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Platinum group elements geochemistry and composition of podiform chromitites from Khaje Jamali ophiolite complex, Neyriz, southern Iran

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Abstract

The subduction of the northern part of the Tethys is documented by arc magmatism from Upper Triassic to Lower Eocene crosscutting the Sanandaj-Sirjan Zone and from Upper Eocene to Plio-Quaternary in the Urumieh-Dokhtar Magmatic Zone, situated north of the SSZ. Neyriz ophiolite is part of Middle Eatern Neo-Tethyan ocean of Mesozoic that geographically is related to ophiolites of NW-SE Iran, along Zagros Suture Zone. The Khaje Jamali ophiolite complex is located in western part of Zagros thrust zone which separates Sanandaj–Sirjan crystalline complex and Zagros thrust belt and is one of the well-exposed mantle peridotites in Neyriz area. A number of rock-types such as isotropic gabbro and sheeted dykes are absent in Khaje Jamali ophiolite complex. Harzburgite is the most abundant ultramafic rock and is associated with the small dunite lenses. Chromite-bearing samples from Cheshmeh Bid and Anjirak areas display various sulfide phases. Such sulfide phases are hosted in serpentinite, chromitite and primary silicates. The most abundant sulfides are pyrrhotite, pentlandite and pyrite. SEM images show sulfide phases such as Os-Cu-Sn alloy, Ni-Fe metallic alloy in serpentinite and Au nuggets. In analyzed samples, a number of elements such as Ti, Al, Ca, Na, P and K are depleted while similar to other peridotites, the ultramafic rocks are enriched in Mg and Co contents and display slight variability (127.8–241.4 ppm). Ni value varies from 1482 to 6101 ppm. Chromite grains show homogeneous composition and are characterized by Cr# $(100Cr/(Cr+Al)=74-80)$, Mg# $(100Mg/(Mg+Fe^{2+})=52-63)$, Fe# and extremely low TiO_2 content (<0.09 wt.%). High Cr# of spinels in Khaje Jamali ophiolite complex is originally related to boninites or high – Mg arc tholeiites. Total PGE contents in analyzed samples ranges from 80 – 299 ppb. The Pd/Ir values change from 0.29 to 4.43. IPGEs contents are systematically reclining in order of layered chromite, nodular chromite, dunite and harzburgite. The $PPGE/IPGE$ changes from 0.11 to 1.96 which can be considered as an indicator feature for podiform chromitites. It is strongly believed that IPGE-enriched chromitites are derived from PGE-enriched magma with high degree of partial melting in supra - subduction environment. A number of samples contain higher values than those of primitive mantle which means PGEs are concentrated in ultramafics from Khaje Jamali ophiolite complex.

Keywords: Platinum Group Elements, Mantle peridotites, Ophiolite, Khaje Jamali, Neo-Tethys, Mesozoic.

1- Introduction

Platinum- group elements together with Fe and Co tend to form metallic bands which put them in siderophile group elements (Maier, 2005). Furthermore, PGEs are more interested in generating covalent bands in sulfur over ionized band with oxygen (Mungall, 2005). Sulfur capacity raise with increasing temperature also MgO, CaO and contents and decreasing and contents in silicate melt, So rock types that originally linked with boninites and komatiites derived from S-undersaturated melts are enriched in PGEs (Zhou, 1996).

PGEs behavior in igneous rocks is controlled by three remarkable phenomenons: 1) partial melting degree of upper mantle 2) fractional crystallization 3) hydrothermal alteration. Many authors proposed that in ophiolitic peridotites like Neyriz ophiolites, partial melting is more likely to participate in PGEs distribution in mantle section of ophiolite sequence (Ahmed and Arai, 2002; Ahmed *et al.*, 2009).

Neyriz ophiolite is considered one of the well-exposed mantle peridotites which composed of some chromite mining districts including Khaje Jamali, Tange Hana, and so on. The Khaje Jamali area comprised of numerous chromite mines such as Cheshmeh Bid, Rajooni, Dotooi, Anjirak, and Hosseinkhani. Ultramafics form almost 90% of rock types of Khaje Jamali area. They display foliated structure that may well be linked to plastic deformation in upper-mantle environment. Ultramafics such as dunite and pyroxenite are called cumulative rocks and are derived from magma crystallization related to partial melting.

IPGEs (Ru, Os, Ir) are compatible during hydrous partial melting in supra-subduction environment (Ahmed and Arai, 2002; Zhou and Robinson, 1997). Typical ophiolitic chromitites are characterized by enrichment in IPGE relative to PPGE. Chromitites have relatively patterns at approximately 0.1 to 1.0 times chondrite, and PPGE abundances about 0.01 times chondrite, probably reflect the preferential partitioning of IPGE into the spinel phase (Capobianco and Drake, 1990). First report on PGEs presented by Rajabzadeh (1998) in which, he proved presence of PGMs, like laurite, erlichmanite, irarsite, Ir–Os, Ru–Ir–Os, Pd–Fe alloys and sulfide solid solution in ultramafic rocks of Neyriz area. There is brief information about PGEs mineralization and their concentrations in different ultramafic rocks in khaje Jamali area. In this paper chromite composition and formation setting of Khaje Jamali ophiolite and PGEs concentrations are under consideration, also some sulfide-bearing rocks are introduced.

2- Geological setting

Neyriz ophiolite is located in western part of Zagros thrust zone which separates Sanandaj – Sirjan crystalline complexes and Zagros thrust belt (Fig. 1). Ophiolitic parts expose as individual bodies with large dimensions and are surrounded by Quaternary formations.

Almost 2.5 to 5 km west of Neyriz ophiolite, a mélange formation is exposed along with Zagros thrust zone overlaying Pichakun formation. This melange consists of radiolarite-bearing chert, turbidite limestones, middle Jurrassic oolitic limestones and middle Cretaceous limestones. Neyriz ophiolite is settled on both mélange and Pichakun formations (Babaie *et al*., 2001).

