THE PODIFORM CHROMITE AND PLATINUM GROUP ELEMENTS IN THE NEOPROTEROZOIC OPHIOLITE BOU AZZER (INLIER BOU AZZER - EL GRÂARA, CENTRAL ANTI-ATLAS)

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Abstract

Chromite deposits associated with ophiolites Bou Azzer correspond to podiform chromitites concentrated in the eastern part of the inlier Bou Azzer -El Grâara. They appear as small diamond-shaped body oriented and they cross a fracture system reflecting their implementation mode. Tectonics which affects the body is polyphase. Synchronous phase of their implementation is transtensive. This is evidenced by the forms of “pull-aparts” common to the pods and breccia textures. Also, this was observed in metallographic microscope and SEM (scanning electron microscope), and earlier in serpentinization. This tectonic would also control the dyking system to which chromitite pods are associated.

The distribution of the deposits along the inlier Bou Azzer shows a regional zonation, western chrome enrichment (52% Cr2O3), and a loss to the east (30% Cr2O3). The massive chromite is the chromite with a 62% in Cr2O3 and with enrichment in magnesium and trivalent iron depletion. Disseminated chromite can be divided into two types. The disseminated chromite podiform which is similar to the massive chromite geological context and the setting mode is relatively poor with Cr2O3 contents below

50%. The second type includes chromite and chromospinelles which are scattered in serpentine and in association with sulphides and nickel arsenides. It is by far the most widespread, but has an average content of 14%.
Chromitites Bou Azzer are characterized by a low ratio [P-EL / I-PGE] typical ophiolitic chromitites alpine poor in sulfides, with predominance of I-PGE, variable contents of Rh, and low levels of Pt and Pd. The sum of the contents (PGE) chromitites of Inguejem Aït-Ahmane is about 187-221 ppb. The microprobe analysis shows that the unaltered chromites Bou Azzer have little variable composition and are not aluminous Cr / Al> 1. The Cr_2O_3 content is high and ranges from 55.85 to 58.85%, while the TiO_2 content is less than 0.20%, which allows them to be placed in the area of rich chromites Cr and poor chromites Ti.

Keywords: Bou Azzer, ophiolite, chromite, Ni-Co, PGE

Geological Setting of the inlier **Bou Azzer-El Graara**

The inlier of Bou Azzer-El Graara is along the massive Siroua more NW. This is a pivotal area along the major accident of the Anti-Atlas (Choubert, 1947), which would divide the Precambrian terrains of the Anti-Atlas into two distinct areas (Choubert 1963). These areas include the cratonic area in SW and a recent Pan NE area (Fig.1).

The Precambrian terrains of the inlier Bou Azzer-El Graara are divided into two sets in the simplified table of FIG. 2.

- A metamorphic entire south is composed of crystalline rocks which comprises of gneisses, amphibolites, serpentinites, and mica schists. The unit is intruded by basic rocks and granites. Recent dating yielded ages of 755 ± 9 Ma for protholites orthogneiss and 695 ± 5mA for leucogranites having two micas.
- Neoproterozoic platform deposits Tachdamt-Bleida group are composed of basaltic rocks, limestones and quartzites, volcano-sedimentary units, and shale and sandstone roof built on the northern margin of the West African craton (Taghdoute-Lkest Group). This is sandstone, siltstone, and carbonates with a thick middle basaltic unit.
- Volcanic and sedimentary series of arcs affinity group (Tichibanine Ben Lgrad) which is attributed to an intra-oceanic volcanic arc dated between 760 and 770 Ma.
- The ophiolite complex Bou Azzer-Ait Ahmane is composed of ultrabasic rocks of characters tectonites to the west and it evolves to a transition zone and the base complex and volcano-sedimentary east going towards Bleida.

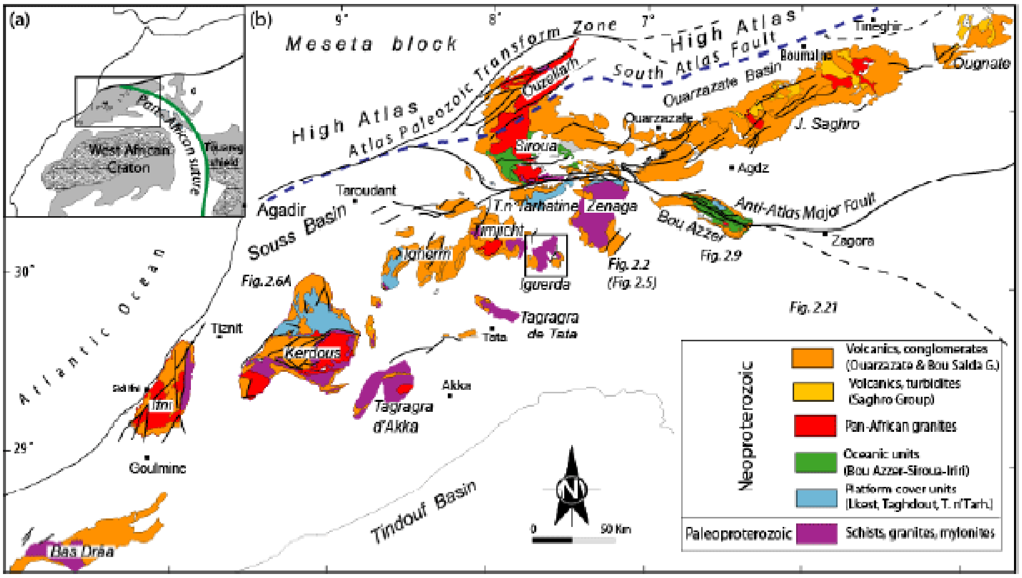


Fig.1. Geological sketch map of the Anti-Atlas Proterozoic belts in southern Morocco.

