

## Nature of Chromite parent magma In Sabzevar ophiolite (North-East of Iran)

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**Abstract:** Significance of chromite, as the unique source for chromium, a metal with key role in industry, has inspired many geologists to investigate its genesis and natural distribution as an important contribution to its exploration in many parts of the world. To do this, geochemistry of chromite, which is considered to be the reflection of the nature of its parent magma and the geotectonic setting in which it is generated, is extensively used by many researchers. To reveal the nature of chromite's parent magma, its chemical composition is used as a petrogenetic indicator. In this regard many authors have classified chromite deposits as either high-Al ( $\text{Al}_2\text{O}_3 \geq 25$  wt %) or high-Cr ( $\text{Cr}_2\text{O}_3 \geq 45$  to 60 wt %) and have demonstrated that Al-rich chromites are generated from tholiitic and Cr-rich ones from Mg-rich boninitic magmas, two melts generated in distinct and different geotectonic setting. In this study on the basis of geochemistry of chromite samples from three nearby mining districts in Sabzevar Ophiolite Range, in the North-East of Iran, the nature of chromite parent magma and its geotectonic setting is investigated. Chromite samples are analyzed by EPMA method. The layered chromitite bodies, embedded in serpenitnized dunite, are displayed to belong to high-Cr deposits. Considering high Cr# (86-88), moderate Mg# (44-51), low  $\text{TiO}_2$  content (0.1-0.2 wt %) and other geochemical features of chromite, the parent magma dominantly accords with a high Mg# boninitic melt. According to the results of the previous works and petrography, geochemistry (especially Cr#, Mg#,  $\text{Fe}^{+3}$  and  $\text{TiO}_2$  contents) and field observations represented in this work, the chromitites must be generated in a suprasubduction zone setting. Sea floor hydrothermal processes have probably caused especially, the Mg# not to be as high as expected.

**Keywords:** *Ophiolite; chromite; boninite; Foroumad; Sabzevar; NE Iran.*

### Introduction

Genesis of chromite, as a valuable metallic ore in steel and refractory industry, had been the subject of many detailed geologic studies in different parts of the world including Iran, a country containing several important zones of potential and developed chromite-producing massifs.

Chromite as a spinel, is a very stable crystallochemical phase and remains unaltered in a wide range of geological P-T-fluid conditions and is hence an important petrogenetic indicator in peridotites [1-3]. On this basis, its chemistry can be used to infer the nature of its parent magma [1,2].

Chromitite is generated in different mafic-ultramafic geologic environments such as

ophiolites [4], Uralian-Alaskan-type complexes [5] and stratiform or layered complexes [6]. Podiform chromites, which occur in ophiolites, are classified geochemically by many authors as either High-Al ( $\text{Al}_2\text{O}_3 \geq 25\%$ ) or High-Cr ( $\text{Cr}_2\text{O}_3 \geq 45\%$  to 60%) [4,7]. This classification reflects actually, the nature of chromite parent magma [8,9], as Al-rich and Cr-rich chromites are generated from tholiitic and High-Mg boninitic magmas respectively [10].

Sabzevar ophiolite, as one of the best developed ophiolites in Iran, contains diverse kinds of igneous, metamorphic, sedimentary, hydrothermal and volcanosedimentary rocks in its different localities which makes it a geologically attractive environment. This ophiolite which is now about 65

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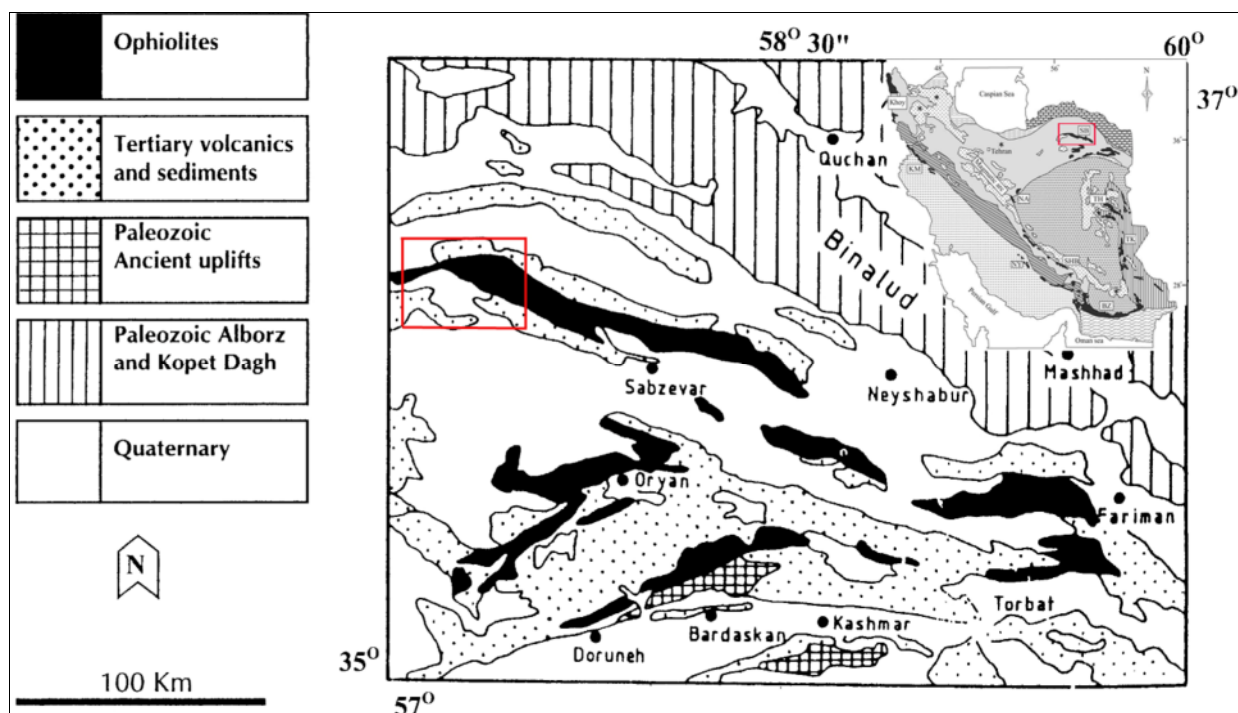
to 80 percent altered and serpentinized, contains important potential and developed chromite deposits and relatively small, disperse and faulted chromite bodies are being exploited for more than five decades in it, which makes it economically important either. In this study, using chromite microprobe chemical data, we intend to demonstrate the geochemical affinities of chromite deposits and the nature of its parent magma in a part of this ophiolite. Study like this can provide a better insight to the ore genesis and lead to a more effective and economic exploration and mining practices. It may also draw the attention to the pervasive serpentinization and low temperature hydrothermal processes and reactions which have affected the original mineral chemistry of the ophiolite and lead to new questions for the future works.

