10 | 7.71  | 1741  | 561   | 2063  | 340   | 1186  | 0.38  | 581   | 30.10 | 7.57  | 1774  | 577   | 2076  | 343   | 1221  | 1.76  | 576   | 30.44 | 7.89  | 1776  | 580   | 2272  | 363   | 1179  | 0.89  | 593   | 30.58 | 7.88  | 1774  | 580   | 2332  | 371   | 1033  | 1.17  | 587   | 31.60 | 8.28  | 1732  | 573   | 2281  | 369   | 1092  | 1.33  | 586   | 30.30 | 8.04  | 1749  | 581   | 2145  | 349   | 1232  | 1.79  | 578   | 31.70 | 7.46  | 1768  | 576   | 2136  | 352   | 1239  | 2.12  | 583   | 30.50 | 7.70  | 1716  | 575   | 2191  | 342   | 1237  | 3.20  | 613   | 30.30 | 7.38  | 1761  | 573   | 2121  | 342   | 1211  | 1.36  | 559   | 30.10 | 8.16  | 1747  | 569   | 2172  | 349   | 1185  | 1.65  | 610   | 30.80 | 8.23  | 1783  | 583   | 2383  | 383   | 952   | 0.83  | 617   | 29.00 | 9.18  | 1763  | 577   | 2402  | 385   | 949   | 0.90  | 603   | 28.30 | 7.90  | 1789  | 580   | 2030  | 334   | 1265  | 2.19  | 586   | 30.70 | 7.92  | 1738  | 574   | 2233  | 356   | 1118  | 0.71  | 579   | 30.00 | 7.47  | 1755  | 580   | 2083  | 341   | 1241  | 5.00  | 574   | 30.60 | 6.85  | 1744  | 576   | 2059  | 334   | 1253  | 0.65  | 583   | 30.03 | 7.73  | 1711  | 567   | 2124  | 333   | 1246  | 2.78  | 557   | 31.00 | 7.81  | 1746  | 572   | 2040  | 334   | 1256  | 1.15  | 563   | 31.60 | 7.90  | 1747  | 574   | 2037  | 335   | 1254  | 1.16  | 572   | 29.60 | 8.30  | 1749  | 577   | 2135  | 345   | 1194  | 16.00 | 568   | 30.10 | 8.49  | 1786  | 574   | 2406  | 378   | 966   | 0.45  | 632   | 29.30 | 7.66  | 1738  | 569   | 2388  | 372   | 942   | 0.82  | 593   | 28.90 | 6.85  | 1744  | 576   | 2059  | 334   | 1253  | 0.65  | 583   | 30.03 | 7.73  | 1711  | 567   | 2124  | 333   | 1246  | 2.78  | 557   | 31.00 | 7.81  | 1746  | 572   | 2040  | 334   | 1256  | 1.15  | 563   | 31.60 | 7.90  | 1747  | 574   | 2037  | 335   | 1254  | 1.16  | 572   | 29.60 | 8.30  | 1749  | 577   | 2135  | 345   | 1194  | 16.00 | 568   | 30.10 | 8.49  | 1786  | 574   | 2406  | 378   | 966   | 0.45  | 632   | 29.30 | 7.66  | 1738  | 569   | 2388  | 372   | 942   | 0.82  | 593   | 28.90 | 8.01  | 1755  | 575   | 2218  | 354   | 1136.3 | 2.12 | 589.3 | 30.26 |
| Element | Type | Sc  | Ti  | V   | Mn  | Co  | Ni  | Cu  | Zn  | Ga  |
|---------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| B69-3   | High-Cr | 11.21 | 1912 | 919 | 2916 | 361 | 1081 | 1.06 | 705 | 35.60 |
| B69-4   | High-Cr | 11.13 | 1942 | 926 | 2835 | 360 | 1124 | 0.77 | 718 | 34.70 |
| B69-5   | High-Cr | 11.82 | 1934 | 920 | 2971 | 379 | 1067 | 0.82 | 706 | 34.10 |
| B69-6   | High-Cr | 11.25 | 1920 | 928 | 2908 | 366 | 1078 | 1.26 | 691 | 34.60 |
| B69-7   | High-Cr | 11.04 | 1988 | 954 | 2954 | 379 | 1062 | 0.78 | 701 | 34.80 |
| B69-8   | High-Cr | 11.89 | 1932 | 944 | 2888 | 365 | 1124 | 1.08 | 717 | 34.60 |
| B69-9   | High-Cr | 11.84 | 1952 | 929 | 2869 | 365 | 1100 | 0.96 | 688 | 35.30 |
| B69-10  | High-Cr | 11.36 | 1921 | 933 | 2884 | 367 | 1043 | 1.24 | 728 | 34.00 |
| B69-11  | High-Cr | 11.68 | 1916 | 924 | 2846 | 357 | 1091 | 1.55 | 699 | 34.00 |
| B69-12  | High-Cr | 11.54 | 1976 | 947 | 2965 | 367 | 1092 | 0.67 | 700 | 33.90 |
| B69-13  | High-Cr | 11.95 | 2006 | 951 | 2954 | 380 | 1098 | 0.81 | 728 | 34.70 |
| B69-14  | High-Cr | 13.10 | 2035 | 940 | 3056 | 385 | 1052 | 1.49 | 712.4 | 34.36 |
| KO33-1  | High-Cr | 9.96  | 1506 | 595 | 2271 | 373 | 836 | 1.90 | 508 | 23.99 |
| KO33-2  | High-Cr | 9.75  | 1535 | 597 | 2349 | 374 | 865 | 1.64 | 493 | 25.30 |
| KO33-3  | High-Cr | 9.65  | 1492 | 602 | 2275 | 376 | 873 | 1.80 | 479 | 24.66 |
| KO33-4  | High-Cr | 9.29  | 1476 | 592 | 2305 | 371 | 829 | 1.60 | 492 | 23.60 |
| KO33-5  | High-Cr | 9.16  | 1471 | 597 | 2345 | 371 | 840 | 2.00 | 502 | 24.49 |
| KO33-6  | High-Cr | 9.50  | 1470 | 596 | 2331 | 369 | 843 | 1.57 | 497 | 24.50 |
| KO33-7  | High-Cr | 9.35  | 1471 | 590 | 2252 | 366 | 840 | 1.61 | 493 | 24.40 |
| KO33-8  | High-Cr | 8.28  | 1471 | 594 | 2266 | 365 | 833 | 2.02 | 509 | 24.40 |
| KO33-9  | High-Cr | 9.38  | 1530 | 608 | 2329 | 375 | 853 | 1.85 | 500 | 25.67 |
| KO33-10 | High-Cr | 8.16  | 1498 | 594 | 2260 | 372 | 821 | 1.68 | 498 | 24.18 |
| KO33-11 | High-Cr | 9.11  | 1437 | 585 | 2282 | 365 | 831 | 1.74 | 490 | 24.17 |
| KO33-12 | High-Cr | 9.39  | 1512 | 593 | 2289 | 366 | 837 | 2.10 | 503 | 24.12 |
| KO33-13 | High-Cr | 7.33  | 1494 | 591 | 2334 | 370 | 841 | 1.89 | 495 | 23.87 |
| KO33-14 | High-Cr | 8.40  | 1403 | 573 | 2287 | 365 | 799 | 1.62 | 506 | 23.23 |
| KO33-15 | High-Cr | 9.08  | 1511 | 591 | 2314 | 371 | 836 | 1.84 | 512 | 24.20 |
