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Hydrothermal alterations associated with Gold-sulphide occurrences in the eglab massif, southwestern algeria

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DEDICATION

To my father and mother,
For your unconditional love, your endless sacrifice, and your unwavering faith in my future.
You have been my first teachers and my greatest supporters.

To my beloved aunts — from my mother's side and my father's side —
Who opened their homes to me with such generosity and warmth while I was working on this thesis.
Your hospitality, your kindness, and your patience made this journey possible.
I could not have done this without your support.

To my brothers and sisters,
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To all those dear to me,
Who carried me, encouraged me, and believed in me, even in moments of doubt.

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الملخص

تُعد كتلة إيجلاب، الواقعة في جنوب غرب الجزائر، الجزء الأقصى شرقاً من درع الريجيبات ضمن الكرياتون الغربي الأفريقي. تركز هذه الدراسة على توصيف التجميعات المعدنية للتغيرات الحرارية المائية المرتبطة بترسبات الكبريتيد-الذهب في منطقة ،. مع التركيز الخاص على مؤشر ذهب أكيليت دليل(Y-EJZ) التقاء بيتي-إيجلاب

من خلال التحليل البتروغرافي العياني والمجهري لعشر عينات، تم تحديد ثلاثة أنواع رئيسية من السحنات الصخرية: الرواسب الصخرية (الميتاغرايواك)، الكوارتزيت (الميتاكوارتزيت)، والميتاسوماتيت. كشفت الدراسة عن سبعة أنواع متميزة من التغيرات الحرارية المائية: التسرسيتة، والتكلورة، والتكلسن، والتسيليسة، والتبديتة، والتغير الصودي، والأكسدة الفوقية. وثلاثة أجيال من الكوارتز (V1 دقيقة الحبيبات، تقطع :V2 غنية بالكربونات؛ :V1) جيلان من العروق الحرارية المائية .يشيران إلى تاريخ حراري مائي معقد ومتعدد المراحل (العقيق المجهري :Q3 ذاتي الشكل؛ :Q2 خشن الشكل الغريب؛ :Q1)

-Y) تُعد تجميعات التغيرات مميزة لأنظمة الذهب الأوروجينية، وتخضع للتحكم البنيوي من قبل منطقة القص بيتي-إيجلابEيوجد الذهب على شكل ذهب الخالص في الشقوق الدقيقة داخل الزرنيخيت والجالينا المتحطمة، وعلى شكل شوائب .(SZ داخل الكالكوبيريت والجالينا، مما يشير إلى ترسيب متأخر. أدت التغيرات الفوقية الشديدة إلى تكوين هيدروكسيدات الحديد والنحاس المرتبطة بالإثراء الثانوي للذهب، مما يفسر الدرجات العالية على السطح (حتى 311 غ/طن ذهب) مقارنة بالعمق .(~1.5 غ/طن)

تشير بيانات الشوائب السائلة إلى سوائل حرارية مائية منخفضة الحرارة (160-280°م) من أصل جوي محتمل تتداول عبر الفوالق القشرية العميقة، مع إسهام مغماتي محتمل. يُفسر الترسب على أنه حدث معدني متأخر من العصر الإبورني يأتي بعد 2.065 مليار سنة. تسهم هذه النتائج في فهم التكوين المعدني للحقبة الباليوبروتيروزوية وتقدم إرشادات للاستكشاف في كتلة .إيجلاب

الكلمات المفتاحية: كتلة إيقلاب، نطاق القص ياتي-إيقلاب، تمعدن ذهبي، تغير حراري مائي، أكيليت دليل، أوروجيني، كبريتيدات، الدرع الغرب إفريقي، توالد معدني، إثراء فوقي.

RÉSUMÉ

Le massif de l'Eglab, situé dans le sud-ouest de l'Algérie, représente la partie la plus orientale du Bouclier de Reguibat au sein du Craton Ouest-Africain. Cette étude porte sur la caractérisation des assemblages d'altération hydrothermale associés à la minéralisation or-sulfures dans la Zone de Jonction Yetti-Eglab (ZJYE), avec un accent particulier sur l'indice d'or d'Akilet Deilel.

Grâce à l'analyse pétrographique macroscopique et microscopique de dix échantillons, trois faciès lithologiques principaux ont été identifiés : le conglomérat (métagrauwacke), le quartz filonien et la métasomatite. L'étude a révélé sept types distincts d'altération hydrothermale
: la séricitisation, la chloritisation, la carbonatisation, la silicification, l'épidotisation, l'altération sodique et l'oxydation supergène. Deux générations de veinules hydrothermales (V1 : riche en carbonates ; V2 : plus fine opaque minerals, recoupante) et trois générations de quartz (Q1 : xénomorphe grossier ; Q2 : automorphe ; Q3 : calcédoine microcristalline) indiquent une histoire hydrothermale complexe et pluriepisodique.

Les assemblages d'altération sont caractéristiques des systèmes aurifères orogéniques, structuralement contrôlés par la Zone de Cisaillement Yetti-Eglab (ZCY-E). L'or se présente sous forme d'or natif dans les microfractures de l'arsénopyrite et de la galène bréchées, et sous forme d'inclusions dans la chalcopyrite et la galène, indiquant une précipitation tardive. Une altération supergène intense a produit des hydroxydes de fer et de cuivre associés à un enrichissement aurifère supergène , expliquant les teneurs élevées en surface (jusqu'à 311 g/t Au) comparées à la profondeur (~1,5 g/t Au).(ORGM,2002)

Les données sur les inclusions fluides suggèrent des fluides hydrothermaux de basse température (160–280°C) d'origine probablement météorique circulant à travers des failles crustales profondes, avec une possible contribution magmatique. La minéralisation est interprétée comme un événement métallogénique tardi-Éburnéen tardif postérieur à 2,065 Ga. Ces résultats contribuent à la compréhension de la métallogenèse paléoprotérozoïque et fournissent des orientations pour l'exploration dans le massif de l'Eglab.

Mots-clés : Massif des Eglab, zone de cisaillement Yetti-Eglab, minéralisation aurifère, altération hydrothermale, Akilet Deilel, orogène, sulfures, Craton Ouest-Africain, succession paragénétique, enrichissement supergène.

ABSTRACT

The Eglab massif, located in southwestern Algeria, represents the easternmost part of the Reguibat Shield within the West African Craton. This study focuses on the characterization of hydrothermal alteration assemblages associated with sulphide-gold mineralization in the Yetti-Eglab Junction Zone (Y-EJZ), with particular emphasis on the Akilet Deilel gold occurrence.

Through macroscopic and microscopic petrographic analysis of ten samples, the investigation revealed three main lithological facies were identified: conglomerate (metagreywacke), quartz veins, and metasomatite. Two generations of hydrothermal veinlets (V1: carbonate-rich; V2: finer opaque-grained, cross-cutting) and three quartz generations (Q1: coarse xenomorphic; Q2: automorphic; Q3: microcrystalline chalcedony) and seven distinct hydrothermal alteration types: sericitization, chloritization, carbonatization, silicification, epidotization, sodic alteration, and supergene oxidation which indicate a complex, multi-stage hydrothermal history.

