Evaluatins Impact Factor
IBGM
2017 – 2018
IRAQI BULLETIN OF GEOLOGY AND MINING
Arcif: 0.0755
GIF: 0.936

Iraqi Bulletin of Geology and Mining *Special Issue, No.8, 2019,*
The Geology and Economic Potential of Mineral Deposits and Occurrences of Iraq *p 65 – 85*

CHROMITITE AND PLATINUM GROUP ELEMENTS IN THE IRAQI ZAGROS SUTURE ZONE, NE KURDISTAN REGION, IRAQ: AN OVERVIEW

Tola A. Mirza[1] and Saman Gh. Rashid[2]

Received: 14/ 07/ 2018, Accepted: 14/ 02/ 2019
Key words: Chromitite; Ophiolite; Platinum Group Elements; Kurdistan Region; Iraq

ABSTRACT

The podiform chromitite ore-fields of the Iraqi Kurdistan Region have been investigated by various authors in Mawat, Penjween, Qalander and Rayat localities; all of which are situated in the Iraqi Zagros Suture Zone (NE of Kurdistan Region). They are found in a serpentinized dunite halo hosted within peridotite units that represent the remains of the obducted ophiolite complexes of Iraq. Their original sites of crystallization imply ocean spreading and plate convergence, followed by subsequent re-emplacement by thrusting. Tectonically, the chromitite of Mawat and Penjween ophiolite complexes as well as those of N-Shitna area are considered as supra-subduction type, whereas the chromitites at N-Qalander and Rayat can be interpreted as the products of MORB-like melts. Chromite forms small lensoidal ore bodies in the northeastern part of the ophiolite sequences, surrounded by dunite envelops of variable thickness and dimensions and show transitional boundaries to harzburgite. The chromite occurrences in the Iraqi Zagros Suture Zone resemble the world Cretaceous and Tertiary ophiolite ores with respect to their peridotite host rocks, geochemical characters and podiform shape. The composition of ore-forming chromites in depleted mantle rocks of Kurdistan Region are rather uniform, showing high Cr-number [Cr/ (Cr+Al)]; mostly (0.7 – 0.8), while the values of Mg-number [Mg/ (Mg+Fe^{2+})] are more variable (0.44 – 0.73). Two textural types of inclusions are distinguished in the chromite: **1)** Silicate minerals (mainly serpentine chlorite, amphibole, olivine and clinopyroxene) and **2)** Platinum group minerals (mainly laurite RuS_2). The perfect euhedral shape and sharp boundaries of the laurite crystals suggest early precipitation from a primitive magma, free growth at high temperature and later entrapment, as laurite inclusions, in the chromian-spinel. The presence of Os-rich inclusion in the chromites of Qalander and Mawat ophiolite complexes suggests that sulfide-undersaturated parent magma was involved in the formation of the chromitites.

الكروميتايت ومجاميع عناصر البلاتين في نطاق زاكروس، شمال شرق إقليم كردستان، العراق نظرة عامة

توڵه احمد ميرزا محمد و سامان غريب رشيد

المستخلص

تمت دراسة تمعدنات خامات الكروميتايت في اقليم كردستان العراق من قبل باحثين مختلفين في مواقع ماوات وبنجوين وقلندر ورايات وكلها تقع في نطاق الالتحام في زاكروس العراق (شمال شرق اقليم كردستان). وقد تم العثور

---

[1] College of Science, Geology Department, University of Sulaimani, Sulaymaniyah, Iraq, e-mail: tola.merza@univsul.edu.iq

[2] Directorates of Oil and Minerals in Sulaimani, Sulaymaniyah, Iraq

عليها ضمن هالة الدونايت السربنتيني مستضافة داخل وحدات البريدوتايت والتي تمثل بقايا تسلقات معقدات الافيولايت في العراق. تشير مواقع التبلور الاصلية الخاصة بالمعقدات الى انتشار وتباعد قاع المحيط وتقارب الصفائح ويليه اعادة التموضع لاحقا عن طريق الفالق الدسري. من الناحية التكتونية، تعتبر كرومايت معقدات أفيولايت ماوات وبنجوين بالاضافة الى تلك الموجودة في منطقة شمال شيتنا من نوع الغوران الفوقي بينما الكرومايت في شمال قلندر ورايات يمكن ان يفسر على أنه يشبه نتائج ذوبان الحدبات المحيطية. يشكل الكرومايت جسيمات خام عدسية صغيرة في الجزء الشمال الشرقي من تتابعات الافيولايت محاطة بمغلفات الدونايت بسماكات وابعاد مختلفة وتظهر حدود انتقالية الى الهزبركايت. تشبه رواسب الكرومايت في نطاق التحام زاكروس العراق خامات الافيولايت العالمية لعصري الطباشيري والثلاثي فيما يتعلق بصخور البريدوتايت المستضيفة لها من ناحية الخواص الجيوكيميائية وشكل المتضمنات. ان تركيب الخام المكون للكرومايت في صخور الجبة المنضبة في اقليم كردستان متشابه الى حد ما ويظهر ارتفاع في عدد الكروم Cr [Cr/ (Cr+Al)]؛ في الغالب يكون (0.7 – 0.8) بينما تكون قيم عدد المغنسيوم Mg [Mg/ (Mg+Fe^{2+})] أكثر تغيرا وفي حدود (0.73 – 0.44). تم تمييز نوعين من المظاهر النسيجية في الكرومايت: **1)** المعادن السليكية (بشكل رئيسي كلورايت سربنتين والامفيبول والاوليفين والكلاينوبايروكسين) و **2)** معادن مجموعة البلاتين (بشكل رئيسي لورايت RuS_2). يشير الشكل البلوري المثالي والحدود الحادة لبلورة اللورايت الى الترسب المبكر من الصهير الأولي والنمو الحر في درجات الحرارة العالية وثم الانحباس كما في متضمنات اللورايت في الكرومايت سبينيل. ان وجود اوزميوم (Os) الغني ضمن الكرومايت في معقدات أفيولايت قلندر وماوات يشير الى أن الصهارة الأولية غير المشبعة بالكبريتيدات كانت مسؤولة عن تكوين الكرومايت.

INTRODUCTION

This is an overview article, based on published literature, mainly by Buda, (1988); Mirza, (2008); Ismail *et al*., (2009); Ismail *et al.* (2010) and (2014). Chromitite is the main economic source for chromite and subsequent source of the metal chromium. Chromitites in the Kurdistan Region (NE Iraq) are mentioned in regional geological investigation reports of ultramafic rocks in different locations of Iraqi Zagros Suture Zone (IZSZ). Most of the primary work was carried out around the middle of the last century by geologists of the Site Investigation Company (UK), Russian geologist groups and Iraq Geological Survey (Buda, 1988). The primary internal works emphasized on stratigraphy and structural conditions without detail study on petrology and geochemistry. Recently, some published and unpublished researches on the chromitites and chromian spinel with their host rocks attempted to expose petrogenesis, geochemical, petrological and tectonic accepts. The chromitite bodies occur in ultramafic rocks of some different Tethyan ophiolite sequences of the Iraqi Zagros Suture Zone, such as Penjween, Mawat and Bulfat (Cretaceous ophiolites) and N-Qalander and Rayat (Tertiary ophiolites) (Fig.1). The chromitites bodies are mainly lensoidal in form and called podiform chromitite, but some occur as veins, disseminated, stringers and linear or planer segregation chromites. Furthermore, some placer chromite was reported from Kani Sard village, NE of Sulaymaniyah City which was probably derived from the Mawat Massif.

The chromitites of Iraq have been the subject of extensive geological investigations, but limited geophysical and geochemical exploration and preliminary attempts to estimate the chromite resources and platinum group elements (PGEs). The previous studies have attempted to describe in detail the chemistry and petrology of individual occurrences (e.g., Buda and Al-Hashmi, 1977; Mahmood, 1978; Buda 1988; Al-Chalabi, 2004; Mirza, 2008; Ismail 2009; Ismail *et al*., 2009; Ismail *et al*., 2010; Ismail *et al*., 2014 and Mirza *et al*., 2016). The individual geophysical study on the chromite has been done by Mirza *et al.* (2016) that showed the extension and dimension of the chromite ore bodies at Kuradawi village in the Mawat Ophiolite Complex. This article is a compilation of the available literature on the geology of the chromitite deposits in the Kurdistan Region based upon the published work by various authors. Emphasis on published work is justified to facilitate further reading. Discussion of the various features of the chromitites is considered separately for each topic within the article.

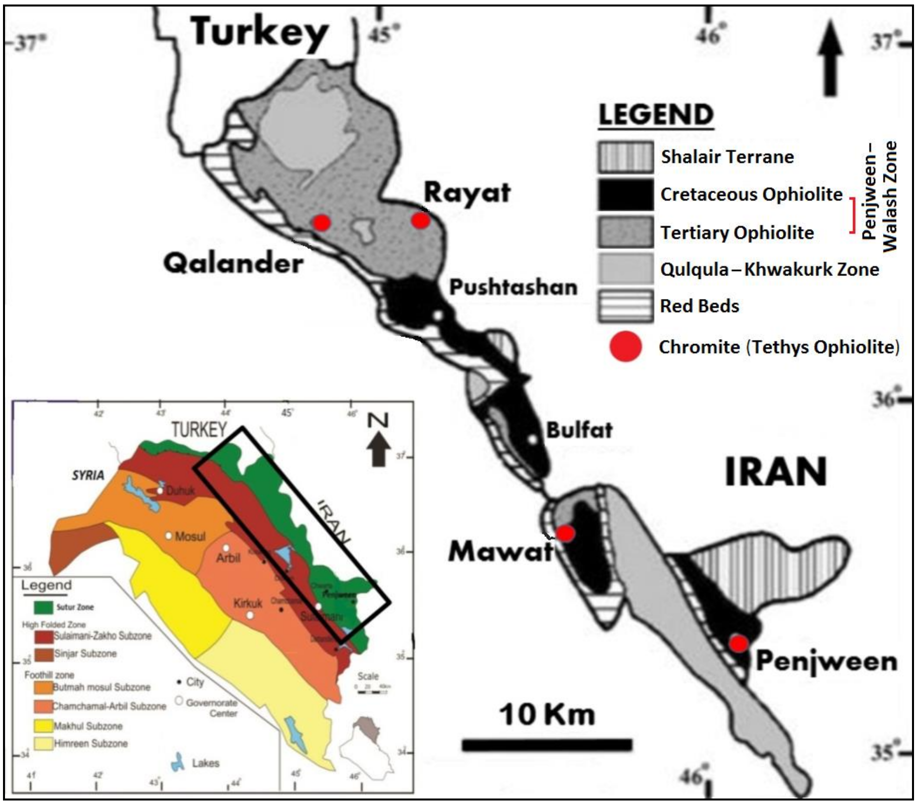

Fig.1: Location map and simplified geological sketch of the Iraqi Zagros Suture Zone along the Iraq – Iran border, showing the main ophiolites in Iraq. [Modified from Ismail *et al.* (2014) after Moores *et al.* (2000) and Sissakian (2000)]

GEOLOGICAL SETTING AND CHROMITE DISTRIBUTION

Two types of chromitite occur in the mantle peridotites of ophiolite complexes; pods of chromitite hosted by harzburgite and less commonly lherzolite, and chromitite layers present in the dunites of the lower cumulate and transition zone (Gervilla and Leblance, 1990). Podiform chromitites are most commonly located in the upper mantle tectonites of harzburgite ophiolite types (Roberts, 1988 and Pearce *et al*., 2000). The Mesozoic Tethyan ophiolite belt is a heterogeneous remnant of oceanic crust and/or supra-subduction zone assemblages that were formed during the closure of the Tethyan Ocean as a result of collision between Eurasia and Gondwana (Alavi, 2004). This closure produced an arcuate ophiolite belt extending from the Balkan Peninsula through Anatolian Taurus Mountains to the Iranian Zagros Mountains (Dilek *et al*., 2007). As part of this system, about 2000 km-long Zagros Orogenic Belt extends from southeastern Turkey through northern Syria and north-northeastern Iraq to western and southern Iran. It is interpreted to have formed during the closure of the Neo-Tethyan Ocean and subsequent oblique collision of the Afro-Arabian Plate with the Iranian micro-continent in the Late Cretaceous – Early Tertiary (Alavi, 2004). The IZSZ represents sites of the ongoing collision between the Arabian and the Iranian plates, and the Arabian and Turkish micro-continents in northeastern and northern Iraq, respectively (Numan, 1997). The IZSZ occupies an area of ~5000 Km^2 along the Turkey – Iraq – Iran borders. Tectonically it is divided into: Qulqula – Khwarkurk and Penjwen – Walash zones and Shalair Terrane (Fig.1) (Jassim and Goff, 2006).