### Regional geological setting

Sabzevar ophiolite is situated in the North of Sabzevar city, which itself is located in the North-East of Iran (Fig. 1). This ophiolite builds up an East-West mountain range about 200 km long and 3 to 22 km minimum and maximum width

respectively. This range is referred to as “Joghati Mountain Rang” in geographical maps having a maximum height of 2950 m from sea level.

Based on age, ophiolites in Iran are classified into two main groups: the less abundant Paleozoic and the more abundant Mesozoic ophiolites [9, 10]. These ophiolites are further classified, on the basis of geodynamic and geographic situation, into four subgroups of which only the first one belongs to Paleozoic [13-15]: (1) ophiolites of northern Iran along the Alborz Mountain Range, (2) ophiolites of the Zagros Suture Zone, including Neyriz and Kermanshah ophiolites, which appear to be coeval with the Oman ophiolite (3) ophiolites of the Makran Accretionary Prism in the South-East of Iran (4) ophiolites and colored melanges which mark the boundaries of the Central East Iran Microplate (CEIM), including Shahre-Babak, Nain, Baft and Sabzevar ophiolites. Sabzevar ophiolite, as a 200-km-long band, is located between Iran's two principal tectonostratigraphic domains: “Alborz Mountain Range” in the North and “Central East Iran Microplate” in the South (Fig. 1).



**Fig 1.** Geologic map of Sabzevar ophiolite (in the north of Sabzevar city) and its nearby ophiolites. The ophiolites are shaded black. The rectangle, in the upper left, marks the studied area in Sabzevar ophiolite. The inset shows location of Sabzevar ophiolite, in the north-east of Iran. The map is simplified from GSI 1/250000 series maps, by M. R. Sahandi (Sabzevar map) and N. H. Nazer (Jajarm map).

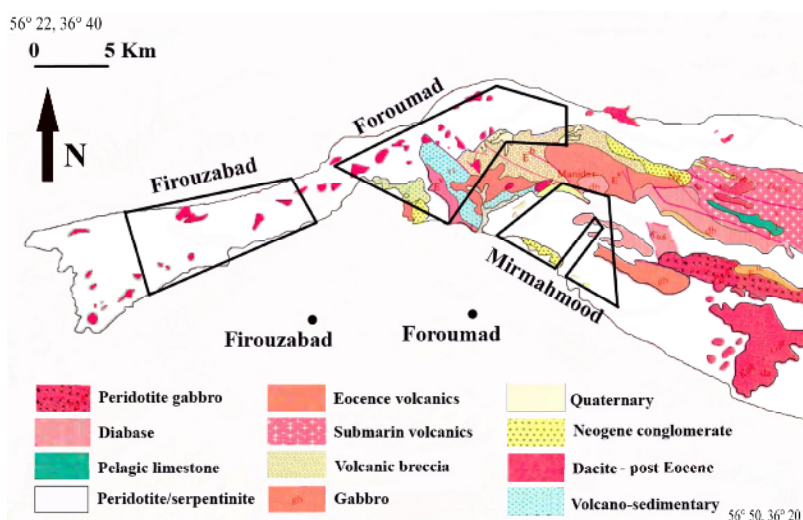
“Sabzevar ophiolite”, in spite of being highly faulted and altered, is one of the best developed ophiolites in Iran. Although a complete, contiguous and orderly section of an “ophiolite suite” is not yet observed due to faulting and tectonic displacements, it contains all pseudostratigraphic members of a conventional “ophiolite suite” including: ultramafic mantle tectonites, mafic and ultramafic layered cumulates, isotropic gabbro, tonalite, plagiogranite and granophyre, sheeted diabase dikes and (spilitic) pillow basalts interbedded with oceanic fossiliferous pelagic limestone and radiolarite [17]. The foregoing sequence is overlain in some areas by upper Cretaceous-Paleocene volcanosedimentary sequences as probable parts of an immature volcanic arc [16]. All the different chronological and lithological igneous, metamorphic (dynamothermal and ocean-floor hydrothermal) and sedimentary units and formations in this ophiolite are divided into two general genetic groups namely: ophiolitic (Campanian-Maestrichtian) and post-ophiolitic (Eocene-Quaternary) rock sequences [17]. In [18] a back-arc extensional environment in this ophiolite has been introduced, created due to the northward subduction of oceanic lithosphere. Author of [19] believes that this ophiolite is the remains of limited cretaceous oceanic lithosphere. [16] claim that the geochemical data clearly identifies that the extrusive rocks have formed from three distinct types of basaltic melts; (i) the group-1 basaltic rocks, which formed from an initial melt with N-MORB-like (LREE depleted) chemical signatures