Fig 2. Recent lithostratigraphic nomenclature subdivisions adopted for the inlier Bou El

Age		Complex /Group/formation
Upper Néoprotérozoïc to low Cambrian	Upper Ediacarian and Cambrian	Tata Group Adoudounian formation
Upper and terminal Néoprotérozoïc (No metamorphic complex)	Upper Ediacarien (NP3)	- Ouarzazate Group (≈□580-534 Ma) - Tidilline Group (≈□625-600 Ma)
Middle Néoprotérozoïc (metamorphic complex)	Upper Cryogenian (NP2s)	Bou Azzer Group : - Bou Azzer ophiolitic Complex - Skouraz volcano-sedimentairy Complex (≈ 660-640Ma)
	Lower Cryogénian (NP2i)	Assif n'Bougmmane and Takroumt plutonic and-metamorphic complex (≈□750 to 700Ma)
		Tichibanine and Ben Lgrad Group (≈760 Ma)
	Tonian to Cryogenian (NP1-2)	Tachdamt – Bleïda and Taghdout Group (≈ 800Ma)

Azzer Graara (Admou et al., 2011)

The structural map of the button which is shown below (Figure 3) takes into account the new distribution stratigraphic based on recent geochronological data found in the buttonhole.

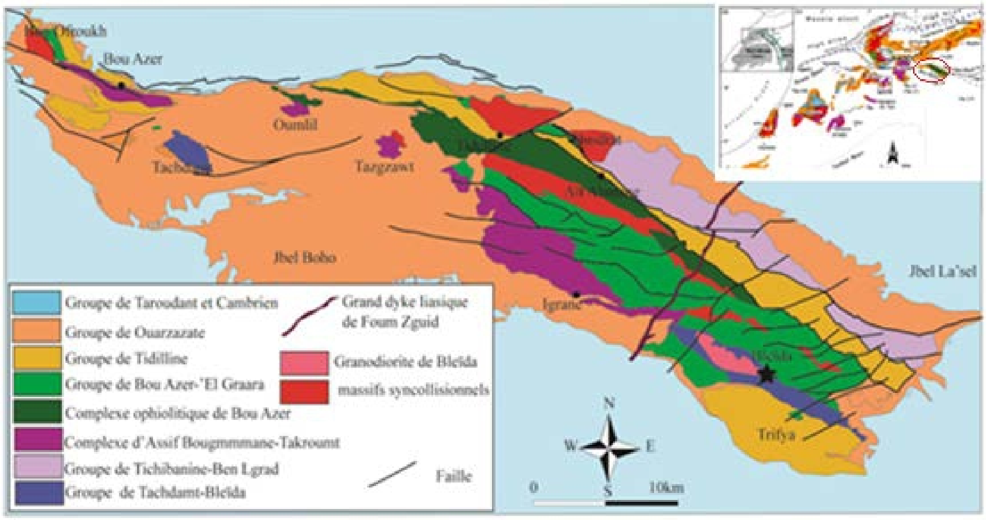


Fig. 3. Geological map of the inlier Azzer Bou -El Graara

All these metamorphic units are intruded by plutonic intrusions of the Middle Neoproterozoic to syntectonique character Ait Ahmane and post-tectonic intrusions from the upper Neoproterozoic (NP2-3). Thus, this includes the massive multi-phase (Taghouni type) and granodiorite Bleïda.

Geological and Structural Contexts of Chromite Deposits

Chromites accessory minerals in basic and ultrabasic ophiolite series of Bou Azzer - El Graara, sometimes forms lenticular body or podiform chromitite to massive texture and are usually disseminated (Wafik, 2001; Wafik et al., 2001). The Chromitites pods which is surrounded by a halo of dunites are cashed within harzburgite transition zone, where they are generally consistent with sub-concordant to the primary bedding of ultrabasites serpentinized. The chromite deposits Bou El Graara are concentrated in the eastern portion of the inlier and they originated from the Ambed area (Fig. 5). Nevertheless, the occurrences were recently highlighted in the western part near the Mechoui deposit.

On a metallogenic plan, there are three types of podiform chromitite deposit. These include:

The pods shaped like cigars, developed mainly in the areas of Ait Abdellah Ait and Ahmane. They are slightly intersecting the primary magmatic manufactures of ultrabasites.

Concordant layers shaped pods of the Ambed area and ingajjam. They are the most important in terms of size and content.

Chromites scattered in the lateral terminations of layers or small independent levels are also consistent. Mineralization podiform chromite type is associated with levels of dunite dykes, concurring in sub-concordant to the magmatic layering and surrounded by a halo of dunite serpentinized (Fig.6).

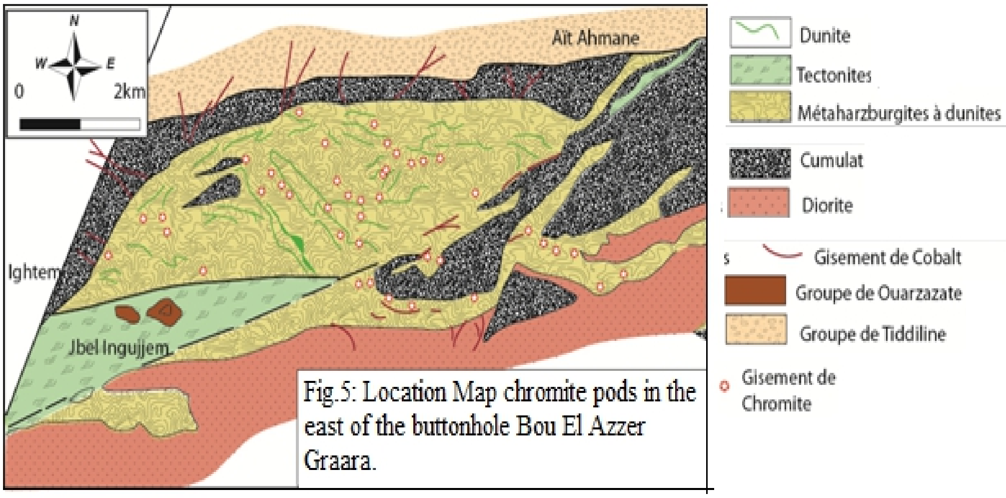


Fig.5: Location Map chromite pods in the east of the buttonhole Bou El Azzer Graara.