The alteration assemblages are characteristic of orogenic gold systems, structurally controlled by the Yetti-Eglab Shear Zone (Y-ESZ). Gold occurs as native gold in microfractures within brecciated arsenopyrite and galena, and as inclusions in chalcopyrite and galena, indicating late-stage precipitation. Strong supergene alteration produced iron and copper hydroxides associated with supergene gold enrichment, explaining high surface grades (up to 311 g/t Au) compared to depth (~1.5 g/t Au)(ORM,2002)

Fluid inclusion data suggest low-temperature hydrothermal fluids (160–280°C) of probable meteoric origin circulating through deep crustal faults, with possible magmatic contribution. The mineralization is interpreted as a late tardi-Eburnean event post-dating 2.065 Ga. These findings contribute to the understanding of Paleoproterozoic metallogenesis and provide exploration guidelines for the Eglab massif.

Keywords: Eglab massif, Yetti-Eglab shear zone, gold mineralization, hydrothermal alteration, Akilet Deilel, orogenic, sulphide-gold, West African Craton, paragenetic succession, supergene enrichment.

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Chapter 1 : General introduction

1.1 Introduction

The Eglab massif, located in southwestern Algeria, represents the easternmost part of the Reguibat rise, which belongs to the West African Craton (WAC). The study area is bounded by coordinates 25°N to 27°N latitude and 6°W to 8°W longitude (Fig. 1). The Reguibat shield contains exposed Paleoproterozoic units to the east and Archean units to the western part (Mauritania) (Potrel et al., 1998, in Benramdane, 2007). It's characterised by crystalline basement rocks with multiple magmatic metamorphic and deformation phases . The Eglab massif exhibits an Eburnean evolution compared to the southern West African Craton (Peucat et al., 2005). The area features an significant mineral resources, and hydrothermal activity (Benramdane, 2007).

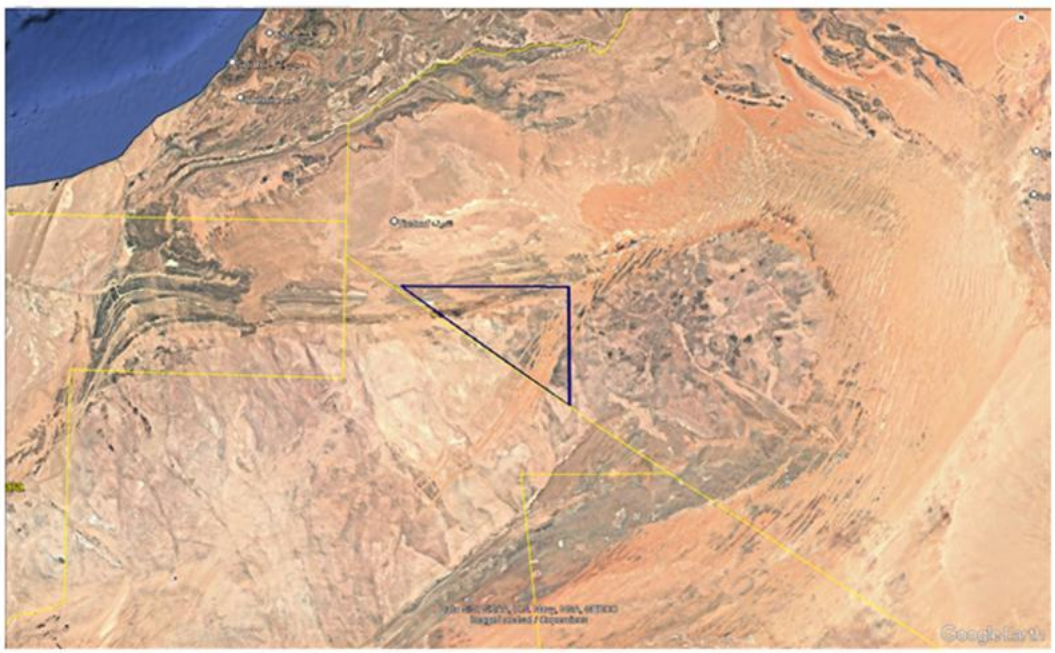


Fig. 1: Google Earth satellite image of the western Sahara, study area delineated by a blue polygon.

Gold mineralization in the West African Craton remains the subject of extensive research due to its economic importance and complex geological evolution (Milési et al., 1989, in Benramdane, 2007).

The primary objective of this research is to characterize the hydrothermal alteration assemblages associated with sulphide-gold mineralization in the Yetti-Eglab junction zone. This investigation contributes to the broader understanding of Paleoproterozoic metallogenesis and provides valuable insights for mineral exploration in Eglab massif.

1.2 Geography

The study area is located in southwestern Algeria in the southern part of Tindouf Wilaya, near Mauritanian border (approximately 20-30 km east). The region belongs to the western Saharan desert zone. The nearest major city is Tindouf town to the northwest . Smaller water sources located throughout the region (Gara Djebilet, Laouinet, Chenachane, Chegga). Access to the study area is primarily via desert tracks and requires specialized transportation due to the challenging terrain and remote location.

The Eglab massif forms a relative topographic high within the surrounding desert landscape (Tindouf, specify Taoudeni sedimentary basin), with elevations ranging from approximately 200 to 600 meters above sea level. The terrain is characterized by relatively subdued relief compared to hoggar area, with occasional inselbergs and residual hills of more resistant lithologies called "**Guelb**" and it's mean hill or piton. The landscape exhibits typical desert weathering features, including deflation surfaces called **Regs**, dunes and **Ergs** (Erg Iguidi and Erg Chech).

The climate is hyper-arid, with annual precipitation typically less than 50 mm. Temperatures show extreme diurnal and seasonal variations, with summer maxima exceeding 45°C and winter nights occasionally dropping below freezing. The strong winds, particularly from the northeast, contribute to active sand transport and aeolian landform.

Vegetation is sparse, it consists primarily of drought-adapted shrubs and concentrated in ephemeral riverbeds (oued channels). The remote and inhospitable nature of the region has historically limited geological exploration.

1.3 Previous Work

The southwestern region of Algeria has long attracted the attention of geologists due to its mineral potential. Early pioneers such as N. Metchnikoff, Th. Monod, and P. Gevin provided the first general outlines of the geology of this vast area (in Lagraa, 2014).

Over the years, numerous exploration campaigns and research studies have been conducted on the Eglab massif. However, most of these works focused on the magmatic and crystalline basement with a metallic potential (Mo,Cu,Zn…) of the region. The gold remained largely unknown until recent decades.

1.3.1 Early Exploration and Mapping

The first systematic exploration of the Eglab massif began with the B.I.A. (Bureau d'Investigation en Afrique) between 1958 and 1960, which produced several unpublished geological maps at 1/200,000 scale and discovered numerous mineral occurrences. These were followed by the S.E.R.M.I. (Société d'Étude et de Réalisations Minières et Industrielles) between 1963 and 1965, which completed the B.I.A. work and published a synthesis geological map of the Eglab and the northern Yetti at 1/500,000 scale in 1965.

Between 1979 and 2004, the E.R.E.M. (now O.R.G.M.) conducted multiple exploration campaigns, updating geological maps, producing thematic maps (indices, hydrothermal alteration, geophysics), and identifying new prospects in areas such as Guelb El Hadid (Central Eglab), Arieguet Lemha (West Eglab), and Bled M'Dena – Sebkha En Nhass (West Eglab).