| KO33-16 | High-Cr | 9.87  | 1472 | 589 | 2336 | 368 | 759 | 1.62 | 519 | 25.00 |
| KO33-17 | High-Cr | 8.04  | 1462 | 574 | 2260 | 371 | 814 | 2.69 | 507 | 23.10 |
| KO33-18 | High-Cr | 9.46  | 1523 | 587 | 2284 | 373 | 846 | 1.86 | 523 | 23.22 |
| KO33-19 | High-Cr | 9.22  | 1512 | 588 | 2316 | 378 | 839 | 1.39 | 514 | 25.00 |
| KO33-20 | High-Cr | 9.73  | 1532 | 594 | 2330 | 376 | 838 | 2.16 | 519 | 24.30 |
| KO33-21 | High-Cr | 7.32  | 1521 | 601 | 2344 | 374 | 840 | 1.55 | 527 | 24.29 |
| KO33-22 | High-Cr | 8.50  | 1557 | 599 | 2378 | 381 | 861 | 2.10 | 527 | 23.86 |
| KO33-23 | High-Cr | 9.73  | 1507 | 587 | 2388 | 378 | 850 | 1.71 | 503 | 23.10 |
| KO33-24 | High-Cr | 8.53  | 1506 | 591 | 2358 | 377 | 846 | 1.77 | 513 | 24.60 |
| KO33-25 | High-Cr | 9.05  | 1503 | 584 | 2376 | 381 | 856 | 1.56 | 530 | 23.51 |
| KO33-26 | High-Cr | 9.55  | 1525 | 580 | 2419 | 391 | 892 | 1.82 | 552 | 23.19 |
| KO33-27 | High-Cr | 8.34  | 1491 | 577 | 2341 | 381 | 844 | 1.66 | 527 | 23.24 |
| Element | Sc | Ti | V | Mn | Co | Ni | Cu | Zn | Ga |
|---------|----|----|---|----|----|----|----|----|----|
| **Average** | 0.73 | 32.73 | 8 | 44 | 6 | 24.05 | 0.26 | 15.74 | 0.69 |
| KO31-1 | High-Cr | 6.55 | 1096 | 557 | 1571 | 263 | 887 | 4.94 | 384 | 19.03 |
| KO31-2 | High-Cr | 6.55 | 1126 | 551 | 1586 | 265 | 881 | 6.12 | 388 | 18.96 |
| KO31-3 | High-Cr | 6.34 | 1143 | 547 | 1549 | 261 | 881 | 6.32 | 385 | 18.57 |
| KO31-4 | High-Cr | 6.77 | 1128 | 539 | 1604 | 260 | 835 | 3.54 | 387 | 18.36 |
| KO31-5 | High-Cr | 6.27 | 1125 | 530 | 1552 | 261 | 911 | 8.50 | 384 | 18.44 |
| KO31-6 | High-Cr | 6.49 | 1112 | 511 | 1570 | 263 | 899 | 9.16 | 371 | 18.30 |
| KO31-7 | High-Cr | 6.56 | 1128 | 496 | 1608 | 263 | 873 | 5.33 | 375 | 17.91 |
| KO31-8 | High-Cr | 6.49 | 1111 | 493 | 1594 | 268 | 846 | 4.42 | 388 | 18.01 |
| KO31-9 | High-Cr | 6.08 | 1106 | 476 | 1572 | 263 | 878 | 5.88 | 379 | 18.72 |
| KO31-10 | High-Cr | 6.23 | 1106 | 470 | 1592 | 263 | 876 | 5.48 | 381 | 18.05 |
| KO31-11 | High-Cr | 6.98 | 1109 | 474 | 1585 | 263 | 866 | 5.32 | 372 | 17.98 |
| KO31-12 | High-Cr | 6.43 | 1098 | 468 | 1560 | 261 | 874 | 5.98 | 370 | 17.55 |
| KO31-13 | High-Cr | 6.30 | 1099 | 510 | 1565 | 258 | 881 | 5.31 | 372 | 17.70 |
| KO31-14 | High-Cr | 6.28 | 1125 | 520 | 1550 | 261 | 941 | 8.65 | 375 | 18.70 |
| KO31-15 | High-Cr | 6.80 | 1102 | 522 | 1576 | 263 | 867 | 5.86 | 382 | 18.18 |
| KO31-16 | High-Cr | 6.61 | 1140 | 552 | 1570 | 262 | 892 | 4.00 | 389 | 19.93 |
| KO31-17 | High-Cr | 6.41 | 1114 | 537 | 1538 | 264 | 892 | 6.50 | 379 | 18.54 |
| KO31-18 | High-Cr | 6.32 | 1069 | 508 | 1621 | 268 | 821 | 4.93 | 367 | 18.52 |
| KO31-19 | High-Cr | 6.58 | 1112 | 521 | 1610 | 266 | 860 | 3.34 | 369 | 17.58 |
| KO31-20 | High-Cr | 6.44 | 1123 | 524 | 1582 | 269 | 881 | 5.79 | 374 | 18.90 |
| KO31-21 | High-Cr | 6.48 | 1094 | 496 | 1608 | 265 | 829 | 1.12 | 376 | 16.93 |
| KO31-22 | High-Cr | 6.63 | 1087 | 502 | 1588 | 266 | 841 | 4.92 | 369 | 18.58 |
| KO31-23 | High-Cr | 6.22 | 1098 | 479 | 1594 | 266 | 875 | 5.64 | 381 | 18.10 |
| KO31-24 | High-Cr | 6.57 | 1101 | 477 | 1594 | 267 | 882 | 5.72 | 383 | 18.41 |
| KO31-25 | High-Cr | 6.27 | 1092 | 476 | 1575 | 264 | 857 | 3.80 | 371 | 17.99 |
| KO31-26 | High-Cr | 6.67 | 1018 | 455 | 1626 | 271 | 781 | 3.42 | 379 | 17.04 |
| KO31-27 | High-Cr | 6.46 | 1075 | 466 | 1592 | 263 | 851 | 3.53 | 393 | 18.52 |
| KO31-28 | High-Cr | 6.56 | 1139 | 489 | 1580 | 265 | 877 | 4.92 | 381 | 19.02 |
| KO31-29 | High-Cr | 6.90 | 1100 | 497 | 1572 | 264 | 910 | 5.74 | 368 | 18.42 |
| KO31-30 | High-Cr | 6.74 | 1123 | 500 | 1573 | 268 | 879 | 5.11 | 378 | 17.79 |
| KO31-31 | High-Cr | 6.42 | 1110 | 546 | 1566 | 277 | 858 | 4.39 | 392 | 17.87 |
| KO31-32 | High-Cr | 6.71 | 1127 | 568 | 1584 | 268 | 863 | 4.12 | 385 | 18.41 |
| KO31-33 | High-Cr | 6.02 | 1140 | 566 | 1570 | 267 | 875 | 4.98 | 379 | 18.90 |
| KO31-34 | High-Cr | 6.59 | 1162 | 574 | 1574 | 268 | 876 | 4.66 | 372 | 18.59 |
| KO31-35 | High-Cr | 6.45 | 1116 | 550 | 1565 | 270 | 897 | 7.00 | 382 | 19.29 |
| KO31-36 | High-Cr | 6.36 | 1132 | 556 | 1603 | 270 | 882 | 5.79 | 374 | 17.92 |
| KO31-37 | High-Cr | 6.56 | 1139 | 574 | 1568 | 268 | 894 | 4.11 | 381 | 18.69 |
| KO31-38 | High-Cr | 6.22 | 1057 | 550 | 1580 | 258 | 839 | 3.24 | 352 | 17.25 |
| KO31-39 | High-Cr | 6.18 | 1115 | 524 | 2011 | 347 | 709 | 1.88 | 492 | 16.90 |
| **ST DEV** | 0.21 | 16.15 | 34 | 72 | 14 | 38.01 | 1.61 | 19.96 | 0.64 |
| **Average** | 6.47 | 1110 | 517 | 1592 | 267 | 867.1 | 5.11 | 381 | 18.27 |