Structural Settings

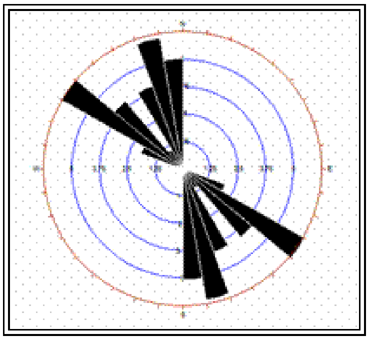
Pods chromites, cashed within dunite have a metric size and can reach several tens of meters thick to over approximately 5m wide. They commonly have rhomboid shapes bounded by NE and NW faults, inheriting the structural control of their set up. They are also affected by the subsequent deformation evidenced by folding dykes which they are associated with. In addition, they are also affected by the extrusion of the chromite pods; and they overlap the structure in blocks arranged in stair treads. The structural study shows that all the surveyed lodgings, is predominantly affected by brittle tectonics, expressed by several faults and fractures (Fig. 7 and Fig. 8). Therefore, this involves filling quartz-carbonate, talc, and sometimes giobertite or without filling. Ductile structures are rare and are represented by the cleavage of either flow or fracture, and a few wrinkles.

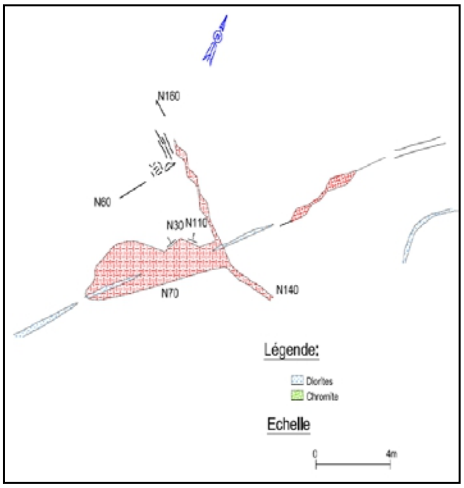
The brittle structures are in the forms of faults, either carbonated or quartz-carbonate or talc filler. In Chromite pods, there are carbonated filling structures and talco-carbonated. The main and major directions affecting these chromite pods are two families of EW and NE-SW structures.

Thus, the following families were distinguished.

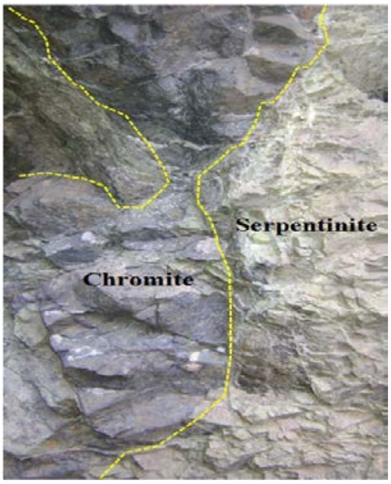
N50 to N70, N120 N150, NS and EW, but with the dominance WNW-ESE NNW-SSE

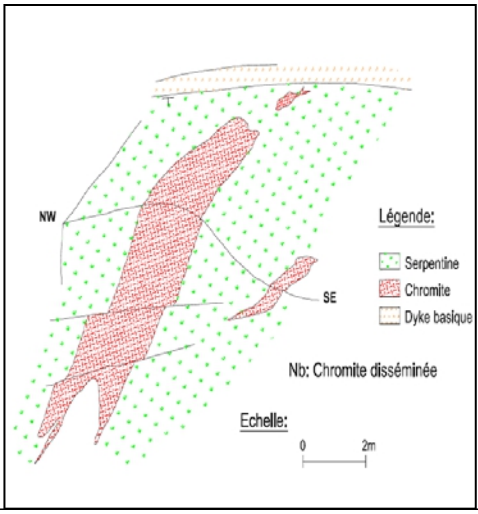
Rosette showing the two dominant families fractures





A





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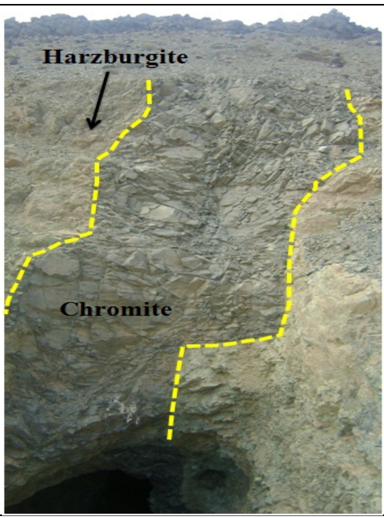


Fig 8. Illustration of the relationship with the country rock pods, the structural control of the mineralization, and the posterior thrust tectonics

(A) and (B): index of chromite in the region of Agoudal (Bou Azzer East)

The cleavage was highly developed in serpentinites, majoring direction between N127 ° and N135 ° and dip varying from 72 ° to 87 ° to the north (Beibe Ould, 2012).

The stretching lineation is observed in the serpentinite where it is marked by the stretching of minerals. Consequently, the major direction is EW (Fig.9-a and 9-b).