Chromitites and chromian spinel have been studied in many ophiolite localities in the Kurdistan Region and the details of their occurrence are given in the following paragraphs.

The localities are ordered from southeast to northwest along the orientation of the ophiolite exposures (Fig.1). Most of the Kurdistan chromite are podiform, brecciated, and disseminated (Fig.2), while commercial chromite deposits are found mainly in two forms namely stratiform and podiform.

- **Mawat Chromite**

Complete ophiolitic rock sequences occur in the Mawat Ophiolite Complex (MOC). The ultramafic rocks are mostly serpentinized harzburgite, wherlite and dunite with chromitite (Buda and Al-Hashimi, 1977). The upper part of the ultrabasic body contains olivine websterite, which forms dikes in the peridotite. Above the ultrabasic rocks there is about 1000 m thick gabbroic body emplaced tectonically (Buda, 1988). The structural features of the chromitite pods in the MOC show that such ore bodies have internal structure making angle of 10 – 12° with dunite wall and surrounding peridotite which indicates that the chromite ore bodies are of subconcordant type. According to Cassard *et al*. (1981), subconcordant deposits are generally tabular in shape and lie within 10 to 25° in strike and/ or dip to the foliation. Hence, the chromitite rocks of the MOC are considered as subconcordant deposits.

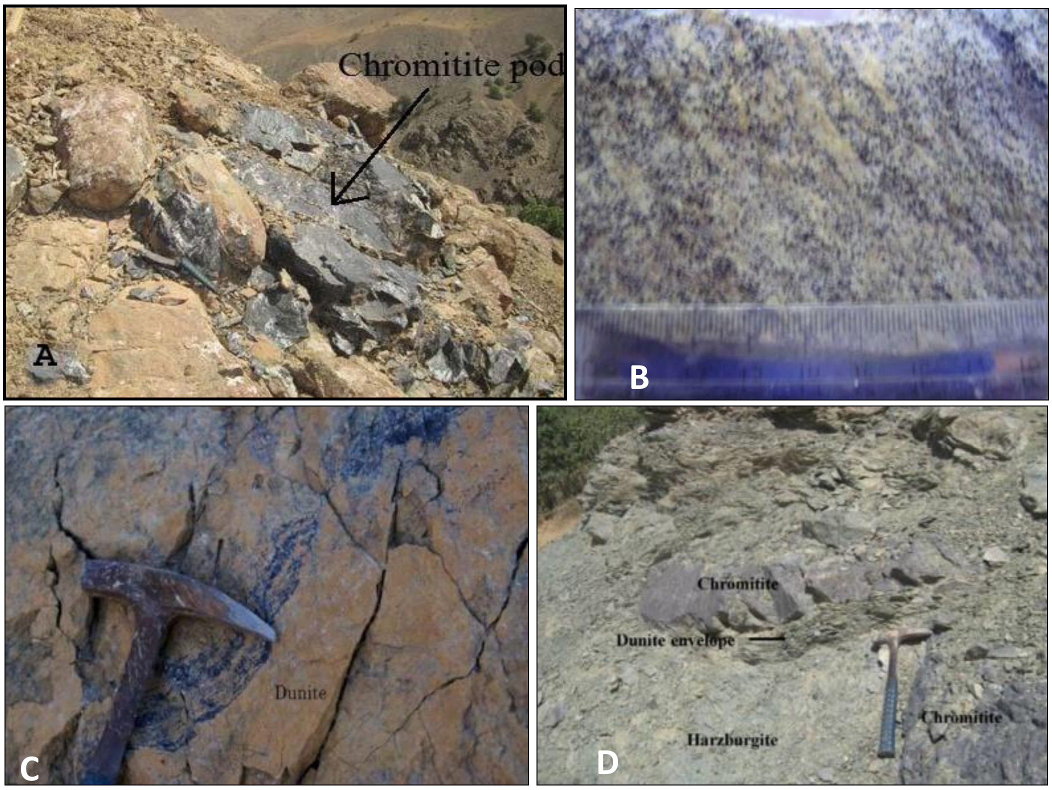

Fig.2: Some of the chromitite textures in IZSZ: **A)** Podiform chromite in Mawat Ophiolite Complex, **B**) Densely disseminated chromite in Ser Shiw valley, Mawat Ophiolite; **C**) Banded chromite in Penjween ultramafic body; **D)** Qalander Ophiolite. [Figs.2A and 2B from Mirza (2008); Fig.2C from Mohammad (2008) and Fig.2D from Ismail *et al*. (2014)]

Three types of chromitite are associated with peridotite rocks in the MOC which are podiform, brecciated and disseminated. They are mostly located in Ser Shiw valley-Shakha Root area for about 2 Km NE of Kuradawi village (Mirza, 2008) (Figs.2A and B). Nine pods of chromitite are found in NE of Kuradawi village and always rimmed by a dunite envelope in each pod, separated from others by harzburgite (Fig.2A). Their size varies from 0.3 to 2 m width and from (0.5 – 12) m length. Variation in inclusions content has been observed in all of chromitite pods. The brecciated and disseminated chromitite rocks are more enriched in mineral inclusions than the associated massive ores. Inclusions of silicate minerals are common in chromian spinel of the chromitite, associated dunite envelope rocks and peridotite host rocks. The silicate inclusions have various sizes being less than 1 mm across, with subhedral to anhedral shape. The silicate mineral inclusions are in order of decreasing abundance; chlorite, serpentine, amphibole, olivine and clinopyroxene. The massive chromitite is characterized by platinum minerals inclusion and the main type is laurite with minor content of iridium disulfide (IrS_2) (Mirza, 2008).

- **Penjween Chromite**

Chromite occurs as disseminated grains in all of the Penjween peridotites, but podiform chromite is concentrated in certain locations. The Penjween igneous complex represents an ophiolite sequence within the larger Zagros Suture Zone. It is a northwest-southeast trending elongated body (35 Km^2) within the Iraqi territories. The remnant parts are located within the adjacent Iranian territory (Mahmood, 1978). The Penjween ophiolite sequence is bounded in the east by phyllite and calcschist of the Qandil Unit and in the west by the Merga Red Beds of the Tertiary Red Bed Series (Fig.3). There are three localities which show greater concentration of chromite: **1)** west to southwest of Penjween town, **2)** near Buban village where as much as fifteen lenses are present, and **3)** west of Ragan village where some chromite veins with small irregular bodies are present.

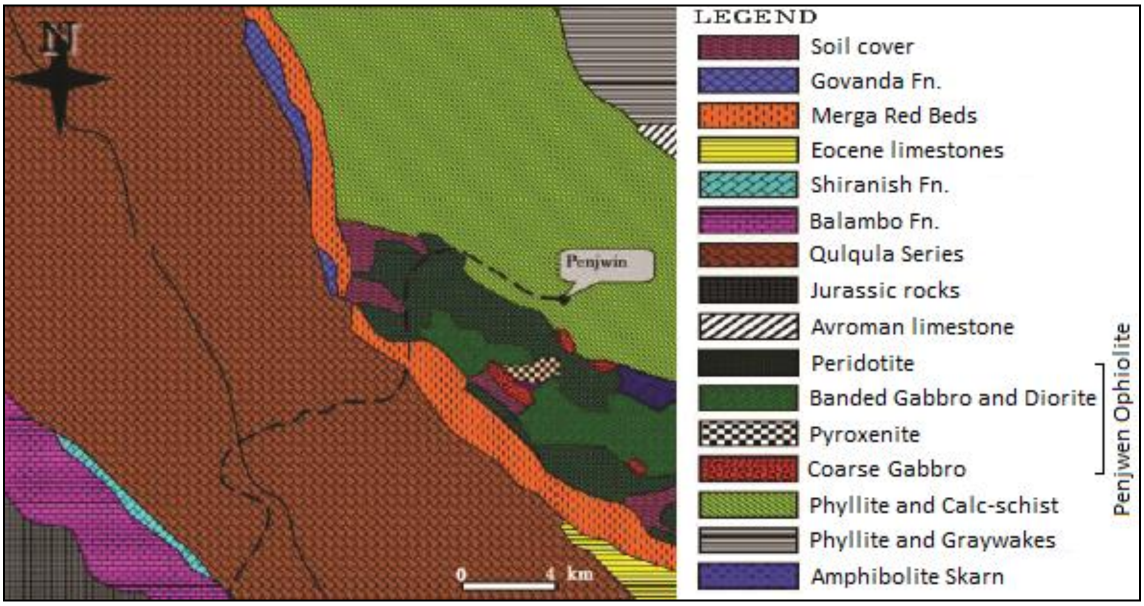

Fig.3: Geological map of Penjween Ophiolite Complex (modified after Buday and Jassim, 1987; in Mohammad, 2008)

Commonly, the chromitites are hosted in harzburgite, although they are typically enveloped by dunite. Structurally, the chromitites bodies are mainly podiform, but some occur as irregular schlieren bands, veins, stringers and linear or planer segregation (Fig.2C) The mutual relationship in these different types of concentrations is not always clear; in some areas gradation occurs from massive to schlieren and disseminated types (Mahmood, 1978). The dimensions of the chromitites are highly variable, generally ranging from (2 – 3) m long and (0.5 – 2) m thick. Most chromitite bodies are concordant with the foliation in the host peridotite. The contact between the chromitites and host dunite or harzburgite is usually sharp, but some chromitite bodies grade into the dunite envelope by increasing in modal olivine (Mohammad, 2008).

