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# The Cu-Mo±Au Mineralizations Associated to the High-K Calc-Alkaline Granitoids from Tifnoute Valley (Siroua massif, Anti-Atlas, Morocco): an Arc-Type Porphyry in the Late Neoproterozoic Series

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**Abstract**

The Tifnoute valley Cu-Mo±Au mineral occurrences are located NW of Siroua massif in the central Moroccan Anti-Atlas. This mineralization appears to be associated to the Imourkhssan granite and the Asskaoun granodiorite dated respectively 561 ± 3 and 558 ± 2 Ma. These highly potassic granitoids show an arc signature and are in-placed in an extensional tectonic setting typical of the post-collision Late Pan-African period. In places, these rocks are strongly to slightly affected by hydrothermal alterations of phyllic, propylitic and argillic types with development of a pyritic facies around the Imourkhssan granite.

The mineralization can be divided into two types:

A molybdenite mineralization and some sulphides spatially linked to the Imourkhssan granite. It is disseminated in the granite or appears in lamellar or pluri-millimetric fragments. It also occurs as spots and nets along chloritized fractures planes oriented NNE-SSW and dipping 40 to 60 SE. The paragenesis consists of molybdenite, pyrite, chalcopyrite and sphalerite.

Talat N'Lbnour Cu-Au mineralization linked to NS fractures affecting Askaoun granodiorite. The vein is about 0.5 to 2 m thick that extends about 400 m. The mineralized fractures are filled essentially with quartz, siderite and chlorite. Metallographic study reveals a diverse paragenesis that consists of pyrite, chalcopyrite, gold, bornite and chalcocite.

The secondary paragenesis consists of chalcopyrite, covellite, bornite, malachite, azurite and hematite.

These features of these mineralizations are discussed in the context of an arc-type Cu-Mo±Au porphyry mineralization.

**Keywords:** Anti-Atlas, Siroua, Molybdenum, Copper, Gold, Porphyry.

## Introduction

A mineralized porphyry is a disseminated low grade deposit associated with a plutonic system of shallow deep (5 km), polyphased, often but not always with rocks of porphyritic texture (hence its name), just below a volcano (Jébrak et Marcoux, 2008). The porphyry copper deposits are predominantly associated with calc-alkaline magmatism of subduction zones. Examples of spatial and/or genetic associations between a mineralization and a type of igneous rock are well described in the literature: gold-potassic rocks (Müller et Groves, 1993) or I-type granitoids and porphyry (Mason et MacDonald, 1978 ; Hine et Mason, 1978). All porphyry copper deposits lie in a particular geotectonic environment of continental plate margin in a late-orogenic stage (in Wang, 2006). This constitutes a major type of copper deposits. Mineralizations contain mainly Cu and Mo. W an Sn may also be of major metals. Pb-Zn, Au and Ag associations are also found. This type of deposit is well documented in the world: West America, Caribbean, Iran, Bougainville, Bulgaria, Greece …Chuquicamata deposit in Chile is the most striking example of this type of mineralization. In term of reserves, it contains 10.8 billion ore for a 60 Mt copper metal stock. More than half of the world copper production (55%), approximately 16% gold and 65% molybdenum come from these deposits.

The globally known Cu-Mo-Au porphyry are hosted by porphyritic rocks of thickness ranging between 100m an several kilometres, forming cupolas above deeper pluton of intermediate to felsic composition (Sillitoe, 1996). In the porphyry, mineralization occurs in various form: stockwerks, veinlets, dissemination, breccias pipes, or replacement areas (Brown, 1976).

Mineralizations as well as hydrothermal alterations show a characteristic zonation (***figure 1***). The different mineralized zones are roughly concentric around a sub-sterile core, forming a system of cylinders fitted together (Beane et Titley, 1981). The alteration series intensity decreases from the center to the edge. The ideal sequence of these alterations is the following:

- Internal zone, of potassic alteration: represents the high temperature assemblage. It is generally associated with fluids of high salinity. It is characterized by the development of K-feldspar, biotite,

 

pyrite and quartz. It is sometimes superimposed by a sodic alteration with secondary albite.
- Intermediate zone, phyllitic or argillic with sericite, illite and various clay minerals (kaolinite, monrmorillonite, smectite ...), quartz and pyrite. This is a rich disseminated pyrite zone (up to 10%), but depleted in copper.
- Peripheral zone, propylitic and more extensively developed in quartz, epidote, chlorite, carbonate and kaolinite, showing only a poor disseminated ore of pyrite veinlets.

In Morocco, many Cu-Mo occurrences are reported mainly in the eastern Anti-Atlas but because of the lack of detailed studies, none of these deposits is called porphyry. For example, we include Qualaat M'gouna west (867 ppm Mo with 115 ppb Au and 1.46% Au), Tagmout and Bouskour deposits.

In this paper, we propose to identify various characteristics of Cu-Mo-Au occurrences in the Tifnoute valley region and their relationships with the associated high-K calc-alkaline granitoids.

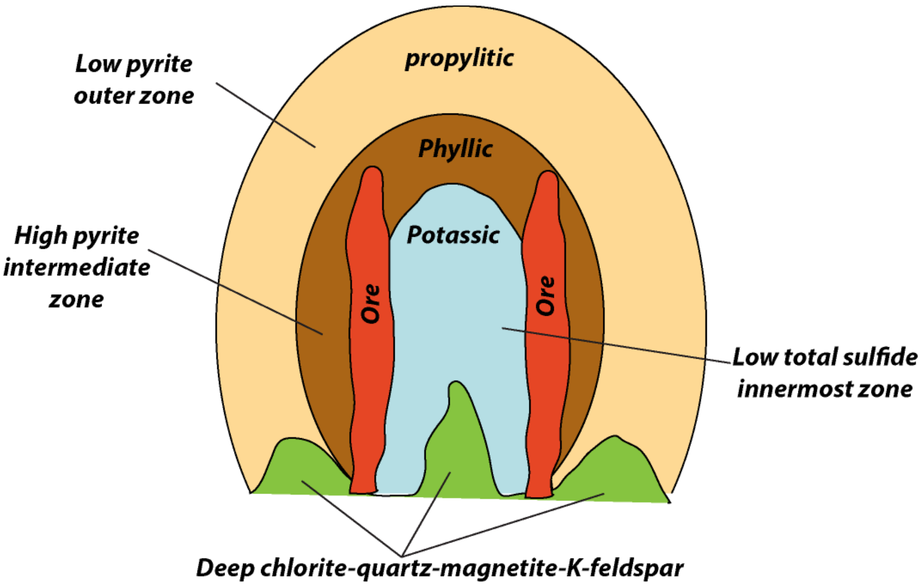


***Figure 1.*** Cross section of a porphyry copper deposit showing idealized alteration zoning (after Lowell and Guilbert, 1970).

**Geological outline**

The Moroccan Anti-Atlas belt (***figure 2***) is situated on the northern edge of the West African Craton (Reguibat Shield); known to be broadly Palaeoproterozoic in age (Charlot, 1976; Gasquet *et al.,* 2005, 2008). It is separated from the High Atlas to the north by the South Atlas Fault, which marks the northern boundary of the West African Craton (Ennih and Liégeois 2001,2008). The Precambrian rocks within the Anti-Atlas belt outcrop through windows called 'boutonnières' or inliers, and expose Paleoproterozoic to Neoproterozoic metamorphic and igneous basement rocks that are nonconformably overlain by a thick Ediacaran to Lower Paleozoic volcanic to sedimentary transgressive cover sequence (Choubert, 1963; Cahen et al., 1984; Destombes et al.,1985; Benziane and Yazidi, 1992; Thomas et al., 2002, 2004; Walsh et al., 2002; Álvaro et al., 2008; Michard et al., 2008a). These inliers are the result of large-scale updoming and crossfolding during the Hercynian or Alpine Orogenies (Thomas et al., 2002). The Anti-Atlas belt is affected by four orogenic events: (1) Eburnian orogeny of paleoproterozoïc age (2.2-2.0 Ga); (2) Panafrican orogeny of Neoproterozoïc age (750-550 Ma); (3) Variscan orogeny (Late Carboniferous to Early Permian times) (Burkhard et al., 2006) and (4) Alpine orogeny (Late Mezozoïc and Cenozoïc times).

The High Atlas represents the highest mountain belt of Morocco, with peaks of over 4000 m (Toubkal, 4165 m). It is formed by a Precambrian and Paleozoic basement and a Mesozoic to Cenozoic succession (Michard et al., 1982; Hoepffner et al., 2006). In the Western High Atlas, the Precambrian basement outcrops mostly in the Ouzellarh Block, being composed by metamorphic and granitoids rocks topped by late Precambrian volcanics (Baouch, 1984; Ouazzani et al., 2001; Eddif, 2002). The blocks of Precambrian materials situated in the western part of the High Atlas, were moderately deformed by the Variscan and Alpine tectonics. The original position of these blocks is still subject to debate (Gasquet et al., 2005).

