Distribution of Platinum-Group Elements in Chromite Ores of the Sorkhband Ultramafic Complex, Kerman, Southeastern Iran

Alireza Najafzadeh1, Mohsen Arvin2,3, Hamid Ahmadipour2, Yuanming Pan3

1 Department of Geology, Payame Noor University, Tehran, Iran
2 Department of Geology, Shahid Bahonar University of Kerman, Kerman, Iran
3 Department of Geological Sciences, University of Saskatchewan, Saskatoon, Canada

E-mail address: najafar@yahoo.com

Abstract. The Ordovician Sorkhband ultramafic complex lies in southern Kerman Province of Iran. The wedge shape complex covers an area of more than 100 km$^2$ and is divided into: lower part comprises of dunites, largest podiform chromitite deposits in Iran (Faryab mine), olivine clinopyroxenite dykes and massive's, wehrlite and olivine websterite dykes; and upper part comprises of clinopyroxene bearing harzburgites, with subordinate lenses and dykes of dunite, massive and dyke like olivine clinopyroxenite and minor orthopyroxenite dykes with no significant chromitite mineralization. Chromitite orebodies exhibit variable sizes and shapes, forming pods, lenses, bands, vein-like bodies and rich dissemination. Podiform chromitites in dunite form tabular to lenticular bodies although may occur also as pencil-like masses. The chromitites occur in four distinct textural modes. Massive, disseminated, banded and nodular chromitites are the most common textural types and commonly grade into one other. Massive chromitites have sharp contacts with the enclosing dunite whereas disseminated bodies grade outward into dunite and occasionally pass into interbanded chromitite and dunite. A detailed electron microprobe study reveals very high Cr#, Mg# and very low TiO$_2$ contents for chromian spinels in chromitites. The Sorkhband chromitites contain up to 440 ppb total PGE, and display a systematic enrichment in IPGE relative to PPGE, with a steep negative slope in the PGE spidergrams and very low PPGE/IPGE ratios, a feature typical of ophiolitic podiform chromitites worldwide. The mineral chemistry data and PGE geochemistry of the chromitites indicates that the Sorkhband ultramafic complex was generated from an arc-related magma with boninitic affinity in a supra-subduction zone setting.

1. Introduction

The Ordovician Sorkhband ultramafic complex is situated in the coloured melange, between the main Makran accretionary prism and the Bajgan/Durkan complex in the southwestern part of the Makran region (Figure 1a). The Bajgan/Durkan complex is believed to be the continuation of the Sanandaj-Sirjan zone of Iran and the Bitlis massif of Turkey [1]. In this context the Sanandaj-Sirjan microcontinental sliver continues eastwards, through the Makran and is referred as the Sanandaj-Sirjan / Bajgan-Durkan block (SS/BD) (Figure 1a). The SS/BD block consists of metamorphic rocks (garnetiferous schists, quartzite and marbles) of probable Early Paleozoic age or older. In this study, the Sorkhband chromitites, have been investigated through petrology, field relations, petrographic
analyses, and mineral chemistry. The objectives are: (1) to elucidate the origin of these podiform chromitites; and (2) to determine the paleo-geodynamic setting of the Sorkhband ultramafic complex.

2. Geological setting
The Sorkhband ultramafic complex, an association of dunite, chromitite, diopsidic harzburgite, olivine clinopyroxenite dykes, wehrlite, olivine websterite and orthopyroxenite dykes, is situated in the southwestern part of the Makran region, in southern Kerman Province of Iran and covers an area of more than 100 km$^2$ (Figure 1a, 1b) and has a northwest trending wedge shape [2]. The Sorkhband ultramafic complex (Figure 1b) can be divided into (a) a northern (lower) layered and (b) a southern (upper) massive part. The lower layered part is characterised by rhythmic layering, in which layers range from 5 mm to 60 m in thickness, and the presence of chromitite deposits (Faryab district). It is the largest chromite mining district in Iran with numerous chromite deposits. Reserves plus past production of chromite are estimated to 5–10 million tone [3]. The upper part of the Sorkhband ultramafic complex consists of mainly foliated diopsidic harzburgite with minor amounts of dunite, olivine clinopyroxenite and orthopyroxenite dykes and no significant chromitite deposits. The coloured melange to the south of the SS/BD blocks is a classic ophiolitic melange of tectonic origin, without matrix, consisting of two main lithological basic and sedimentary associations (Figure 1b).