- **Rayat Chromite**

The Rayat chromite occurrences are situated to the east of Rayat village within the northeastern corner of Iraq; about 110 Km east of Erbil city and 10 Km west of the Iraqi – Iranian border (Fig.1). The chromitites in the area are found in an ophiolite mélange belt of the IZSZ. The massive and brecciated chromitite rocks in the Rayat area was studied by Ismail *et al*. (2009). The ultramafic body at Rayat is relatively small, about 1 km long and 200 to 400 m wide in plain (Vasiliev and Pentelikov, 1962), forming a thin lens-shaped sheet striking northeastward The ophiolite is of Tethyan type (e.g., Moores *et al*., 2000), and the ophiolite belt is continuous both northwestward to Turkey and southeastward to Iran. The Chromitite occurs as pods mostly <1 m across within strongly sheared serpentinite. This chromitite is associated with sheared serpentinite. The serpentinite forms a mélange complex, composed of strongly sheared and comminuted serpentinite with various kinds of blocks including serpentinized peridotites and chromitites. Due to the highly sheared nature of the serpentinite, the dunite envelope was not recognized just around the chromitite pods (Ismail *et al*., 2009).

- **Qalander Chromite**

The Qalander ophiolite is part of the Qalander Mountain, Bradost area, which lies ~100 Km northeast of Erbil City. This is a small and incomplete ophiolitic sequence that forms part of the IZSZ situated within the Walash and Naopurdan groups, tectonically overlain by a thrust sheet composed of Miocene Red Bed Series (Fig.1). The ultramafic bodies hosting chromitites in the Qalander area are relatively small (2.0 Km long and 0.3 – 0.5 Km wide in map view), NE – SW trending, lens-shaped in isolated blocks of serpentinized dunite and harzburgite rocks. The chromitite rocks occur mainly as small lenticular bodies within sheared and serpentinized rocks of the Qalander ophiolite at the northern end of Shitna village (N-Shitna) and in the northern side of Qalander Mountain (N-Qalander) (Fig.2D). The chromitite pods have different chemical characteristics and are concordant to near-concordant with the host rocks. The massive chromitites at N-Shitna are generally highly fractured and enveloped by serpentinized dunite (Al-Chalabi, 2004 and Ismail *et al*., 2014).

PETROGRAPHY OF THE CHROMITITES

Most of the chromitites in the IZSZ have massive (about 80% chromite) or disseminated texture and exhibit pull-apart texture (Cassard *et al*., 1981) (Fig.4A), but sometime they show brecciated texture (Fig.4B). Mineral inclusions and veinlets, such as silicate minerals and calcite, have been observed clearly in most of the chromite grains (Fig.4C). Generally, massive chromite is subhedral, transected by cracks and altered along the rims and cracks into iron-rich chromite.

Chromite in the massive chromitites of Penjween is typically medium grained (1 – 4) mm across occurring mainly in serpentinized dunites. Disseminated chromitites occur as aggregates of (0.5 – 1) mm crystals. Chromitites in the different localities have similar petrographic properties, however, some differences in geochemical characteristics can be observed in some of these bodies (Table 1). Common banded texture is also present (Fig.3C). Olivine and tremolite are the most abundant silicate minerals in the chromitites and occur as matrix minerals and as inclusions in chromite (Mirza, 2008 and Mohammad, 2008). The chromitite grains are of anhedral to subhedral forms with variable size and are dark red to nearly opaque. Harzburgite contains disseminated, generally anhedral and rarely subhedral chromite with comparatively smaller grain size having the same physical and optical characteristics as above.

Chromitite occurrences within the MOC are mostly present as small bodies of massive and disseminated ores with chromite content ranging from >75 volume % in massive chromitites, to (40 – 60) volume % in disseminated types (Mirza, 2008). Dunite and harzburgite contain (4 – 10) volume % and (<4) volume % of accessory chromite respectively. Chromitite pods in the MOC are lensoidal in shape (0.3 – 2) m across and (0.5 – 12) m long with relatively sharp and in some cases diffuse contacts with the enclosing dunite (Fig.2A). Chromite grains are (0.5 – 3) mm in the massive pods and (0.1 – 2) mm in the disseminated type. They are dark brown in thin section, and subhedral to anhedral in shape, but late shearing and faulting obliterate these primary textures forming cataclastic, pull-apart and brecciated textures (Mirza, 2008 and Mirza *et al*., 2016).

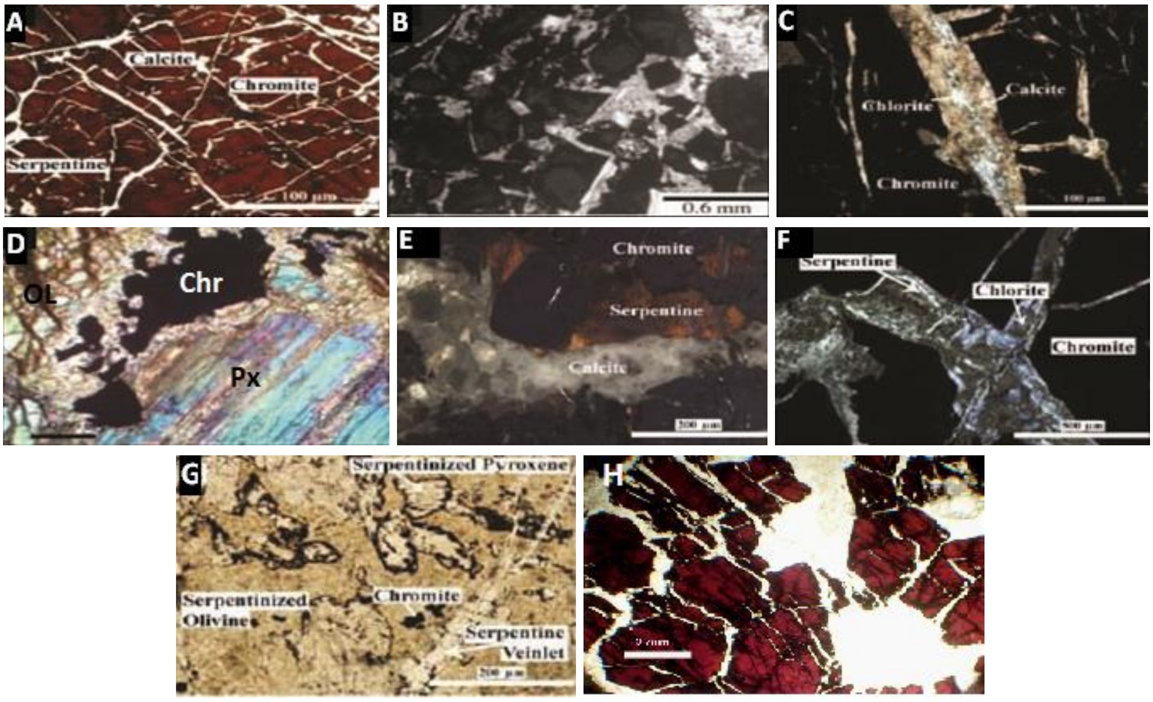

Fig.4: Photomicrographs of different chromitite textures in the IZSZ with mineral inclusions.

A) Massive chromite crystal aggregates as pull-apart texture, traversed by a network of serpentine and calcite-filled veinlets, reflected cross nicols. **B**) Brecciated chromitite with fragmentary spinel grains. The matrix is mostly replaced by carbonates, plane-polarized light. **C**) Veinlets filled by calcite and chlorite (central parts) traversing chromite crystal aggregates, reflected polarized light. **D**) Vermicular chromite grain with olivine and pyroxene in harzburgite rocks, cross-polarized light. **E)** Dunite: chromite crystal aggregates in a matrix of serpentine and calcite (RXN); **F)** Dunite: chromite crystal aggregates separated by veinlets of mixed serpentine and chlorite (TXN); **G)** Harzburgite: serpentinized olivine and pyroxene as well as a rim of magnetite surrounding altered pyroxene crystals formed as a result of serpentinization process (TPL); **H)** Brecciated chromitite intergrowth with pyroxene (PPL). (Figs.4A, C, E, F and G from Ismail *et al*., 2014; Fig.4B from Ismail *et al*., 2009 and Figs.4D and 3H from Mirza, 2008)

Table 1: Average of microprobe analysis of massive (M), brecciated (B) and disseminated (D) chromite in the main IZSZ ophiolites. Cr# = Cr/ (Cr + Al), Mg# = Mg/(Mg + Fe^{2+}), Fe^{3+}# = Fe^{3+}/(Fe^{3+} + Cr +Al). (Source of data: Penjween after Buda, 1988; Mawat after Mirza, 2008; Rayat after Ismail *et al*., 2009 and Qalander after Ismail *et al*., 2014)

Locality	**Penjween**			**Mawat**			**Rayat**		**N-Qalander**		**N-Shitna**	
Deposit type	M	B	D	M	B	D	M	D	M	D	M	D
Cr_2O_3	54.06	57.32	51.17	51.35	51.02	53.78	53.91	43.41	42.6	33.96	60.12	56.88
SiO_2	0.35	0.27	0.05	0.05	0.02	0.03	0.01	0.001	0.01	0.01	0.01	0.03
Al_2O_3	9.22	10.24	12.62	13.95	13.68	11.48	16.14	25.22	25.65	35.23	10.10	10.53
FeO_t	26.97	18.17	29.58	21.72	24.17	24.69	13.47	17.85	13.98	12.05	14.96	18.29
TiO_2	0.09	0.15	0.22	0.23	0.15	0.125	0.18	0.055	0.32	0.01	0.11	0.01
MnO	0.84	0.41	0.48	0.38	0.417	0.44	0.22	0.27	0.29	0.51	0.23	0.68
MgO	9.30	13.21	6.03	10.37	7.96	7.3	16.21	13.07	17.11	17.89	15.42	13.42
Total (wt.%)	**100.83**	**99.77**	**100.15**	**98.05**	**97.42**	**97.85**	**100.1**	**99.88**	**99.96**	**99.66**	**100.95**	**99.84**
Atom per Formula												
Cr	1.416	1.47	1.36	1.33	1.35	1.431	1.32	1.045	0.99	0.76	1.49	1.44
Si	0.012	0.007	0.002	0.001	0.00	0.001	0.00	0.00	0.00	0.00	0.00	0.001
Al	0.36	0.39	0.50	0.54	0.54	0.455	0.59	0.90	0.89	1.18	0.37	0.4
Fe^{+2}	0.521	0.354	0.627	0.45	0.51	0.521	0.28	0.41	0.25	0.23	0.27	0.34
Fe^{+3}	0.204	0.122	0.19	0.15	0.17	0.174	0.082	0.042	0.1	0.06	0.12	0.15
Ti	0.002	0.004	0.005	0.005	0.004	0.003	0.004	0.001	0.007	0.007	0.002	0.00
Mn	0.024	0.011	0.014	0.01	0.012	0.013	0.006	0.007	0.007	0.01	0.006	0.018
Mg	0.459	0.64	0.30	0.51	0.40	0.366	0.75	0.59	0.75	0.76	0.72	0.64
Cr#	0.80	0.79	0.73	0.71	0.71	0.76	0.71	0.54	0.53	0.39	0.80	0.78
Mg#	0.47	0.64	0.32	0.53	0.44	0.41	0.74	0.59	0.75	0.77	0.73	0.65
Fe^{3+}#	0.10	0.06	0.09	0.07	0.08	0.08	0.04	0.02	0.05	0.03	0.06	0.08

The interstitial matrix of the chromite grains consists mainly of secondary chlorite and amphibole, together with rare primary olivine. Chromite grains in these chromitite pods contain inclusions of silicate and PGE minerals. These silicate inclusions comprise chlorite and amphibole group minerals, which are usually linked to the matrix by irregular veinlets of these secondary minerals. Rare grains of primary olivine are preserved as inclusions within the chromite. Chromian spinel is brown to reddish brown under the plane polarized light. Arai (1997) related this color of chromian spinel to high Cr# content. Chromian spinel abundance is (≤3) volume % in harzburgite of the MOC and are frequently vermicular and intergrowths with orthopyroxene and/or clinopyroxene (Figs.4D and H), whereas it is (>3) volume % in dunite (Mirza, 2008).