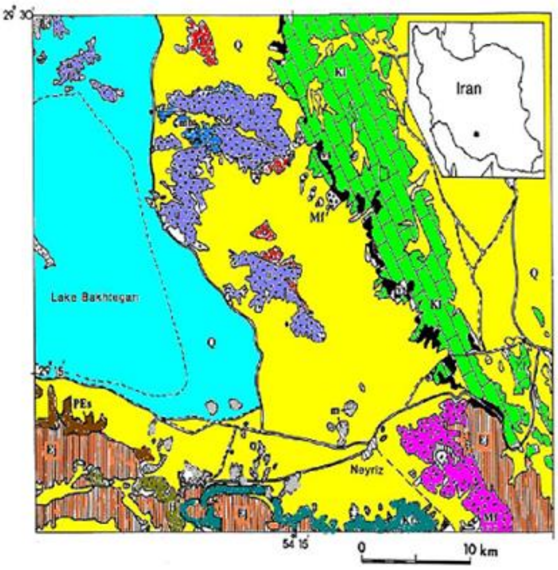


Figure1) Geological map of Neyriz area. Q (Quaternary); Mf (Eocene±Miocene conglomerate and sandstone); Ej (Eocene Alveolina limestone, Jahrum Fm.); PEs (Paleocene±Eocene gypsiferous marl, limestone, sandstone, conglomerate, Sachun Fm.); Kt (Campanian±Maestrichtian, Tarrbur Fm.); vs (Late Cretaceous, Hassanabad Unit); Kl (Cretaceous orbitolina limestone); m (Mesozoic melange); d (Late Cretaceous ocean floor basalt); u (Late Cretaceous ultramafics); mb (marble); H (Infracambrian Hormuz salt diaper)(Babaie et al, 2001).

The contact between metamorphic mélange and ophiolite represents by low-angle thrust fault. This metamorphic mélange contains amphibolite, kyanite schist, gneiss, blue schist and eclogite (Sarkarinejad, 2003). Neyriz ophiolite from bottom to top consists of tectonized mantle units containing harzburgite, lherzolite and dunite and a transition zone including mafic-ultramafic inter-layered and crustal sequence.

According to spectrometry from biotite-bearing layers in garnet of amphibolite, related to mafic and ultramafic rocks of Neyriz ophiolite, primitive age of ophiolite replacement is middle Jurassic (170Ma) and metamorphic stage was in last Cretaceous (Haynes and Reynolds, 1980).

Khaje Jamali ophiolite complex is located in an area about 16 km length and 11 km width. This complex contacts with Jahrom formation limestones (Eocene) and Sarvak formation (upper-Cretaceous) to the north and northeastern and underlying two mentioned formations. The contact between ophiolite mass and upper units is covered by Roshan Mountain debris (Jahrom limestone). This complex from west and southwest linked with Sarvak formation and radiolarite-bearing alluviums.

In comparison with a complete ophiolite sequence, all the rock-types including isotropic gabbro and sheeted dykes do not exist in Khaje Jamali ophiolite complex, and according to Dilek classification of different ophiolites (Dilek, 2003) and supra-subduction zone originality, it is considered as Mediterranean ophiolite-type. Generally, ultramafics consist of harzburgite, harzburgite-dunite sequence, dunite, chromitite and mafics containing pillow lava and basalt and numerous gabbroic dykes, pelagic sediments and altered rocks like serpentinite, rodingite, marble and listvenite. Diabase and pyroxenite dykes intersect Khaje Jamali ophiolite complex. In some cases the peridotites are crossed by diabase dykes with certain reactive margins.

Using petrological investigation and PGEs distribution in various ultramafics, rock samples are gathered from Khaje Jamali ophiolite complex. Samples gathered from residual mantle units such as harzburgite, serpentinized harzburgite, dunite and altered units including harzburgite lenses, pyroxenite dykes and chromite-mineralized zones and the host rocks using 1:20000 scale geological map (Fig. 2).

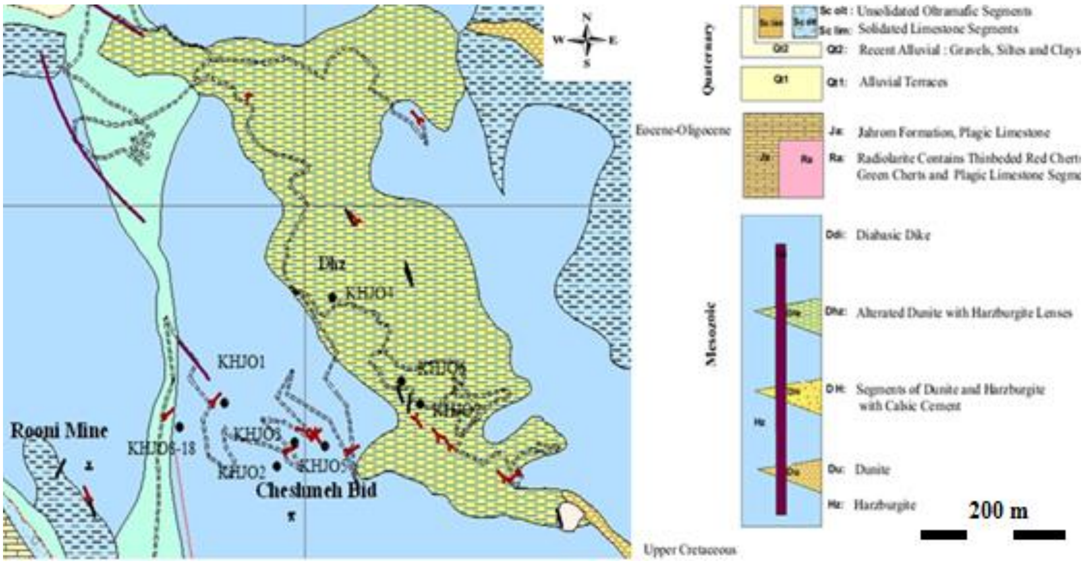


Figure 2) 1:20000 geological map of Khaje Jamali with sample locations.

Dunite unit forms 10 to 15% of total Khaje Jamali ophiolite complex. This unit appears in two different shapes: 1) Dunites which are as dyke, pod and leyered shapes have small and parallel outcrops. This unit exposes at three locations: a) in residue harzburgite from partial melting b) in the transition zone between harzburgite and cumulus dunite and c) in chromite lenses that surround them as pods. 2) Large scale and widespread units exceed 1km length that slightly covered with dunite gravels and have rocky fresh and rounded outcrops.

3- Analytical methods

Polished sections of different rock-types were studied, achieving more information about the mineralogical characteristics of the Khaje Jamali area. The sections gathered from harzburgite, dunite, chromitite, pyroxenite rock-types. They were studied by optical microscope and four sections were analyzed by scanning electron microscope (SEM). Primitive investigations performed in SEM laboratory of Amirkabir University of Technology and then more detailed analyses conducted at Razi metallurgy institute using VEGA\\TESCAN-XMU scanning electron microscope. Whole rock major elements of ultramafics and trace elements (Co, Ni, Cu, Zn, Sr, Mo, Pb, Ba) were determined by X-ray fluorescence spectrometer utilizing rhodium target X-Ray tube at Amirkabir university of technology. Five samples for PGEs analyzed using ICP-AES in ALS Chemex institute of Canada. Chromite composition analysis of Cheshmeh Bid samples determined at metallurgy faculty of University of Tehran using electron microprobe. Determination of Pd, Pt and Au carried out at Zar Azma institute using lead-collection fire-assay analysis of a 40gr sample, with high sensitivity ICP-OES. Detection limits for Au, Pt and Pd are 1, 5, 5 ppb, respectively.