**Zhob**

| Z100-1 | High-Al | 4.92 | 1845 | 1339 | 1894 | 307 | 1786 | 0.00 | 880 | 72.90 |
| Z100-2 | High-Al | 4.32 | 1919 | 1347 | 1734 | 297 | 2008 | 1.27 | 788 | 70.90 |
| Z100-3 | High-Al | 5.22 | 1871 | 1282 | 1786 | 289 | 1765 | 2.60 | 784 | 62.90 |
| Element   | Type     | Sc     | Ti     | V      | Mn     | Co     | Ni     | Cu     | Zn     | Ga     |
|----------|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Z100-4   | High-Al  | 5.81   | 1913   | 1300   | 1797   | 296    | 1769   | 0.00   | 828    | 64.80  |
| Z100-5   | High-Al  | 5.47   | 1871   | 1309   | 1754   | 301    | 1999   | 2.82   | 800    | 68.70  |
| Z100-6   | High-Al  | 6.86   | 1846   | 1282   | 1783   | 292    | 1939   | 2.19   | 767    | 64.40  |
| Z100-7   | High-Al  | 6.26   | 1764   | 1279   | 1804   | 293    | 1970   | 2.66   | 791    | 66.40  |
| Z100-8   | High-Al  | 5.14   | 1888   | 1318   | 1724   | 294    | 2058   | 3.39   | 794    | 68.00  |
| Z100-9   | High-Al  | 5.58   | 1923   | 1358   | 1755   | 301    | 2130   | 3.12   | 821    | 71.50  |
| Z100-10  | High-Al  | 4.84   | 1929   | 1332   | 1825   | 299    | 1888   | 0.00   | 781    | 64.80  |
| Z100-11  | High-Al  | 5.58   | 1961   | 1371   | 1747   | 303    | 2055   | 1.53   | 866    | 72.40  |
| Z100-12  | High-Al  | 4.89   | 1873   | 1342   | 1839   | 303    | 1915   | 1.04   | 879    | 69.70  |
| Z105a-1  | High-Al  | 5.89   | 1913   | 1351   | 1755   | 296    | 2138   | 3.12   | 823    | 68.10  |
| Z105a-2  | High-Al  | 5.98   | 1852   | 1367   | 1743   | 302    | 2207   | 0.00   | 836    | 72.50  |
| Z105a-3  | High-Al  | 5.02   | 1942   | 1344   | 1714   | 308    | 2127   | 1.85   | 858    | 67.10  |
| Z105a-4  | High-Al  | 6.10   | 1846   | 1333   | 1789   | 301    | 1844   | 1.68   | 869    | 70.20  |
| Z105a-5  | High-Al  | 5.08   | 1908   | 1346   | 1816   | 297    | 1949   | 2.30   | 824    | 67.90  |
| Z105a-6  | High-Al  | 3.57   | 1972   | 1385   | 1742   | 309    | 2157   | 1.33   | 895    | 66.80  |
| Z105a-7  | High-Al  | 6.14   | 1884   | 1352   | 1778   | 303    | 2137   | 4.95   | 811    | 68.30  |
| Z105a-8  | High-Al  | 6.13   | 1954   | 1369   | 1763   | 308    | 2173   | 2.81   | 856    | 72.00  |
| Z105a-9  | High-Al  | 6.18   | 1880   | 1348   | 1779   | 304    | 2108   | 3.04   | 844    | 69.80  |
| Z105a-10 | High-Al  | 5.59   | 1944   | 1386   | 1771   | 308    | 2135   | 2.82   | 863    | 70.70  |
| Z105a-11 | High-Al  | 6.15   | 1857   | 1366   | 1780   | 308    | 2035   | 2.63   | 861    | 73.10  |
| Z105a-12 | High-Al  | 5.50   | 1911   | 1388   | 1798   | 307    | 2179   | 1.99   | 850    | 70.90  |
| Z105a-13 | High-Al  | 5.03   | 1943   | 1352   | 1790   | 300    | 1981   | 0.00   | 789    | 67.20  |
| Average  |          | 5.49   | 1896   | 1342   | 1778   | 301    | 2018.1 | 2.45   | 830.3  | 68.88  |