1.3.2 Studies on Magmatic and Crystalline Rocks

Several researchers have contributed to the understanding of the magmatic and crystalline rocks of the Eglab massif, we cited:

- P. Gevin (1951-1960) distinguished three ancient series and three types of granites (Chegga, Yetti, and Aftout) and defined the Guelb El Hadid series.
- Buffière and his team (1966-1970) extensively studied the Precambrian magmatism of the Eglab massif.
- Sabaté and his team (1971-1979) made important contributions to the petrography, geophysics, geochemistry, and geochronology of volcanic and volcano-sedimentary series, specifically in the Yetti-Eglab junction zone.
- Azzouni Sekkal and her students (1972-2003) defined the petro-geochemical characteristics of granitoids and basic to ultrabasic intrusions in the Yetti-Eglab junction zone.
- Kahoui (1988) studied the volcano-plutonic annular complex of Djebel Drissa in the Central Eglab.
- Mahdjoub and Kahoui (1994-2008) demonstrated the "Archean" style of evolution of the Paleoproterozoic series of the Yetti-Eglab massif through a multidisciplinary approach.
- Peucat et al. (2005) provided a comprehensive synthesis of the petrography and geochemistry of the magmatic rocks of the Eglab massif.
- Tabeliouna (2009) studied mafic-ultramafic stock in the Yetti and annular structure of Bled M'Dena in the west Eglab.

1.3.3 Geochronological Framework

The geochronology of the Eglab granitoids has been refined over time. Early Rb/Sr dating by Lasserre et al. (1970), Sabaté et al. (1977), and Vachette et al. (1973) gave an age of 1925 ± 41 Ma. More recently, Peucat et al. (2005) in the synthesis of new geochronology data proposed ages between 2.2 Ma and 2065 ± 2 Ma, indicating the Eburnean orogeny.

1.3.4 Geophysical Surveys

Geophysical campaigns have played an important role in understanding the subsurface structures of the Eglab massif:

- S.O.N.A.R.E.M. (1974) conducted aeromagnetic and aeroradiometric surveys over the entire region.
- Sabaté and Lomax (1975) used paleomagnetic measurements on basic rocks to define the stratigraphic succession of magmatic phases in the Yetti-Eglab junction zone.
- E.R.E.M. (1987) then O.R.G.M. (1998-2001) carried out a detailed geophysical survey on the Bled M'Dena circular structure and conducted a ground magnetic survey that revealed three significant anomaly zones.
- Aïfa and Lefort (1993-2004) provided details on the dip and arrangement of tectonic blocks in the Yetti and East Eglab.
- Allek and Hamoudi (2008) regional-scale aeromagnetic studies of southwestern Algeria highlighting major tectonic lineaments.

1.3.5 Mineral and Gold occurrences in the Eglab massif

The first mineral occurrences were discovered by BIA (1960) and S.E.R.M.I (1965) mainly, Pn-Zn, Fe, Cu.

The first gold occurrence on the massif was the "Caroline" index, discovered by B.I.A. (1960b), located 50 km northeast of the study area, with grades of 11.7 g/t Au and 9 g/t Ag. (BIA, 1960,in Benramdane ,2007).

Between 1979 and 1983, E.R.E.M. concluded an multi technique (geochemical, geologic, geophysics) surveys at 1/200.000 and 1/500.000 scales and highlighted new polymetallic occurrences (Ag, W, Ti, Hg, Zr, REE, Nb, Y) in the Central and East Eglab. However, these occurrences still remained poorly studied.

Between 1998 and 2002, ORGM prospectors returned to the massif targeting molybdenum, gold, and diamond occurrences. The main discovery was the Akilet Deilel gold occurrence. But the gold potential still poorly known.

Benramdane (2007) provided the first detailed geological and metallogenic study of the gold mineralization in the Yetti-Eglab junction zone, characterizing the Akilet Deilel occurrence.

More recently, Lagraa (2014) studied the Mo-Cu porphyry occurrence of the Bled M'Dena circular complex through hydrothermal alteration and fluid inclusion studies.

Students from Oran 02 University contribute in some studies of the massif under masters degree graduation .

1.4 Work Objective

The first interest in this research is to characterize the hydrothermal alteration assemblages associated with sulphide-gold mineralization in the Yetti-Eglab Junction Zone. The objective of this work is:

- A bibliographic synthesis of the study area (West Eglab, Yetti-Eglab junction zone);
- A detailed petrographic study (macroscopic and microscopic) of three main facies (conglomerate, quartzite, and metasomatite) from the study area;
- Characterization of hydrothermal alteration assemblages associated with sulphide-gold mineralization in the Yetti-Eglab junction zone;
- Identification of alteration minerals and paragenetic sequence.

This investigation contributes to the broader understanding of gold mineralization and provides valuable insights for gold exploration in Eglab massif.

1.4.1 Methodology

This study was conducted on samples provided for this disposal. Following macroscopic examination, 10 samples were selected and some (8) thin sections and polished sections were prepared in the laboratory at Earth Sciences Department of Oran 2 University.

Microscopic examination allowed us to identify both transparent and opaque minerals (sulfide types), as well as rock fragments. Based on this study, the samples were grouped into three facies, which are described below:

- Volcanosedimentary (volcanodetrital) facies with quartz veins
- Vein quartz facies
- Metasomatic facies (metasomatite)

For language improvement and clarity, I used AI-based tools to assist with grammar, phrasing, and text organization. The geological data, observations, interpretations, and conclusions presented in this work are entirely the author's own.

1.5 Regional Geological Setting

1.5.1 The West African Craton

The West African Craton (WAC) is one of Earth's major Precambrian shields in Africa (Fig. 2). It is recognized in the Anti-Atlas in the north Reguibat Shield in centre and the Leo-Man Shield in the south, separated by the large Taoudeni Basin. The craton is bounded by younger mobile belts: the Mauritanides to the west, the Pan-African belt to the east (Kahoui et al., 2008). The West African Craton is bounded by younger mobile belts: the Mauritanides to the west, Ougarta chain to the northeast, and the Pan-African mobile belt to the east. These boundaries represent zones of later tectonic reactivation associated with the Pan-African orogeny (Ennih et al, 2001) (Fig. 3).