The studied Tifnoute Valley region is located in the Ouzellarh-Siroua Salient (OSS) (***figure 3***), this designation given by (Tommite et al., 2012) is justified by the continuity of the Neoproterozoïc basement from the so-called Ouzellarh Block (Western High Atlas) and the Sirwa Massif (Central Anti-Atlas) (Choubert 1942, 1952; Michard et al., 2010). It is a northern Anti-Atlas bulge located across the South Atlas fault (Tommite et al., 2012). The majority of rocks in the OSS, consists of Ediacaran plutonic, volcaniclastic and volcanic rocks of the

 

Ouarzazate Supergroup and related rhyolitique and microgranitic dikes. The ***Taghdout Group*** (Thomas et al., 2004), consists of a passive margin shallow-water sequence preserved along the northern edge of the Zenaga Complex at the time of rifting of the West African Craton. The sequence is present just to the south of the Anti Atlas Major Fault (AAMF) above the Eburnian basement of the Zenaga inlier, and forms a small, fault-bounded inlier of highly tectonized quartzite and jasperized volcaniclastic rocks (Thomas et al., 2002; 2004). The ***Bou Azzer Group*** includes all the ophiolitic fragments of the Anti-Atlas associated with the ocean floor. It extends along the AAMF and is abundant to the south of the OSS (Thomas et al., 2002; 2004). the ***Sarhro Group*** is represented in the Tifnoute vally field by volcanosedimentary rocks of Zgounder Subgroup, associeted to orogenic basin-fill, flysch-type Thomas et al., 2002. It is covered by the ***Bou Salda Group*** in wich two associated rhyolites (Tadmant and Tamriwine Rhyolites) have given identical U–Pb SHRIMP ages of 605 Ma (Thomas et al., 2002). The whole sequence is covered by ***Ouarzazate Group*** (580-545 Ma) (Thomas et al., 2004; Gasquet et al., 2005, 2008). These two late groups which are deposited after the Anti-Atlas Supergroup (dated to the Cryogenian period) have been grouped into the Ouarzazate Supergroup (OSG), accorded to the Ediacaran period dated between 615-545 Ma and corresponding to the late- and post-orogenic formations (Gasquet et al., 2005, 2008; Pouclet et al., 2007).

In the OSS, the plutonic rocks of OSG are subdivided into three suites: (1) the Assarag suite (Askaoun and Tamtattarn pluton); (2) the Amassine suite (Imourkhssan pluton), and (3) The Ougougane suite. These granitoïds belong to an alkali-calcic series (high-K calc-alkaline) (Thomas et al., 2002; 2004; Toummite et al., 2012). During the time spanned by the intrusion of the Assarag Suite, a restricted sequence of bimodal volcanic (basalts and rhyolites) and coarse-clastic rocks was being deposited in fault-bounded grabens according to a pull-appart bassins, which is interpreted in a sinistral transpressional regime initiated by continued post-collision convergence through the AAMF (Thomas et al., 2004). In the upper part of the OSG, volcanic and volcaniclastic rocks of the Ouarzazate Group outcrop on the high-lying areas in the southern, western and northeastern parts of the Assarag map sheet.

The OSG formations are crosscut by numerous doleritic dykes trending NE-SW to NS. They belong to a N30 trending swarm. In the NW part of the studied area, these dykes fed the overlying basaltic pile (Pouclet et al., 2007). This basic activity is considered as a late manifestation of the Ouarzazate Group (Thomas et al. 2002).

The discontinuous volcanic *Ouarzazate Group* and the continuous base of the sedimentary cover (***Taroudant Group***) are now considered to belong to a unique extensional cycle (Piqué, 2003; Gasquet et al., 20

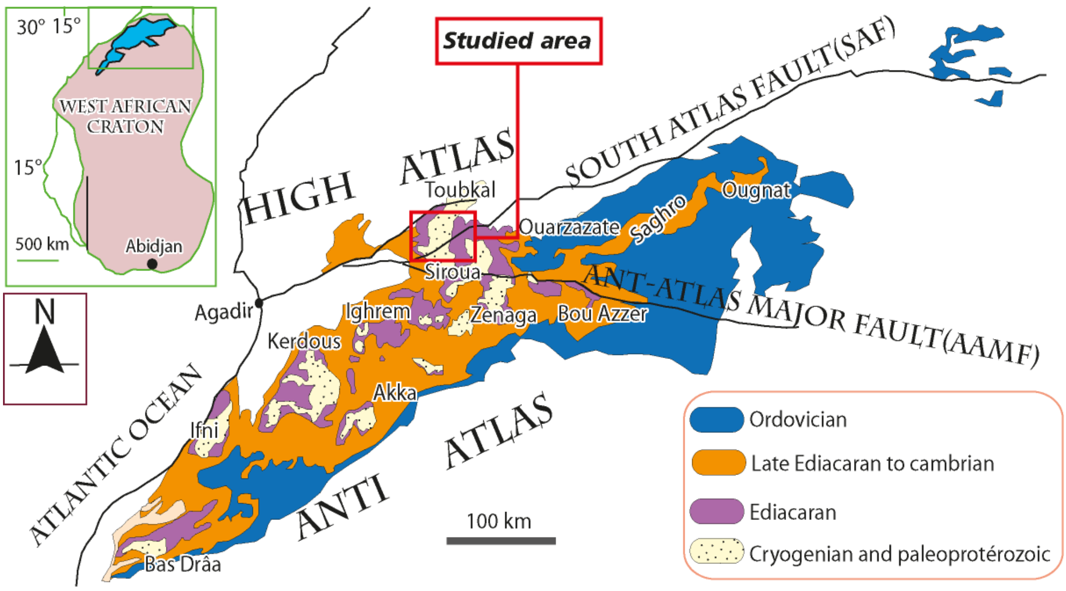


Figure 2. Location of the study area. Sketch map of the Anti Atlas modified from Gasquet et al. (2005).

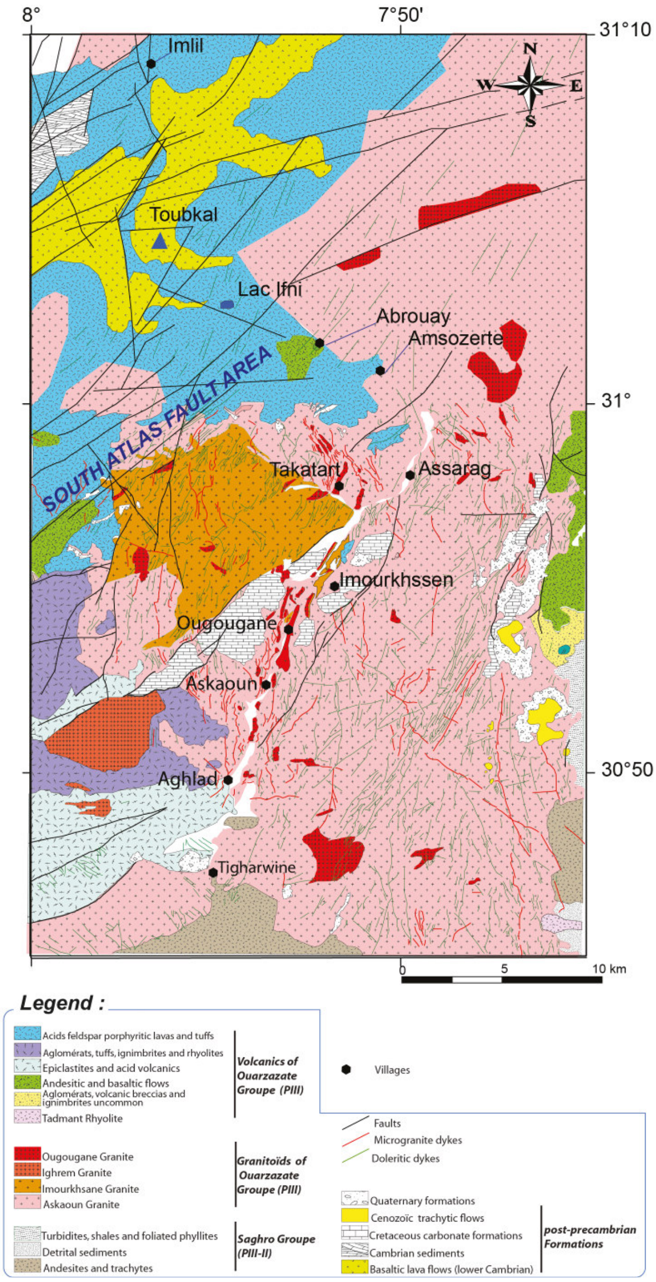


*Figure 3.* Geological map of the Toubkal-Siroua area

**Material and method**

Fieldwork conducted in the Tifnoute Valley area lead to:

(i) draw a geological map (1/50 000) of Imourkhssam sector (***figure 4***), (ii) characterize alteration styles and mapping of the pyritization degree around the Imourkhssan granite; (iii) describe 14 thin sections and 25 polished sections from surrounding rocks and from mineralization.