4- Petrography

Petrographic investigations on thin sections from Khaje Jamali ophiolite complex demonstrates that mantle sequence contains harzburgite, dunite, pyroxenite with chromitite, and crustal sequence including basalt, minor gabbro and pelagic sediments.

Harzburgite and serpentinized harzburgite are the most abundant ultramafic rocks in Cheshmeh Bid area (Fig. 3a). Harzburgite observes in the most part of the area and occasionally accompanied with small dunite lenses. Such rocks are almost cumulus and sometimes have foliated structure (Fig. 3b). Foliated shape is known as the result of plastic deformation of upper mantle peridotites during magmatic replacement (Boudier *et al*., 1996).

Orthopyroxene (enstatite) is almost fresh and somewhat has parallel and altered fractures. Serpentinite group minerals in dunite (Fig. 3c) are more abundant compared to harzburgit.

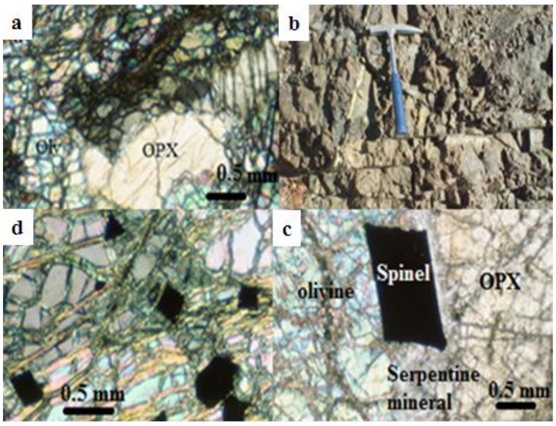


Figure 3) Dunite and harzburgite samples from Khaje Jamali ophiolite complex. a) Typic section of harzburgite from Cheshmeh Bid. b) Foliated harzburgite in Cheshmeh Bid (view to north). c) Low-grade alteration in harzburgite from Cheshmeh Bid. d) Typical section of dunite from khaje Jamali area.

In our case study area, pyroxenite is subdivided into orthopyroxene and clinopyroxene. Orthopyroxene reveals as dykes with few centimeters to 1m length and in maximum cases up to 5 meters (Sarkarinejad, 2003). Such rocks consist of pyroxene crystals up to 1cm and more, bronze and grey in color with pearly luster. Orthopyroxenite contains more than 95% orthopyroxene (enstatite), minor clinopyroxene and olivine and Cr-spinel as accessory mineral less than 1%. Such rocks are almost fresh and serpentinite group minerals are absent in mentioned rocks. Pyroxenites are coarse grained rocks, orthopyroxenes are bronzite and enstatite. The clinopyroxene mineral is augite. Pyroxene grain sizes varies from 400-500µm to 4-5mm in pyroxenite dykes. Clinopyroxene content is not exceeded more than 5 volume percent in dunite and harzburgite rocks.

In almost cases serpentinization has been developed along fractures of the rocks. It looks that orthopyroxene was less serpentinized than olivine but in highly serpentinized harzburgite, it was altered to bastite.

Dunite is the most serpentinized rock between the mantle peridotites. Increasing degree of alteration is expressed by growth of secondary minerals along cracks and grain boundaries, leading ultimately to small islands of fresh olivine giving a mesh texture of serpentine and olivine minerals. Dunite envelopes associated with chromitites are extensively serpentinized and mostly fractured. Olivine is transformed to lizardite (Fig. 3c) also minor antigorite is may present. Mineralogical composition of dunite comprised of 95-99% olivine, minor orthopyroxene, 1-3% Cr-spinel and opaque minerals (Fig. 3d).

All studied polished sections, such as chromite-bearing samples from Cheshmeh Bid and Anjirak areas exhibit various sulfide phases. Such sulfide phases are almost accompanied with chromite, sometimes are in serpentine minerals or in primary silicates phases as secondary minerals. The most plentiful sulfides are pyrrhotite, pentlandite and pyrite. Such minerals were first investigated and recognized by mineralographical studies, and then they were determined according to EDX diagrams and map images of SEM results. Other newly reported phases are Os-Cu-Sn alloy, Ni-Fe metallic alloy in serpentinite and Au nuggets (Fig. 4). The mentioned alloys are containing minor PGEs.

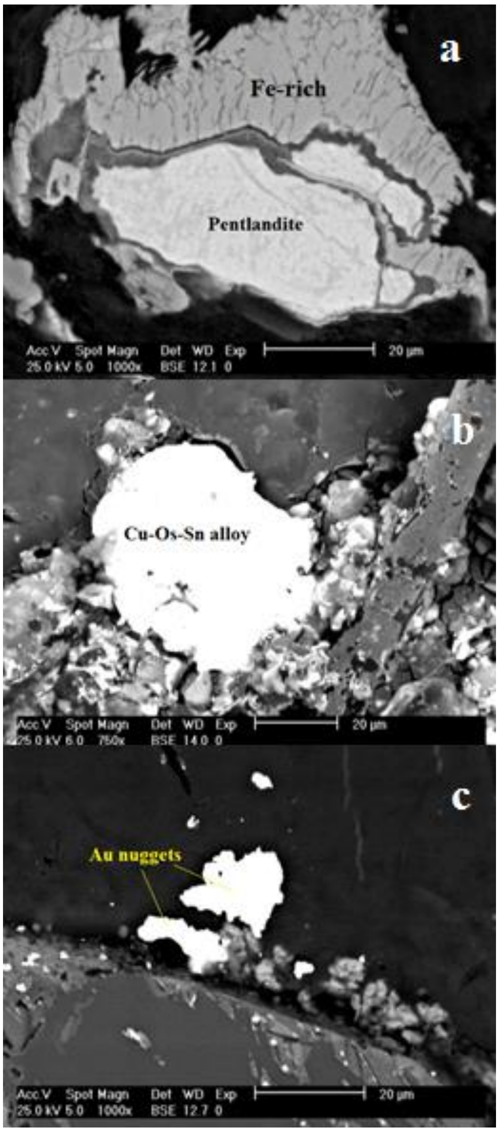


Figure 4) Back-scattered electron images of analyzed samples from khaje Jamali area. a) Pentlandite together with secondary Fe-rich phase. b) Cu-Sn-Os alloy from sample of Anjirak area. c) Au nuggets less than 20 µm in size from analyzed samples.