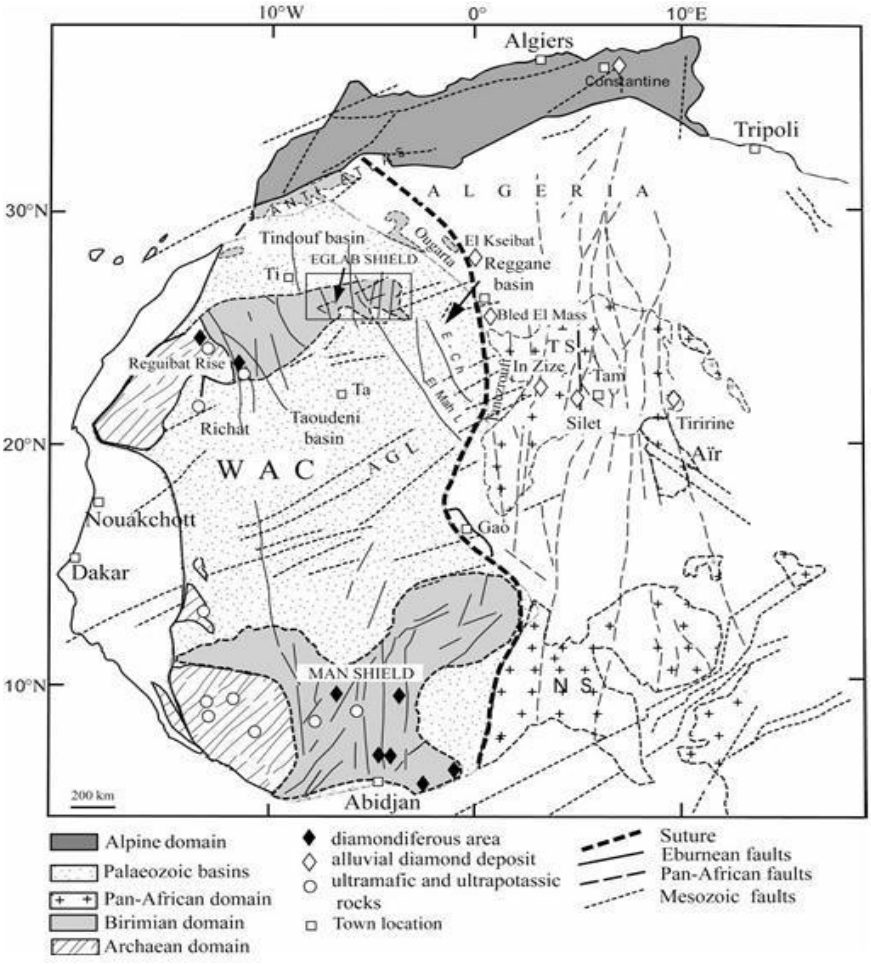


Fig. 2: Geological map of the West African craton showing the Reguibat Shield, Leo-Man Shield, Taoudeni Basin, Tindouf Basin, and major lineaments. (Kahoui, 2007)

The craton's internal structure comprises distinct Archean and Paleoproterozoic domains, respect in west and east separated by major shear zones and characterized by contrasting lithological assemblages and metamorphic histories (Thiéblemont et al., 2004).

The structural evolution involved multiple deformation phases, including early ductile deformation under amphibolite to granulite facies conditions, followed by progressive cooling and brittle-ductile to brittle deformation (Feybesse & Milési, 1994).

Major shear zones represent crustal-scale structures that juxtaposed different tectonic domains and served as conduits for magma ascent and hydrothermal circulation (Tshibubudze et al., 2009).

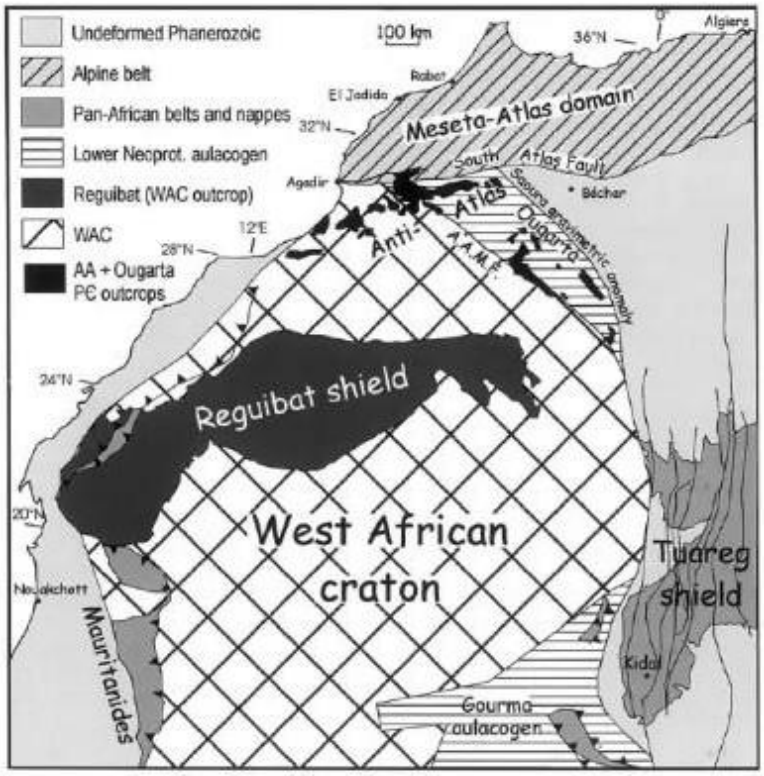


Fig.3: Sketch map of the West African Craton (WAC) placing the Anti-Atlas into its regional context and showing the proposed northern and northeastern boundary of the craton. The boundary follows the Saoura gravimetric anomaly north of the Ougarta region and the South Atlas Fault (SAF). AA + O = Anti-Atlas + Ougarta (Ennih et al, 2001)

1.5.2 The Reguibat Shield

The Reguibat Shield exhibits a fundamental east-west division, with Archean crust dominating the western portion and Paleoproterozoic terranes in the east (in Benramdane, 2007) (Fig. 4).

The regional structural architecture is dominated by north-northeast to south-southwest trending shear-zones and fold belts developed during the Eburnean orogeny (Peucat et al., 2005). These structures controlled the emplacement of granitoid plutons, the distribution of supracrustal sequences, and subsequent hydrothermal fluid flow (Vidal et al., 2009).

The metamorphic history of the Reguibat sheild is complex, involving multiple thermal events and varying pressure-temperature conditions across different domains. The earliest metamorphic event affected Archean basement rocks, producing granulite to upper amphibolite facies assemblages (Potrel et al., 1998).

The sedimentary cover is recognized in the Tindouf or Taoudeni basins; it consists of Neoproterozoic to palaeozoic covers and later by cenozoic and Quaternary deposits.

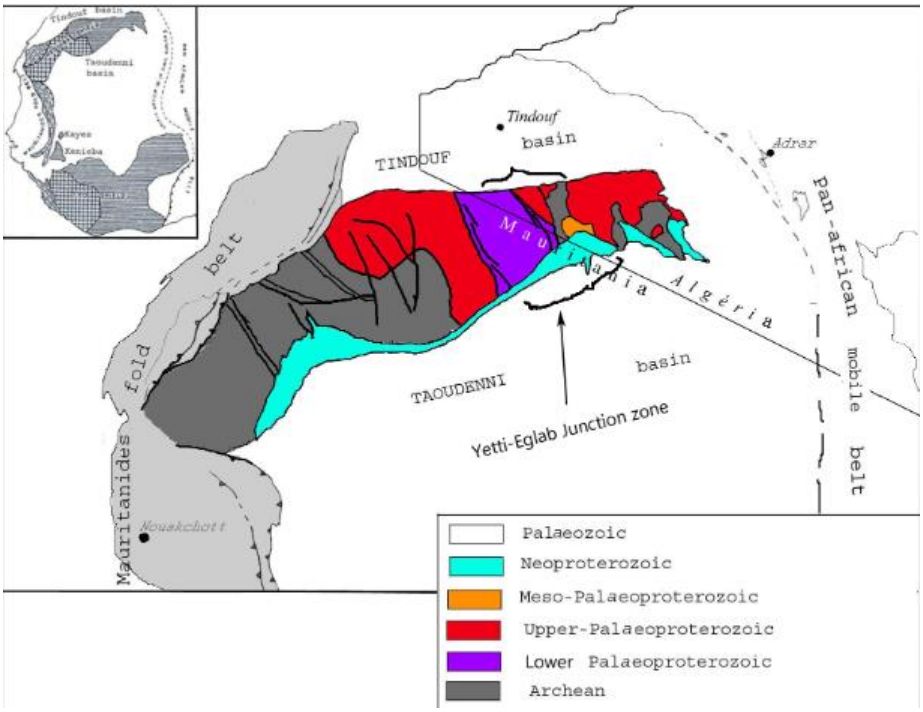


Fig. 4: Geological map of the Reguibat Sheild; (Benramdane, 2007).