and are petrogenetically related to the gabbros, (ii) group-2 basaltic rocks which have E-MORB chemical signatures, and (iii) group-3 basaltic rocks with LREE-enriched signatures and incompatible trace element patterns that suggest an island arc affinity (or magma that was modified by crustal contamination). In [21] it has explained that this ophiolite is a remnant of the Mesozoic oceanic basins on the northern margin of Neotethys that were consumed during the Arabia-Eurasia convergence history and subduction of short-lived back-arc oceanic basins accompanied the long-lasting history of the Neotethyan subduction in the region.

As can be conceived from the foregoing paragraphs, all the major authors [16-21], especially on the basis of field observations, the sedimentary rocks facies, geochemistry of the volcanic rocks and comparison with well-known ophiolites in the world, believe in Sabzevar ophiolite is the disrupted, faulted and altered remains of a true cretaceous oceanic lithosphere generated in an extensional setting which has suffered subsequent compression, subduction and closure in its later geologic history.

#### Sampling and analytical method

Chromite samples are taken from three discrete mining concessions namely: Mirmahmoud, Foroumad and Firouzabad which are located between  $56^{\circ} 22'$  and  $56^{\circ} 50'$  East longitudes and  $36^{\circ} 20'$  and  $36^{\circ} 40'$  North latitude in a total area of  $156 \text{ km}^2$  (Fig. 2).



**Fig. 2.** Geologic map of a part of north sabzevar ophiolite and location of the three mining areas, where the samples are taken (thick black line). The thin black line marks the ophiolite boundary. All the units are upper cretaceous in age, unless otherwise stated in the legend. The widespread white background in the ophiolite is peridotite/serpentinite complex. The base map is taken from GSI 1/250000 series maps, N. H. Nazer, Jajarm map.

**Table 1.** Chemical analyses of chromite samples from the studied areas in weight percent. Cations calculate to 6 Oxygen. Fe<sup>+2</sup> and Fe<sup>+3</sup> calculated by [39] method.

Ele	SZD 1	SZD 2	SZD 3	SZD 4	SZD 5	SZD 6	SZD 7	SZD 8	SZD 9	SZD 10	SZD 11	SZD 12	SZD 13
MgO	13.53	13.82	13.69	13.67	13.61	15.01	15.12	15.22	15.17	15.10	14.72	14.78	14.92
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeOt	15.61	15.67	15.67	15.40	16.00	13.80	13.96	14.08	13.82	14.02	14.59	14.39	14.58
CaO	0.00	0.08	0.03	0.00	0.08	0.00	0.03	0.05	0.03	0.01	0.00	0.02	0.00
ZnO	0.02	0.13	0.00	0.03	0.02	0.09	0.09	0.13	0.04	0.05	0.05	0.04	0.02
Al <sub>2</sub> O <sub>3</sub>	10.00	10.60	10.09	10.45	10.21	11.87	11.91	11.93	11.79	12.04	12.18	12.22	12.05
V <sub>2</sub> O <sub>3</sub>	0.10	0.11	0.09	0.09	0.09	0.09	0.06	0.10	0.09	0.08	0.08	0.10	0.11
Cr <sub>2</sub> O <sub>3</sub>	61.49	60.64	61.40	61.10	61.24	59.94	59.81	60.08	60.50	59.59	59.10	59.50	58.80
TiO <sub>2</sub>	0.10	0.16	0.14	0.13	0.21	0.17	0.11	0.09	0.09	0.14	0.19	0.13	0.17
Total	100.84	101.22	101.11	100.86	101.47	100.98	101.08	101.68	101.52	101.02	100.90	101.18	100.64
Mg	8.16	8.33	8.26	8.25	8.20	9.05	9.12	9.18	9.15	9.10	8.88	8.91	9.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe <sup>+2</sup>	10.37	10.10	10.27	10.27	10.47	8.86	8.71	8.69	8.77	8.80	9.27	9.23	8.97
Fe <sup>+3</sup>	0.88	1.04	0.95	0.85	0.98	0.94	1.07	1.13	0.99	1.05	1.03	0.98	1.18
Fet	12.13	12.18	12.18	11.97	12.44	10.73	10.85	10.94	10.74	10.90	11.34	11.19	11.33
Co	0.00	0.07	0.03	0.00	0.06	0.00	0.02	0.04	0.02	0.00	0.00	0.02	0.00
Zn	0.01	0.10	0.00	0.02	0.02	0.07	0.07	0.11	0.03	0.04	0.04	0.03	0.02
Al	5.29	5.61	5.34	5.53	5.41	6.28	6.30	6.31	6.24	6.37	6.44	6.47	6.38
V	0.07	0.08	0.06	0.06	0.06	0.06	0.04	0.07	0.06	0.05	0.06	0.07	0.07
Cr	42.07	41.49	42.01	41.81	41.90	41.01	40.92	41.11	41.39	40.77	40.44	40.71	40.23
Ti	0.06	0.10	0.08	0.08	0.13	0.10	0.06	0.05	0.06	0.08	0.11	0.08	0.10
O	32.86	33.08	32.97	32.96	33.05	33.47	33.48	33.68	33.64	33.47	33.41	33.52	33.32
Total	100.66	101.04	100.93	100.66	101.27	100.78	100.87	101.49	101.33	100.79	100.71	100.99	100.45
Cr#	89	88	89	88	89	87	87	87	87	86	86	86	86
Fe#	56	55	55	55	56	49	49	49	49	49	51	51	50
Mg#	44	45	45	45	44	51	51	51	51	51	49	49	50