Metallographic observations were supported by analyzes carried out by scanning electron microscope (SEM) at the UQAT university, Rouyn Noranda, Canada.

37 mineralized samples were analyzed using X-ray fluorescence spectrometry (XRF) at ONHYM laboratory, Rabat (Morocco). Results are given in ***table 1***. 14 representative samples of different granitoid units have been analyzed for major and trace elements by Toummite et al., 2012 at the Royal Museum for Central Africa, Tervuren in Belgium.

 

Table 1. Composition of some mineralized samples.

| **Samples** | **Au** | **Ag** | **As** | **Co** | **Cu** | **Fe** | **Mo** | **Ni** | **Pb** | **Zn** |
|---|---|---|---|---|---|---|---|---|---|---|
| **N°** | **ppb** | **ppm** | **ppm** | **ppm** | **ppm** | **ppm** | **ppm** | **ppm** | **ppm** | **ppm** |
| **E-1** | <5 | < 1 | 30 | 65 | 31 | 12300 | 18 | 18 | 88 | 27 |
| **E-2** | **4959** | 2 | 36 | **270** | **659** | **31017** | **1487** | 21 | 85 | 18 |
| **E-4** | 21 | < 1 | 22 | 63 | 73 | 27820 | 20 | 21 | 40 | 57 |
| **E-7** | 6 | < 1 | < 20 | 112 | 36 | 5447 | 21 | 14 | 34 | 6 |
| **E-10** | <5 | < 1 | < 20 | 102 | 17 | 11597 | < 10 | 15 | 27 | 7 |
| **E-11** | 11 | < 1 | **167** | 105 | 450 | **105925** | 17 | 22 | 31 | 20 |
| **E-13** | <5 | < 1 | 28 | 63 | 19 | 31814 | < 10 | 23 | 42 | 53 |
| **E-17** | 39 | 7 | 65 | 115 | **31544** | **49786** | 14 | 37 | 27 | 129 |
| **E-18** | <5 | < 1 | 26 | 91 | **1266** | **26547** | < 10 | 27 | 33 | 63 |
| **E-21** | **29779** | 9 | 36 | 93 | **1440** | **51592** | 12 | 18 | 58 | 24 |
| **E-22** | **224** | 1 | 43 | 44 | **675** | **67241** | < 10 | 45 | 83 | 130 |
| **E-24** | 18 | < 1 | < 20 | 46 | 28 | 33349 | < 10 | 25 | 48 | 81 |
| **E-25** | 11 | < 1 | < 20 | 82 | 66 | 30801 | < 10 | 22 | 51 | 68 |
| **E-30** | 8 | < 1 | 34 | 59 | **150** | **39558** | < 10 | 35 | 45 | 66 |
| **E-32** | 5 | < 1 | 30 | 58 | 21 | **76248** | < 10 | 22 | 42 | 88 |
| **E-35** | 5 | < 1 | 24 | 106 | 26 | 13583 | < 10 | 18 | 42 | 35 |
| **E-36** | <5 | < 1 | < 20 | 95 | 8 | 2830 | < 10 | 13 | 27 | 5 |
| **E-37** | <5 | < 1 | < 20 | 114 | 16 | 12434 | 17 | 12 | 27 | 9 |
| **E-38** | <5 | < 1 | < 20 | 94 | **675** | **29835** | < 10 | 17 | 26 | 59 |
| **E-39** | <5 | < 1 | 64 | 64 | 7 | 36030 | < 10 | 29 | 29 | 88 |
| **E-44** | 5 | < 1 | < 20 | 113 | 16 | 29713 | 19 | 17 | 22 | 28 |
| **E-46** | <5 | < 1 | < 20 | 130 | 13 | 11338 | < 10 | 12 | 25 | 8 |
| **E-47** | 5 | < 1 | < 20 | 178 | 13 | 6798 | 109 | 9 | 22 | 7 |
| **E-49** | <5 | < 1 | < 20 | 122 | 6 | 43407 | 327 | 9 | 25 | 23 |
| **E-50** | 6 | < 1 | < 20 | 71 | 6 | 34591 | < 10 | 21 | 32 | 63 |
| **E-51** | 5 | < 1 | < 20 | 47 | 40 | **103340** | < 10 | 18 | 43 | 117 |
| **E-52** | <5 | < 1 | < 20 | 57 | 52 | 38186 | < 10 | 19 | 44 | 54 |
| **E-53** | <5 | < 1 | 27 | 41 | 178 | 55479 | < 10 | 33 | 42 | 85 |
| **E-33** | <5 | < 1 | 32 | 47 | 15 | **82602** | < 10 | 23 | 54 | 160 |
| **E-55** | <5 | < 1 | 42 | 61 | 14 | **55620** | < 10 | 49 | 43 | 73 |

**Results**

Depending on the type of mineralization and surrounding rocks, we divided the area into two main sectors (***figure 4***):

- Imourkhssan area: this site consists mainly of Cu-Mo mineralization spatially associated with the Imourkhssan granite.
- Talat N'lbour area: this site is mainly composed of Au-Cu mineralization related to the NS fractures affecting the Askaoun granodiorite.

 

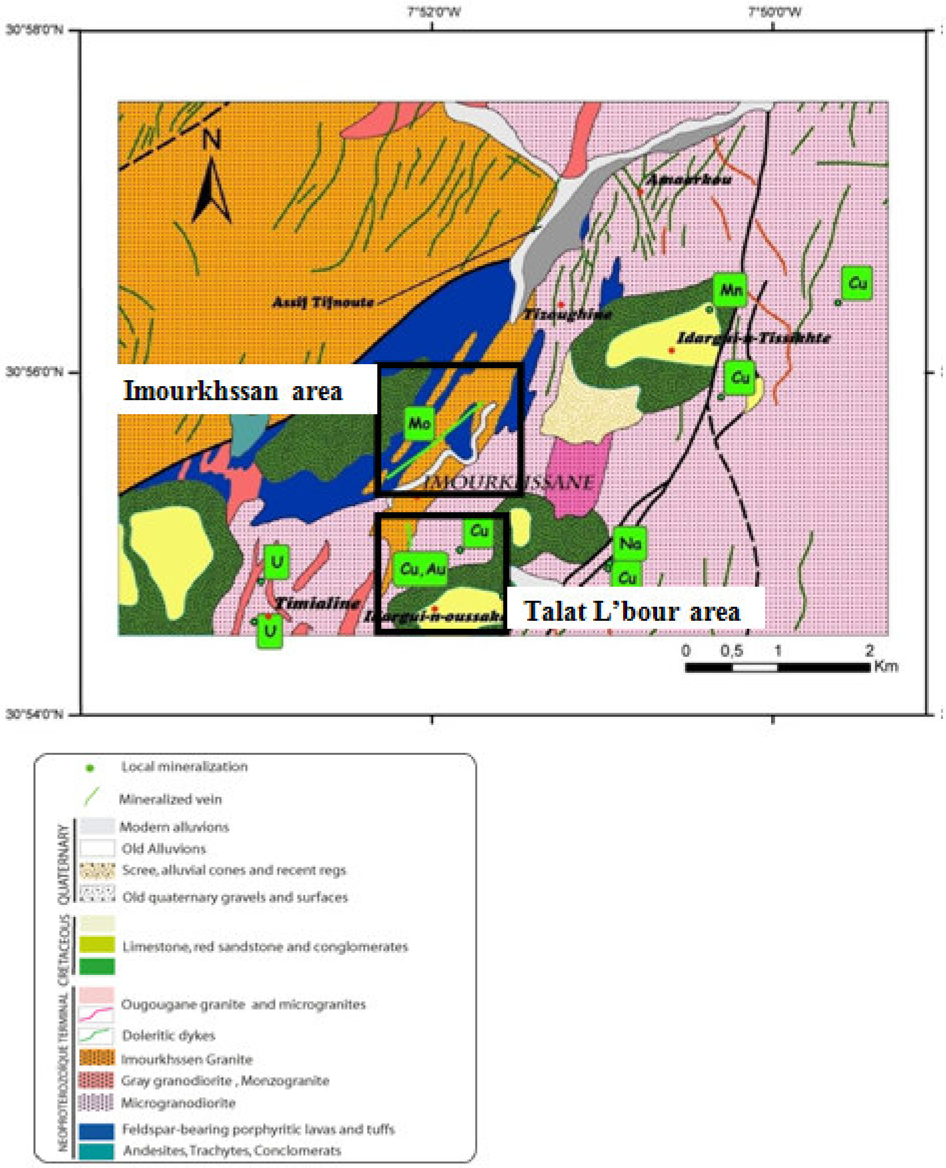


Figure 4. Geology of the Imourkhssane and Talat L'bour area and distribution of different mineral occurrences

<u>Imourkhssan area</u>

Imourkhssan granite is intrusive in the volcanic rocks (andesites and trachytes) of Saghro Group (***figure 3***). This Group were deformed during the closure of the back-arc basin and collision of the juvenile island arc with the Reguibat Shield during Pan-African times at about 600 Ma (Thomas et al., 2002).