3. Field observations and petrography
Chromitite orebodies exhibit variable sizes and shapes, forming pods, lenses, bands, vein-like bodies and rich dissemination. Podiform chromitites in dunite form tabular to lenticular bodies although may occur also as pencil-like masses. Ten separate chromitite orebodies (~ 40 km$^2$) of variable dimensions and shapes have been mapped in this study (Figure 1b). Most of these orebodies have been mined for over 50 years since early 1960s. The chromitites occur in four distinct textural modes. Massive, disseminated, banded and nodular chromitites are the most common textural types and commonly grade into one other (Figure 2a).

Figure 1. (a) Location of the study area in southeastern Iran. (b) Simplified geological map of the Sorkhband ultramafic complex modified after [1].
Massive chromitites have sharp contacts with the enclosing dunite whereas disseminated bodies grade outward into dunite and occasionally pass into interbanded chromitite and dunite.

Massive chromitites consist of 80 vol.% of coarse subhedral-anhedral to subrounded interlocking chromian spinel grains (Figure 2b) with pull-apart texture being invariably present. Individual chromian spinel grains are mostly 1 to 20 mm in size and closely. Disseminated chromitites composed of 25-80 vol.% of smaller chromian spinel grains, 0.3 to 1 mm in size and more regular in comparison to those in massive varieties. Banded chromitites occur as alternating chromian spinel- and olivine-rich layers in some chromitite pods. The banding is usually parallel to the long axes of the chromitite pods or lenses that are usually parallel to the foliation in the host dunite. Many bands show small-scale folding, faulting and cataclasis (Figure 2c). In brecciated chromitites, disseminated chromian spinel fills spaces between dunite fragments. In some samples, dunite fragments contain nodular chromitites, indicating a multistage magmatic origin. Nodular chromitites consist of small densely packed spherical to elliptical aggregates of chromian spinel (0.5-1.5 cm in diameter) in a moderately to highly serpentinized matrix (Figure 2d). Nodular texture is a characteristic feature of the podiform chromitite deposits, may show some evidence of compaction or deformation under load. Host dunites display a xenoblastic texture and consist mainly of olivine, with minor chromite (1-5 modal %), and interstitial clinopyroxene (<5 modal %). Olivine (Fo 90-95) shows internal deformation of strained polarization in form of faint, broad and kink bands. Clinopyroxene occurs as 0.2-1 mm subhedral grains. Chromian spinel (0.1 - 0.3 mm in diameter) occur as dark brown to weakly translucent rounded, subhedral to euhedral grains.

4. Mineral chemistry and PGE in chromitites
The composition of chromian spinels in chromitites varies within the following ranges: Cr₂O₃: 40.9-65 wt.%, Al₂O₃: 6.31-12.7 wt.%, MgO: 8.96-15.8 wt.%, NiO: 0.01-0.15 wt.%, FeO: 11.6-19.6 wt.%, TiO₂: 0-0.21 wt.% and Fe₂O₃: 1.09-3.6 wt.%. In the massive chromitites of the Sorkhband complex, chromian spinels exhibit a uniform and restricted composition around a High-Cr variety and are characterized by Cr# [=Cr/ (Cr+Al) atomic ratio] usually in a narrow range from 0.76 to 0.84, and Mg# [=Mg/ (Mg+Fe²⁺) atomic ratio] from 0.60 to 0.79 (Figure 3). All samples exhibit negative correlation between the Al₂O₃ versus Cr₂O₃, and MgO versus FeO. The low Fe³⁺/(Cr+Al+Fe³⁺) values (<0.1) also reflect crystallization under low oxygen fugacities.

The total PGE contents of the Sorkhband chromitites vary from 72 to 440 ppb, with an average of 104 ppb in correlation with the range of PGE in other ophiolites (144-1064 ppb) (Table 1). The PGE concentrations in chromitites show wide variations: 9.08-48.4 ppb Os, 15.97-87 ppb Ir, 23.3-98 ppb Ru, 3.72-45.9 ppb Rh, 1.10-84 ppb Pt, 1.82-126 ppb Pd and 1.48-19 ppb Au. The chondrite-normalized PGE patterns of chromitites are characterized by enrichment in Os, Ir and Ru (Ir-subgroup elements or IPGE) relative to Pt and Pd (Pd-subgroup or PPGE; Figure 4a), a feature typical of ophiolitic podiform chromitites, e.g. [4].
The IPGE are dominated by Ru ($XRu = Ru / (Os + Ir + Ru)_N = 0.24-0.52$; $XOs = 0.15-0.29$; $XIr = 0.28-0.48$), which are also typical of ophiolitic chromitite deposits (e.g. Vourinos) and have been attributed to the presence of laurite [$(Ru, Os, Ir)S_2$] inclusions in chromian spinel. In the Sorkhband ultramafic complex, laurite in chromitites has been confirmed by SEM analyses.