Chemical analyses of chromite were performed in IMRC (Imaging Media Research Center) with EPMA (Electron Probe Micro Analyze) method (Table 1). The analytical conditions were 20 KeV accelerating voltage and 15 nA beam current.

Iron content of chromite was first determined as total FeO and Fe<sup>+2</sup>/Fe<sup>+3</sup> ratio was then calculated on the basis of 4 oxygens and 3 cations.

### Field observations

In the three mining areas, the following lithological units are observed: layered ultramafic and mafic rocks, isolated gabbro dikes, pillow basalts interbedded with pelagic limestone and chert, and chromite layers as “ophiolitic” units and Eocene volcanic and volcanosedimentary rocks, Miocene subvolcanic dacites, and quaternary sediments as “post-ophiolitic” units.

Chromitite bodies are enclosed in dunite and are usually tectonized, dismembered or even sometimes chaotic but evidences of lenses, layers, seams or tabular forms, macroscopically concordant with host peridotite phase layering can be observed (Fig. 3A, B).

The contact of chromitite with enclosing peridotite is either gradational or sharp, changing from chromitite to dunite to harzburgite, from center to outer parts. The enclosing peridotite is usually deeply serpentinized due to hydrothermal

alteration. Chromite is observed as layers and lenses with massive, nodular and densely to thinly disseminate textures enclosed in dunite. Dunite is generally altered and observed macroscopically as a white, pale yellow or brown mass between chromite crystals/nodules as can be seen in Fig. 3C which shows leopard texture in a hand sample.