In Imourkhssan area these rocks are porphyritic (P***late 3; Pic. 1A***) and affected by an important N-S and N75° trending fissural system (P***late 1***). N-S structures are more dominant and are filled by mineralized quartz (1% pyrite and 2 % chalcopyrite) (P***late 3; Pic. 1B***). These quatz veins may also contain high concentrations of hematite indicating a high degree of hematization (P***late 3; Pic. 1F***).

 

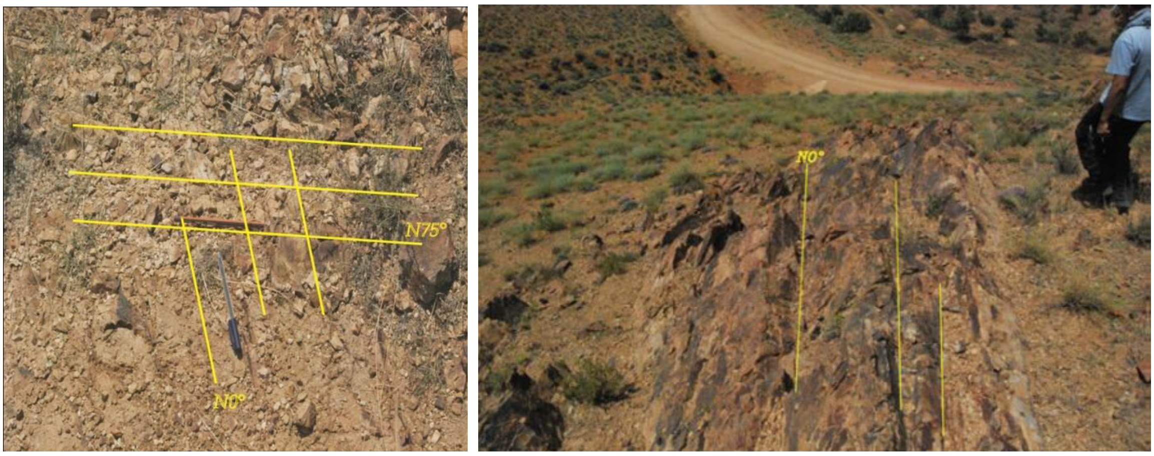


Plate 1. fissural system affecting the andesites of Saghro Group

An important silicification is noted in the contact between Imourkhssan granite and andesites (P***late 3;*** **Pic. 1C**). This silification is reflected by mineralized quartz veins.
It should be noted also that Imourkhssan granite shows highly albitized and potassic zones. The potassic zone is pink, coarse-grained and K-feldspar rich (P***late 3; Pic. 1D***). Pyrite is an ubiquitous mineral occurring within the mineralized zone (P***late 3; Pic. 1E***).

- Talat L'bour area

This area is located approximately 300 m in the southwest of Imourkhssan village on the Askaoun granodiorite (***figure 4***). This formation is injected by numerous microgranite dykes and quartz veins oriented N-S (***Plate 2***). In this area, the Cu-Au mineralization is linked to N-S fractures affecting the Askaoun granodiorite.
The most mineralized vein extend about 400 m, but its structure seems complex. The gangue of the mineralized vein is formed essentially of quartz, siderite and chlorite (***Plate 2***). The thickness varies between 0,5 and 2 m and the walls are strongly chloritized. Siderite is generally present as decimetric lenses, associated with quartz. Supergene mineralization is expressed by malachite and azurite.

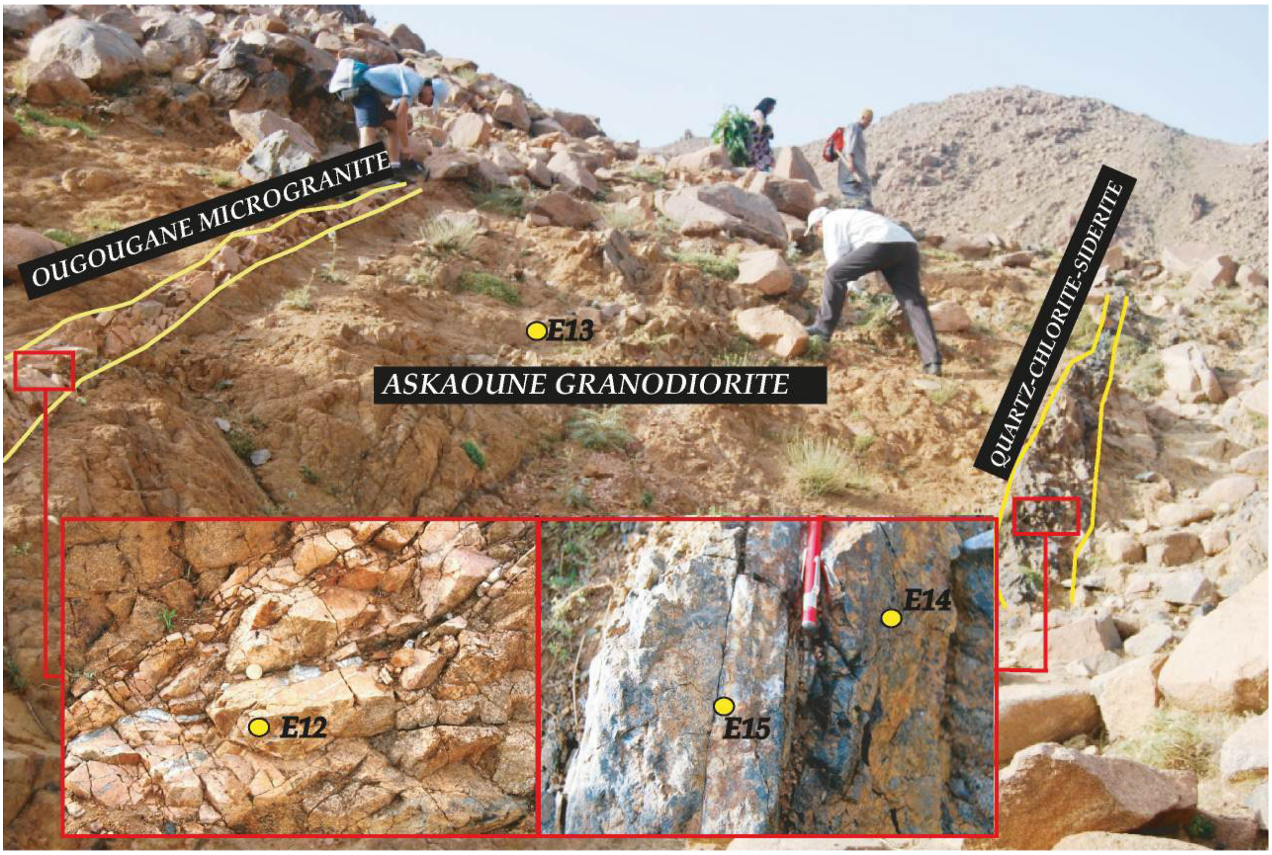


Plate 2. Quartz-chlorite-sederite vein and microgranite dyke in the Askaoun granodiorite