The Eglab massif is the easternmost part of the Reguibat rise (SW of Algeria). It is limited to the north by the Palaeozoic Tindouf basin, to the east by the dunes of Erg Chech and the Palaeozoic Reggane basin, and to the south by the Neoproterozoic Hank series and the Palaeozoic cover of the Taoudeni basin.

Chapter 2: Geology of Eglab Massif

Geology of Eglab Massif

2.1 Overview and Subdivision

The Eglab Massif (called also Yetti-Eglab massif) constitutes the eastern extremity of the Reguibat Shield located in SW of Algeria, it is subdivided into two domains: ***Yetti*** domain to the west and ***Eglab*** domain to the east, these two domains differing in their structural, lithological and metamorphic characteristics are intruded by Paleoproterozoic granitoids(Fig.5)

The Eglab massif is defined as a "proton", which is a part of the Earth's crust that has attained stability in the Early to Middle Proterozoic (2.05Ga) (Janse, 1992, in Kahoui et al., 2008).

The massif exhibits a specific Eburnean evolution with two major orogenic stages (Peucat et al., 2005):

- the first orogenic stage corresponds mainly to 2.21-2.18 Ga magmatic activity forming a metamorphosed batholith composed of various juvenile calc-alkaline orogenic suites, compatible with a mature island-arc setting. This early phase of the Eburnean orogeny involved the development of extensive volcanic arcs and associated intrusive complexes, recording active subduction along the margins of the growing continent.
- the second orogenic stage is characterized by active-margin magmatic suites emplaced and deformed at approximately 2.09 Ga that represent by syntectonic Chegga granite, intruded by large volumes of high-K post-orogenic magmas covering over half of the area of the Eglab massif it interpreted as resulting from slab roll-back processes and asthenospheric upwelling at 2.07 Ga.

2.2 Lithological Units

2.2.1 lower Basement

The oldest rocks in the Eglab massif consist of Paleoproterozoic 2.21-2.18 Ga gneissic complexes series (Chenachane-Erg Chech and Chegga series) that form the substrat for younger Paleoproterozoic units (Peucat et al., 2005). The lower metamorphic basement includes one 2.73 Ga-old relic of Archean Ocean crust. These Archean components are represented by high-grade gray gneisses, amphibolites, and migmatites that record multiple phases of deformation and metamorphism to upper amphibolite facies conditions (Peucat et al., 2005).

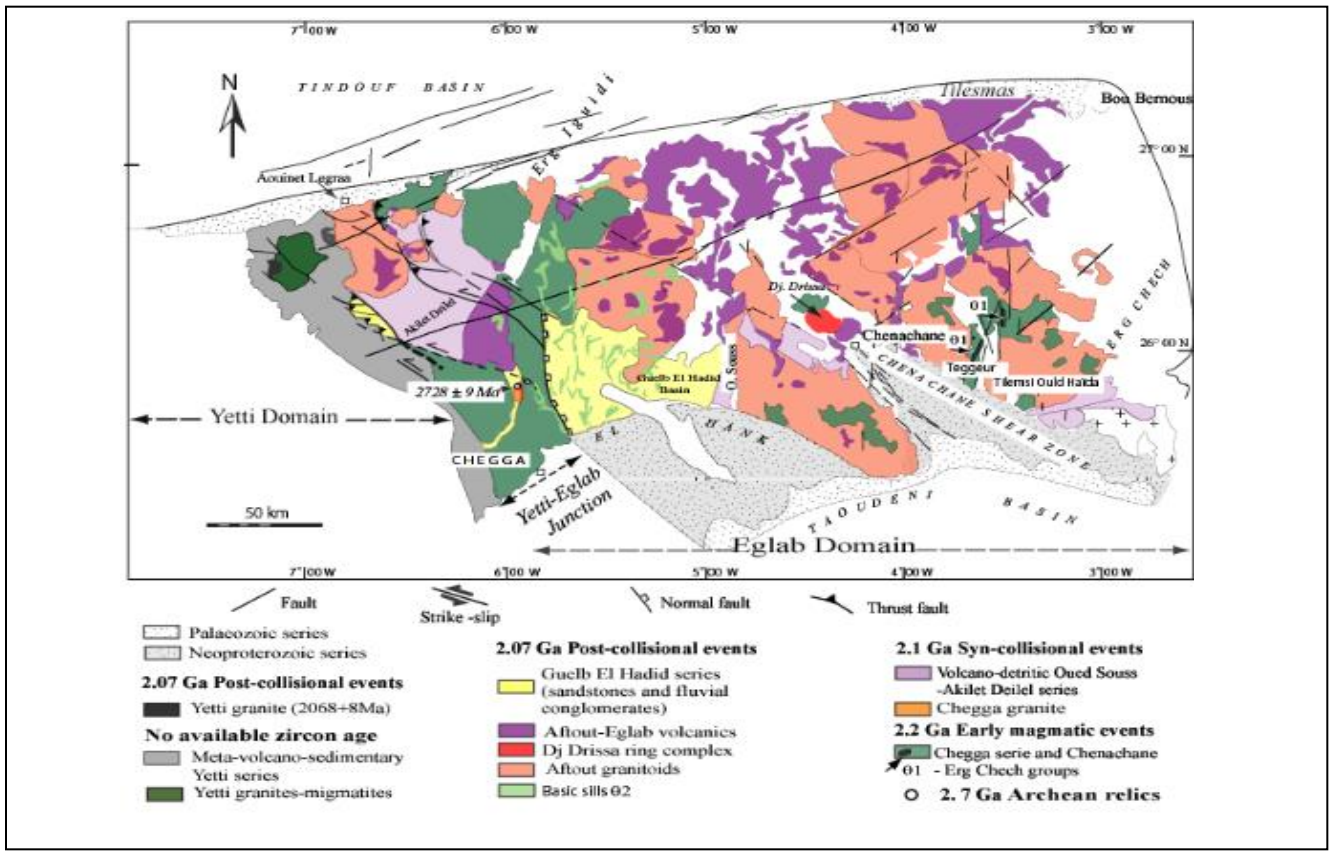


Fig.5: Geological sketch map of the Yetti-Eglab massif (Mahdjoub , 2007).