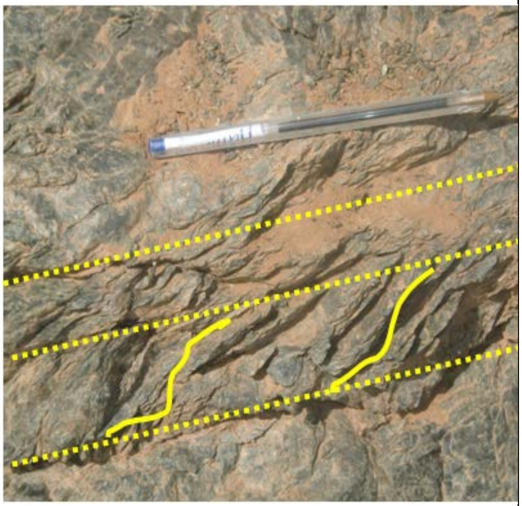
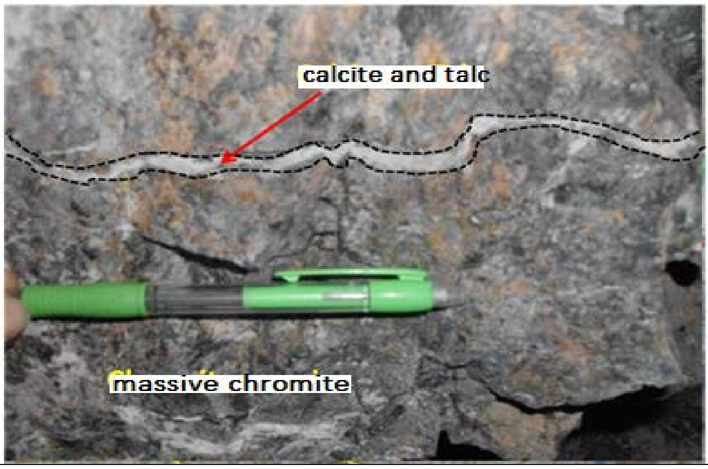
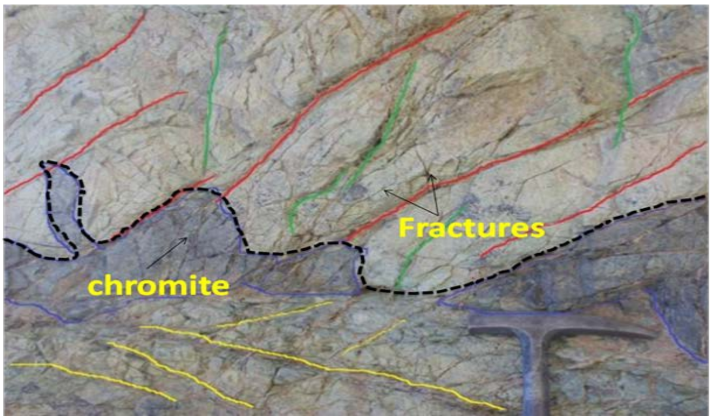


Fig 9-a. Microstructure: map C / S (Ait Ahmane Sector)	Fig 9-b. Sinistral movement within serpentinite (Ait Ahmane)

The main tectonic structures that is brittle and ductile and which characterize the study area are shown in the table below.

Structures (Description)	Figures
Brittle structures filling: The brittle structures are in the forms of faults, either carbonated or quartz-carbonate or talc filler.	
Structures without filling: They affect all the formations of serpentinite, microgabbros, and quartz diorite.	
Cleavaged structure and Stretching lineation: The cleavage is highly developed in serpentinites, majoring direction between N127 ° and N135 ° and dip varying from 72 ° to 87 ° to the north.	

The Petrographic Study

In peridotite, primary minerals are completely replaced by serpentine minerals psoeudomorphose or filling open fractures. The serpentine mineral pseudomorphs or veinlets consist mainly of chrysotile, the clinochrysotile of lizardite, and antigorite. The only visible primary minerals are relics of chromite spinels themselves and altered curbs in ferritochromite, magnetite, and stichtite. Thus, this underlines the magmatic foliation tectonites.

Microscopically, we distinguished between two categories according to the degree of deformation of Chromitites. Some chromitites are slightly deformed, by which flattened nodules show a direction (S0) perpendicular to the direction of the collapse nodules. Other chromitites are distorted, and generally show two directions superimposed. Early direction (S0) mimicking cleavage and parallel sometimes line up with silicate inclusions. This direction is limited to chromite crystals which appears prior to the serpentinization and the magma. Furthermore, late direction (S1) (S0) passes through the entire chromitite. The latter direction is manifested by fracturing pull apart massive chromitite that show straight edges or are serrated showing a delayed dissolution. It is represented by open fractures filled with serpentine minerals and is contemporaneous with the serpentinization.

The podiform chromite deposits associated with ophiolites Bou Azzer-El Grâara are concentrated in the eastern part of the buttonhole. They come in the form of small diamond-shaped body oriented. Also, it crosses a fracture system which reflects their implementation mode. Tectonics which affects the body is polyphase. Synchronous phase at their implementation is transtensive and witness various forms of “pulls aparts" common to the pods. At a microscopic level, chromite is often anhedral to subautomorphe millimeter grains.

Consequently, it has disseminated or multi- granular islands and is often associated with magnetite especially in the region of Inguijem and Talc (Fig.10). Chromite grains are typically altered or fractured and are surrounded by halos of piping, chlorite, and stichtite (Fig.11-a and 11-b) (chromium and magnesium carbonate hydrated). This is in agreement with what was found by Wafik (2001), Wafik et al. (2001 and 2012), and Ould Beibe (2012). In the deformed areas, chromite acquires brecciated textures which are fibrous identified across the outcrop and macroscopic and microscopic, as well as the SEM (scanning electron microscope) (Fig.12-a and 12-b) and earlier to serpentinization.