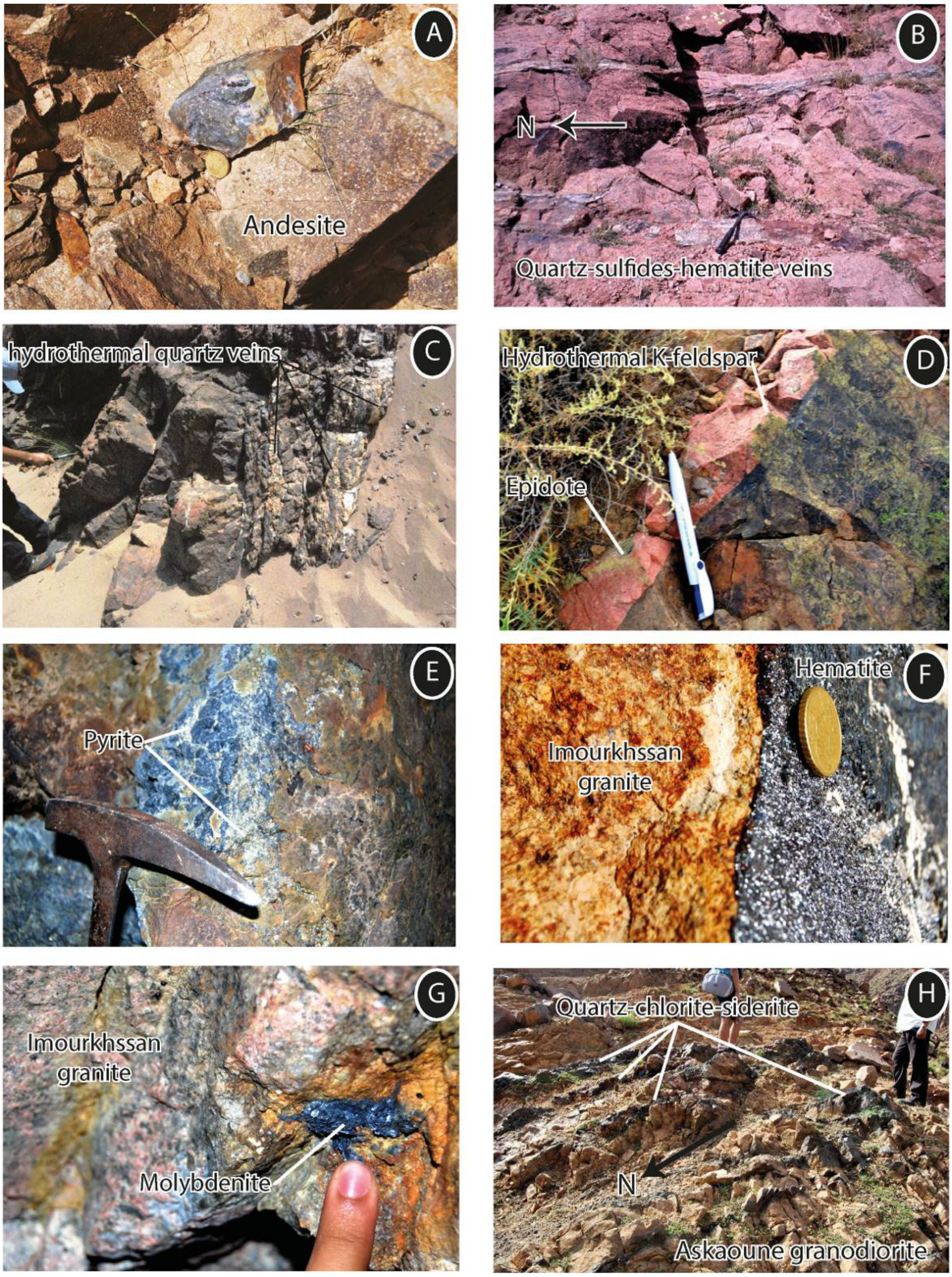


**Plate 3**. A: Porphyritic andesite of Saghro Group; B: N-S trending quartz-sulfides-hematite veins; C: Hydrothermal quartz veins; D: hydrothermal K-feldspar and epidote vein; E: pyrite veins, F: hematite vein; G: Lamellar molybdenite in Imourkhssan granite; H: N-S trending Quartz-chlorite-siderite veins in Askaoune granodiorite.

**Petrography of granitoïds and associated rocks**

*The Askaoun pluton:*

The Assarag magmatic suite is represented by the Askaoun pluton, which covers a surface of about 600 km$^2$. In its eastern part, the contact with the hosting volcanodetrital rocks of the Saghro group is sharp. The Askaoun pluton includes quartz diorite and amphibole-biotite granodiorite. The Askaoun granodiorite is grey to pink colored and medium-grained; in addition to plagioclase, amphibole and biotite, the quartz crystals form interstitial or poikilitic megacrysts and the K-feldspar (perthitic orthoclase or kaolinitized microcline) appears as anhedral megacrysts. Secondary chlorite, sericite, epidote, and opaque minerals are present. Accessory minerals are apatite, zircon and epidote with rare titanite.

*The Imourkhssan granite*

The Imourkhssan granite is well exposed in the groove of Tifnout valley in the Imourkhssan region. This granite massif is part of the Amassine suite (Thomas et al., 2002). It intrudes the volcanodetrital series of the Ouarzazate Group as well as the Askaoun intrusion.

This granite is pink colored and coarse-grained and consists of plagioclase (31 %), K-feldspar (30 %), quartz (37 %) and chloritized biotite (<2 %). Accessory minerals include opaque minerals and rare epidote. Texturally, this homogeneous granite is marked by large pink subhedral crystals of K-feldspar and xenomorphic crystals of quartz.

*Ougougane magmatic suite*

The small intrusions of this suite intrude the Askaoun and Imourkhssan plutons. They are essentially made of microgranite with the occurrence of some quartz microdiorite in the Takatart area. The quartz microdiorite is a grey colored and fine-grained rock with abundant and large phenocrysts of plagioclase and hornblende (4 mm) in a matrix of quartz and plagioclase. Brown biotite occurs as scattered chloritized phenocrysts. Opaque minerals and epidote occur with hornblende and biotite. The pink colored and fine-grained microgranite (grain size<1 mm) contains abundant interstitial quartz (37 %) and perthitic orthoclase (40 %); the plagioclase occurs as scattered zoned phenocrysts (3 mm in size) and rarely in the matrix. Accessory minerals are biotite, euhedral Fe-Ti oxides and epidote.

*Mafic dykes*

The mafic dyke swarm is microdioritic, with a slightly porphyritic microlitic groundmass composed of plagioclase with rare Fe-Mg minerals transformed into epidote.

**Alterations:**

Based on field observations and microscopic study of thin sections, the evidence of hydrothermal alteration are noticed reflecting changes in the host-rock mineralogy in response to water/rock interactions. Thus, the general categories of alteration (for example, potassic) can consist of different combinations of a typical minerals; depending upon fluid and host-rock compositions:

*Potassic alteration:*

This alteration assemblage is represented by K-feldspar (orthoclase), biotite, quartz, and magnetite, developed as selvages to small quartz veins containing disseminated pyrite, chalcopyrite, and molybdenite. The most visible evidence of potassic alteration is the presence of secondary K-feldspar (**Plate 3; Pic 1D**) and secondary biotite. This alteration is more expressed in the core of Imourkhssan granite. Magmatic biotite grains subjected to potassic alteration are either partially chloritized or completely recrystallized to secondary biotite. Chemical compositions of some biotites from Askaoun granodiorite are presented in the ternary diagram of Nachit et al., 2005, which shows they lay within the re-equilibrated field (**figure 5**).

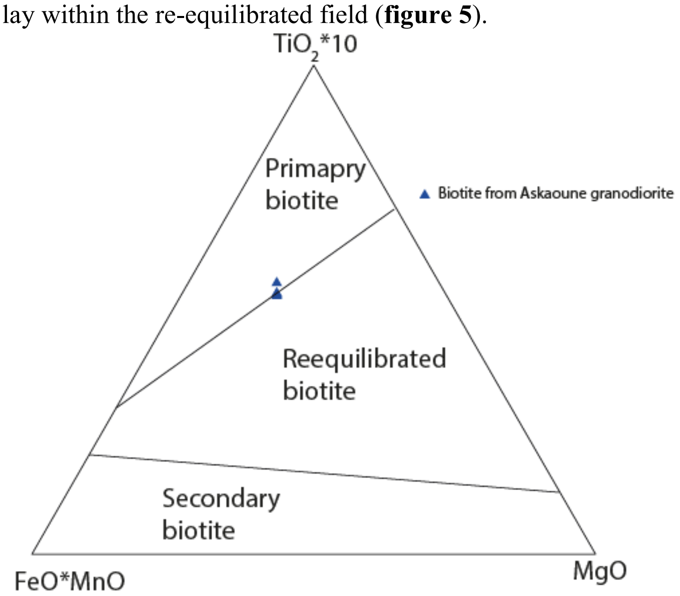


Figure 5: Ternary 10*TiO2-(FeO+MnO)-MgO composition of biotite from Askaoun granodiorite (Toummite, 2012). The discrimination field boundaries are from Nachit et al., 2005

*Phyllic alteration*

Quartz, sericite, and pyrite constitute the phyllic alteration assemblage. This alteration is the most commonly observed alteration. It is associated with quartz, which occurs as several generations of stockwork veins and veinlets and as disseminations. Plagioclase is altered to sericite, and biotite and hornblende to chlorite. A quick estimation of the presence of pyrite around Imourkhssan granite was mapped (**figure 6**).