The Rayat chromitite is massive and contains (>70) volume % chromian spinel. The chromian spinel is brecciated and the matrix is rich in carbonates (dolomite and calcite) to various extents. Chlorite flakes with grayish brown interference colors are commonly associated with carbonates. Lizardite/chrysotile serpentinite is also found in the matrix. No primary silicates (olivine, pyroxene) have been preserved in pods or in host rocks (Ismail, 2008). The brecciation is enhanced in parallel with the degree of carbonation. The chromian spinel is dark reddish brown in thin section, indicating high Cr character (Ismail *et al*., 2009).

The Qalander chromitite shows higher content of chromite, predominantly of massive character that becomes disseminated near the contacts with the enclosing dunite and forms small, isolated ellipsoidal bodies, (0.5 – 1) m wide and up to (1.5) m long (Fig.2B). The massive chromitites contain (>90) volume % chromite (Fig.4A). The primary silicate minerals in the chromitites are pervasively altered to chrysotile, lizardite or chlorite (Figs.4A and 4C). These bodies have sharp contacts with the surrounding dunite and harzburgite (Fig.2D) and are composed of subhedral to euhedral, medium to coarse-grained aggregates of chromite (up to 1 mm) (Figs.4E and F) traversed by veinlets of serpentine, chlorite and calcite (Fig.4E – G). Some of the magnetite grains in these rocks were formed as a result of serpentinization of their ultramafic host rocks which form a rim around the serpentinized olivine and pyroxene crystals (Ismail *et al*., 2014) (Figs.4D and G).

MINERAL CHEMISTRY OF THE CHROMITES

Chromite structure can be compared with the formula AB_2O_4, where A denotes divalent cations (Fe^{2+} and Mg^{2+}) occupying tetrahedral sites, and B denotes trivalent cations (Cr^{3+}, Al^{3+} and Fe^{3+}) occupying octahedral sites (Albers, 1986). The results of Electron Probe Microanalysis of chromite grains in massive, brecciated and disseminated chromitite rocks of the IZSZ are listed in Table (1), showing mostly the unaltered grains or cores of altered grains. There is a little compositional variation from grain to grain and from sample to another in the different pods of the same or different area in the analysed chromian spinel. In general, two different occurrences of chromian spinel grains are found in the peridotite rocks of the IZSZ ophiolites including fresh and altered grains. Despite the metamorphic overprint that has affected the ophiolites, alteration is limited to the development of ferrian chromite along cracks and at the contact among different crystals. As a result, the magmatic composition of the chromite has been analysed in the preserved core of spinel grains (Mirza, 2008 and Mirza *et al*., 2016).

The cores of altered spinel grains from serpentinized harzburgite appear to retain their original igneous chemistry and are similar to fresh chromian spinel grains, indicating that alteration has not reached the core of the mineral grains. Alteration along rims and fractures show depletion of Cr, Al, and Mg accompanied by enrichment in Fe as major elements. For minor elements, there is enrichment in Mn, Ti and Si (Ismail, 2009). Chromites from different tectonic environments have distinctive Cr#, which reflect differences in magma composition (Arai, 1992; Arai and Yurimoto, 1995 and Arai *et al*., 2004). The relationship between Al_2O_3 - Cr_2O_3 - Fe_2O_3 indicates that all the IZSZ chromite, in massive chromitites samples, plot in the field of aluminum chromite (Fig.5). The range of Cr# is between (0.53 – 0.80) which is higher than those of MORB (0.2 – 0.54; Allen *et al*., 1988), and lower than those of boninites (0.80 – 0.90; Roeder and Reynolds, 1991). The only high Al-chromitites are found in N-Qalander occurrences, which are similar to those of the northern Oman ophiolites (Rollinson, 2005 and 2008) and can be interpreted as the products of MORB like melts (Fig.6). Generally, they are close to ophiolitic podiform chromitite where Cr# ranges between (0.6 – 0.8) usually (0.7 – 0.8) (Arai, 1997). The chemistry of the IZTZ chromite in all localities is typical of the podiform chromitites in Alpine-type peridotites (Fig.7).

The Penjween massive chromites exhibit high iron content (FeO = 18.79 wt.%, Fe_2O_3 = 8.18 wt.%) and the aluminum content is low (Al_2O_3 = 9.22 wt.%), while Cr_2O_3 content is about (54.06) wt.% (Table 1). Increasing pyroxene content of the rocks resulted in a relative enrichment of Al (Buda, 1988). Buda (1988) mentioned that the most chromian spinel associated with dunites, which crop out in the eastern part of the complex, are fresh with no evidence of alteration, whereas, in the western part of the complex, the grains show different degrees of alteration within harzburgite lherzolite rocks.

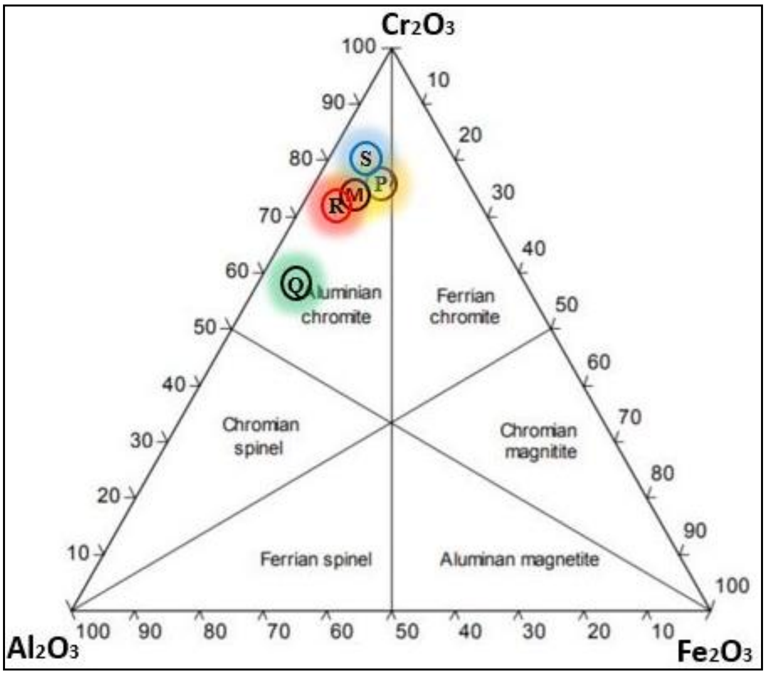

Fig.5: Cr_2O_3-Al_2O_3-Fe_2O_3 diagram for podiform chromitite rocks in IZSZ
(P: Penjween, M: Mawat, R: Rayat, Q: N-Qalander and S: N-Shitna)
(Field labels from Steven, 1944). (Source of data: Penjween after Buda, 1988; Mawat after Mirza, 2008; Rayat after Ismail *et al*., 2009 and Qalander after Ismail *et al*., 2014)

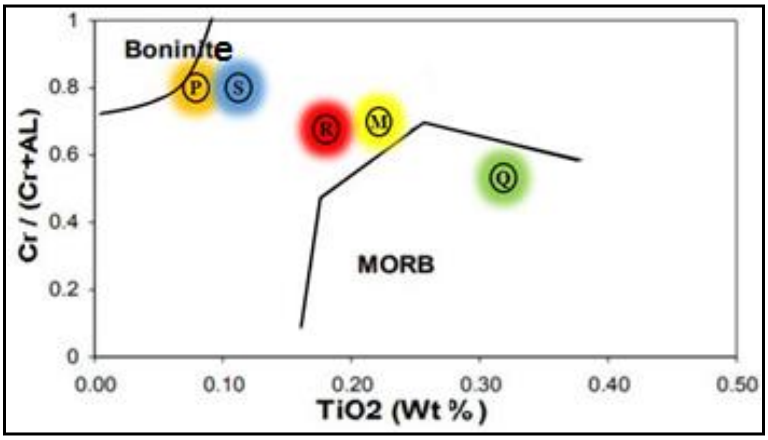

Fig.6: Cr# vs. TiO_2 content for chromite in the IZSZ chromitites
(P: Penjween, M: Mawat, R: Rayat, Q: N-Qalander and S: N-Shitna). The fields labeled Boninites and MORB are from Arai (1992). (Source of data: Penjween after Buda, 1988; Mawat after Mirza, 2008; Rayat after Ismail *et al*., 2009 and Qalander after Ismail *et al*., 2014)

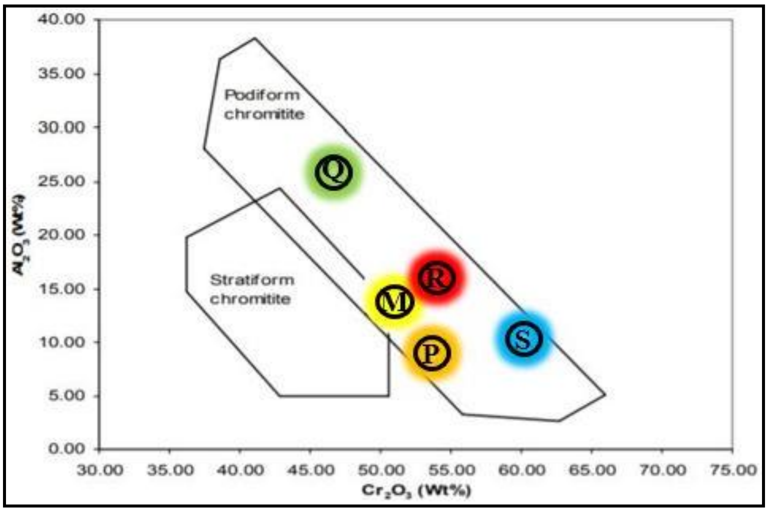

Fig.7: Plot of Cr_2O_3 vs Al_2O_3 in chromite from the IZSZ podiform chromitite. Compositional fields from Bonavia *et al*. (1993). (P: Penjween, M: Mawat, R: Rayat, Q: N-Qalander and S: N-Shitna) (Source of data: Penjween after Buda, 1988; Mawat after Mirza, 2008; Rayat after Ismail *et al*., 2009 and Qalander after Ismail *et al*., 2014)

The MOC Chromites show little compositional variation from one sample to another within and between different chromitite pods. They have Cr_2O_3 and Al_2O_3 contents of (50.02 – 53.78) wt.% and (11.48 – 13.95) wt.%, respectively. The Cr_2O_3 contents equate to high Cr# values (mean 0.73), whereas Fe# is mostly about (0.08), which is extremely low. The TiO_2 content is also low with a mean of (0.17) wt.%. Low Ti-chromites are common in ophiolitic peridotites (Dick and Bullen, 1984 and Arai, 1992) which are considered characteristic of high-Cr# podiform chromitites (Dickey, 1975; in Ismail *et al*., 2010). The Cr# vs. TiO_2 of the Mawat chromitites plot outside the fields defined by boninites (Fig.6); they actually fall within the compositional range defined by Cr-rich chromite (Mirza, 2008).