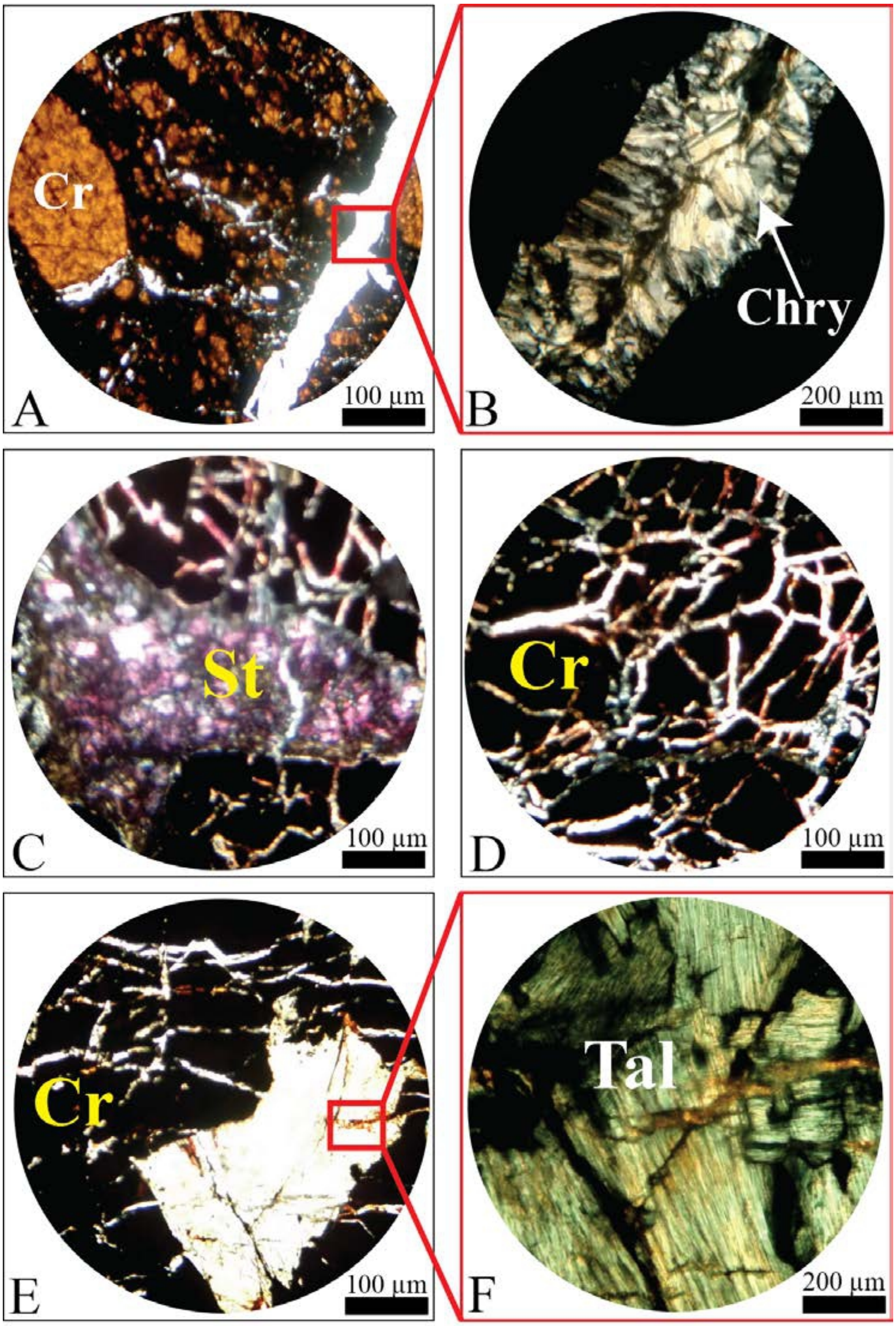


Fig.10. Microscopic observation of chromites Bou Azzer (Cr: chromite; Chry: chrysotile St: stichtite; Tal: Talc)

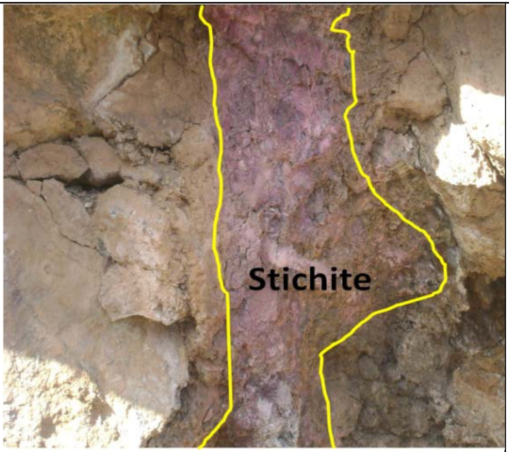


Fig.11-a. alteration of chromite for stichtite wide outcrop

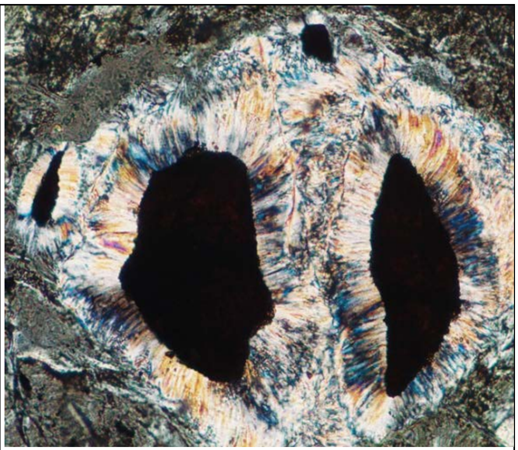


Fig.11-b. Fragments spinels crowned with stichtite fibroradiée (LP)

Consequenly, minerals chromites show multiple microscopic textures. Thus, that is to say that the chromite minerals are distributed either homogenously throughout the ore body. Chromium ore occurs in joined crystals. The interstitial space is reduced, or they appear in angular or sub-angular elements of different sizes. This is held together by serpentine minerals and they are dispersed in the matrix in the form of more or less euhedral crystals.

Photo 1

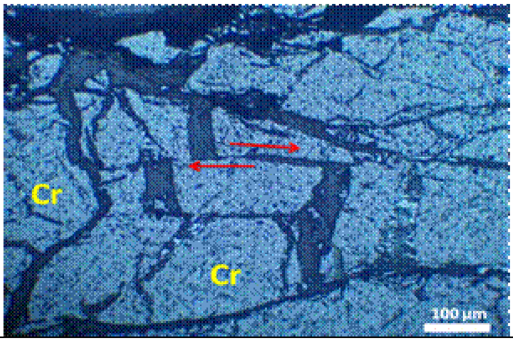


Photo 2

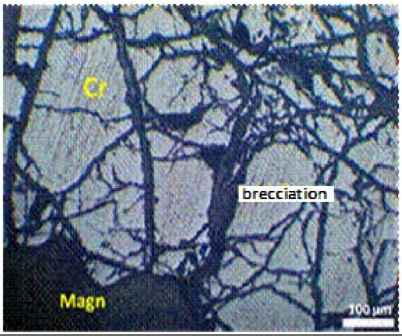


Photo 3

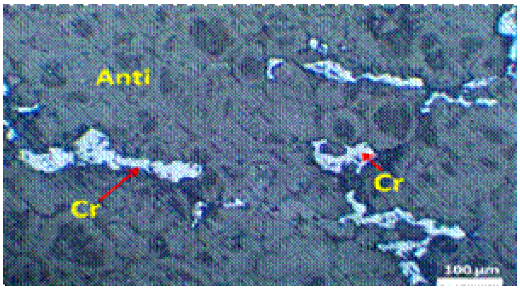


Photo 1: Texture massive within chromitite view of the metallographic microscope natural light.
Photo 2: Texture breccia within chromitite view of the metallographic microscope natural light.
Photo 3: Texture disseminated within chromitite view of the metallographic microscope natural light.
Anti: antigorite, Cr: chromite, Magn: Magnetite