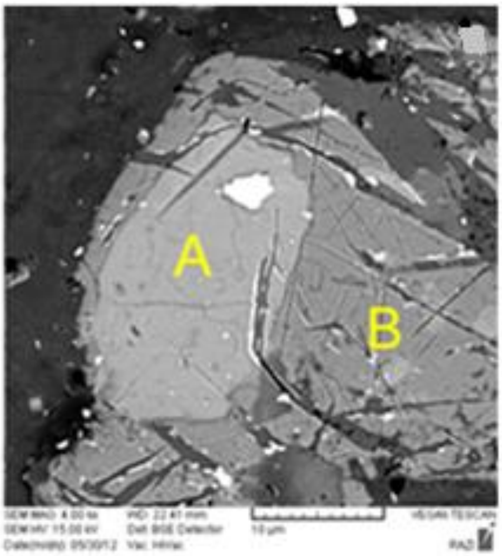
Since platinum group elements occur as sulfides, alloys, arsenides, tellurides, and minor solid solution in pentlandite so this mineral was investigated in order to discern distribution of elements especially Ni, Co, PGEs and its Fe-Oxide context from Anjirak, Two EDX-spectrums are taken by SEM. The chalcophile affinity of platinum group elements caused them to be concentrated in sulfide minerals such as pentlandite. Pt and Ir have similar concentrations in two mentioned crystals. But inverse concentration pattern is observed in the case of Ru, Rh, Os and Sn (Fig. 5a and b).

5- Whole rock geochemistry

5-1. Major elements

Major oxides contents in different ultramafic rocks from Khaje Jamali ophiolite are summarized in table 1. Some of samples composed of the host rock and chromite mineralized zones. Average contents for dunite, harzburgite and pyroxenite are 36 wt%, 40.96 wt% and 22.9 wt%, respectively. In analyzed samples, elements including Ti, Al, Ca, Na, P and K depleted while, similar to other peridotites, the ultramafic rocks are enriched in Mg.

The contents (with the average of 0.06 wt%) are less than the primitive mantle (0.23 wt%) corresponding to relatively high partial melting degree. Also ratio ranges between 0.62 and 7 for dunite samples compared to primary upper mantle (0.8), reflects high degree of partial melting.



A

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K Series	2.56	2.64	9.98
Oxygen	K Series	0	0	0.01
Silicon	K Series	0.1	0.1	0.16
Sulfur	K Series	31.2	32.18	45.52
Iron	K Series	27.61	28.48	23.13
Cobalt	K Series	1.09	1.12	0.87
Nickel	K Series	21.41	22.08	17.06
Rhodium	L Series	0.38	0.39	0.17
Palladium	L Series	0.22	0.22	0.1
Tin	L Series	0.39	0.41	0.16
Osmium	M Series	0.09	0.1	0.02
Iridium	M Series	0.07	0.07	0.02
Gold	M Series	11.82	12.19	2.81

Total: 96.94%

B

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K Series	0.96	1.08	5.19
Oxygen	K Series	0.82	0.92	3.33
Silicon	K Series	0.13	0.14	0.29
Sulfur	K Series	1.05	1.18	2.12
Chromium	K Series	0.67	0.75	0.83
Iron	K Series	71.79	80.99	83.63
Nickel	K Series	0.13	0.14	0.14
Ruthenium	L Series	0.09	0.1	0.06
Palladium	L Series	0.35	0.4	0.22
Osmium	M Series	0.23	0.26	0.08
Iridium	M Series	0.03	0.04	0.01
Gold	M Series	12.4	13.98	4.09

Total: 88.65%

Figure 5) Two phases of chromite-bearing harzburgite in Anjirak , pentlandite(A), Fe-oxide background(B). EDX results are containing concentration of elements in above phases (A and B).

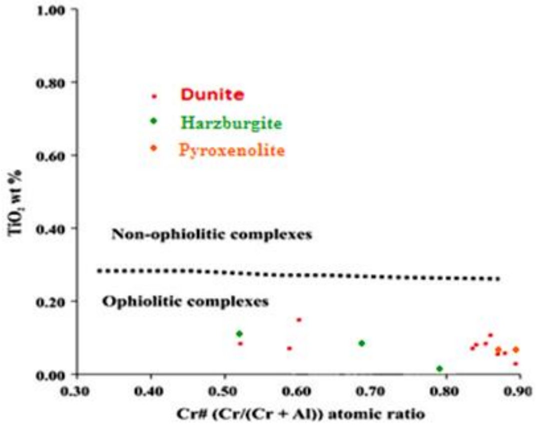


Figure 6) Variation of Cr# $(Cr/(Cr+Al))$ *vs* TiO_2 *wt% of chromian spinels of harzburgite, dunite and pyroxenite samples from Khaje Jamali ophiolite. Low* TiO_2 *content is a feature of ophiolitic complexes demonstrates partial melting rule (Ferrario and Garuti, 1988).*

Dunite samples of Khaje Jamali ophiolite complex are proportionately homogenous with CaO (0.08–0.35 wt%), (0.02–0.49 wt%), (34.15–39.75 wt%) and MgO (37.78–43.48 wt%). Cr# atomic ratio) in chromian spinels of harzburgite, dunite and pyroxenite samples ranges 0.52–0.79, 0.52–0.89 and 0.87–0.89, respectively (Fig. 6).

Table 1) Chemical composition of major oxides of ultramafic rocks from the Khaje Jamali ophiolite, Neyriz. (XRF data).