The Rayat chromite data is close to those of the MOC; the unaltered part of the chromian spinel is relatively high in Cr#, (0.70 – 0.72). The TiO_2 content of spinel is around (0.2) wt.%. The disseminated chromian spinel in serpentinized harzburgite is lower in chromian ratio (Cr# ~0.54), than that in chromitite (Cr# ~0.71) (Fig.6). Alteration drives the spinel composition ultimately to magnetite through ferritchromite. High Cr# and low Fe^{3+} spinels, which are different from ferritchromite formed during relatively high temperature alteration stage, can be easily discriminated from the primary spinels by optical characteristics (high reflectivity and inclusions of secondary hydrous minerals in the former) (Arai *et al*., 2006b).

The unaltered cores of the Qalander chromite grains are the only ones considered in the interpretation of primary chromite composition. The chromite crystal chemistry of the chromitite from the two varieties of N-Qalander ophiolite show considerable differences in their major and minor elements (Table 1). The N-Shitna massive chromitites consist of Cr-rich chromite with average Cr#, Mg#, and Fe^{3+}# of (0.80, 0.73, and 0.06) respectively, whereas those of the disseminated-type are (0.78, 0.65, and 0.08), respectively. The N-Qalander massive-type chromitites consist of Al-rich chromites with average Cr#, Mg#, and Fe^{3+}# of (0.53, 0.75 and 0.05) respectively, whereas, those of the disseminated-type are 0.39, 0.77 and 0.03 respectively and plot in the MORB-field (Ismail *et al*., 2014) (Fig.7), which is confirmed by the discriminate diagram of Kamentsky *et al*. (2001) (Fig.8).

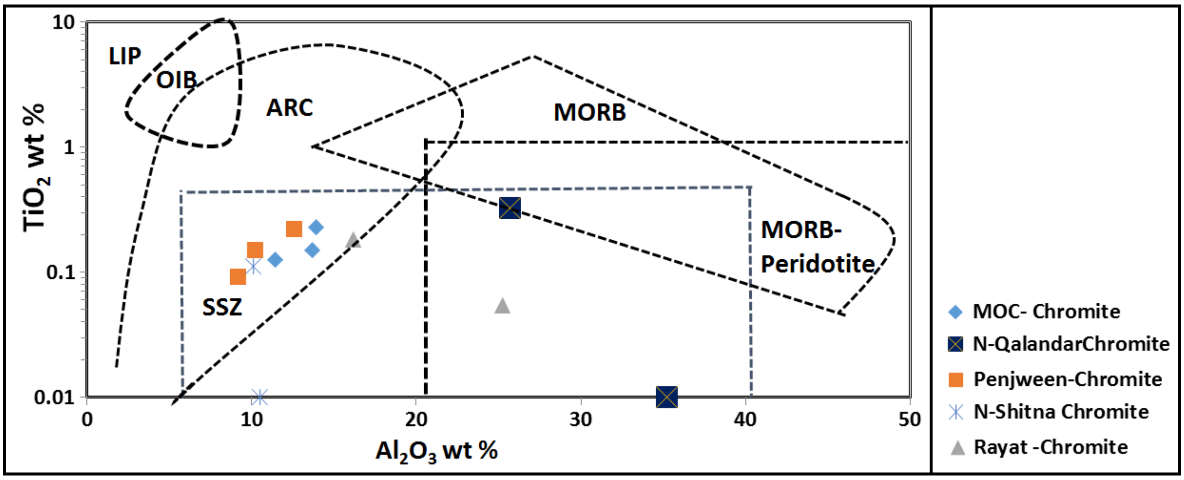

Fig.8: Relation between TiO_2 vs. Al_2O_3 of chromite in the IZSZ. Fields after (Kamentsky *et al*., 2001). **SSZ:** Supra-Subduction Zone; **LIP:** Large Igneous Province; **MORB:** Mid Ocean Ridge Basalt; **OIB:** Ocean Island Basalt. (Source of data: Penjween after Buda, 1988; Mawat after Mirza, 2008; Rayat after Ismail *et al*., 2009 and Qalander after Ismail *et al*., 2014)

PLATINUM GROUP ELEMENTS

Platinum Group Elements (PGEs) represent a coherent group of siderophile elements. They include poorly soluble elements (Ir, Os, and Ru) and more soluble elements (Rh, Pt, and Pd) in basaltic melts (Amosse *et al*., 1990). Due to their siderophile nature, PGEs have been concentrated mainly in the earth's core and mantle during the early stages of the planet history (Jagoutz *et al*., 1979; Arculus & Delano, 1981 and OíNeill, 1991). The PGEs are considered as one of targets for mining exploration in ophiolites (Leblance, 1991). The PGE abundance is systematic, provides information on the petrological nature and evolution of the mantle source from which they were derived and to lesser extent can reflect the post magmatic events that have affected their host rocks. There are three processes controlling the PGE concentration in igneous rocks; namely partial melting of upper mantle, crystal fractionation and alteration (e.g., Barnes *et al*., 1985; Ahmed and Arai, 2002).

▪ Geochemistry of the PGE in the chromitite of the IZSZ

The PGEs (Pt, Pd, Rh, Ir, Ru and Os) display a wide range of chemical and mineralogical similarities (Ismail *et al*., 2010) and considered to be potential geochemical indicators of processes involving material transfer from the mantle to the crust (Naldrett, 1981 and Garuti *et al*., 1997). Because of the different degrees of S-saturation and PGE contents of boninitic and tholeiitic magmas, the PGE concentrations can provide useful information about chromitites and their genesis (Hamlyn *et al*., 1985). The PGE patterns of high-Cr chromitite are the result of interaction of S-undersaturated boninitic magma with harzburgites depleted by prior partial melting. Whereas, the PGE patterns of the high-Al chromitite reflect interaction between initially S-saturated tholeiitic magmas and depleted harzburgites (Zhou *et al*., 1998 and Ahmed and Arai, 2002).

Comprehensive studies on the PGE content in the chromitites of the IZSZ are mentioned by many authors (e.g., Mirza, 2008; Ismail *et al*., 2010 and Ismail *et al*., 2014) (Table 2). However, no detail study about PGE content in the Penjween chromitite and their hosts was found. Leblance (1991) classified the PGE concentration in ophiolitic complexes into rich

PGE (>750 ppb) and poor PGE (<750 ppb). Accordingly, most of the chromitites of the IZSZ belong to the poor PGE content type. The PGE contents and distribution patterns are widely variable in rocks from the MOC in which the average total PGE content is (644.7) ppb in the massive chromitite; (257.1) ppb in the brecciated and (54.5) ppb in the disseminated type, while in dunite and harzburgite they are (50) and (85) ppb respectively (Table 2). The chondrites-normalized PGE patterns of chromitite samples, including massive, brecciated and disseminated ores, are characterized by enrichment in IPGE (Os, Ir, Ru) relative to PPGE (Rh, Pt, Pd) with (IPGE/PPGE = 5.7; 6.06 and 2.11, respectively) (Table 2) and (Fig.9). The relative enrichment of IPGE in chromitite samples are also reflected by slightly negative slopes from Ru to Pt (Ru/Pt = 4.6, 11.54 and 4.7, respectively).

Table 2: Average PGE content (ppb) in the chromitite and their host peridotite and dunite rocks. (Source of data: MOC from Mirza, 2008 and N-Qalander from Ismail *et al.*, 2014)

Locality	**Mawat Ophiolite Complex**					**N-Qalander**		**N-Shitna**	
Types	**M**	**B**	**D**	**Dun.**	**Harz**	**M**	**Dunite**	**M**	**Harz**
Os	61	39	6	5	9	53	17	39.4	14
Ir	252.7	54.7	7.5	6`	8	31.8	7	31.2	6
Ru	234.7	127	23.5	11	17.5	60.8	15	87.4	14
Rh	16.3	10.7	3	2	4.5	7.5	3	11.4	3
Pt	51	11	5	12	28	18.8	15	6.2	12
Pd	29	14.7	9.5	14	19	19.8	22	7.8	9
∑PGE	644.7	257.1	54.5	50	85	192	79	183	57
∑IPGE/∑PPGE	5.7	6.06	2.11	0.785	0.67	3.28	1	6.26	1.42
Pd/Ir	0.11	0.27	1.27	2.333	2.375	0.63	3.14	0.25	1.5
Ru/Pt	4.6	11.54	4.7	0.917	0.625	3.12	1	14.41	1.17

(M: Massive chromitite; B: Brecciated; D: Disseminated; Du: Dunite and Harz: Harzburgite)

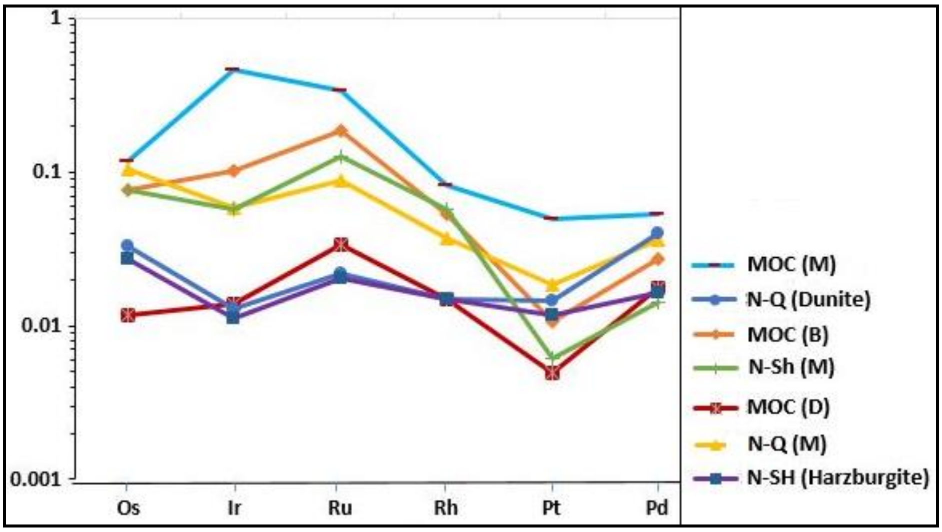

Fig.9: Chondrite-normalized PGE patterns of podiform, brecciated and disseminated chromitites samples from the Mawat Ophiolite Complex (MOC); high Al-chromitites of N-Qalander and Dunite, high Cr-chromitites of N-Shitna with harzburgite rocks. (Source of data: chondrite values from Naldrett and Duke, 1980 (cf. 514, 540, 690, 200, 1020 and 545 ppb for Os, Ir, Ru, Rh, Pt and Pd, respectively); MOC from Mirza, 2008; N-Qalander and N-Shitna from Ismail *et al*., 2014)

These patterns and the low PGE abundances are typical of ophiolitic chromitites elsewhere (Page and Talkington, 1984; Ahmed and Arai, 2002; Proenza *et al*., 2007; Uysal *et al*., 2007 and Chen and Xin, 2008). The Pd/Ir value is an indicator of PGE fractionation (Naldrett *et al*., 1979). The Pd/Ir in the chromitite of the MOC ranges between (0.11 – 1.27) (Table 2). The PGE-sulfides form the main platinum group minerals (PGM) in the MOC chromitites, comprising mainly laurite [RuS_2] and rare iridium disulfide (IrS_2) (Fig.10) (Mirza, 2008).