Fig.12-a. Microscopic observation of chromites in metallurgical microscope

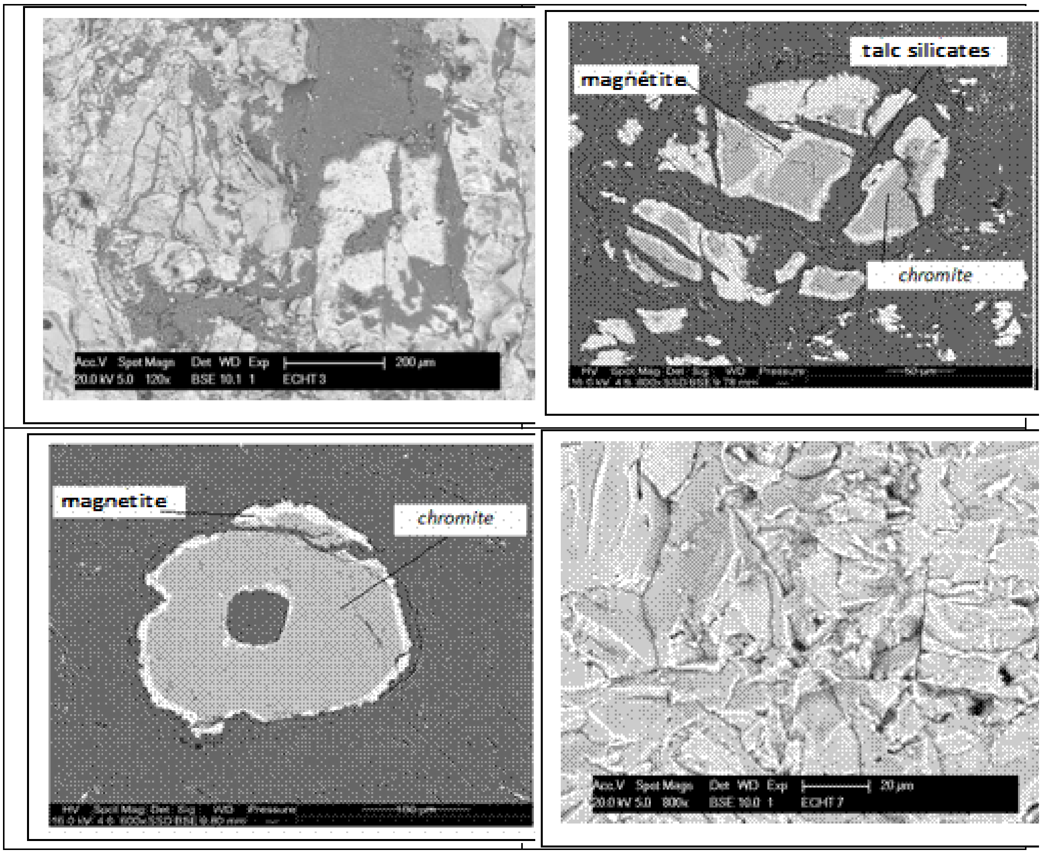


Fig.12-b. Observation of chromites through the scanning electron microscope

Chemism Settings of Chromites

Geochemically, the massive chromite type is relatively chromite, Cr_2O_3 with a content varying between 54.48% and 62%. It is also magnesium with a report [100 * (Mg / Mg + Fe^{2+})] of about 73.42, and low in trivalent iron (Fe_2O_3 <2.78%). The type of disseminated chromite is poorer in chrome Cr_2O_3 = 48% and less in magnesium. The titanium content is fairly constant and low, and it remains below 0.14% TiO_2 in weight percent.

The Geochemical difference showings Cr have a great variation of the chromium in this area. Also, it has a positive correlation with some elements (Co, Zn, and As) on the one hand, and a negative correlation with other elements (Ni, Pb, Cu, and Sn) on the other hand.

Furthermore, according to the work of Elghorfi (2006), Chromitites Bou Azzer are characterized by a low ratio [Pt-PGE / Ir-PGE]. [Pt-PGE]: platinum group (Pt), palladium (Pd), and gold (Au), while [Ir-PGE]: group of iridium (Ir), Rudhium (Ru), ruthenium (Rh) - typical ratio of ophiolite chromitites alpine poor in sulfides, with predominance of Ir-PGE. Rh contents of variables, and low levels of Pt and Pd. The sum of the contents (PGE) chromitites of Ingajjam Aït-Ahmane is about 187-221 ppb. This is essentially: i.) laurite [RuS2] ii) osmium alloys, iridium, ruthenium, and sometimes trace amounts of rhodium and platinum [Os-Ir- (Ru)], and [Rh-Pt]; iii) bowieite [Rh2S3] and prassoite [Rh17S15]. These PGE minerals (PGM) are either fresh inclusions in chromite or are disseminated in the serpentinized matrix.

The microprobe analyzes show that the unweathered chromites Bou Azzer have little variable composition and are not aluminous Cr / Al> 1. The Cr2O3 content is high and ranges from 55.85 to 58.85%, while the TiO2 content is less than 0.20%. Thus, this places them in the area of rich chromites Cr and poor in Ti.