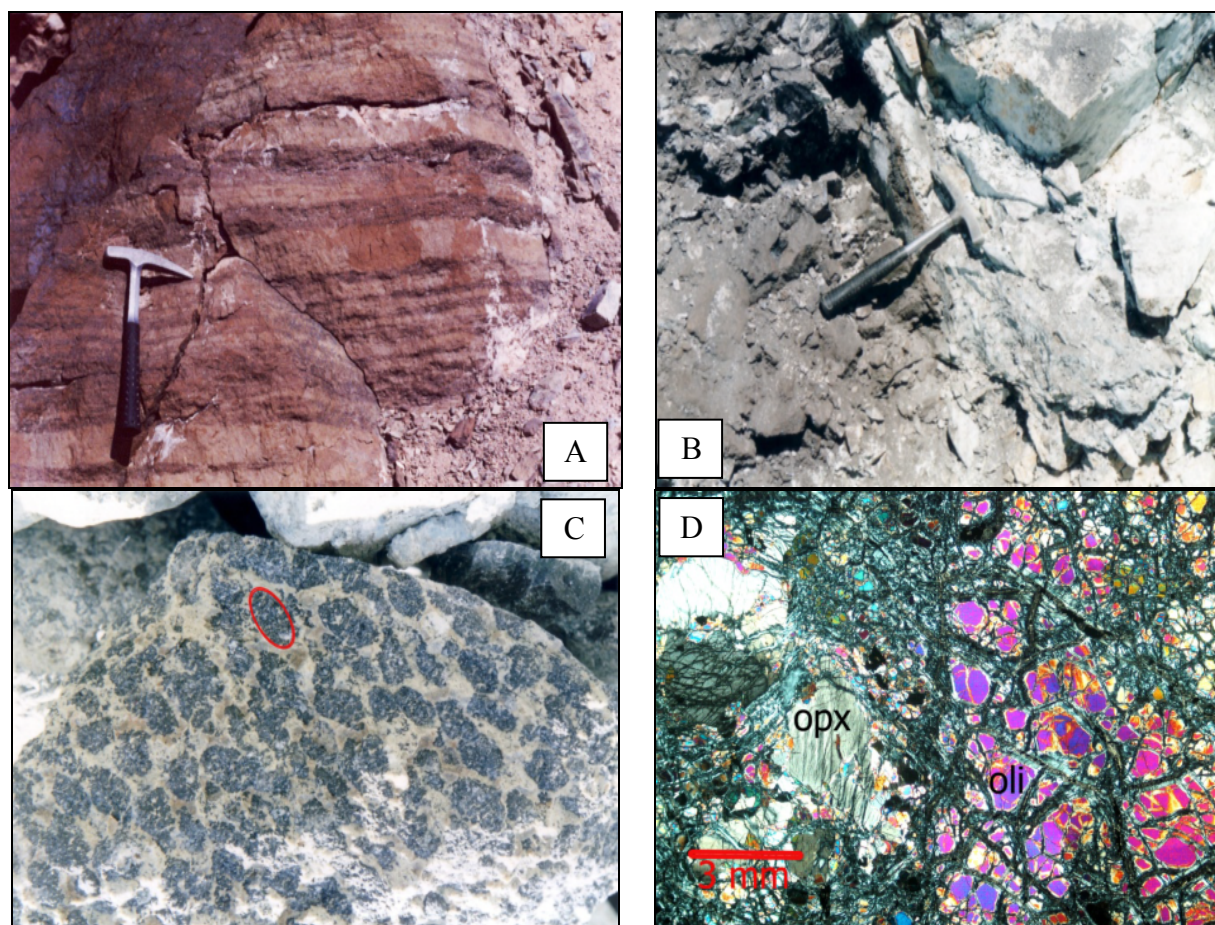
The dimensions of chromitite bodies are very different but their estimated dimensions range from a few to a maximum 50 m long and a few centimeters to a maximum of 5 m thick. In general the mined chromitite bodies' dimensions are relatively small.

### Petrography

#### Harzburgites and dunites

Harzburgite and dunite are the most abundant ultramafic rocks in the studied area respectively. Their thin sections were studied prior to chemical analyses. No conclusive sign of mantle high or low temperature microstructures or textures, such as kink banding, mechanical twinning, deformation, foliation, mylonitization or melt impregnation were conceived in the petrography of 32 studied ultramafic rocks (Fig. 3D). According to petrography and field observations their textures and structures are more consistent with ultramafic cumulate rocks rather than mantle tectonites.





**Fig. 3.** **A.** Cumulate peridotite phase layering in Foroumad area. The lighter layers are dunite and the darker ones harzburgite, which are serpentinized differently according to their mineralogy. **B.** Chromitite layers in Mirmahmood mining area. Chromite layers (dark area in the left) are embedded in dunite (light area in the right). Note the hammer for scale. **C.** Macroscopic leopard texture in chromitite hand sample. Nodules of chromite (darker) lie in a serpentinized matrix (lighter). The length of the nodule, marked by red, is 1 cm. Width of the photo is 10 cm. **D.** Crossed polarized light photomicrograph of moderately serpentinized harzburgite from Foroumad area. Disregarding serpentine as the secondary phase, 85 and 14 % of this rock is made of olivine and orthopyroxene respectively as the original volume proportion. The remaining 1% is occupied by chromite. The cracks and fractures are filled with serpentine, seen in black, blue and grey (XPL). Oli= Olivine, Opx= Orthopyroxene.

### Chromitites

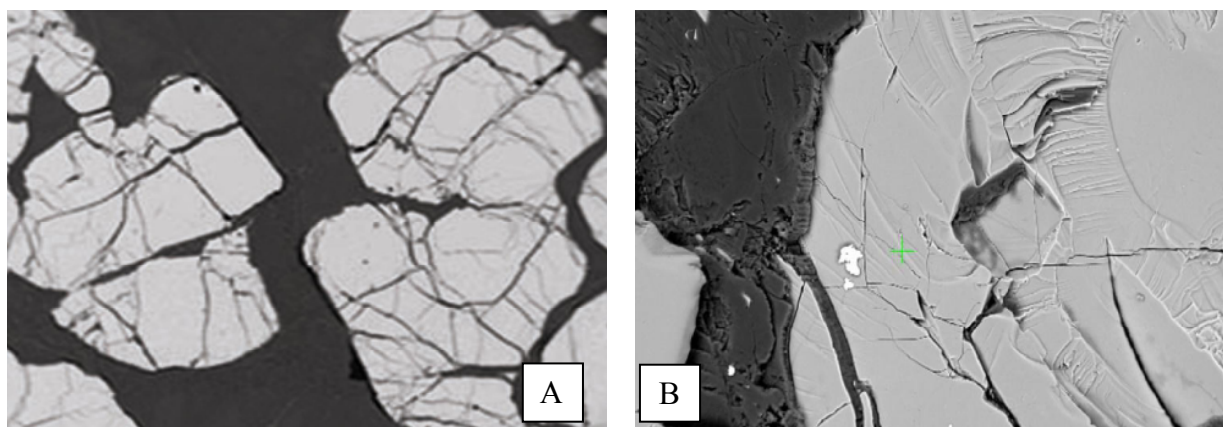
Polished sections of chromitite samples were first studied by optical methods. Olivine, often serpentinized, is the most abundant silicate mineral in chromitites and occurs usually as matrix with a variable modal proportion with chromite. The distribution of chromite crystals is usually as disseminated or nodules in a serpentinized matrix. Chromite crystals in chromitites are usually subhedral to euhedral up to 1 cm in size. They are sometimes cracked and observed as pull-apart texture (Fig. 4A). Sometimes late shearing and faulting, obliterating original textures, give rise to secondary mylonitic, cataclastic or brecciated textures (Fig. 4B).