| ST DEV   | 0.71    | 47.43  | 32     | 39     | 6      | 134.74 | 0.91   | 36.66  | 2.88   |
|----------|---------|--------|--------|--------|--------|--------|--------|--------|--------|

Table 2. (Continued)
ments contents in amphibole range between 0.92 to 2.80 wt% for Na$_2$O, 0.01 to 0.03 wt% for K$_2$O and 0.17 to 0.79 wt% for TiO$_2$.

### Discussion

#### Nature of Parental Melts of the Zhob Valley Chromitite

The Al$_2$O$_3$ and TiO$_2$ (wt%) contents of chromite spinel are characteristics for determining the origin and tectonic setting of parental melt of chromitites (Auge, 1987; Melcher et al., 1997; Kamenetsky et al., 2001; Uysal et al., 2007a; Rollinson, 2008; Page and Barnes, 2009; Zaccarini et al., 2011). The parental melts occurring chromitites are formed by various processes such as partial melting (Kelemen et al., 1992; Arai, 1994; Zhou et al., 1996), melt/rock reaction and melt/melt interaction (Zhou et al., 1998; Melcher et al., 1999; Kamenetsky et al., 2001; Uysal et al., 2005, 2009). Several authors noted that the concentration of Al$_2$O$_3$ (wt%) and TiO$_2$ (wt%), and FeO/MgO ratios of chromite spinel are

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#### Table 3. Composition of olivine and amphibole inclusions in chromite. Ol=Olivine and Amp=Amphibole, N=Number of spot analysis, bdl= below detection limit

| Sample No | B43 | B43a | B44 cr | B63 cr | KO30 | Z100 | Z100c | Z103c | B43 | KO30 | Z100 |
|-----------|-----|------|--------|--------|------|------|-------|-------|-----|------|------|
| Mineral   | Ol  | Ol   | Ol     | Ol     | Ol   | Ol   | Ol    | Ol    | Ol  | Ol   | Ol   |
| Type      |     |      |        |        |      |      |       |       |     |      |      |
| SiO$_2$   | 42.55 | 41.50 | 41.59 | 41.99 | 42.93 | 43.06 | 42.97 | 42.51 | 52.41 | 51.08 | 46.89 |
| TiO$_2$   | bdl  | bdl  | 0.01   | 0.04   | 0.02  | 0.26  | bdl   | 0.03  | 0.17  | 0.79  | 0.70  |
| Al$_2$O$_3$| 0.22 | 0.78 | 0.54   | bdl    | 0.75  | 0.06  | 0.57  | 0.19  | 6.55  | 7.04  | 11.76 |
| Cr$_2$O$_3$| 0.29 | 0.27 | 0.35   | 0.62   | 0.36  | 0.64  | 0.41  | 0.80  | 1.76  | 0.90  | 1.70  |
| FeO       | 3.25 | 3.62 | 2.70   | 2.88   | 3.21  | 3.48  | 3.38  | 2.86  | 3.35  | 1.60  | 2.08  |
| MnO       | 0.50 | bdl  | 0.20   | bdl    | 0.27  | 0.10  | 0.18  | 0.30  | bdl   | 0.04  | 0.02  |
| NiO       | 0.80 | bdl  | 0.28   | 0.69   | 0.05  | 0.21  | 0.05  | 0.50  | 0.15  | 0.30  | 0.15  |
| MgO       | 52.76 | 52.92 | 53.51 | 54.53  | 51.88 | 51.85 | 51.76 | 52.25 | 21.19 | 21.02 | 20.01 |
| CaO       | bdl  | bdl  | 0.03   | 0.02   | 0.06  | 0.15  | 0.05  | 0.07  | 11.48 | 12.07 | 12.11 |
| Na$_2$O   | 0.36 | bdl  | bdl    | bdl    | bdl   | 0.06  | bdl   | bdl   | 0.92  | 1.40  | 2.80  |
| K$_2$O    | 0.05 | bdl  | 0.04   | bdl    | 0.03  | 0.28  | 0.04  | 0.40  | 0.01  | 0.02  | 0.03  |
| Total$\Sigma$ | 99.46 | 99.10 | 99.24 | 100.78 | 99.12 | 99.90 | 99.33 | 99.92 | 97.88 | 96.24 | 98.25 |