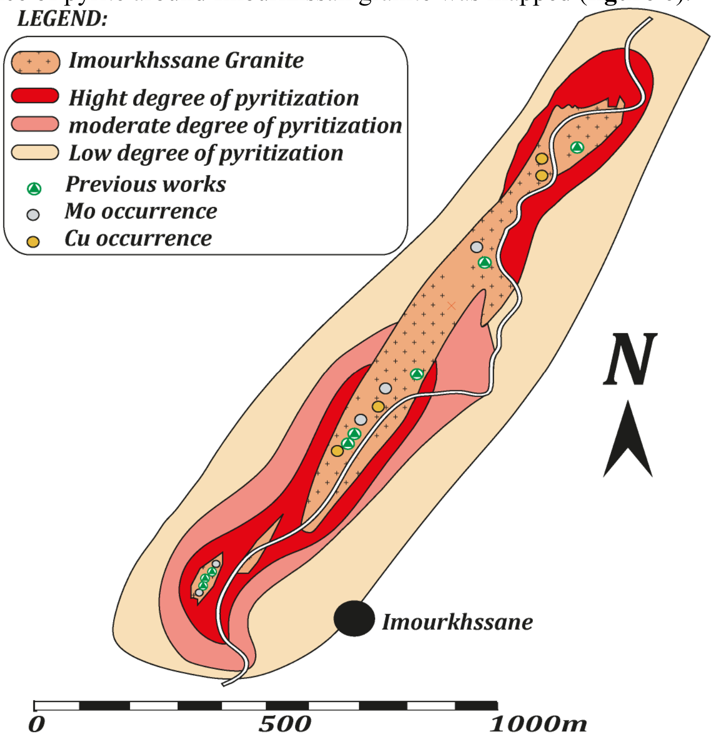


Figure 5. Estimated pyritization degree around Imourkhssan granite

*Propylitic alteration*

This alteration assemblage is characterized by epidote, chlorite, sericite, quartz, kaolinite and carbonate, which replaced biotite, hornblende, plagioclase, and groundmass. Biotite phenocrysts are partially altered to chlorite and epidote.

*Silicification*

This alteration is mostly observed in the contact between imourkhssan granite and andesites (***Pic 1C***) suggesting an intensive mobilization of silicified fluid, and the interaction of this fluid with the andesites of Saghro Group.

*Argillic alteration*

Kaolinite and sericite characterize this alteration assemblage. It is highly destructive, completely replacing the original mineral phases (mainly the K-feldspar to kaolinite).

**Geochemistry**

The Tifnoute valley plutonic rocks of this study are composed of Askaoune granodiorite, Imourkhssan granite and Ougougane granite.

These granitoïds are peraluminous, and belongs to the high-K calc-alkaline and potassic series (Toummite et al., 2012).

REE patterns (**figure 6**) are parallel and typical of alkali-calcic series. They show high total REE with enrichment in LREE and a moderate Eu anomaly.

Spidergram (**figure 6**) are also alkali-calcic in character with enrichment in LILE (Large Ion Lithophile Element, K to Th), depletion in Sr and P, resulting from the fractionation of plagioclase and apatite respectively, and Nb-Ta negative anomaly. This anomaly is of variable importance. It reflects the source characteristic (Toummite et al., 2012). The low K and Ba contents can be explained as a consequence of albitization.

These features lead to

 

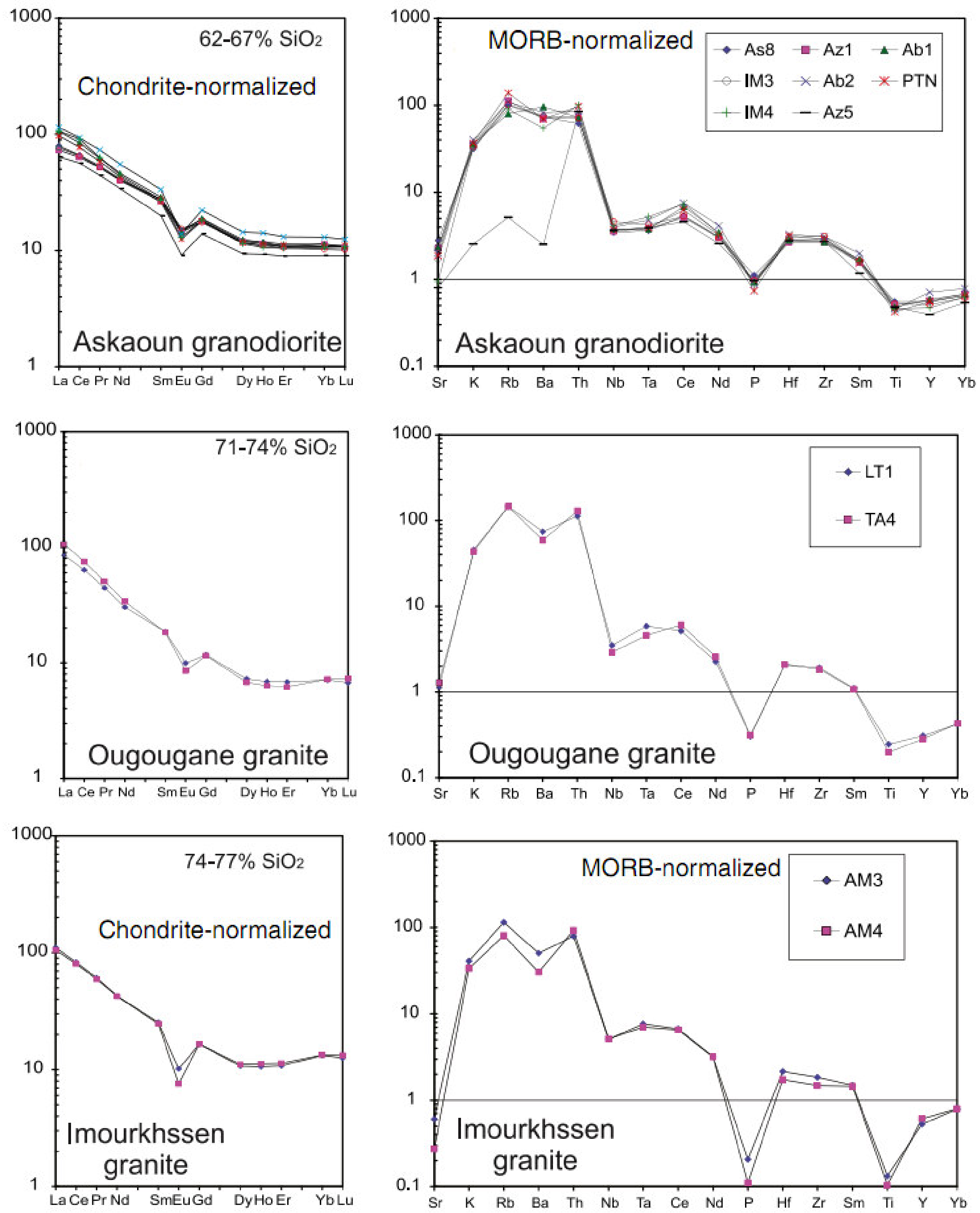


Figure 6. Chondrite-normalized REE (Evensen et al. 1978) and MORB-normalized (Pearce 1980; Pearce et al. 1984) patterns for the Tifnoute Valley granitoids (Toummite et al., 2012)

**Evaluation of the alteration effects**

It should be noted that the selected samples are less altered, since they are intended for a study of the petrography and the geochemistry of the protolith (Toummite, 2012). This appears clearly on the low contents of LOI wich range between 0.87 and 2.25% and on the discriminated diagram of Houghes, 1973 (**figure 7**). In this diagram, all samples are poloted in the field of fresh rocks, with the exception of one sample of Askaoune granodiorite wich is poloted in the field of potassic rocks.