### Geochemistry

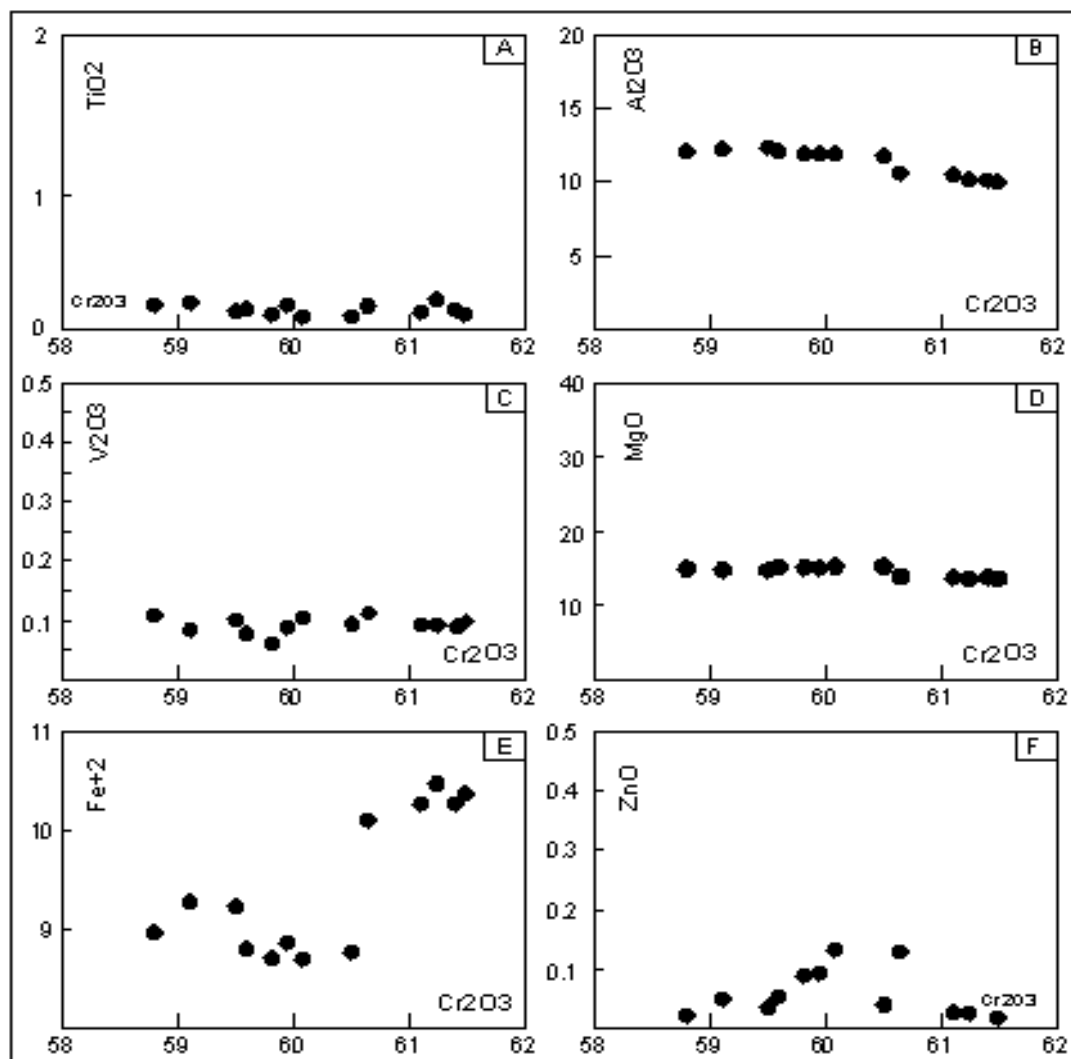
Table 1 represents weight percent chemical analyses of the thirteen chromite samples. Variation diagrams of  $\text{Cr}_2\text{O}_3$  versus  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{MgO}$ ,  $\text{V}_2\text{O}_5$ ,  $\text{ZnO}$  and  $\text{FeO}$  are shown in Fig. 5 A-F. Except for  $\text{Cr}_2\text{O}_3$  vs.  $\text{FeO}$ , which shows some scatter, other plots show fairly well interelemental coherent trends.