Cations (structural formula on the basis of 4 oxygen for olivine and 23 oxygen for amphibole)

| Si   | 1.02 | 1.00 | 1.00 | 0.99 | 1.03 | 1.03 | 1.03 | 1.01 | 7.25 | 7.14 | 6.53 |
| Ti   | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.08 | 0.07 |
| Al   | 0.00 | 0.02 | 0.02 | 0.00 | 0.01 | 0.01 | 0.02 | 0.01 | 1.07 | 1.16 | 1.93 |
| Cr   | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.19 | 0.10 | 0.19 |
| Fe$^{2+}$ | 0.07 | 0.07 | 0.05 | 0.06 | 0.06 | 0.07 | 0.07 | 0.06 | 0.39 | 0.19 | 0.24 |
| Mn   | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| Ni   | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| Mg   | 1.88 | 1.89 | 1.91 | 1.92 | 1.85 | 1.84 | 1.84 | 1.86 | 4.37 | 4.38 | 4.16 |
| Ca   | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.70 | 1.81 | 1.81 |
| Na   | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.38 | 0.76 |
| K    | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 |
| Total$\Sigma$ | 2.98 | 2.99 | 2.99 | 2.99 | 2.96 | 2.96 | 2.96 | 2.97 | 15.22 | 15.25 | 15.70 |
| Mg#  | 0.96 | 0.96 | 0.97 | 0.97 | 0.97 | 0.96 | 0.96 | 0.97 | 0.92 | 0.96 | 0.95 |

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Figure 7. Comparison of average trace elements concentrations in high-Cr and high-Al chromitites, showing distinct differences between the two types.
in direct relation with the composition of the parental melts (Kame-
netsky et al., 2001; Rollinson, 2008).

The equation developed by Rollinson (2008) based on the data of
chromite spinels from 36 different igneous suites from oceanic, arc,
and intraplate tectonic setting of Kamenetsky et al. (2001), can be used to
derive the composition of parental melts:

\[
\begin{align*}
\text{Al}_2\text{O}_3_{\text{melt}} & = 5.2181 \times \ln (\text{Al}_2\text{O}_3_{\text{chromite}}) - 1.50505 \\
\ln (\text{TiO}_2_{\text{melt}}) & = 1.0963 \times (\text{TiO}_2_{\text{chromite}})^{0.7863}
\end{align*}
\]

(i) (ii)

The calculated \( \text{Al}_2\text{O}_3 \) (wt\%) and \( \text{TiO}_2 \) (wt\%) compositions of the
parental melts of both high-Cr and high-Al chromitites from the Zhob
valley ophiolite are presented in Table 1. The concentrations of \( \text{Al}_2\text{O}_3 \)
of the parental melts of high-Cr chromitites ranges from 9.2 to 13.8
wt\%, while for the high-Al ones it varies between 14.9 and 15.4 wt\%.
Furthermore, the \( \text{TiO}_2 \) concentration of parental melts of high-Cr and
high-Al chromitites varies from 0.02 to 0.53 wt\% and from 0.17 to
0.42 wt\%, respectively. The \( \text{Al}_2\text{O}_3 \) contents of the inferred parental
melts of high-Cr chromitites (9.2–13.8 wt\%) are in agreement with
\( \text{Al}_2\text{O}_3 \) concentrations of chromitites of the Elekdag Ophiolite (nor-
thern Turkey) (9.4–13.2 wt\%; Dönmez et al., 2014), Kop Mountain
(Turkey) (10.1–13.5 wt\%; Uysal et al., 2007a), Thetford Mines Ophi-
olite (9.2–12.9 wt\%; Page and Barnes, 2009), Oman Ophiolite (11.8–
12.9 wt\%; Rollinson, 2008), and Luobusa Ophiolite (13.8 wt\%; Zhou
et al., 2014). In addition, the \( \text{Al}_2\text{O}_3 \) (wt\%) values of high-Cr chromi-
tites fall within the range of composition of chromite derived from
boninite melt (10.6–14.4 wt\%; Wilson, 1989). However, the calculated

Figure 8. 100*Cr# vs. Fe\(^{2+}\)# for chromite from podiform chromitites in the Zhob valley ophiolite. Boninite and MORB values taken from
Page and Barnes, (2009). Fields for chromite from MORB and boninite are from Barnes and Roeder (2001). Hess Deep (a MOR setting)
(Arai and Matsukage, 1998) and Japan Arc Xenolith (a supra-subduction setting) (Arai and Abe, 1994), Tari-Misaka (Arai and Yurimoto,
1994), TMO (Page and Barnes, 2009). Average contents of TMO, Tr and TM are plotted. MOR=Mid ocean ridge, SSZ=Supra-subduction
zone, Tr= Turkish deposits, TM, Tari-Misaka, TMO=Thetford Mines Ophiolite.
Al$_2$O$_3$ (wt%) values of the parental magma of studied high-Al chromitites (14.9–15.4 wt%) are similar to the high-Al chromitites of southern Turkey (14.5–16.2 wt%; Akmaz et al., 2014), Sagua de Tanamo (eastern Cuba) (15–16 wt%; Gonzalez-Jimenez et al., 2011), Kempirsai-Batamshinsk (Kazakhstan) (13.5–16.7 wt%; Melcher et al., 1997), and Sartohay Ophiolite (16.3 wt%; Zhou et al., 2014) and comparable to the Al$_2$O$_3$ (wt%) concentrations with MORB melts (16 wt%; Wilson, 1989). Thus, the data indicates that parental magma of high-Cr chromitites were boninitic while high-Al chromitite was crystallized from MORB-like melts.