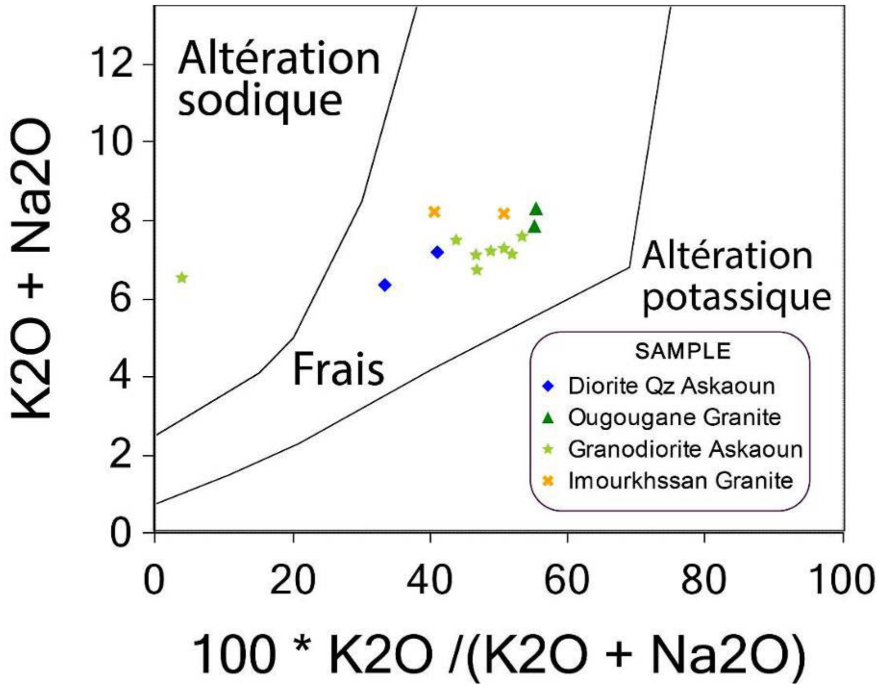


Figure 7. Houghes's K2O+Na2O vs 100*K2O/( K2O+Na2O) diagram, 1973 for the Tifnoute valley granitoïds

In order to visualize the relationships between the major elements on one hand and the traces elements on the other, we conducted a statistical procedure based on principal component analysis (PCA). The results are shown in ***figure 8***. These results were compared to the major oxides and trace elements vs SiO2 diagrams made on these same rocks by Toummite, 2012.

For major elements : there is an array of elements (group 1) that consists of $Fe_2O_{3\ tot}$, $TiO_2$, MgO, $P_2O_5$, MnO, CaO, $Al_2O_3$ and LOI which opposes the $SiO_2$ according to the F1 axis. While $K_2O$ is opposed to $Na_2O$ according to the F2 axis. Indeed, all elements of group 1 has an inverse character in relation to the behavior of silica (Toummites, 2012). This explains clearly that the vector F1 reflects the phenomenon of fractionation. However, $Na_2O$ and $K_2O$ show no significant change compared to $SiO_2$.The vector F2 seems to reflect the impact of secondary processes.

We have projected all trace elements in addition to $SiO_2$ and $Fe_2O_{3tot}$ on the same diagram, since these two elements are perfectly correlated. An important dispersion for these elements was noted.

- Incompatible elements Zr and Hf in addition to V are plotted near the $Fe_2O_{3tot}$ and present a conjugate character versus $SiO_2$, reflecting the crystallization of accessory minerals.
- The position of Sr and Eu near $Fe_2O_3$, reflects the abundance of plagioclase in the less evolved terms.
- The position of Nb, Ta and Th near the $SiO_2$ reflects the abundance of these elements in the differentiated terms.

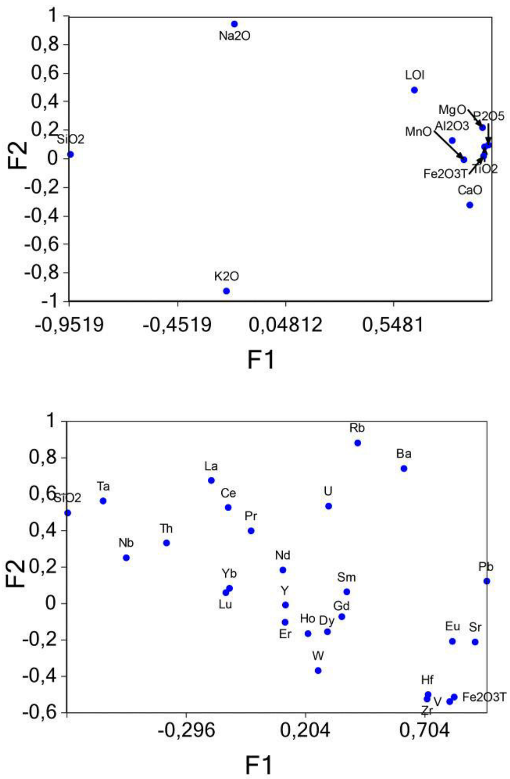


Figure 8 : F1-F2 diagram showing the dispersion of major and trace elements of the Tifnoute Valley granitoids according to a statistical procedure based on principal component analysis (PCA)

**Mineralization**

In the Imourkhssan area, the Cu-Mo mineralization is spatially associated to Imourkhssan granite. It occurs as a disseminated or lamellar mineralization on the NNE-SSW trending quartz veins or on stokwork.

The metallographic observations, supported by SEM analysis led to identify the mineral paragenesis of this deposit. It consists of chalcopyrite, pyrite, molybdenite, sphalerite and covellite (***Plate 4***). Molybdenite and chalcopyrite occur as disseminated grains (0,2 mm-1 cm). Pyrite occurs either as euhedral crystals or massive pyrite. Chalcopyrite occurs as euhedral to anhedral grains (locally up to 1 to 2%). It is partially replaced by covellite. The analysis of mineralized samples in this area show some contents up to 5 ppm Au, 660 ppm Cu and 1487 ppm Mo (sample E-1).

In the Talat N'bour area, the Cu-Au mineralization is controlled by N-S trending fractures affecting the Askaoun granodiorite. The filling of the mineralized fractures consists essentially of quartz, siderite and chlorite. The analysis of mineralized samples in this area show some contents up to 30 ppm Au, 3 % Cu and 50 % Fe.

Metallographic study reveals a mineral paragenesis consisting of pyrite, chalcopyrite, bornite, chalcocite, and covellite. Bornite, chalcopyrite and pyrite occur as a disseminated grains in the quartzic gangue. The borders of primary bornite are overgrown by chalcocite and covellite. When bornite is replaced by covellite, we notice the appearance of a fissural secondary chalcopyrite. This chalcopyrite is more enriched in copper compared to primary chalcopyrite. The latter shows borders which are lately corroded by the secondary bornite (**Plate 5**).

The textural relationships between minerals lead to draw the paragenesis succession of the Cu-Mo-Au Tifnoute valley deposit. It is represented by a primary chalcopyrite, bornite, sphalerite, pyrite, molybdenite, and bornite, as a disseminated mineralization in Imourkhssan granite or in N-S quartz-chlorite veins (Imourkhssan area), or associated to the quartz-siderite-chlorite N-S trending veins in the Askaoun granodiorite (Talat-L'bour area). A secondary paragenesis consists of secondary bornite and chalcopyrite, hematite and carbonates (malachite and azurite). This paragenetic sequence is shown in ***table2***.

The presence of gold is only proved by analysis (table x) and was not observed in any studied sample.

Tableau 2. paragenetic sequence of Tifnoute valley deposit

| | **Paragenesis I** | **Paragenesis II** |
|---|---|---|
| **Chalcopyrite** | ▬▬▬▬▬▬ | |
| **Bornite** | ▬▬▬▬▬▬ | |
| **Molybdenite** | ▬▬▬▬▬▬ | |
| **Gold** | ▬▬▬▬▬▬ | |
| **Pyrite** | ▬▬▬▬▬▬ | |
| **Sphalerite** | ▬▬▬▬▬▬ | |
| **Covellite** | | ▬▬▬▬▬▬ |
| **Bornite II** | | ▬▬▬▬▬▬ |
| **Chalcopyrite II** | | ▬▬▬▬▬▬ |
| **hematite** | | ▬▬▬▬▬▬ |
| **Malachite** | | ▬▬▬▬▬▬ |
| **Azurite** | | ▬▬▬▬▬▬ |