The PGE abundances in the N-Qalander ophiolites are lower than MOC, averaging (187.5) ppb in massive chromitite, (57) ppb in harzburgite and (79) ppb in dunite (Table 2). The total PGE concentration in the podiform chromitites are within the values generally reported for ophiolitic chromitites (<300 ppb; El Ghorfi *et al*., 2008). The average PGE abundances in the Cr-rich chromitites of N-Shitna and Al-rich chromitites of N-Qalander are listed in Table (2). The Pd/Ir, Ru/Pt and IPGE/PPGE ratios are (0.25, 14.41 and 6.26, respectively) for Cr-rich chromitites (N-Shitna) and (0.63, 3.12 and 3.28, respectively) for Al-rich chromitites (N-Qalander) (Table 2).

The harzburgite samples from the N-Qalander ophiolite are enriched in PGE relative to the upper mantle as also indicated by Barnes *et al*. (1988), and depleted relative to their abundances in the associated chromitite. In general, the average PGE concentration in dunite samples of MOC is slightly lower than that of the accompanying harzburgite (Table 2) and higher than upper mantle (McDonough and Sun, 1995). While the average PGE concentration in dunite samples of the N-Qalander area is higher than that of harzburgite. The analysed chromitites are ~3 times enriched in PGE relative to the associated ultramafic rocks.

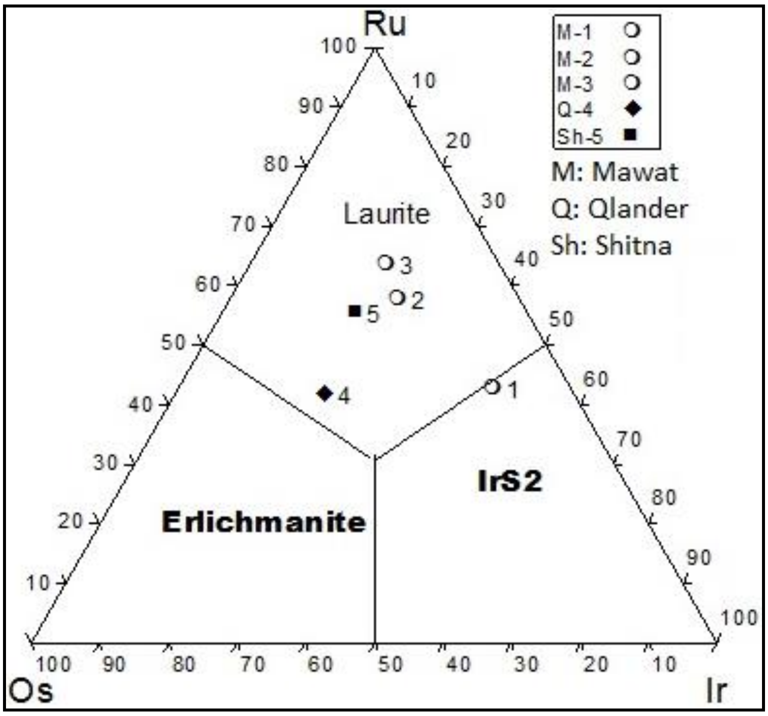

Fig.10: Triangular diagram of Harris and Cabri, (1991) illustrating the composition of Platinum Group Minerals of MOC, N-Qalander and N-Shitna chromitites. (Source of data: MOC from Mirza, 2008; and N-Qalander from Ismail *et al*., 2014)

The PGE concentrations in the chromitites of N-Qalander ophiolite are comparable with similar podiform chromitites of six ophiolites in Turkey that were studied by Uysal *et al*. (2010). The average concentration of PGE of these Turkish ophiolites is (253) ppb and (170) ppb in the Cr-rich and Al-rich chromitites respectively, corresponding to 183 ppb and 192 ppb of the N-Qalander chromitites. Both; the studied N-Qalander and the Turkish chromitites, show enrichment in IPGE relative to PPGE (Ismail *et al*., 2014).

The platinum group minerals (PGM) in the IZSZ are investigated in the MOC and N-Qalander chromitites by Mirza (2008) and Ismail *et al*. (2014). Based on optical properties and microprobe analysis, laurite (RuS_2) is the only PGM phase. Grain sizes of the laurite are very small, with a maximum size of (5) µm. The EPMA conducted on these laurite inclusions by Ismail *et al*., (2014) correspond to an average formula of $Ru_{0.78}Os_{0.14}Ir_{0.05}Rh_{0.04}Pt_{0.02}S_{2.09}$ (Table 3; Ismail *et al*., 2014). Laurite has euhedral shape and forms inclusions in the fresh chromian spinel minerals within the chromitite rocks. The perfect euhedral shape and sharp boundaries of the laurite crystals suggest that they are free growth at high temperature and that they precipitated early from a primitive magma (Ismail *et al*., 2014). Then, they became entrapped as laurite inclusions in the chromian spinel. The EPMA shows that the laurite minerals are of the Os-rich variety and this suggests that the parent magma involved in the formation of the Qalander chromitites was sulfide-undersaturated (Ismail *et al*., 2014). In terms of laurite composition, the Qalander chromitites are similar to Oman ophiolitic chromitites.

Table 3: EPMA of laurite inclusions (wt.%) in the High-Cr chromitites of the Qalander Ophiolite (Data from Ismail *et al*., 2014)

S. No	**QA1-1**	**QA1-2**	**QA1-2-1**	**QA1-1**	**Mean**
S	31.17	31.46	35.07	33.57	32.82
Ru	36.93	38.49	41.54	37.83	38.7
Os	10.16	14.03	15.22	10.81	12.56
Ir	6.48	2.66	2.85	7.97	4.99
Pt	4.33	1.18	0.12	1.29	1.73
Rh	1.56	2	2.3	1.69	1.88
Pd	n.d	n.d	n.d	n.d	n.d
Cr	3.17	4.68	1.77	2.28	2.97
Al	1.33	0.16	0.05	0.04	0.4
Mg	1.22	0.44	0.0	0.05	0.43
Fe	0.73	1.31	0.56	0.52	0.78
Total	97.08	96.41	99.48	98.05	97.26
Apfu					
S	1.978	2.028	1.183	2.178	2.092
Ru	0.744	0.787	0.82	0.779	0.782
Os	0.109	0.152	0.16	0.118	0.135
Ir	0.069	0.029	0.03	0.086	0.053
Pt	0.045	0.013	0.001	0.014	0,018
Rh	0.031	0.04	0.045	0.034	0.037
Pd	n.d	n.d	n.d	n.d	n.d
Cr	0.124	0.186	0.068	0.091	0.117
Al	0.101	0.013	0.004	0.003	0.03
Mg	0.102	0.037	0	0.005	0.036
Fe	0.027	0.048	0.02	0.019	0.029
∑cation	1.356	1.306	1.15	1.155	1.242
Total	3.333	3.333	3.333	3.333	3.333

n.d: not detected

- **Genesis of Chromite**

The genesis of podiform chromite is a complicated and controversial subject; numerous models have been proposed (McElduff and Stumpfl, 1991; Arai *et al*., 2004; Uysal *et al*., 2005; and Pagé and Barnes, 2009). However, some aspects of podiform chromite genesis are agreed upon. It is widely accepted that environmental setting is responsible for the genesis of podiform chromitite and it is associated with the formation of oceanic crust (Pearce *et al*., 1984). Chromium metal occurs exclusively in rocks formed by the intrusion and solidification of molten lava or magma, which is very rich in the heavy, iron-containing minerals such as pyroxene and olivine (El Ghorfi *et al*., 2008). Chromium spinel is a heavy mineral and it concentrates through gravity separation from most of the other molten material in the magma during crystallization from the cooling magma (Uysal, *et al*., 2010). Two types of chromitite occur in the mantle peridotites of ophiolite complexes: **1)** pods of chromitite hosted by harzburgite and less commonly lherzolite, and **2)** chromitite layers present in the dunites of the lower cumulate and transition zone (Edwards, 1991).

The extensive early crystal fractionation of olivine and chromite, such as that observed in the supra-subduction zone ophiolites, reflects the association of podiform chromitite deposits with such a tectonic setting (Pearce *et al*., 1984; Roberts, 1988 and Edwards, 1991). Petrographic and geochemical characteristics of chromitite and associated ultramafic rocks of the IZSZ can be used to constrain the tectonic setting of the ophiolites in part of the IZSZ (Ismail *et al*., 2010). Kamenetsky *et al.* (2001) have compiled a database of Al_2O_3 and TiO_2 compositions of chromite and have recognized fields with varying degrees of overlap that can be used to distinguish six different tectonic settings. On the basis of these parameters, chromite compositions for all IZSZ ophiolites samples plot in the arc and supra-subduction zone fields and MORB (Fig.8). In addition, the discriminant diagram presented by Arai (1992) was used to distinguish the genesis of chromitite rocks of the IZSZ, and indicates that these podiform chromites of MOC; Penjween and N-Shitna are generated from an arc-related magma while the podiform chromitite of Rayat and N-Qalander are related to (MORB) origin (Fig.11). The low Ti-chromites are common in ophiolitic podiform chromitites and characterized by Cr# >0.60 (Dick and Bullen, 1984 and Arai, 1992).

Chromite composition can be an indicator of magma affinity (Melcher *et al*., 1997, Ismail *et al*., 2010); high-Cr chromitite [Cr# >0.60; where Cr# = atomic ratio of Cr/(Cr + Al)] indicates crystallization from boninitic compositions, whereas high-Al chromitite (Cr# <0.60) indicates derivation from MORB-like tholeiitic magmas (Zhou *et al*., 1994 in Ismail *et al*., 2010). The chromitite of MOC, Penjween and N-Shitna are characterized by high Cr# values (>0.6) which indicates formation from a magma generated in the Supra Subduction Zone, while the Cr# values of N-Qalander and Rayat are (<0.6) which is characteristic of MORB melt (Figs.6 and 8). These melts are generated at low degrees of partial melting, usually less than 20%, which is not sufficient to remove all mantle sulfide, and thus produce melt with low level of PGE (Zhou *et al*., 1998 and Ahmed and Arai, 2002). The chondrites-normalized PGE patterns of the podiform chromites in the MOC and N-Qalander are similar to those of podiform chromitites elsewhere. They are enriched in IPGE (Os, Ir, Ru) relative to PPGE (Rh, Pt, Pd), resulting in a general negatively sloping patterns. These patterns and the low PGE abundances are typical of ophiolitic chromitites elsewhere (Ahmed and Arai, 2002, Uysal *et al*., 2007 and Ismail *et al*., 2010).