The Sorkhband chromitites contain up to 440 ppb total PGE, and irrespective of their PGE abundances, they display a systematic enrichment in IPGE (55-191 ppb, average=105 ppb) relative to PPGE (7-256 ppb, average=39 ppb) and very low PPGE/IPGE ratios (mean Pd/Ir ratio of 0.1), a feature typical of ophiolitic podiform chromitites worldwide (Figure 4b). The Pd/Ir values, an indicator of PGE fractionation, are relatively constant in all chromitites and vary from 0.04 to 0.25 (Table 1). These patterns and the low PGE abundances are typical of ophiolitic chromitites elsewhere.

5. Results and Discussions
There are a line evidences which suggest that the Sorkhband chromitites have a magmatic origin. In the field, structures such as massive chromitite pods, and thin massive chromitite bands indicate that these ore deposits have been crystallized from the magma. Under the microscope, cumulate textures also indicate a magmatic origin for these chromitites. Mineral chemistry of chromian spinels in the studied chromitites and comparing them with the well-known chromitites in the world demonstrate that they are of magmatic origin and crystallized from boninitic melts.

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such as Luobusa and Kempirsai ophiolites (Figure 4b) and indicating a high degree of partial melting of the mantle source very similar to nearby mafic-ultramafic complexes of Soghan and Abdasht [6, 7].

Table 1. PGE (p.p.b.) abundances and metal ratios of the chromitites in Sorkhband complex.

| Sample | NY5 | NY6 | NY21 | NY25 | NY26 | NY27 | NY25 | NY36 | NY39 |
|--------|-----|-----|------|------|------|------|------|------|------|
| Ru     |    66 | 31  | 33.5 | 35.5 | 43   | 63.2 | 54.9 | 23.3 | 60.1 |
| Rh     |    17 | 6.1 | 9.93 | 7.32 | 7.6  | 12.2 | 10.4 | 5.02 | 8.72 |
| Pd     |    1.8 | ud | 5.6  | 2.11 | 0.89 | ud   | 3.13 | 4.7  | 2.48 |
| Re     |    ud | ud  | ud   | ud   | ud   | ud   | ud   | ud   | ud   |
| Os     |    16 | 21  | 11.59| 9.08 | 12.7 | 17.2 | 48.4 | 12.8 | 18.7 |
| Ir     |    40 | 32  | 18.1 | 16   | 21.9 | 32.9 | 87.3 | 19   | 25.3 |
| Pt     |    5.5 | 1.3 | 4.16 | 9.35 | 1.1  | 1.11 | 1.5  | 7.32 | 2.88 |
| Au     |    8  | 11  | 1.48 | 18.4 | 16.8 | 7.42 | 3.94 | 19.4 | 3.8  |
| ΣPGE   |   145 | 93  | 82.87| 75.7 | 87.2 | 127  | 206  | 72.1 | 118  |
| IPGE   |   121 | 84  | 63.19| 60.5 | 77.6 | 113  | 191  | 55   | 104  |
| PPGE   |    24 | 7.4 | 19.69| 15.2 | 9.59 | 13.3 | 15   | 17   | 14.1 |
| Pd/Ir  |    0.1 | *  | 0.31 | 0.13 | 0.04 | *    | 0.04 | 0.25 | 0.1  |
| Pt/Pd  |    3  | *  | 0.74 | 4.43 | 1.24 | *    | 0.48 | 1.55 | 1.16 |

The binary plots of TiO$_2$ wt.% vs. Cr#$^{##}$ show that the massive and most disseminated chromian spinels fall in the boninitic field (Figure 5a). The (Al$_2$O$_3$)$_{melt}$ and (FeO/MgO)$_{melt}$ average values for the massive chromitites are estimated as 10.05wt.% and 0.7 respectively, also corroborating a boninitic parentage (Figure 5b). Furthermore, massive chromitite on TiO$_2$ wt.% vs. Al$_2$O$_3$ wt.% plots (Figure 5c) occupy mainly the field of supra-subduction zone and arc related peridotites.

6. Conclusions

As a conclusion, the mineral chemistry data and PGE geochemistry, along with the calculated parental melts in equilibrium with chromian spinel of the Sorkhband chromitites indicates that the Sorkhband ultramafic complex was generated from an arc-related magma with boninitic affinity above a supra-subduction zone setting.

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