Sample	Harzburgite (KHJO1)	Harzburgite (KHJO2)	Harzburgite (KHJO3)	Altered dunite (KHJO4)	Chromitite (KHJO5)	Pyroxenite (KHJO6)	Pyroxenite (KHJO7)
	%						
SiO_2	42.7	38.9	41.3	29.5	0.87	37.9	**7.9**
Na_2O	<0.01	<0.01	<0.01	0.06	<0.01	0.443	**<0.01**
MgO	38.1	34.1	32.8	30.3	14.5	24.4	**18.6**
Al_2O_3	0.17	0.29	0.54	3.29	6	2.36	**8.6**
P_2O_5	0.013	0.0076	0.0094	0.06	0.0069	0.0056	**0.0093**
SO_3	0.027	0.098	S=0.064	0.13	0.022	0.027	**0.02**
K_2O	0.004	<0.01	0.0058	0.01	<0.01	0.039	**<0.01**
CaO	0.55	0.87	1.02	0.94	0.109	3.45	**0.2**
TiO_2	0.0076	0.0109	0.014	0.03	0.13	0.07	**0.07**
Cr_2O_3	0.51	0.52	0.46	14.62	60.6	16.7	**46**
MnO	0.19	0.18	0.17	0.13	0.15	0.18	**0.16**
Fe_2O_3	13.5	11.9	11.4	10.78	16.6	11.6	**16.8**
LOI %	3.02	11.8	11.1	9.7	0.4	2.08	**0.7**
Total %	99.3	99.1	99.31	99.85	99.61	99.46	**99.35**

Table 1 (Continued)

Sample	Dunite KHJO8	Dunite KHJO9	Dunite KHJO10	Dunite KHJO11	Dunite KHJO12	Dunite KHJO13	Dunite KHJO14	Dunite KHJO15	Dunite KHJO16	Dunite KHJO17	Dunite KHJO18
	%										
SiO_2	30.8	34.15	37.54	36.17	37.22	37.38	38.11	36.45	39.75	36.34	39.25
Al_2O_3	3.45	0.49	0.04	0.24	0.08	0.03	0.08	0.07	0.02	0.07	0.21
Fe_2O_3	9.83	9.06	9.26	10.25	8.7	9.3	9.18	8.9	8.97	9.02	9.52
CaO	0.83	0.35	0.12	0.21	0.08	0.17	0.15	0.1	0.14	0.1	0.13
Na_2O	0.06	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03
K2O	0.02	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
MgO	29.2	42.81	39.59	38.56	40.49	43.48	42.54	42.22	37.78	41.12	37.91
TiO_2	0.04	0.016	0.009	0.011	0.009	0.009	0.009	0.01	0.008	0.009	0.01
MnO	0.13	0.114	0.111	0.122	0.105	0.111	0.111	0.108	0.105	0.109	0.114
P_2O_5	0.08	0.03	0.015	0.014	0.001	0.027	0.01	0.002	0.04	0.02	0.03
Cr_2O_3	13.58	0.62	0.23	0.19	0.29	0.2	0.25	0.28	0.19	0.23	0.22
SO_3	0.12	0.265	0.001	0.158	0.001	0.001	0.005	0.001	0.001	0.001	0.001
Fa	10.39	9.65	10.59	11.83	9.78	9.74	9.82	9.62	10.7	9.97	11.25
Fo	89.81	90.35	89.41	88.17	90.22	90.26	90.18	90.38	89.3	90.03	88.75
LOI %	10.3	11.93	12.41	13.36	12.55	8.62	8.94	10.9	12.1	12.19	12.02
Total	98.44	99.9	99.35	99.31	99.55	99.35	99.41	99.06	99.12	99.23	99.46

Table 2) XRF results of trace elements contents in different ultramafic rock-types from Khaje Jamali ophiolite complex.

Sample	Pyroxenite (KHJO7)	Altered dunite (KHJO4)	Harzburgite (KHJO1)	Harzburgite (KHJO3)	Harzburgite (KHJO2)	Chromitite (KHJO5)	Pyroxenite (KHJO6)
	mg/kg						
Co	241.4	156.2	191.7	177.5	156.2	191.7	127.8
Ni	2028	2808	4290	3666	3588	1560	1482
Cu	<1	85.8	<1	<1	<1	<1	<1
Zn	249.6	117	<1	<1	<1	163.8	<1
Sr	<1	<1	18.04	32.8	22.14	<1	10.66
Mo	<1	<1	<1	<1	<1	50.4	<1
Sum (La..Lu)%	0.08	0.016	0.016	0.014	0.02	0.09	0.03

Table 2 (Continued)

Sample	Dunite KHJO9	Dunite KHJO10	Dunite KHJO11	Dunite KHJO12	Dunite KHJO13	Dunite KHJO14	Dunite KHJO15	Dunite KHJO16	Dunite KHJO17	Dunite KHJO18
	mg/kg									
Ni	4010	5328	4887	5447	4854	4813	5538	6101	5158	5852
Cr	4250	1545	1274	1962	1381	1692	1913	1309	1582	1505
Cu	9	6	5	4	4	5	7	8	7	5
Sr	12	10	13	16	15	11	14	12	15	14
Zn	43	54	53	49	45	47	44	52	50	48
Pb	4	7	9	4	7	14	8	10	11	7
Ba	195	172	16	112	131	115	10	31	76	14

5-2. Trace elements

Trace elements display sensitive behavior during magmatic evolutions. Some trace elements are compatible and concentrated in crystalline phases, although others are more compatible with magma and are increasing in melt, so getting upward in ophiolite sequence corresponds to raising incompatible elements contents. Such elements are more abundant in residue mantle than in partial melting products. Trace elements contents in the ultramafic rocks from Khaje Jamali ophiolite complex are presented in Table 2.

There are nearly constant Co values for all ultramafic rock types from Khaje Jamali ophiolite complex (127.8–241.4 ppm). Other trace elements (Cu, Sr, Zn, Pb) show approximately constant distribution in dunite samples (Table 2). Ni value ranges from 1482 to 6101 ppm for all ultramafic rock types from Khaje Jamali ophiolite complex. Average content of Ni is 4200 ppm. The average content is relatively higher than that of introduced by Coleman (2400 ppm for dunite, 1977) for dunites (5198.8 ppm). Nickel is a siderophile and chalcophile element in core and mantle, concentrates in olivine in upper mantle (Ishimura, 2008).

Nickel behavior in upper mantle is controlled by fractionation between olivine and magma during segregation of magma–melt. Ni content in residue peridotites from partial melting is less than that of cumulus rocks (Ishimura, 2008). Extrand (1975) concluded that serpentinization process will increase metallurgy nickel content and make it economically important. Due to desulfurization of PGEs and base metals during serpentinization process, sulfur content became so much low that could not be useful for metal phase determination in Khaje Jamali ophiolite complex (Ahmed and Aria, 2003).

Table 3) Electron microprobe analyse results (wt%) from massive Cr-mineralized and Hz – Du host rocks from Cheshmeh Bid, Khaje Jamali ophiolite complex, Neyriz.