In the Fe$^{2+}$#/Cr# diagram, chromitites from the Zhob valley ophiolite plot in the high-Cr and high-Al fields of podiform chromitites, which further extends from the high-Cr boninitic field to the high-Al MORB field (Fig. 8). With the exception of a few samples that have

Figure 9. (a) Ti vs. Cr#, (b) Ga vs. Cr#, (c) V vs. Cr#, (d) Sc vs. Cr#, (e) Zn vs. Cr#, (f) Co vs. Cr#, (g) Ni vs. Cr#, (h) Mn vs. Cr# for chromites from Zhob valley ophiolite. LO=Luobusa Ophiolite (Zhou et al., 2014), SO=Sartohay Ophiolite (Zhou et al., 2014), AO=Acoje Ophiolite (Zhou et al., 2014), CO=Coto Ophiolite (Zhou et al., 2014). Podiform chromitite, MORB and BON fields, other data source and acronyms are as in Figure 8. Note that average contents of elements are plotted.
higher Fe\(^{3+}\), high-Cr chromitites of the Zhob valley ophiolite exhibit an identical range of compositions to the Thetford Mines Ophiolite (TMO), supra-subduction zone (SSZ), and high-Cr chromite from Troodos Ophiolite (Fig. 8) (Arai and Abe, 1994; Arai and Yurimoto, 1994; Panktuce and Cabri, 1995; Page and Barnes, 2009). The compositions of high-Al chromites shows a similar range to the high-Al chromitites from the Tari-Misaka Complex (TM), and MOR (Auge, 1987; Arai and Yurimoto, 1994; Ahmed and Arai, 2002).

Ga, Ti, Zn, Ni and V concentrations of chromite from the Zhob valley chromitites show negative correlation with Cr\(^{#}\) (Fig. 9) which reflects crystal fractionation in the parental melt of chromite (Page and Barnes, 2009). High-Cr chromitites from the Zhob valley ophiolite have a similar range of Ti contents to the northern Oman (NO), Luobusa Ophiolite (LO), and chromitites from supra-subduction zone, while high-Al chromitites have similar contents of Ti to the Tari-Misaka Complex (TM) and Sartohay Ophiolite (SO) (Fig. 9a). Gallium, vanadium and nickel show a more pronounced inverse correlation with Cr\(^{#}\) than Ti and Zn (Fig. 9). Ga in high-Cr chromitites is similar with the TMO and Acoce ophiolite (AO) and close to chromites in boninites (Fig. 9b), while high-Al chromitites are enriched in Ga contents compared to those of the Sartohay Ophiolite and close to MORB content. Vanadium in high-Cr chromitites exhibits a similar range to the TMO and northern Oman chromitites while it is lower than chromitites in boninites. High-Al chromitites are in agreement with TM and Sartohay chromitites in terms of vanadium contents (Fig. 9c). The depletion of V in high-Cr chromite is believed to be the result of various oxidation conditions of boninitic parental melts (Page and Barnes, 2009). It is partly related to oxidizing conditions that vary from the mantle to the top of the crust or to oxidation of boninite magmas during shallow ascent and eruption (Page and Barnes, 2009).

Sc contents of high-Cr and high-Al chromitites show similar ranges to the TMO and boninite and Sartohay, Coto Ophiolites (CO) and MORB, respectively (Fig. 9d). In high Cr chromitites, Zn and Ni contents are comparable with boninite, TMO and LO, but Co and Mn are higher than boninite (Fig. 9e, f, g, h). On the other hand, high-Al chromite is enriched in Ni, Mn, Zn and Co as compared to those from MORB (Fig. 9e, f, g, h). Similarly, Mn, Zn and Co enrichments are interpreted as metamorphism of chromitites in the literature (Colàs et al., 2014; Uysal et al., 2018). Similarly high concentrations of these elements are reported from highly altered chromite from Morocco (Gahan and Arai, 2007), Greece (Parasekopoulos and Economou, 1981; Michailidis, 1990; Economou-Eliopoulos, 2003), Dobromirtsi Chromitites, Bulgaria (Gonzállez-Jimenez et al., 2015) and some deposits from southeastern Turkey (Akmaز et al., 2014).

Trace elements of chromitites from the Zhob valley ophiolite were normalized to chromite compositions from MORB and arranged on the pattern of Page and Barnes (2009) in Figure 10. Moreover, high-Cr chromitites were compared to Luobusa Ophiolite (LO) (Zhou et al., 2004) and Thetford Mines Ophiolite (TMO) (Page and Barnes, 2009) whereas high-Al chromitites were compared to Sartohay Ophiolite (SO) (Zhou et al., 2014) and Zambales Ophiolite (ZO) (González-Jimenez et al., 2012) (Fig. 10). With minor exceptions, concentrations of almost all elements of high-Cr chromitite are in agreement with TMO while they are partially enriched in Ga, Ti, Zn, and Mn compared with Luobusa Ophiolite (Fig. 10a). The high-Al chromitites show a similar pattern to the Zambales Ophiolite (ZO) and Sartohay Ophiolite (SO). However, they are slightly enriched in Zn, Co, Mn (ppm) and Cr\(_2\)O\(_3\) (wt%) and depleted in Al\(_2\)O\(_3\) (wt%) and MgO (wt%) compared with those in ZO and higher in terms of Ga, Ni, Zn, Co, Mn (ppm) and Cr\(_2\)O\(_3\) (wt%) compared to these elements in SO (Fig. 10b). The Ti, V, Ni, Zn and Ga contents in high-Al chromitites more enriched than high-Cr ones suggest that parental melts from which high-Al chromitites were formed. The similarity of high-Cr chromitite from studied deposits to the boninite and TMO indicates genetic link between them and suggests that high-Cr chromitites from Zhob valley ophiolite crystallized out from boninitic melts. On the other hand, high-Al chromitites exhibit similar patterns to the MORB. But high-Al chromite is slightly depleted in Al\(_2\)O\(_3\) and Ti compared to those from MORB while similar to those from Sartohay Ophiolite which reveals high-Al chromitites have thilitic/MORB affinity.