In the Cr2O3 / FeO * diagram, chromite occupies a vertical field from the ophiolitic field chromites to the intersection area with the stratiform chromites (Figure 13-a). In the diagram (Cr * 100) (Cr + Al) to (Mg * 100) / (Mg + Fe 2+), chromites Bou Azzer shows very little change. They belong to the chromites group with high Cr / Cr + Al and low Mg / Mg + Fe (Figure 13-b) with a net increase in the last report. This indicates a change of the stratiform complex field to the alpine complex. This is confirmed by the other diagrams of the same figure. Comparing chromites Bou Azzer with other global locations, Wafik (2001) and Wafik et al. (2001 and 2012) showed an intermediate composition between those of Acoje, Philippines, and Poum, and New Caledonia studied by Leblanc and Nicolas (1992) for chromites Bou Azzer.

The diagram of Mg * 100 / (Mg + Fe 2+) vs Fe 3 * 100 / (Cr + Al + Fe 3+) (Fig13-c) shows that the Proterozoic Bou Azzer chromite is closer to the complex field tratiformes as Alpine ophiolites. This could be a source of natural intermediary between magmas at the origin of Archean stratiform complexes (Canadian and European). In addition, magmas at the origin of Alpine ophiolite chromites could reflect a change in the composition of the mantle through time.

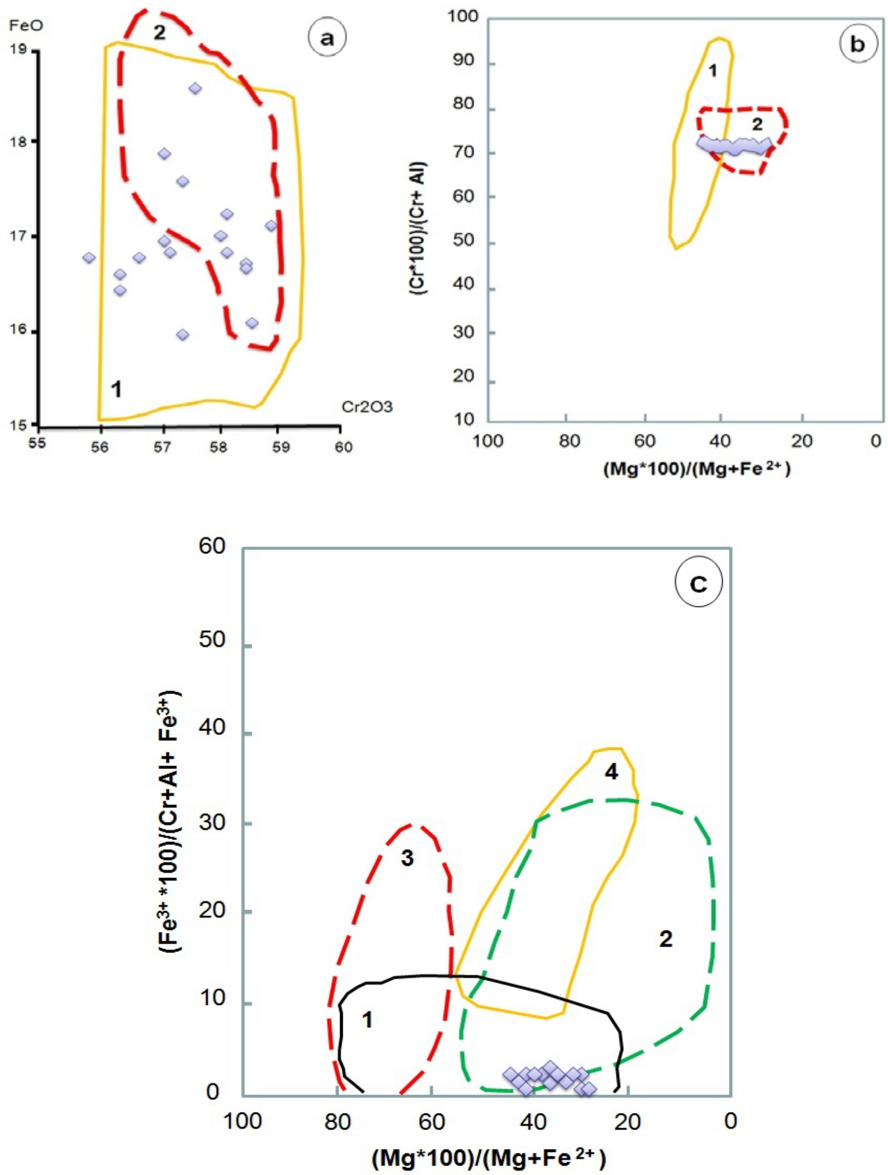


Fig. 13. Location of chromites Bou Azer in the Dick and Bullen diagram (1984). 1- Alpine ophiolite complexes field; 3- field of magmatic xenoliths; and 4- field concentric complex (Irvine, 1967) (based on Wafik et al., 2001).

Discussions

The results of our work combined with episodes to bibiographiques data on magmatic chromium, nickel and PGE buttonhole (El Ghorfi, 2006; Maacah et al., 2012), allows us to draw some successive metallogenic.

The deposit of chromite early form of chromo-spinels in association with primary nickel sulphide (pentlandite) concentrates at the upper part of mantle units of Ambed and Bou Azzer East (study areas). Sulphide precipitation in large quantities conditioned sulfur fugacity for subsequent deposits

The filing of the rich and peneconcordante chromite with the zone of dunite of Amded and Inguijem is associated with the transition zone.

The cumultas filing came to seal these two episodes, and joins a new metallogenic system copper mineralization and platinum (Jbel Oumarrou) and gold and Palladium (Bleida Fawest).

Regarding the podiform chromite in this study, the geological setting of ophiolites Bou Azzer, mineral paragenesis Cr and PGM, and the chemical composition of chromites and reporting (P-EL / I-PGE), incite rank in the Alpine ophiolite type whose implementation would be in a geodynamic site convergent plate as shown in chromite compositions alpine (Dick and Bullen, 1984). However, Wafik (2001) and Wafik et al. (2001) attributed these podiform chromitites to the area of intersection between the type Archean stratiform and Alpine podiform kind diagrams in FeO * / C2O3 and Mg * 100 / (Mg + Fe 2+) vs Cr * 100 / (Cr + al) (Wafik, 2001 and Wafik et al., 2001).