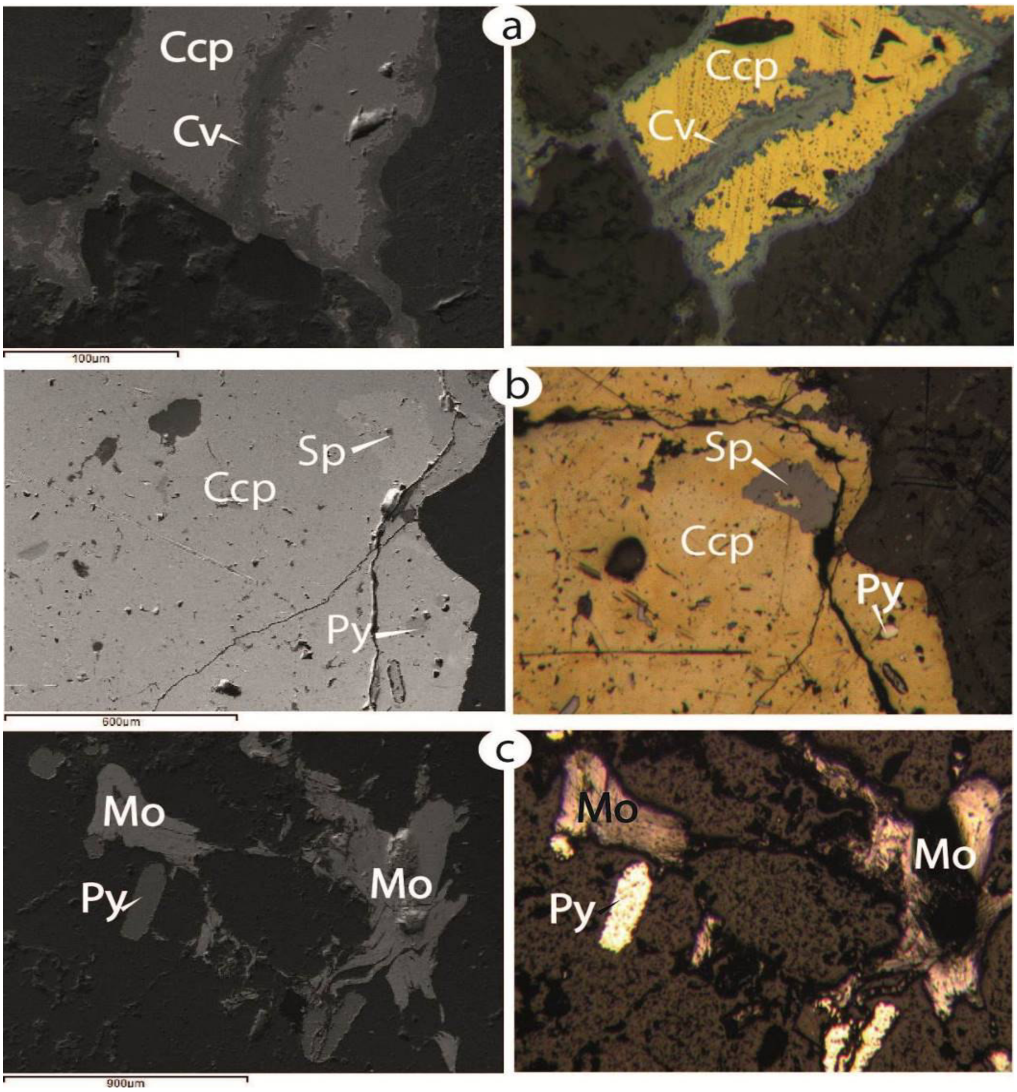


**Plate 4 :** Mineralogical association identified in the Imourkhssan area

**(A)** Chalcopyrite (Ccp) replaced by covellite (Cv) along the edges

**(B)** chalcopyrite (Ccp) associated with sphalerite (Sp) and some pyrite (Py) inclusions on the chalcopyrite.

**(C)** Euhedral pyrite and lamellar molybdenite (Mo).

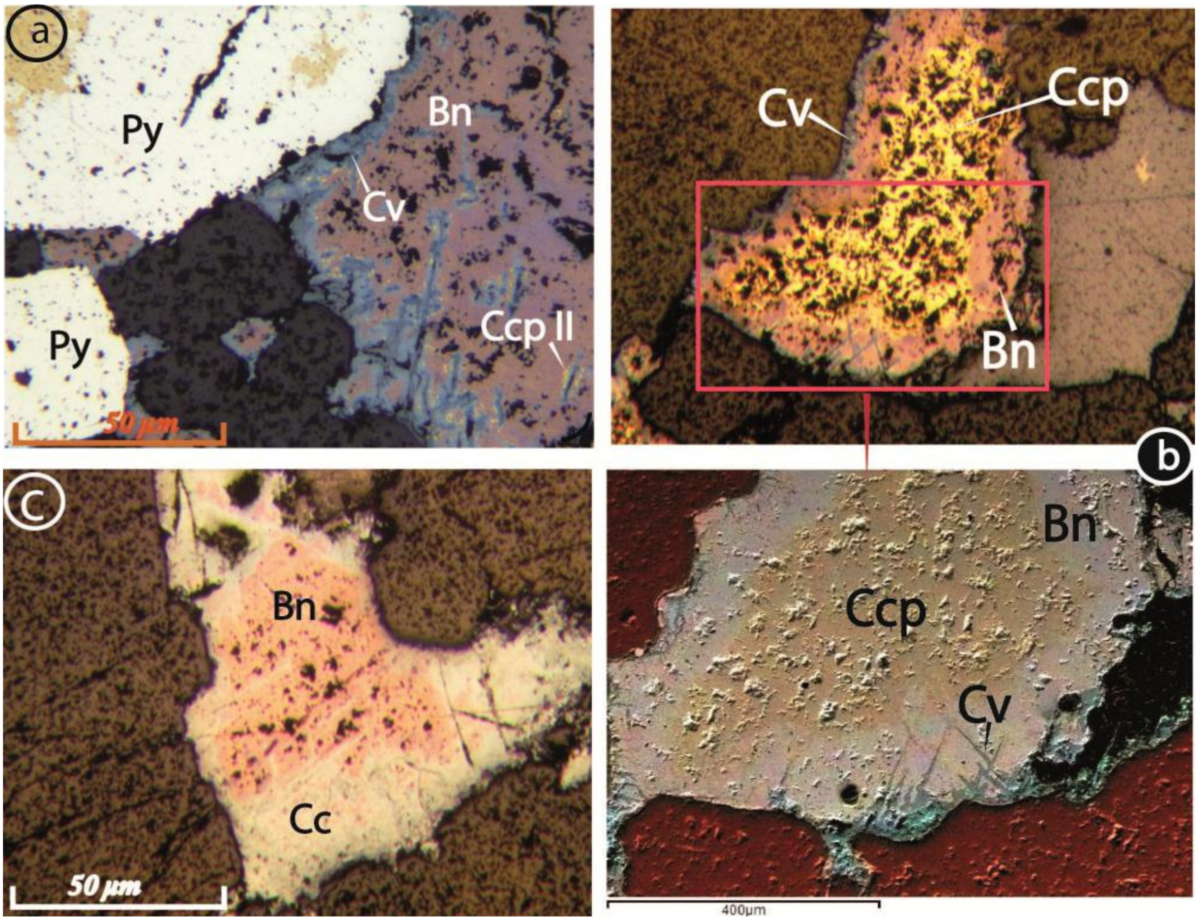


**Plate 5.** Mineralogical association identified in the Talat'Lbour area.

**(A)** Euhedral pyrite (Py) and primary bornite (Bn) which is partially replaced by coveilite (Cv) and secondary chalcopyrite

**(B)** destabilized chalcopyrite (Ccp) developing in a secondary bornite (Bn II) and chalcopyrite (Ccp II)

**(C)** Primary bornite invaded by chalcocite (Cc).

**Discussion and conclusion**

The obtained results show clearly the evidences of hydrothermal alteration. Indeed, this alteration is identified and its effects consist of:

- The presence of secondary k-feldspar and secondary biotite.
- Kaolinitization of k-feldspar.
- Transformation of plagioclase and mafic minerals to sericite, chlorite and epidote.
- Presence of silicified zone mainly along the contact between Imourkhssan granite and andesite.
- Growth of pyritic facies around the Imourkhssan granite.
- Growth of N-S trending quartz-hematite veins.

The Cu-Mo-Au mineralization is hosted exclusively in the Imourkhssan granite and Askaoun granodiorite in various forms: (i) dissemination, (ii) stockwork and (iii) quartz-sedirite-chlorite veins related to N-S structures.

In addition, the style of mineralization often as N-S trending veins or stockwork and metal association of Cu-Mo-Au mineralization of Tifnoute valley are typical of a porphyric deposits. Indeed, It has been shown in porphyry systems, that the orientation of mineralized veins and stockworks are not random, and the fractures open in an organized manner, in response to the maximum constraints (Jébrak et Marcoux, 2008).

The Askaoun granodiorite and the Imourkhssan granite have been dated by LA-ICPMS on zircon at 558±2Ma and 561±3Ma, respectively (Toummite, 2012). Geochemically, these granitoids belong to an alkali-calcic series (high-K calc-alkaline) affinity with typical Nb-Ta negative anomalie (Toummite et al., 2012). These authors proposed a geodynamical model where these granitoids were generated during the post-collisional metacratonic evolution of the northern boundary of theWest African craton.

The mentioned petrographic and geochemical characteristics of the host rocks, the nature of the hydrotheramal and the nature and forms of mineralization confirm a mineralization liked to an arc-type porphyry system.

This study reveals the presence of a Cu-Mo-Au arc-type porphyry deposit, associated with the calc-alkaline granitoids of Tifnoute Valley. This mineralization may be related to metallogenic event linked to the late Ediacaran extension known in the Anti-Atlas and documented by several authors Levresse (2001); Cheilletz et al. (2002); Marcoux et al. (2003); Levresse et al., (2004); et Tuduri, (2005).
Despite the arc type geochemical signature of the Tifnoute valley granitoids, they are emplaced within a transtensional tectonic regime (Toummite et al., 2012). Indeed, during the Neoproterozoic Pan-African collision, the Anti-Atlas was in a passive margin configuration.

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