**Compositional Variation and Alteration in Chromites**

The profile analyses of chromite grains of both types of chromitites show that most of them are unzoned. However, in some grains of high-Cr chromitite, Cr contents decrease while Al\(_2\)O\(_3\) (wt%) and FeO\(_{total}\) (wt%) contents increase from core to rim. Therefore, the Cr\(^{#}\) values are decreasing from core to rim in high-Cr chromite grains (Fig. 6b).

This kind of zoning is considered to be the results of fractionation of melt during the formation of chromite, hence, reflect magmatic zoning (Akmaز et al., 2014). On the other hand, in some grains of high-Al chromitites, Al\(_2\)O\(_3\) (wt%) and MgO (wt%) contents decrease from core to rim while Cr and FeO\(_{total}\) (wt%) contents increase from core to rim, resulting in an increase of Cr\(^{#}\) from core to rim (Fig. 6a). This kind of zonation indicates that secondary processes had affected the chromite grains which had resulted in the formation of ferritchromite.

The alteration process observed in ophiolitic chromitites is associated with many events which are serpentinization (Burkhard, 1993), regional metamorphism (Barnes, 2000; González-Jiménez et al., 2009), decomposition (Pooley, 2004) and lateritization (Economou-Eliopoulos, 2003). As a result of petrographic investigations, any decompositional and lateritization process was not observed in Zhob valley chromitites. Therefore, the main cause of ferritchromite formation can be explained as serpentinization and/or metamorphism (Kapsiotis, 2015).

The formation of ferritchromite in the Kalkan chromitites (southern Ural, has been described and three stages were suggested for its development (Merlini et al., 2009). In first stage chromite grains equilibrated with surrounding olivine. The second stage involved the serpentinization (lizardite and chrysotile) of the matrix rich with olivine at approximately 200 to 300 °C (Auzende et al., 2006; Hajialioghi et al., 2007). Almost all lizardite/chrysotile transformed by prograde metamorphism at more than 300 °C into the polymorph antigorite in the third stage. The metamorphic reaction 2 (Mg\(_{2-x}\)Fe\(_{x}\)Al\(_{2}\)O\(_{4}\) [chromite] + 3/2 (Mg\(_{2}\)Fe\(_{2}\)Al\(_{2}\)O\(_{4}\) [Fe-chromite]) Si\(_2\)O\(_3\) (OH)\(_2\) + H\(_2\)O + 1/12O\(_2\) [antigorite] → 7/6 (Mg\(_{2-x}\)Fe\(_x\)Al\(_{2}\)O\(_{4}\) [Cr-chlorite] + 1/2 (Mg\(_{2-x}\)Fe\(_x\)Al\(_{2}\)O\(_{4}\) [Al-chlorite]) (Al\(_2\)Si\(_2\)O\(_{7}\) [OH]) \(_{2}\) [Cr-chlorite]) converts chromite-serpentine into ferritchromite-chromian-chlorite assemblages in the presence of a hydrous fluid phase (Merlini et al., 2009). Thus, according to this reaction, the generation of ferritchromite in chromite grains of high-Al chromitite from the Zhob valley ophiolite indicates that this is due to metamorphic processes (Barnes, 2000; Proenza et al., 2004; Mukherjee et al., 2010; Gervilla et al., 2012).
Genesis and Geotectonic Environment

Today, the formation of podiform chromitites is not fully understood. Fractional crystallization from melt supplied through magmatic conduits is regarded as the primary model for the formation of podiform chromitites (Thayer, 1964; Lebanc and Ceuleneer, 1992). Melt/rock reaction, multi stage partial melting, magma mixing and magma segregation processes can lead to chromite formation (Paktunc et al., 1990; Lebanc and Ceuleneer, 1992). These models consider that melt/rock reactions and eventually melt/melt mixing are significant processes in the genesis of podiform chromitites (Kelemen, 1990; Arai and Yurimoto, 1994; Zhou et al., 1996). A model proposed by Gonzales-Jimenez et al. (2014b) suggests that podiform chromitites form in networks and channels of highly porous dunite, which formed in the mantle peridotite by melt/rock reaction. In high permeability conduits, the mixing and crystallization of new basaltic magma yields a suitable environment for podiform chromitite formation. Size, type and texture of chromitites may indicate the pattern of melt flow at different melt/rock ratios within highly porous networks of channels and a range of temperature contrasts between melt and the host peridotite.

Figure 10. Chromite normalized major-trace elements of high-Cr (a) and high-Al (b) Zhob valley ophiolitic chromitites. Data source for TMO and boninite values were from (Page and Barnes, 2009), ZO chromitites values from (Gonzalez-Jimenez et al., 2012) Luobusa and Sar-torhay chromitites values were from (Zhou et al., 2014). Data source and acronyms are as in Figure 8. Note that average contents of elements are plotted.
Many researchers have revealed that both high-Cr and high-Al chromitites can occur together within depleted peridotite in the same ophiolitic massif as well as in separate massifs (Zhou et al., 1994; Leblanc, 1995; Melcher et al., 1997; Proenza et al., 1999; Ahmed et al., 2001; Gervilla et al., 2005; Uysal et al., 2007a, 2009; Zaccarini et al., 2011; Kapsiotis, 2013). In addition, several authors explained the coexistence of high-Cr and high-Al chromitites in different ways. 1– It has been suggested that the melt responsible for the formation of chromite in a supra-subduction zone environment origins from several depleted mantle sources (MORB to boninitic type melt) (Uysal et al., 2009; Gonzales-Jimenez et al. 2011; Zaccarini et al., 2011). 2– Much depletion of mantle peridotite upwards in mantle sequence, with enhancement of Cr# values in ophiolitic chromitites situated in residual mantle (Leblanc and Nicolas, 1992; Stowe, 1994; Uysal et al., 2007b). Chromitites from the Zhob valley ophiolitic bodies have lenses and pods of variable size that have sharp contacts with their dunite envelopes, and interlayered dunite and chromitites. These are characteristics that support a model in which metasomatic-magmatic processes have occurred in a network of channels through which melts percolated and reacted with peridotite wall rocks.