Zonation of the chemical composition, rich in Cr (68%) and poor in Al (2%), and poor peripheries Cr and Al-rich, shows the importance of nucleation in the background processes of critallisation chromite.

The silicate inclusions (calcic amphibole, olivine, clinopyroxene, Cr-diopside, and the uvarovite andradite) show the stamp of magmatic differentiation. Metallogenic standpoint, have revealed the presence of inclusions of Ni-Co-Fe-Cu-As as sulphides, sulfosalt, and alloys.

As for platinum group elements (PGE), their presence inclusions and texture show their character in the primary mineral assemblage. The low levels of Os and Ru have high content of laurites, and the lack of base metal sulphides. Also, there is the presence of the alloys which are probably due to a deposit in the middle low sulfur fugacity.

Chromitite pods are characteristic of ophiolite complexes (Thayer, 1960). Their origin extensively discussed, is currently assigned to crystallization from basaltic magmas in the upper mantle (Lago et al., 1982; Leblanc and Ceulneer, 1992). Their association with harzburgite and dunite is explained by the reaction of basaltic magma with lherzolite or harzburgite to form a modified magma enriched in silica and residues of depleted harzburgite and dunite. The reaction continues between the melt and the host rock coupled with the precipitation of olivine, which may move the original columnar liquid in the precipitation field chromite (Zhou et al., 1994).

However, this is in the same manner with Chromitites stratiform (Irvine, 1977; Irvine and Sharpe, 1986).

They are usually formed in channels subvertical in the magma chamber of the accretion zone (Juteau, 1975; LeBlanc et al., 1981.). They occupy areas transtensional matching extensions openings magmatic channels (Leblanc and Nicolas, 1992). These initially discordant bodies tend to become parallelize with magmatic foliation (Cassard et al., 1981). Zonation around the chromite pods can be explained by the reaction between the magma from which chromitites crystallized and encloses peridotites (Zhou et al., 1994). Dunitic lode walls are refractory and are derived from the transformation of a harzburgite in contact with a hot magma incongruent melting of pyroxene (Boudier and Nicola, 1972).

As regards the process of setting up podiform chromites, two models were described in this literature.

The model flotation (Cawthorn, 2005) privillégie ascent fluid bubbles were nucleated on a small chromite grain in a crystallizing magma. The accumulation of fluid bubbles causes a pelletizing chromite grains to form polycrystalline nodules. Also, the weight causes the gravity settling and the chromitite formation.

The model by aggregation and snowballing (Lago et al., 1982) is in favor of the development of mantle convection cells in pull-apart openings. This would result in a nucleation of chromite grains, a rise by Bagnold effect, and a patch causing accretion to deposit grains by becoming too dense. In the case of Bou Azzer and in light of the preliminary results of this work, a synchronous transtensive structural control of dyking phenomenon and the end of the implementation of the transition series was concluded upon. These data appears to be consistent with the Snowballing process by Lago et al. (1982).

Conclusion

Chromitites ophiolites are not related to the area of the ophiolite, but appear in the nature of the ophiolite (Nicolas, 1986). LOT-type ophiolites (slow ridges) are poor chromitites, while those type HOT (fast ridge) are richer without prejudice to the specific site (Nicolas Leblanc, 1992). Nicolas and Al Azri (1991) evoke in the case of Oman, the role of temperature. Moderately, rapid wrinkles would be characterized by a thermal structure as basalt would cross the liquidus in the transition zone. Also, precipitation of the chromite is mainly in this area. Rapid wrinkles, on the contrary, are characterized by a heat flow. For instance, basalt would cross the liquidus in the transition zone underlying while chromium remains dispersed in the magma (Leblanc and Nicolas, 1992). The formation temperature is above 1300 ° C (Leblanc, 1980). The parental magma composition appears to be the major factor controlling the composition of chromite. However, small variations may reflect differences in temperature, pressure, and oxygen fugacity (Bullen and Dick, 1984; Arai, 1992). Experimental work (Maurel, 1982; Roeder and Renold's, 1991) shows that chromite crystallizes between 1300 ° and 1200 ° C and that its composition depends on the Al2O3 content of the magma. As against its abundance, it is related to the increase in oxygen fugacity (Ulmer, 1969; Hill and Roeder, 1974; Irvine, 1977 and 1978), which results from the presence of aqueous fluids in magmatic system (Lorand and Ceulneer, 1989; Mc Elduff Stumpfl, 1991).

Rich chromites Cr appears to be the characteristic of podiform body located relatively deeply in the Moho (Leblanc and Violet, 1983). Whereas, those rich in alumina belong to body located near or in contact with pyroxenite and gabbros of the base sequence of the magma (Thayer, 1969; Golding and Johnson, 1971).

The rich chromitite Cr also have high levels of PGE, especially Os, Ir and Ru, than other varieties rich in Al (Baccuta et al., 1988). These elements are highly compatible during partial melting of the upper mantle (Barnes et al., 1985) and their abundance in podiform chromitites reflects the degree of partial melting. Spectra PGE for serpentinite Bou Azzer correspond to those of a depleted mantle and those chromites match that of komatites sulfides (Leblanc and Fisher, 1990). The contents of PGE in residual peridotite are weakly modified if sulfides are not completely dissolved, but they fall sharply when sulfides are completely dissolved (Lorand et al., 1993). This amounts to saying that the mantle sulfides underwent complete dissolution during the melting of the mantle, which was strong.

Microscopic study shows that chromites Bou Azzer are rich in metallic mineral inclusions of Fe, Cu, Ni, which have the same shape as the host crystals. The metal compounds can range from simple sulphides common in basic and ultrabasic magmas in solid solutions sulpho-arsenide or rare alloys, which makes their identification more difficult. On the whole, they reflect the strong transience of S as the magma. Each inclusion is monomineralic and almost homogeneous. Thus, they appears to have evolved in a closed system. In his experimental work, Ballhaus (1999) has highlighted this phenomenon for the study of the Fe-Ni-Cu-O system, deficient in S. This is above 1000 ° C of the individual droplets of (Fe, Ni, Cu) S emerging in the liquid and providing single crystals.

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