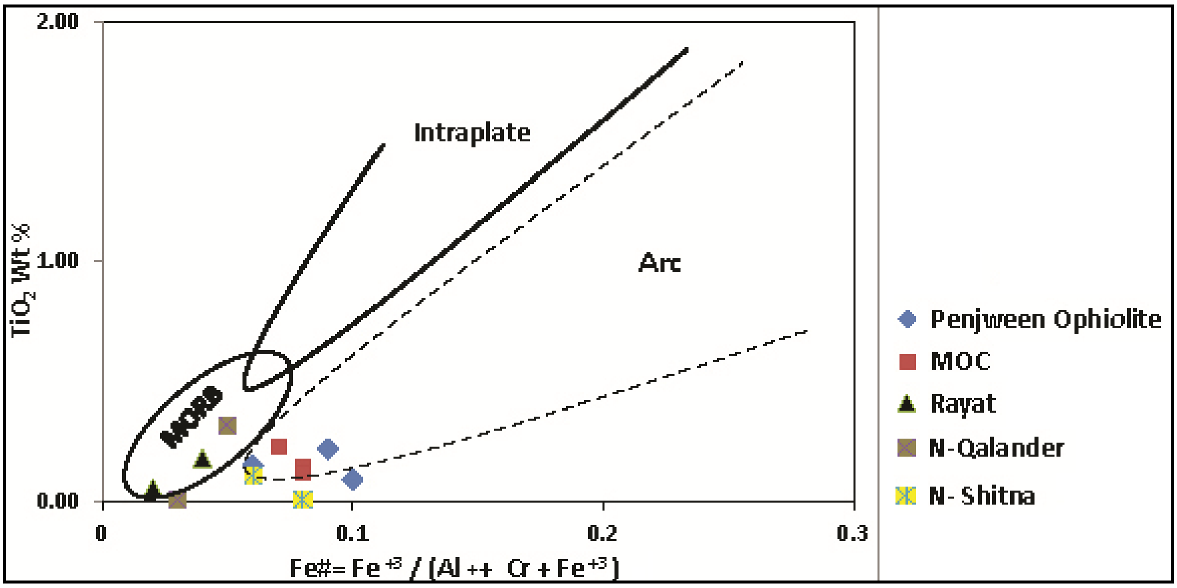

Fig.11: Relationship between [Fe^{3+}/ (Fe^{3+} + Al + Cr)] atomic ratio and TiO_2 wt.% of chromite from the IZSZ ophiolites. The discrimination boundaries of spinel compositions of MORB, Arc magma and intraplate magma are from Arai (1992). (Source of data: Buda, 1988; Mirza, 2008; Ismail *et al*., 2009 and Ismail *et al*., 2014)

ECONOMIC POTENTIAL

Although the geochemical studies of the chromitites along the IZSZ indicate a high grade of chromium content, the economic potential of these Cr-bearing rocks is not assessed until now. One of the few attempts in this respect was carried out by Mirza *et al*. (2016) in the MOC, applying geophysical and geochemical prospecting to determine the lateral and vertical extensions of the chromitite ore-bearing bodies. The result of the gravity survey in the MOC (Mirza *et al*., 2016) enabled the estimation of the area by about 2800 m^2 and the thickness of different chromite pods is estimated in the range of (10 – 35) m, extending from the earth's surface to about 15 m below surface. However, due to the mountainous nature of the area and the rocky surface and cliffs, the gravity survey was not possible in a grid pattern; therefore, the tonnage of the ore was not determined. The assessment of economic potential and estimation of reserves of the chromitites need detailed geochemical, geophysical and structural studies followed by exploratory drilling, all of which are still lacking. Geophysical prospecting by gravity methods can be a successful tool in locating new deposits in the district and provide new information on the localization and attitudes of the known deposits that may be of assistance in planning future exploratory work.

CONCLUSIONS

- The Iraqi Zagros Suture Zone contains interesting exposures of massive, brecciated and disseminated chromitite bodies, occurring in serpentinized peridotites of Penjween, Mawat, Rayat and Qalander ophiolites. Podiform chromitite bodies in the MOC and Penjween ophiolites are of the Alpine type, enclosed in dunite which is in turn, surrounded by harzburgite and seems to have been generated from an arc-related magma, while the podiform chromitite of N-Qalander and Rayat are related to MORB origin.
- Most of the chromitites have massive or disseminated texture and sometimes exhibit pull-apart and brecciated textures. Generally, massive chromite is subhedral transected by

cracks and altered along the rims and cracks into iron-rich chromite. The massive chromitites show podiform chromite enveloped by dunite in harzburgite host.

- Two different occurrences of chromian spinel grains are found in the peridotite rocks of the IZSZ ophiolite complexes including fresh and altered grains. There is little compositional variation in the chromian spinel from grain to grain and from sample to another in the different pods of the same or different area.
- All of the chromitite bodies in the IZSZ belong to the aluminum chromitite and they are originally of the podiform type. The Cr# vs. TiO_2 of the IZSZ chromitite composition mostly plots outside the fields defined for boninites and MORB. Instead, the compositions fall between these fields and within the compositional range defined by Cr-rich chromite.
- The Mawat and Qalander chromitites belong to the poor PGE type, but show higher PGE compared to dunite and harzburgite. The chondrites-normalized PGE patterns of the massive and disseminated ores of the Mawat and Qalander chromitite samples are characterized by enrichment in IPGE relative to PPGE. The only identified PGM in MOC and Qalander chromitites is laurite (RuS_2) which precipitates early from primitive magma under high temperature and can be compared to that of Oman ophiolitic chromitites.

REFERENCESS

Ahmed, A.H. and Arai, S., 2002. Unexpectedly high-PGE chromitite from the deeper mantle section of the northern Oman ophiolite and its tectonic implications, Contrib. Mineral Petrol, Vol.143, p. 263 – 278.

Alavi, M., 2004. Regional stratigraphy of the Zagros Fold-Thrust Belt of the Iran and its proforeland evolution. American Journal of Science, Vol.304, p. 1 – 20.

Al-Chalabi, S.N.A., 2004. Mineralogy and origin of chromitite in Qalander area, Iraqi Kurdistan region, M.Sc, Thesis, Salahaddin University-Erbil, 102pp.

Allan, J.F., Sack, R.O. and Batiza, R., 1988. Cr-rich spinels as petrogenetic indicators:MORB-type lavas from the Lamont seamount chain, eastern Pacific. Am. Mineral., Vol.73, p. 741 – 753.

Albers, J. P., 1986. Descriptive Model of Podiform Chromite; in Mineral Deposit Models. In: D.P. Cox, and D. A. Singer (Eds.), U.S. Geological Survey Bulletin, Vol.1693, 34pp.

Amosse, J., Allibert, M. Fischer, W. and Piboule, M., 1990. Experimental study of the solubility of platinum and iridium in basic silicate melts- implication for differentiation of platinum- group elements during magmatic processes, Jour. Chemical Geology, Vol.81, p. 45 – 53.

Arai, S, 1992, Chemistry of chromian spinel in volcanic rocks as a potential guide to magma chemistry. Mineralogical Magazine. Vol.56, p. 173 – 184.

Arai, S., 1997. Control of wall-rock composition on the formation of podiform chromitites as a result of magma/peridotite interaction. Resource Geology, Vol.47, p. 177 – 187.

Arai, S., and Yurimoto, H., 1995. Possible sub-arc origin of podiform chromitites. The Island Arc, Vol.4, p. 104 – 111.

Arai, S., Uesugi, J. and Ahmed, A.H., 2004. Upper crustal podiform chromitite from the northern Oman ophiolite as the stratigraphically shallowest chromitite in ophiolite and its implication for Cr concentration. Contributions to Mineralogy and Petrology, Vol.147, p. 145 – 154.

Arai, S., Shimzu, Y., Ismail, S.A. and Ahmed, 2006b. Low-T formation of high Cr spinel with apparently primary chemical characteristics within podiform chromitite from Rayat, northeastern Iraq, Mineralogical Magazine, Vol.70, No.5, p. 499 – 508.

Arai, S., Ismaiel S.A., Ahmed, H.A. and Gahlan, H., 2006b. Chromitite and peridotite from Rayat, northeastern Iraq as fragments of a Tethyan ophiolite: a first microprobe work on ophiolitic rocks from Iraq. 6th International Conference on the Geology of the Middle East. Al Aain, UEA, Proceedings.

Arculus, R.J. and Delano, J.W., 1981. Siderophile element abundances in the upper mantle: Evidence for sulfide signature and equilibrium with the core. Geochimica et Cosmochimica Acta, Vol.55, p. 1159 – 1172.

Barnes, S.J., Naldrett, A.J. and Gorton, M.P., 1985. The origin of the fractionation of platinum-group elements in terrestrial magmas, Chemical Geology, Vol.53, p. 303 – 323.

Barnes, S.J., Boyd, R., Korneliussen, A., Nilsson, L.P., Often, M., Pedersen, R.B. and Robins, B., 1988. The use of mantle normalization and metal ratios in discriminating between effects of partial melting, crystal fractionation and sulfide segregation in platinum group elements, gold, nickel and copper: example from Norway. In: H. Prichard, M. Potts, J.F.W. Bowles and S.J. Cribb (Editors.), Geo-Platinum, Vol.87, p. 113 – 143. Barking. Elsevier, Essex

Buda, G, 1988. Chromite occurrences in Iraq Zagros, Journal of. Acta Mineralogica-Petrographica, Szeged, Vol.29 p. 69 – 79.

Buda, G. and Al-Hashimi, W.S., 1977. Alpine-type chromite from Mawat, northeast Iraq. J. Geol. Soc. Iraq, Special issue, Vol.9, p. 61 – 77.

Buday, T. and Jassim, S.Z., 1987. The Geology of Iraq, Vol. 2: Tectonism, Volcanism and Magmatism. In: I.I. Kassab and M.J. Abbas (Editors). GEOSURV, Baghdad, Iraq. Printed by Dar Al-Kutub Pub. House, University of Mosul, 352pp.

Cassard, D., Nicolas, A., Rabinovitch, M., Moutte, J., Leblanc, M., and Prinzhofer, A., 1981. Structural classification of chromite pods in southern New Caledonia. Economic Geology, Vol.76, No.4, p. 805 – 831.

Chen, G. and Xin, B., 2008. Platinum-group elemental geochemistry of mafic and ultramafic rocks from the Xigaze ophiolite, southern Tibet. Journal of Asian Earth Sciences, Vol.32, p. 406 – 422.

Dick, H.J.B. and Bullen, T. 1984. Chromian spinel as petrogenetic indicator in abyssal and Alpine-type peridotite and specially associated lavas, Contrib. Mineral. Petrol. Vol.86, p. 54 – 76.

Dickey, J.S., 1975. A hypothesis of origin for podiform chromite deposits. Geochemica et Cosmochimica Acta, Vol.39, p. 1061 – 1074.

Dilek, Y., Furnes, H. and Shallo, M., 2007. Suprasubduction zone ophiolite formation along the periphery of Mesozoic Gondwana. Gondwana Research, Vol.11, No.4, p. 453 – 475.

Edwards, S.J., 1991. Magmatic and fluid processes in the upper mantle: A study of the Bay of Islands ophiolite complex, Newfoundland [Ph.D. Thesis]. St. John’s, Memorial University of Newfoundland.

El Ghorfi, M., Melcher, F., Oberthur, T., Boukhari, A.E., Maacha, L., Maddi, A. and Mhail, M., 2008. Platinum group minerals in podiform chromitites of the Bou Azzer ophiolite, Anti Atlas, Central Morocco. Mineralogy and Petrology, Vol.92, p. 59 – 80.

Gervilla F. and Leblanc M., 1990. Magmatic ores in high-temperature alpine-type lherzolite massifs (Ronda, Spain. and Beni Bousera, Morocco). Economic. Geology, Vol.85, p. 112 – 132.

Garuti, G., Zaccriani, F., Cabella, R. and Fershatater, G., 1997. Occurrence of unknown Ru – Os – Ir – Fe oxides in chromitite of Nurali-altramafic complex south of Urals, Russia. Canadian Mineralogist, Vol.35, p. 1431 – 1439.