Contents of Al₂O₃ and TiO₂ in chromite are related to the Al₂O₃ and TiO₂ contents of parental melts of chromites which provide useful indicators of tectonic settings (Kamenetsky et al., 2001). Calculated Al₂O₃ (wt%) contents of parental melts of high-Cr and high-Al from Zhob valley ore bodies suggest that they have an arc and MORB geochemical affinity, respectively. The very low TiO₂ content of parental melt of high-Cr chromitites suggests that the chromitites were derived from boninitic melt formed in an island arc environment while parental fluid composition of high-Al chromitites indicates that it has been derived from MORB melts.

Inclusions of silicate minerals in chromite grains have been reported in several podiform chromitites (Johan and Lebel, 1978; Johan et al., 1983; Augé, 1987; Lorand and Ceuleeneer, 1989; Graham et al., 1996; Melcher et al., 1997; Gervilla et al., 2005). Some authors like Johan and Lebel (1978), and Johan et al. (1983) argue that hydrous inclusions are evidence of unmixing of basaltic melt and an aqueous fluid phase and other volatile constituents. Furthermore, hydrous silicates indicate that during the chromite crystallization basaltic melt was contaminated with a fluid phase (Watkinson and Mainwaring, 1980; Lorand and Ceuleeneer, 1989). We have observed mineral inclusions in unaltered chromites of the Zhob valley. Chromite grains of both kinds of chromitites contain a variety of silicate mineral inclusions. These inclusions occur together in a single chromite grain as well as in separate grains. Among the silicate inclusions, olivine and amphibole are detected (Fig. 3f and h). These silicate inclusions are typically anhedral to subhedral in shape and granular in texture. These assemblages and textures of minerals indicate that the mineral inclusions represent crystallization products of trapped liquids during crystallization of chromite (Zhou et al., 2014). The presence of amphibole inclusions and high Cr# values prove that high-Cr chromitites were formed by boninitic type melts in supra-subduction zone environment. However, minor-trace element composition and amphibole inclusions indicate that high-Al chromitites are generated by MORB-

![Figure 11. Tectonic discrimination using 100*Cr# vs. TiO₂ for chromites for podiform chromitites From Zhob valley ophiolite. The podiform chromitite field is from Page and Barnes (2009) and fields for chrome from MORB and boninite are from (Barnes and Roeder, 2001).](image-url)
Cr# values and TiO₂ contents (wt%) of chromite from both chromitites are plotted in the diagram TiO₂ vs Cr# (Fig. 11). Both chromitites fall in the field of ophiolitic podiform chromitites while high-Cr chromitites show good similarities with chromitites that are derived from boninitic melts, generated in supra-subduction zones and high-Al chromitites analyses plot close to the MORB field.

Using the diagram (Al₂O₃ vs TiO₂ wt%) of Kamenetsky et al. (2001) which is used to separate chromites crystallized from OIB, LIP, MORB and arc related basaltic melts (Fig. 12), high-Cr chromitites related the Zhob valley ophiolite exhibit a positive correlation and plot in or near to the arc field which suggests boninitic affinity. The high-Al chromitites plot within or close to the MORB field and display MORB affinity. Further, trace elements also impart suitable evidences for tectonic environments. Ga is compatible in chromian spinel (Malvin and Drake, 1987) and its concentration in chromites is a sensitive indicator of magma compositions and degree of depletion (Paktunc and Cabri, 1995, Zhou et al., 2014). Ga decreases with increasing Cr# (Fig. 9b) (from high-Al to high-Cr chromitite) and inversely correlations with Cr#. Thus, this correlation reveals a switch from a mid-ocean ridge setting to a supra-subduction zone setting (Alabaster et al., 1982; Umino et al., 1990; Dare et al., 2008; Pagé and Barnes, 2009).

Conclusions

In the Zhob valley ophiolite, the Khanozai and Muslim Bagh bodies contain high-Cr (> 0.6) chromitites while the Zhob body includes of high-Al (< 0.6) chromitites. Chromite of high-Cr chromitite is largely uniform in composition but a few grains are partially zoned, with decrease in Cr# from core to rim which reflects the melt fractionation during crystallization of chromite. In the chromite grains of high-Al chromitites, Cr# and FeO total (wt%) decrease from rim to core which suggests that ferrichromite from high-Al chromitites had been generated by secondary processes.

The parental melt composition of high-Cr chromitites and the hydrous
silicate inclusions reflect that the parental magma is boninitic, which formed by high degrees of partial melting of mantle, generating Sundersaturated and hydrous melt. In contrast, the calculated composition of parental melt of the high-Al chromites is MORB-like melt and the presence of amphibole inclusions indicate that high-Al chromite are derived from MORB-like melt reaction with depleted mantle that produced hydrous melt.

Negative correlations of vanadium, gallium, zinc, nickel and titanium with Cr# reveal the fractionation of the parental melt. The trace elements of high-Cr chromite form an identical pattern to the boninitic lava which shows that the parental melt of high-Cr is boninitic in nature. High-Al chromites are enriched in Al, Ga, Ti, Ni, and Mg compared to boninite and form flat patterns similar to MORB and suggest that parental melt is basaltic with MORB affinity.

The field, petrographic and geochemical data suggest that the Zhob valley chromitites are crystallized from ascending melts through a network of channels, formed by melt-rock interactions at different degrees and high-Cr chromite are crystallized out from boninite magma and may be linked to a supra-subduction zone environment, whereas high-Al chromites are derived from MORB-like melt during reaction with depleted mantle, most probably, originated in a back arc basin tectonic environment.

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