2.2.2 Upper units volcano-Sedimentary Sequences

The Paleoproterozoic supracrustal rocks comprise volcanic and sedimentary sequences that record the early stages of the Eburnean orogeny. These units include the ***Oued Souss*** serie dated around 2,086 Ga in the central and eastern Eglab and ***Akilet Deilel*** serie in the west, with volcaniclastic sediments, conglomerates, sandstones (Sabaté, 1978). The volcanic component includes both mafic and felsic varieties, with compositions ranging from basalt to rhyolite, indicating variable magmatic sources and tectonic settings. The volcano sedimentary sequences are typically metamorphosed to greenschist facies and exhibit variable degrees of deformation, from weakly foliated to intensely sheared (Peucat et al., 2005).

2.2.3 Magmatism

Based on recent geochronological and geochemical studies. The granitoid rocks dominate the Eglab massif, representing multiple episodes of magmatism spanning from approximately linked to the first stage (2.21 Ga) to the late stage (2.07 Ga) (Peucat et al., 2005). This magmatic activity is subdivided into three distinct magmatic stages:

- Early stage (2.21 – 2.18 Ga) : This stage is well represented by the ***Erg Chech series*** and the ***Chegga gneissic serie***. Corresponds to the formation of a metamorphosed batholith composed of juvenile calc-alkaline suites (tonalites, trondhjemites, granodiorites, and granites) in a mature island-arc setting.

- Second stage (ca. 2.09 Ga) : This stage corresponds to syntectonic ***the Chegga granite*** (sensu stricto) and intrusion located near the Yetti-Eglab jonction zone. Characterized by active-margin magmatic suites emplaced and deformed during syn-collisional tectonics.

- Late stage (ca. 2.07 Ga) : The ***Aftout and Eglab magmatic units*** cover two-thirds of the Eglab massif's surface area, are undeformed, and were emplaced after the folding and metamorphism of the Oued Souss series (Sabaté, 1978). These post-orogenic intrusions include high-K granites, syenogranites, and alkaline plutons that record the final stages of the Eburnean orogeny and the transition to cratonic stability (Peucat et al., 2005). The compositional evolution from calc-alkaline to alkaline magmatism reflects changing tectonic conditions and mantle sources, corresponds to the emplacement of voluminous post-orogenic high-K to anorogonic plutons (The Djebel Drissa massif) (Kahoui et al., 2004).

2.3 Structural Geology of the massif

The geological units display varying degrees of deformation, metamorphism, and alteration, recording a complex multi stage evolution spanning from the Archean to the late Paleoproterozoic (Peucat et al., 2005). According to the structural scheme proposed by SERMI (1965) and EREM (1983) (in, Benramdane, 2007):

- ✓ the Eglab domain is structured into three zones:
  - the eastern zone (Chenachane – Erg Chech) with relics of granito-gneissic basement, the area is characterized by the presence of lifted basement blocks, folded and faulted zones, and stable zones with late basins and post-Eburnean spurs,
  - (2) the central zone (Aftout – Eglab) dominated by granitoids and volcanites of the Aftout pluton,
  - (3) the western zone (Chegga – Iguidi) where older basement series are again dominant.

- ✓ The Yetti domain, in west shows two blocks:
  - Yetti Eastern block, with granitoïdes et volcanites of Paleoproterozoic ages,
  - Yetti-Karet western block, dominated by birimian volcanosedimentary series.

2.4 Metamorphism of the massif

In the Eglab massif contact metamorphism is locally developed around major intrusions, producing hornfels zones within the Yetti series. Migmatitic zones are also observed, particularly in the lower part of the Yetti series and the Chegga gneissic complex, although these are primarily related to regional metamorphism and crustal anataxis (Benramdane, 2007).

Until now the metamorphism is not completely studied yet. The metamorphic mineral assemblages (ranging from greenschist to amphibolite facies) provide important constraints on the pressure-temperature evolution and can be used to reconstruct the thermal structure of the Eburnean orogen (Peucat et al., 2005).

2.5 Sedimentary Cover

The remnants of sedimentary cover may locally overlie the crystalline basement, particularly along basin margins, though the Eglab massif itself primarily exposes Precambrian rocks called ***Guelb el Hadid serie*** (Buffière et al., 1965). The series is composed of two distinct sequences: (1) a lower volcano-detrital and conglomeratic sequence, locally intruded by Aftout granitoids, and (2) an upper discordant sequence dominated by arkosic sandstones, quartzites, and conglomerates rich in quartz pebbles. These deposits are preserved in small, isolated basins (Bled M'dena, Chegga, and Guelb el Hadid basins) (Buffière et al., 1965, in Benramdane, 2007). This serie corresponds to late- to post-orogenic epicontinental deposits of the Eburnean orogeny around 2.05 Ga.

A Neoproterozoic sedimentary cover (***Hank*** serie), slightly affected by Pan-African tectonics, is recognized only along the southern edge of the massif and his entire massif is surrounded by a Paleozoic sedimentary series that was structured during the Hercynian orogeny into broad synclines (Tindouf and Taoudeni). This cover was structured by tilted block faults, attributed to the back-effects of the Pan-African orogeny on the Eglab massif (after Bertrand-Sarfati et al., 1996 and Tokarski, 1991. The Pliocene and Quaternary deposits are represented respectively by the "***Hamada***" and by recent deposits, primarily the dune belts of the "***Ergs chech*** and ***Erg Iguidi***." in. Benramdane, 2007).

CHAPTER 3 : The overview of the mineralization in The Yetti-Eglab Shear Zone (Y-ESZ)

3.1 Introduction

The Eglab massif hosts various types of mineral occurrences, including porphyry-style deposits, orogenic gold systems, and rare metal mineralizations associated with specialized granites (BIA, 1960 , SERMI,1965, EREM,1983 et ORGM 2002). It is noted that after each prospecting campaign, new gold occurrences are revealed (Fig. 6). Porphyry Molybdenum-copper is recognized in annular Bled M'Dena structure (Lagraa and al, 2017). The mineralization is hosted in quartz-monzodiorite and granodiorite facies occurring mostly in quartz + molybdenite + chalcopyrite stockwork veins marked by widespread propylitic alteration along the selvages (Lagraa et al., 2014). Other occurrences (indices and mineralized points) and other new substances (Ag, W, Ti, Hg, Zr, REE, Nb, and Y) were highlighted in the Central and East Eglab during various campaigns conducted by EREM in the 1980s (EREM, 1983) (in. Benramdane, 2007). These occurrences, however, remain poorly or not studied to be classified and to establish a typology of deposits for this massif. Recently, a campaign (1999–2000) conducted by ORGM on the search for paleo-placer type gold in the Guelb el Hadid series in the Central Eglab was less satisfactory (ORGM, 2002, in Benramdane, 2007).