EPMA chemical analyses of the samples show that their  $\text{Cr}_2\text{O}_3$  content is 59 to 61 wt%,  $\text{Al}_2\text{O}_3$  is 10 to 12 wt% and their Cr# and Mg# lies in the range from 86 to 88 and 44 to 51 respectively.

The most widely accepted discriminating diagrams such as  $\text{TiO}_2$  vs.  $\text{Cr}_2\text{O}_3$  [22], Cr# vs. Mg# [23], Cr-Al-Fe<sup>+3</sup> triangle [24] and Cr# vs.  $\text{TiO}_2$  [25] are used here (Fig. 6A-D).



**Fig.4** **A.** BSE image of subhedral chromite crystals (light), in serpentine matrix (dark), with pull-apart texture. The openings in chromite are filled with serpentine. Width of the photo is 2mm. **B.** BSE image of chromite crystals (lighter) in serpentine matrix (darker) with brecciated or fractured texture. The small white patches in chromite and matrix are precious metal Ag phases. Width of the photo is 400  $\mu\text{m}$ .



**Fig. 5** Variation diagrams of chromite samples.  $\text{Cr}_2\text{O}_3$  is vs.:  $\text{TiO}_2$  in (A),  $\text{Al}_2\text{O}_3$  in (B),  $\text{V}_2\text{O}_3$  in (C),  $\text{MgO}$  in (D),  $\text{Fe}^{+2}$  in (E) and  $\text{ZnO}$  in (F). Except in (E) other diagrams show fairly well interelemental coherent trends.

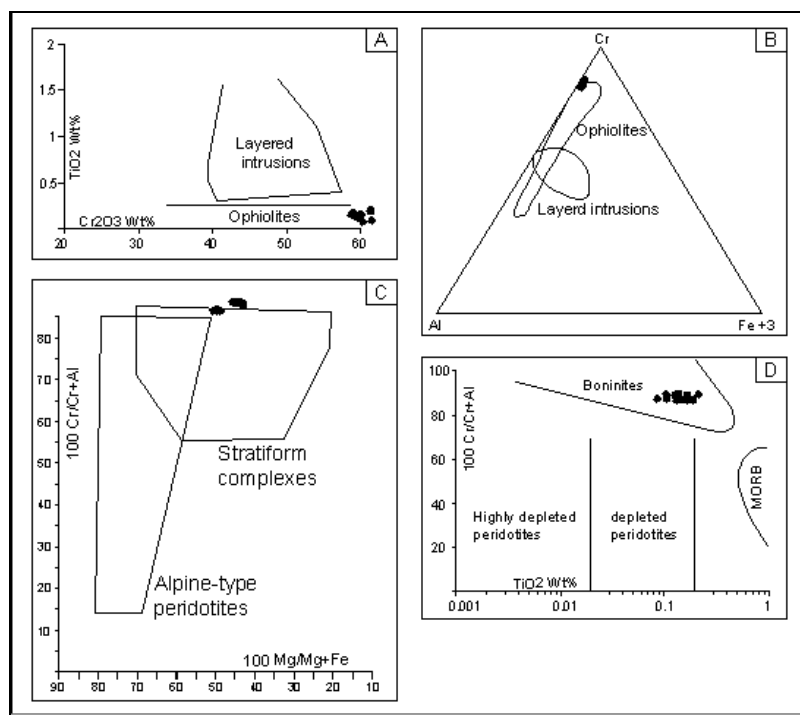
In Fig. 6A-B, which discriminate between layered ultramafic intrusions and ophiolites, the samples plot in the field of ophiolitic chromites. In Fig. 6, diagram C, some of the samples don't plot either in stratiform complexes or Alpine-type (ophiolite) peridotites fields anomalously. In Fig. 6D, which restricts the field for boninite and MORB, the samples plot in the boninite field composition.

### Discussion

Chromite composition is extensively used as a petrogenetic and geotectonic indicator [1] and [25]. Although chromite composition may be controlled by a variety of factors, including oxygen fugacity, pressure, temperature, and subsolidus ion exchange, the Cr/Al ratio of chromite in equilibrium with a melt is controlled predominantly by the total concentration of  $\text{Cr}_2\text{O}_3$  and  $\text{Al}_2\text{O}_3$  in the melt [26, 27]. Podiform chromitites have mostly chromian spinel with high-Cr# (0.7-0.8) [23] which may mean that they were mostly not derived from mid oceanic ridge environment because the rocks with chromian spinel of  $\text{Cr}\# > 0.6$  are actually not available from the oceanic floor [2]. They are most probably derived from supra-subduction zone setting [29]. Intraplate tholiites have also high-Cr# spinels (Cr#

around 0.7) [3] which are also high in  $\text{TiO}_2$  ( $>1$  wt %) [25]. The relatively low  $\text{TiO}_2$  contents of the studied chrome spinels ( $<0.5$  wt %) eliminates the possibility of their origin to be from intraplate magmas; so the chromitites in our study are geochemically consistent with ophiolitic chromitites.