Sample	ChB-1-1	ChB-2-1	ChB-3-1	ChB-4-1	ChB-5-1	ChB-6-1	ChB-7-1	ChB-8-1	ChB-9-1
	%								
TiO_2	0.08	0.08	0.08	0.08	0.06	0.08	0.07	0.09	0.07
Al_2O_3	13.36	13.31	13.27	13.26	13.22	13.38	13.03	13.19	13.14
FeO	13.9	13.84	13.81	13.92	13.75	13.86	15.49	13.74	13.92
MgO	13	12.77	12.88	12.75	13.07	12.81	12.09	13.1	12.96
Cr_2O_3	57.57	57.6	57.78	57.65	57.77	57.83	57.14	57.61	57.37
SiO_2	0.03	0	0.06	0	0.02	0.02	0.01	0.06	0
MnO	0.32	0.28	0.31	0.31	0.31	0.3	0.36	0.3	0.3
NiO	0.19	0.16	0.22	0.18	0.16	0.19	0.13	0.19	0.14
TOTAL	98.45	98.04	98.41	98.17	98.37	98.46	98.32	98.27	97.9
Mg#	63.11	62.22	62.74	62.19	63.49	62.23	59.19	63.67	63.21
Cr#	74.28	74.37	74.49	74.46	74.56	74.35	74.62	74.55	74.54
Fe#	0.49	0.04	0.23	0.15	0.49	0.02	0.88	0.58	0.65

Table 3 (Continued)

Sample	ChB-1-2	ChB-2-2	ChB-3-2	ChB-4-2	ChB-5-2	ChB-6-2	ChB-7-2	ChB-8-2	ChB-9-2	ChB-10-2	ChB-11-2
	%										
TiO_2	0.06	0.06	0.06	0.04	0.06	0.04	0.04	0.05	0.08	0.05	0.05
Al_2O_3	9.85	9.86	10.46	10.55	11.07	11.19	11.23	11.23	11.06	11.26	10.09
FeO	17.78	17.87	17.94	17.95	17.85	17.01	17.62	17.26	17.99	17.95	17.63
MgO	10.39	10.45	10.51	10.56	10.59	11.19	10.63	10.57	10.42	10.46	10.41
Cr_2O_3	59.51	59.4	57.91	58.46	58.08	57.55	57.53	57.46	58.07	57.54	59.56
SiO_2	0	0	0.01	0.01	0.01	0.05	0.07	0.04	0.03	0.03	0.01
MnO	0.38	0.34	0.34	0.32	0.35	0.32	0.37	0.34	0.37	0.36	0.34
NiO	0.17	0.13	0.1	0.13	0.09	0.11	0.09	0.09	0.06	0.14	0.15
TOTAL	98.14	98.11	97.33	98.02	98.1	97.46	97.57	97.41	98.08	97.78	98.24
Mg#	52.31	52.39	52.56	53.01	52.94	52.87	55.94	53.37	53.09	52.09	52.51
Cr#	79.84	80.21	80.16	78.78	78.8	77.87	77.52	44.46	77.42	77.87	77.41
Fe#	1.01	1.34	1.49	1.89	1.71	1.45	1.84	1.5	1.38	1.27	1.53

5-3. Chromitite

Chromite is an accessory mineral in mafic and ultramafic rocks which occasionally constitute individual mineral economic bodies (chromitite pods) in mantle sequences of ophiolites (especially in dunite). Due to serpentinization procedure of minerals that are accompanied with chromite, Cr – spinels are usually remains without significant changes and are not deformed to secondary minerals, so provide important information about magma chemistry, and formation temperature are sufficient indexes for understanding tectonic history (Arai and Yurimoto, 1995; Rollinson, 2005; Zhou and Robinson, 1997). Chromite–bearing samples gathered from host rocks and Cr– mineralized lenses from extraction tunnel in Cheshmeh Bid mine. Results of electron microprobe analyze of Cr–mineralized samples are summarized in Table 3.

Massive chromitites from Cheshmeh Bid area contain SiO_2 (0 – 0.07 wt%), MgO (10.39 – 13.1 wt%) and FeO (13.74 – 17.99 wt%), are consistent with podiform chromitites. Chromite compositions are homogeneous and are distinguished by Cr#[100Cr/(Cr+Al)]=74-80; Mg#[100Mg/(Mg+Fe^{2+})]=52-63; Fe#[100Fe^{3+}/ (Cr+Al+Fe^{3+})<1.89] and extremely low TiO_2 content (<0.09 wt%). High Cr# ophiolites such as Khaje Jamali ophiolite complex are originally related to high–Mg andesites, boninites or high–Mg arc tholeiites (Abu El Ela and Farahat, 2010; Akbulut *et al*., 2010; Zhou and Robinson, 1997).

Chemical compositions of Cheshmeh Bid chromite are plotted in ternary diagram (Fig. 7). The spinel composition has significant effect on amphibolite facies (Abzalov, 1998), also at lowest degree of amphibolite facies, chemistry of main Cr cations preserved and in high metamorphic degrees, significant change occurs in chromite composition or their surrounding silicates (Barnes, 2000). Cheshmeh Bid chromite samples are located in green schist facies and Cr–rich podiform field, so composition of major elements remains almost constant and is used for depicting chromite characteristics in case study area.

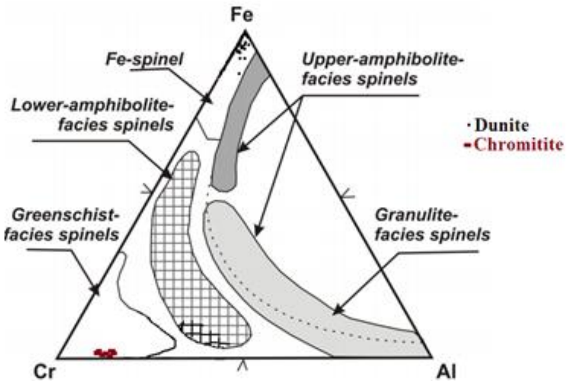


Figure 7) Chemical composition of dunit and chromitite from Khaje Jamali and Cheshmeh Bid in Fe-Cr-Al ternary diagram, various spinel metamorphism fields are shown (Suita and Strider, 1996; Proenza, 2007).

In TiO_2 (wt%) vs Cr# diagram (Pearce *et al*., 1984), nearly all of ultramafic rocks from Khaje Jamali ophiolite complex are plotted in supra – subduction zone environment as result of subduction of the northern part of the Tethys and are derived from depleted upper mantle slab (Fig. 8, a). TiO_2 (wt%) vs Cr# diagram (Fig. 8, b) disclose that various depleted ultramafic units including dunite, harzburgite, chromitite and pyrexonolite are originally derived from boninites or high–Mg fore-arc tholeiite.