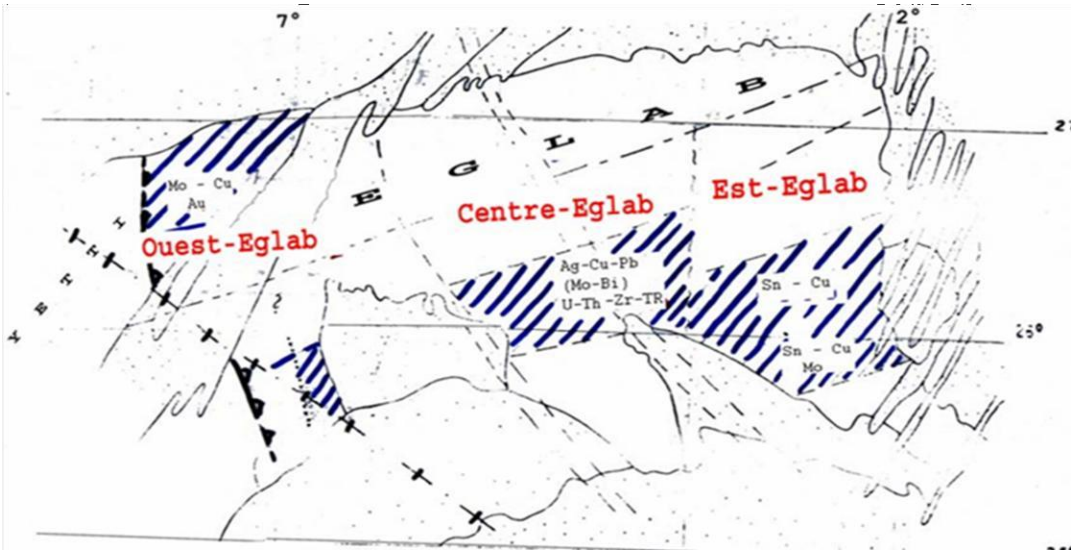


Fig.6: Main metalliferous potential zones of the Eglab domain, (EREM, 1983 and Benramdane, 2007)

East-Eglab zone (Tilemsi Ould Haida - North Kahal Morrat): Sn-Cu-Mo

Central-Eglab zone (Hamada Sefra and North-East Eglab Salem): Ag-Cu-Pb (Mo-Bi) and U-Th-Zr-TR

West-Eglab zone (Chegga - Bled M'Dena): Mo-Cu and Au

The most prominent structural feature is the Yetti-Eglab shear zone (Y-ESZ) (Fig.7) which corresponds to the junction zone between the two domains. This shear zone is framed by two principal mylonitic faults: First is the Chegga mylonitic fault, with a submeridian orientation passing near the 6°W meridian, and second is the Arieguet Lemha – M'dena el Kahla mylonitic fault, oriented NW-SE passing through the 7°15'W meridian (Benramdane, 2007). The Y-ESZ affects two distinct areas :

- ✓ To the East (Eglab domain) : The volcano-sedimentary alternations of the Akilet Deilel series are monoclinal, with submeridian orientation (N10 to 20°) to the south, these alternations continue with a slight flexure to the east (ESE – WNW) the dip is variable, subvertical (85°) near the contact zone and low (15° to 30°) toward the Iguidi.
- ✓ To the West (Yetti domain) : The deformation of the volcano-detrital complex of the Yetti series shows tight, upright folds oriented N140° to N160° with plunging axes; the stretching lineation is sub-parallel to the fold axes; the complex is strongly schistosed along a N150° direction with dip ranging from low (25°) to steep (80°) eastward, and locally westward.

The fault zone corresponds to a band of hectometric width, materialized by a major NW-SE (N320° to N340°) to NNW-SSE trending shear fault, by a N-S lineation, and by discontinuous volcanic dykes that are strongly sheared together with quartz veins. Sub-latitudinal faults (N60° to 90°) are late. Observations made in the southern part of this zone (in Arieguet Lemha sector) indicate that the fault functioned late as a dextral strike-slip fault, with opening of mega-tension gashes and emplacement of a granodiorite sill and acid to basic dykes (Benramdane, 2007).

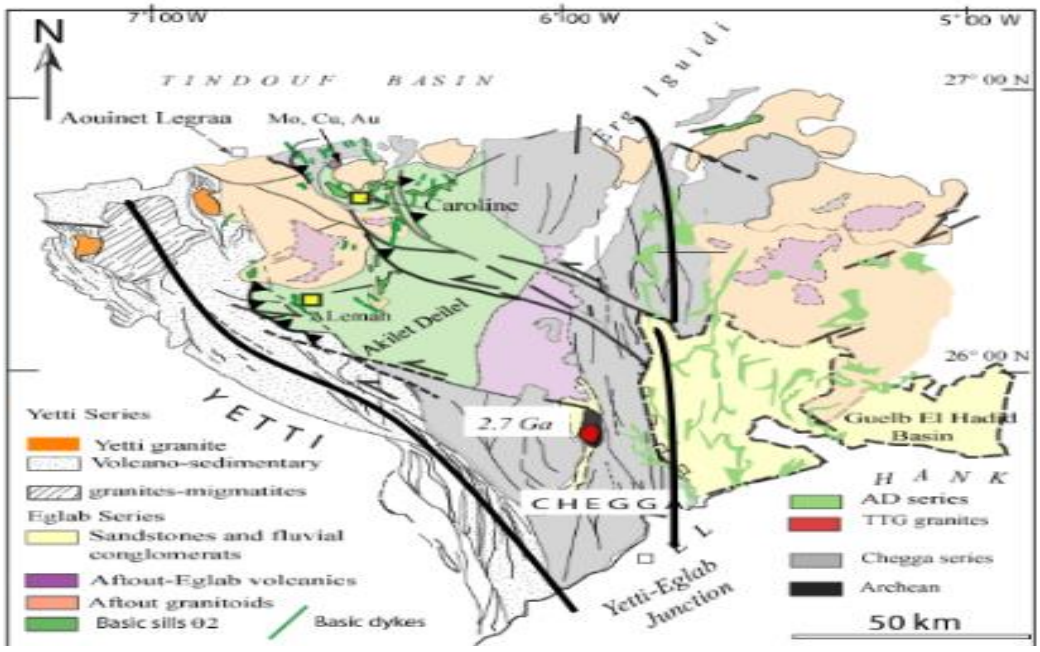


Fig.7: Geological sketch map of Yetti-Eglab junction zone (Mahdjoub & Kahoui, 2007)

This structural framework exerted primary control on the distribution of hydrothermal alteration and mineralization by focusing fluid flow and creating sites of favorable pressure-temperature conditions for ore deposition (Benramdane, 2007).

This shear zone is particularly interesting due to the presence of sulphide and gold occurrences and hydrothermal alterations that related to our objective.

3.2 Gold Mineralization in the Akilet Deilel Occurrence

Concerning the gold potential of the Yetti-Eglab massif, the "***Caroline***" gold is the first gold occurrence discovered by the BIA (1960); it is located 50 km northeast of Laouinat Oasis and shows quite interesting grades (11.7 g/t Au and 9 g/t Ag) (BIA, 1960 (in, Benramdane, 2007).

Some characteristics of mineralization are distinguished from two types of gold mineralization Benramdane (2007) (Fig. 7):

- The first is vein-type mineralization, associated with quartz veins located along the Arieguet Lemha – M'dena el Kahla fault. These veins are discontinuous, with centimeter to decimeter thickness.
- The second is disseminated mineralization, associated with pyroclastic and volcano-detrital levels of the Akilet Deilel series, where pyrite and chalcopyrite are disseminated in the matrix.