In spite of the chemical stability of Cr-spinel in most cases, the possibility of its secondary alteration is not rejected [30] and chemical modifications related to subsolidus re-equilibration and metamorphic or hydrothermal processes can sometimes influence the primary magmatic high-T composition of Cr-spinel significantly [31]. In the variation diagrams (Fig. 5A-F), plots of major and minor elements of chromite samples show interelemental coherent trends except for FeO and to some extent for ZnO vs.  $\text{Cr}_2\text{O}_3$ . As chemical content of chromite can be affected by metamorphism and hydrothermal processes [30- 33] we assign this scatter to the hydrothermal processes which could have occurred after the chromite formation. However with regards to the prevalent coherent trends for most of the elements, which are not affected by secondary processes, a common origin can be inferred for the samples from the three mining areas.



**Fig. 6** Discrimination diagrams of chromite samples. A:  $\text{TiO}_2$  versus  $\text{Cr}_2\text{O}_3$  [17]; B: Ternary diagram of Cr-Al- $\text{Fe}^{+3}$  [19]; C:  $100\text{Cr}/(\text{Cr}+\text{Al})$  vs.  $100\text{Mg}/(\text{Mg}+\text{Fe})$  [18]; D: Cr-number vs.  $\text{TiO}_2$ . Boninite and MORB fields are defined in [20].

In Fig. 6A-B, the samples plot inside, on the borders and outside the ophiolite fields. In Fig. 6C, some of the samples plot inside and the others outside the stratiform complexes field. It seems that Cr and Fe are anomalously enriched in some samples. In the other ophiolites of the world similar Cr and Fe enrichments are reported and the reason for these changes is ascribed to the metamorphic or hydrothermal processes which have affected the chromite crystals chemically [30, 33]. In the variation diagrams, it was observed that the  $\text{Cr}_2\text{O}_3$  vs.  $\text{FeO}$  plot is scattered to some extent which may also be the reflection of these secondary chemical changes. Because of the pervasive and deep serpentinization of the ultramafic rocks in the studied area, these chemical changes may be assigned to the hydrothermal or similar secondary processes taken place in this ophiolite.

$\text{Cr}_2\text{O}_3$  content and Cr number of the studied samples are from 59 to 61 wt% and from 86 to 88 respectively. Al-rich chromites are considered to form from relatively low-Mg tholiitic melt whereas Cr-rich chromites from more magnesian boninitic melts [34]. The results of experimental crystallization studies [35,36] suggest that chromite compositions are controlled mainly by the composition and oxygen fugacity of the melt, and are only weakly dependent on temperature and pressure. According to [35] formula:  $\text{Al}_2\text{O}_3$  chromite =  $0.035 \text{ Al}_2\text{O}_3^{2.42}$  melt. This relation is not highly affected by crystallization temperature and could reasonably be used for computing melt composition. The average  $\text{Al}_2\text{O}_3$  of boninite melts is more than 12 wt%. Using Maurel formula [35], the  $\text{Al}_2\text{O}_3$  content of the parent melt lies between 9.79 and 11.33 wt% which is a little less than average boninitic melts. According to the mentioned chemical dependences, there are discriminating diagrams, which we have used in Fig. 6D to examine the origin of chromites. In this diagram the samples plot in the boninitic field which is in accordance with the chromites being precipitated from a high-Mg boninitic melts, produced in a subduction zone. Occurrence of a subduction zone in Sabzevar ophiolite is previously demonstrated by [18, 20, 21].

Stratiform (layered) and podiform chromitites are found together in many ophiolites around the globe [37,38]. They occur in different pseudostratigraphic levels from mantle to transition zone to crust. In this study, according to field observations and petrography of chromitites

and the enclosing ultramafic rocks, we believe that the sampled chromites are of layered type, embedded in the cumulate ultramafic silicates of this ophiolite.

Further quantitative and qualitative geochemical data, especially trace element and isotopic, would be needed if more constraints are wished to be put on the chromite genesis in this area.

### Conclusion

Geochemical similarities between chromite in studied samples shows that they should have the same origin as cumulates in the three studied mining districts; but this does not reject the probable occurrence of other types of chromitites (e.g. tectonite) in this ophiolite.

$\text{Cr\#}$ ,  $\text{Fe}^{+3}$  and  $\text{TiO}_2$  of the samples, as the most useful geochemical petrogenetic parameters of chromite are more consistent with "ophiolitic" chromite deposits in the studied area.

In the variation diagrams of chromites, the low concentrations of Ti suggest that the parent magma was derived from a refractory mantle source which is in agreement with Sabzevar oceanic lithosphere subduction scenario.

The high  $\text{Cr\#}$ , low  $\text{TiO}_2$  and calculated  $\text{Al}_2\text{O}_3$  content of the parent magma of chromite is more consistent with "boninitic" melt produced by a subducting oceanic lithosphere.

Enrichment of Cr and more or less depletion in Al and Mg, which causes lower  $\text{Mg\#}$  than expected for a boninitic melts, is probably due to penetrative hydrothermal processes, producing vast serpentinite masses in this ophiolite [31], or the result of subsolidus Mg-Fe exchange between Mg-silicate and chromite after cooling [40].

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