High Cr# is corresponding with high partial melting degree or re-melting the previous depleted peridotites (Ahmed *et al*., 2009). Khaje Jamali chromitites pertain to the magnesiochromite series with high-Cr and high-Mg compositions (Fig. 9a) and display Cr_2O_3 and Al_2O_3 values typical for podiform chromitites (Fig. 9b).

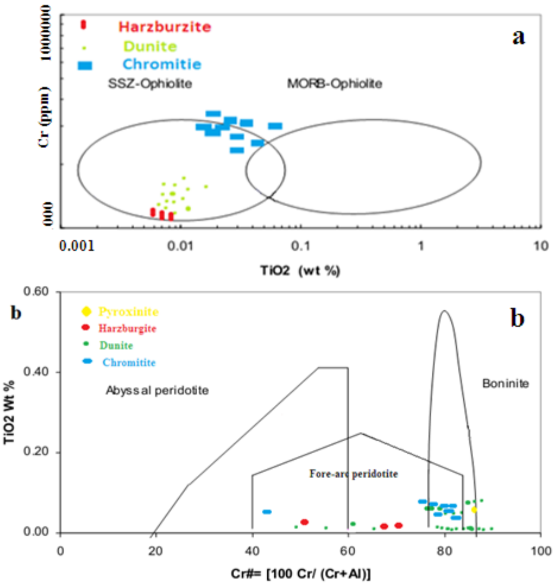


Figure 8: a) Tectonic separation diagram (Pearce et al, 1984) shows supra – subduction zone origin of ultramafic rocks from Khaje Jamali ophiolite complex. b) Cr# variations vs TiO_2 (wt%) for different mantle sequence rocks of Neyriz. Abyssal peridotite field is from Dick and Bullen (1984), fore-arc peridotite is from pearce et al. (1992), Parkinson et al. (1998) and boninite field is from pearce et al. (1992) and Batanova et al. (2000).

5-4. Platinum group elements (PGEs)

Platinum – group elements (Ir, Os, Ru, Rh, Pt, Pd) depict similar chemical characteristics, behaving as siderophile and chalcophile elements. During partial melting, PGEs are divided into two groups: compatible or more refractory elements (IPGE = Os, Ir and Ru), incompatible elements (PPGE = Pt, Pd and Rh) (e.g., Leblanc, 1991; Bockrath *et al*, 2004; Ahmed *et al*, 2009).

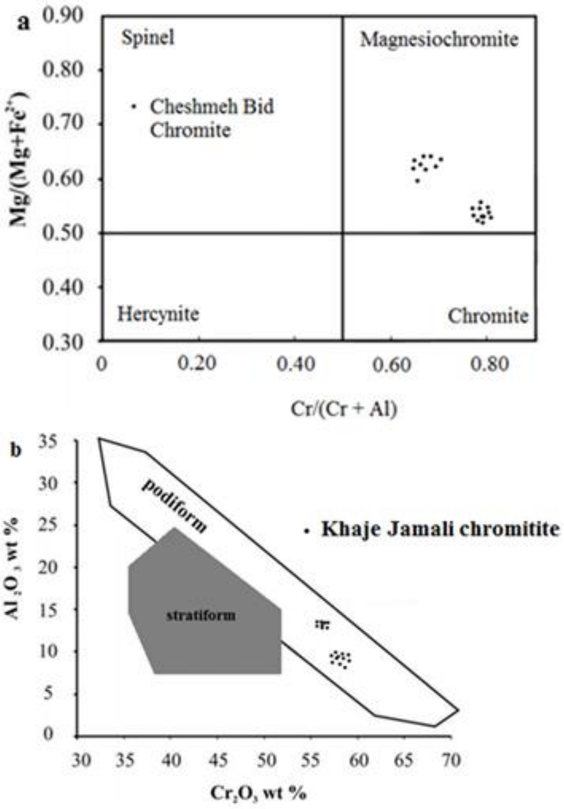


Figure 9) Composition of the chromian spinel from Khaje Jamali ophiolite complex. a) Cr# versus Mg#; b) Cr_2O_3(wt %) versus Al_2O_3 (wt%) (Naldrett and Duke, 1980).

PGE concentrations for different rock types from Khaje Jamali ophiolite complex are presented in table 4. Total PGE contents for analyzed samples vary between 80–299 ppb. These rocks exhibit various PGE concentrations and distribution patterns. This variety increases in individual PGE concentrations. Highest total PGE corresponds to layered chromite (299 ppb) and the lowest content belongs to host dunite with disseminated chromite (80 ppb). Host harzburgite contains totally 106 ppb which is the lowest IPGE contents. Unlike the harzburgite, chromite – mineralized rocks enriched in more refractory elements (IPGE) (Fig 10).

High Ru concentrations probably imply that Ru minerals present in such rocks. $PPGE/IPGE$ Ratio that ranges from 0.11

to 1.96, is an indicator feature of podiform chromitites (Uysal *et al*., 2007).

Table 4) Selected analyses of bulk – rock PGE (ppb) of host and mineralized rocks from Khaje Jamali ophiolite complex.

Sample	Ir	Os	Ru	Rh	Pd/Ir	PPGE /IPGE	Pd	Pt
	ppb							
Harzburgite	7	5	19	8	4.43	1.93	31	36
Disseminated chromite	10	8	26	5	1.4	0.63	14	17
layered chromite	49	56	135	13	0.39	0.17	19	27
Nodular chromite	21	10	66	11	0.33	0.12	-	8
Chromitite	45	62	142	12	0.29	0.11	13	16

Generally, decreasing in Pd/Ir is equivalent with growing total PGE concentrations in mantle derived ophiolitic rocks. The Pd/Ir value ranges from 0.29 to 4.43. IPGEs values are systematically reclining in order of layered chromite, nodular chromite, dunite and harzburgite. Such a reduction is accompanied with increasing in chromite – mineralization degree which means IPGEs are enriched in chromite.

Lowest IPGE and highest PPGE contents are related to harzburgite, implies that PPGE are concentrated in silicate phase. IPGE–enriched chromitites are strongly believed that derived from PGE–enriched magma with high partial melting degree in supra subduction zone environment, while poor examples come from mid ocean ridge zone with low degree of partial melting (Ahmed and Arai, 2002).