Hamlyn, P.R., Keays, R.R., Cameron, W.E., Crawford, A.J. and Waldron, H.M., 1985. Precious metals in magnesian low-Ti lavas: implications for metallogenesis and sulphur saturation in primary magmas. Geochimica et Cosmochimica Acta, Vol.49, p. 1797 – 1811

Harris, D.C. and Cabri, I.J., 1991. Nomenclature of Platinum-group alloys:review and revision, Jour. Canadian Mineralogist, Vol.54, p. 231 – 237.

Ismail, S.A., 2008. The occurrence of platinum group minerals Laurite in the ophiolitic-chromitite rocks, Zagros Thrust Zone, Rayat area, NE Iraq. University of Sharjah Journal of Pure and Applied Sciences, Vol.5, p. 75 – 87.

Ismail, S.A., 2009. Chemistry of accessory chromian spinel in serpentinites from the Penjwen ophiolite rocks, Zagros thrust zone. Kirkuk University Journal for Scientific Studies, Vol.4, No.2, p. 1 – 21.

Ismail, S.A. and Al-Chalabi, S.A., 2006. Genesis of chromitite in Qalander Area, northern Iraq, Employing Cr-rich spinel. Journal of Kirkuk University for Scientific Studies, Vol.1, p. 10 – 29.

Ismail, S.A., Arai, S., Ahmed, A.H. and Shimizu, Y., 2009. Chromitite and peridotite from Rayat, northeastern Iraq, as a fragment of Tethyan ophiolite. Island Arc. Vol.18, p. 175 – 183.

Ismail, S.A., Mirza, T.A. and Paul, F.C., 2010. Platinum-group elements geochemistry in podiform chromitites and associated peridotites of the Mawat ophiolite, northeastern Iraq; Journal of Asian Earth Sciences, Vol.37, p. 31 – 41.

Ismail, S.A., Kettanah, Y.A., Chalabi, S.N., Ahmed, A.H. and Arai, S., 2014. Petrogenesis and PGE distribution in the Al-and Cr-rich chromitites of the Qalander ophiolite, northeastern Iraq: Implications for the tectonic environment of the Iraqi Zagros Suture Zone. Lithos, Vol.202, p. 21 – 36.

Jagoutz, E., Palme, H., Baddenhausen, H., Blum, K., Cendales, M., Dreibus, G., Spettel, B, Lorenz, V. and Wanke, H., 1979. The abundance of major, minor and trace elements in earthís mantle as derived from primitive ultramafic nodules. In: Proc 10th Lunar Planet Science Conference, p. 2031 – 2050.

Jassim, S.Z. and Goff, C. (Eds.), 2006. Geology of Iraq. Published by Dolin, Prague and Moravian Museum, Brno, 341pp.

Leblance, M., 1991. Platinum elements and gold in ophiolitic complexes: Distribution and fractionation from mantle to oceanic floor, In: T.J. Peters, A. Nicolas and R. Coleman, (Editors), Ophiolite Genesis and Evolution of the Oceanic Lithosphere. Ministry of Petroleum and Minerals, Sultanate of Oman, p. 231 – 260.

Kamenetsky, V.S., Crawford, A.J. and Meffre, S., 2001. Factors controlling chemistry of magmatic spinel: an empirical study of associated olivine, Cr-spinel and melt inclusions from primitive rocks. Journal of Petrology, Vol.42, No.4, p. 655 – 671.

Mahmood, L.A., 1978. Petrology and geochemistry of ultramafics around Penjwin, northeast Iraq with special reference to the genesis of the chromites associated with them. M.Sc Thesis, University of Mosul, Iraq, 220pp.

McDonough, W.F. and Sun, S., 1995. The composition of the Earth. Chemical Geology, Vol.120, p. 223 – 253.

McElduff, B. and Stumpfl, E.F., 1991. The chromite deposits of the Troodos Complex, Cyprus – evidence for the role of a fluid phase, accompanying chromite formation. Mineralium Deposita, Vol.26, p. 307 – 318.

Melcher, F., Grum, W., Simon, G., Thalhammer, T.V. and Stumpel, E., 1997. Petrogensis of the Ophiolitic giant chromite deposits of Kempirsai,Kazakhstan: A study of solid and fluid inclusions in chromite. Journal of Petrology, Vol.38, No.10, p. 1419 – 1458.

Mirza, T.A., 2008. Petrogenesis of the Mawat Ophiolite Complex and the associated chromitite, Kurdistan Region, NE Iraq. Unpublished PhD Thesis. University of Sulaimania, 189pp.

Mirza, T.A., Ameen, T.H. and Al-Hakari, S.H.S., 2016. Geophysical, geochemical and structural features of chromite ore in Kuradawe Village/Mawat Ophiolite Complex, Kurdistan Region, NE Iraq. JZS, Vol. 18 – 2, Part-A.

Mohammad, Y.O., 2008. Petrology of ultramafic and related rocks along Iraqi Zagros Thrust Zone. (Doctoral dissertation, Osaka Prefecture University, Japan.

Moores E.M., Kellogg, L.H. and Dilek, Y., 2000. Tethyan ophiolites, mantle convection, and tectonic 'historical contingency': A resolution of the 'ophiolite conundrum'. In: Y., Dilek, E.M., Moores, D., Elthon and A., Nicolas (Editors) Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program, p. 3 – 12. Geological Society of America, Special Paper 349.

Naldrett, A.J., 1981. Platinum-group element deposits. In: L.J. Cabri (Editor), PGE Mineralogy, Geology, Recovery, 23. Canadian Institute Mineralogy Metallurgy, p. 197 – 231.

Naldrett, A.J. and Duke, J.M., 1980. Platinum metals in magmatic sulfide ores. Science, Vol.208, p. 1417 – 1424.

Naldrett, A.J., Hoffman, E.L., Green, A.H., Chou, Chin-Lin, Naldrett, S.R. and Alcock, R.A., 1979. The composition of Ni-sulfide ores, with particular reference to their content of PGE and Au. Canadian Mineralogist, Vol.17, p. 403 – 415.

Numan, N.M.S., 1997. A plate tectonic scenario for the Phanerozoic succession in Iraqi. Geol. Jour., Vol.30, p. 2 – 28.

OíNeill HStC, 1991. The origin of the moon and the early history of the earth, A chemical model. Part 2, The Earth . Geochimica et Cosmochimica Acta, Vol.55, p. 1159 – 1172.

Page, N.J. and Talkington, R.W., 1984. Palladium, Platinum, rhodium, ruthenium, and iridium in peridotites and chromitite from ophiolite complexes in Newfoundland. Canadian Mineralogist, Vol.22, p. 137 – 149.

Pagé, P. and Barnes, S.J., 2009. Using trace elements in chromites to constrain the origin of podiform chromitites in the Thetford Mines Ophiolite, Québec, Canada. Economic Geology, Vol.104, p. 997 – 1018.

Pearce, J.A., Lippard, S.J. and Roberts, S., 1984. Characteristics and tectonic significance of supra-subduction zone ophiolites. Geological Society of London, Special Publication, Vol.16, p. 77 – 94.

Pearce J., Barker P.F., Edwards S.J., Parkinson I.J. and Leat, P.T., 2000. Geochemistry and tectonic significance of peridotites from the South Sandwich arc-basin system, South Atlantic. Contribution to Mineralogy and Petrology, Vol.139, p. 36 – 53.

Proenza, J.A., Zaccarini, F., Lewis, J.F., Longo, F.and Garuti, G., 2007. Chromian spinel composition and the platinum-group minerals of the PGE-Rich loma peguera chromitites, loma caribe peridotite, Dominican Republic. Canadian Mineralogist, Vol.45, p. 631 – 648.

Roberts, S., 1988. Ophiolitic chromitite formation: A marginal basin phenomenon? Economic Geology. Vol.83, p. 1034 – 1036.

Roeder, P.L. and Reynolds, I., 1991. Crystallization of chromite and chromium solubility in basaltic melts. Journal of Petrology, Vol.32, p. 909 – 934.

Rollinson, H., 2005. Chromite in the mantle section of the Oman ophiolite: a new genetic model. Island Arc, Vol.14, p. 542 – 550.

Rollinson, H., 2008. The geochemistry of mantle chromitites from the northern part of the Oman ophiolite: Inferred parental melt compositions. Contribution to Mineralogy and Petrology, Vol.156, p. 273 – 288.

Sissakian, V.K., 2000. Geological Map of Iraq, scale 1: 1000 000. 3rd edition, GEOSURV, Baghdad, Iraq.

Steven, R.E., 1944. Composition of some chromites of western Hemisphere Am. Mineral. Jour., Vol.26, p. 1 – 34.

Uysal, I., Sadiklar, M.B., Tarkian, M., Karsli, O. and Aydin, F., 2005. Mineralogy and composition of the chromitites and their platinum-group minerals from Ortaca (Mug¢la-SW Turkey): Evidence for ophiolitic chromitite genesis. Mineral. Petrol., Vol.83, p. 219 – 242.

Uysal, I., Tarkian, M., Sadiklar, B.M. and Sen, C., 2007. Platinum-group-element geochemistry and mineralogy of ophiolitic chromitites from the Cop Mountains northeastern Turkey. Canadian Mineralogist, Vol.45, p. 355 – 377.

Uysal, I., Sadiklar, M.B., Zaccarini, F., Garuti, G., Tarkian, M. and Meisel, T., 2010. Cr-PGE mineralization in the Turkish ophiolites: the state of the art. 11th International Platinum Symposium, June 21 – 24, 2010, Ontario Geological Survey, Miscellaneous Release – Data, 269pp.

Vasiliev, M.M., and Pentelikov, V.G., 1962. Report on prospecting exploration of Bard-i-Zard chromite occurrence and adjacent areas. GEOSURV, int. rep. no. 298.

Zhou, M.F., Sun, M., Keays, R.R. and Kerrich, R.W., 1998. Controls on platinum-group elemental distributions of podiform chromitites: a case study of high-Cr and high-Al chromitite from Chinese orogenic belts. Geochemiica et Cosmochimica Acta, Vol.62, p. 677 – 688.

About the authors

Dr. Tola Ahmed Mirza is Assistant Professor of the University of Sulaimaniyah, School of Science, Geology. She obtained the BSc. in Geology, the MSc. in industrial rocks and minerals, and Ph.D in ore geology. She has more than 15 researches in her field and in nonmetallic ore deposits. She is an associate editor of the (International journal of applied industrial science). Currently, she is supervising five M.Sc. students in the field of ore geology and industrial rocks and minerals. She participated in the translation of the book (Science for All), (Class Nine Primary School, 2009). She is a member of the Scientific Committee of the School of Science since 2014.

e-mail: tola.merza@univsul.edu.iq

Mr. Saman Ghareeb Rashid Qurbany is working in the Directory of Oil and Minerals in Sulaimaniyah Governorate. He obtained his B.Sc. degree in Geology in 2009 – 2010 and M.Sc. degree in Ore Geology, University of Sulaimany in 2018. He has two publications in the field of ore geology. He has experience in geological survey and mineral investigation and worked in this field since 2012 to the present. He also worked as Wireline geologist and in environmental laboratory during 2010 – 2011, and 2011 – 2012 respectively.

e-mail: Saman.qurbany@yahoo.com ; Saman.qurbany@gmail.com