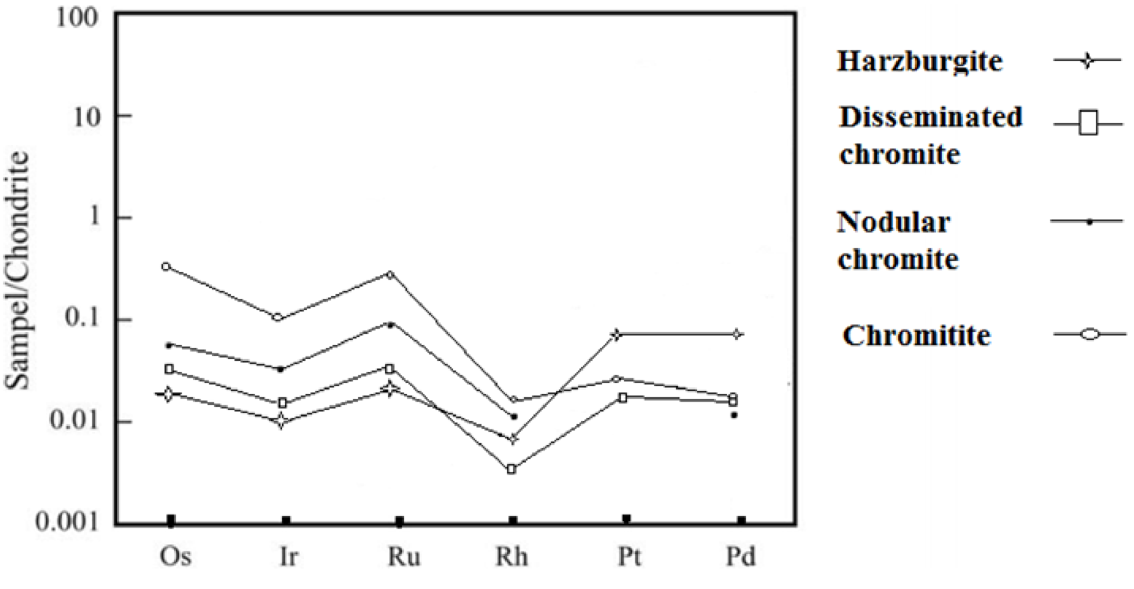


Figure 10) Comparison of the chondrite normalized PGE patterns of different PGE bearing ultramafic rock types from Khaje Jamali ophiolite complex. Normalization contents are from Naldrett and Duke (1980).

IPGEs show similar behaviors in analyzed samples from Khaje Jamali ophiolite complex. Such a similarity is shown in Fig. 11a in which Ru and Ir follow same concentration patterns in ultramafic rocks.

In Pd – Pt diagram (Fig. 11b), the number of samples contain higher contents than primitive mantle; shows PGEs are concentrated in ultramafics from Khaje Jamali ophiolite complex.

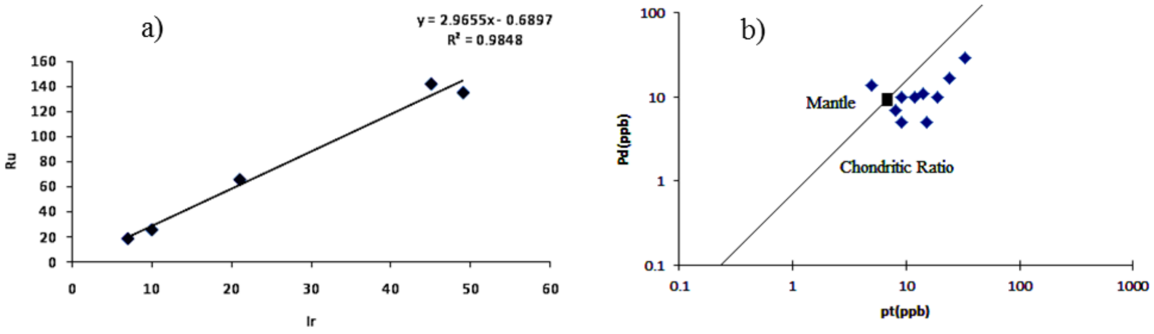


Figure 11: a) Ru–Ir diagram show similar concentration pattern of Ru and Ir in analyzed samples from Khaje Jamali ophiolite complex. b) Pd–Pt diagram (Zhou et al., 1998) shows higher concentration than primitive mantle in analyzed samples from Khaje Jamali ophiolite complex.

6- Conclusions

- Harzburgite is observed in the most part of the area and occasionally accompanied with small dunite lenses. Such rocks are almost cumulus and sometimes have foliated structure.

- According to petrographic studies on polished sections, chromite-bearing samples from Cheshmeh Bid and Anjirak areas have various sulfide phases. Such sulfide phases are almost accompanied with chromite, sometimes in serpentinite or in the silicate phases. The most abundant sulfides are pyrrhotite and pentlandite that are together with pyrite. Also other newly reported phases are Os-Cu-Sn alloy, Ni-Fe metallic alloy in serpentinite and Au nuggets. The mentioned alloys contain minor PGEs.

- In analyzed samples, elements such as Ti, Al, Ca, Na, P and K show low values while, similar to other peridotites, the ultramafic rocks are enriched in Mg. TiO_2 contents (average 0.06 wt%) are lower than the primitive mantle (0.23 wt%) corresponding to relatively high partial melting degree. Also Al_2O_3/CaO ratio ranges between 0.62 and 7 for dunite samples, compared with primary upper mantle (0.8), implies high degree of partial melting.

- In TiO_2 (wt%) vs Cr# diagram, almost all of ultramafic rocks from Khaje Jamali ophiolite complex are plotted in supra-subduction zone and are derived from depleted upper mantle slab. In TiO_2 (wt%) vs Cr# diagram various depleted ultramafic units including dunite, harzburgite, chromitite and pyroxenite are originally derived from boninites or high-Mg fore-arc tholeiite. High Cr# is corresponding to high partial melting degree or re-melting the previous depleted peridotites.

- Highest total PGE corresponds to layered chromite (299 ppb) and the lowest content belongs to host dunite with disseminated chromite (80 ppb). Host harzburgite contains totally 106 ppb and lowest IPGE contents. Unlike the harzburgite, chromite-mineralized rocks enriched in more refractory elements (IPGE). High Ru concentrations probably imply that Ru minerals exist in such rocks. The $PPGE/IPGE$ ranges from 0.11 to 1.96 that is an indicator feature of podiform chromitites.

- IPGEs concentrations are systematically reclining in order of layered chromite, nodular chromite, dunite and harzburgite. Such a reduction is together with increasing in chromite-mineralization degree, IPGEs are enriched in chromite. IPGE enriched chromitites are strongly believed that derived from PGE–enriched magma with high partial melting degree in supra subduction zone environment.

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