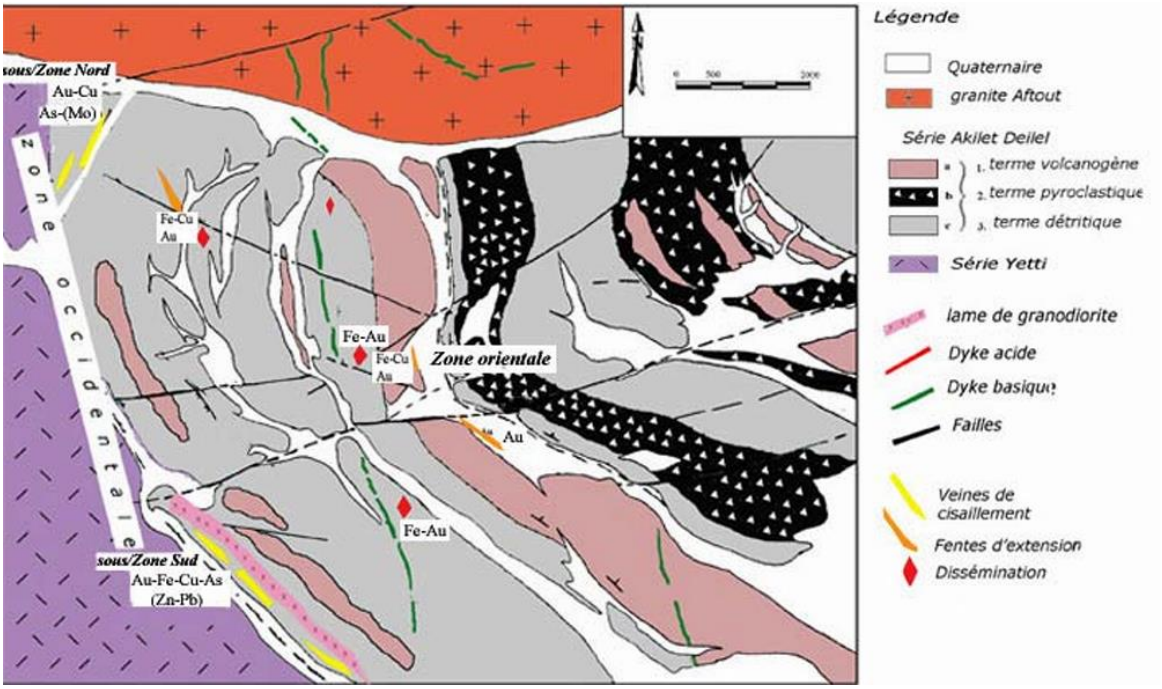


Fig.8:Geological map of the Akilet Deilel gold occurrence (modified and completed after Benramdane et al., 2001)



Fig.9: 2 subparallel veins gold bearing quartz hosted in Upper part of Yetti serie (Benramdane, 2007);

• N35° - 50°NW

•L: X 100m l: 0,2m (max 0,5m)



Fig.10: Highly disturbed mineralized quartz vein, with a general orientation of N140° (view towards the NNW) (Benramdane, 2007)



Fig.11: Coarse level or passage



Fig.12: White milky quartz with iron hydroxides,
sulphides and native gold.



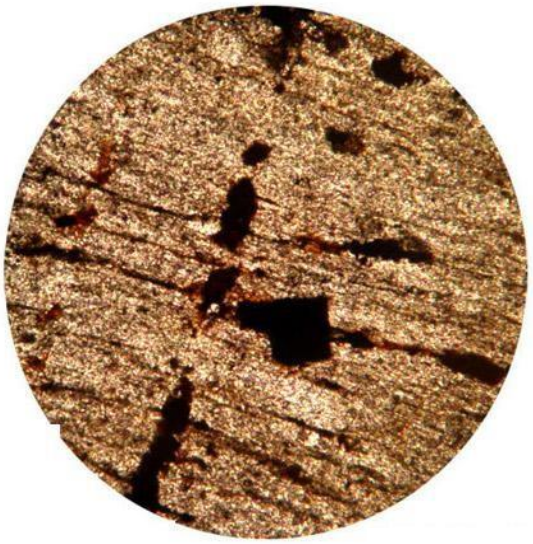
Fig.13: Polished section in binocular observation quartz veinlet with sulphides (pyrite, chalcopyrite), native gold, iron hydroxides and malachite.

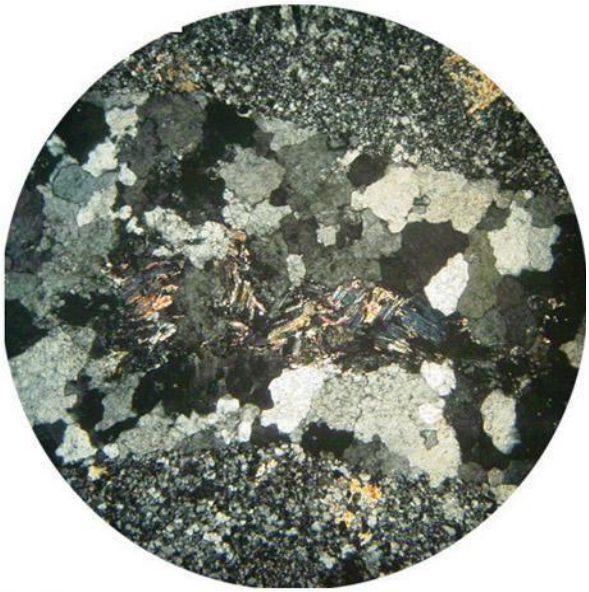


Fig.14:Metasomatite

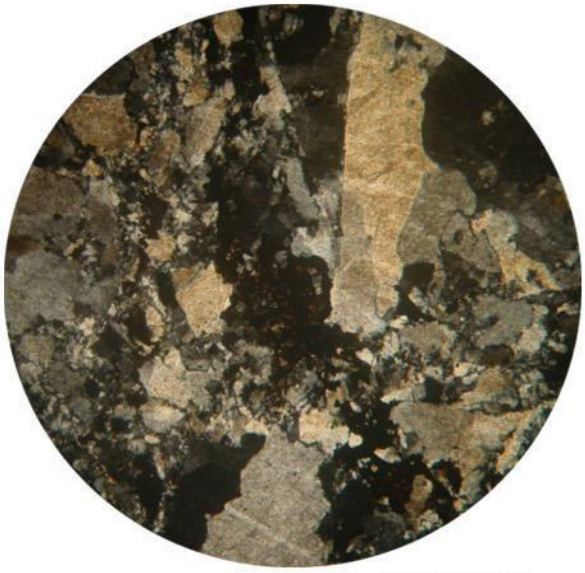
The ore mineral of assemblage of Akilet Deilel documented by Benramdane (2007) includes native gold, chalcopyrite, pyrite, galena, arsenopyrite, sphalerite, tetrahedrite (copper-grey), pyrrhotite, chalcocite, and covellite, hosted in a quartz gangue with secondary carbonates, sericite, chlorite, and epidote (Plate 1,2 and 3).

A).Opaque minerals superimposed on schistosity planes and filling veinlets. (PPL, 5x)



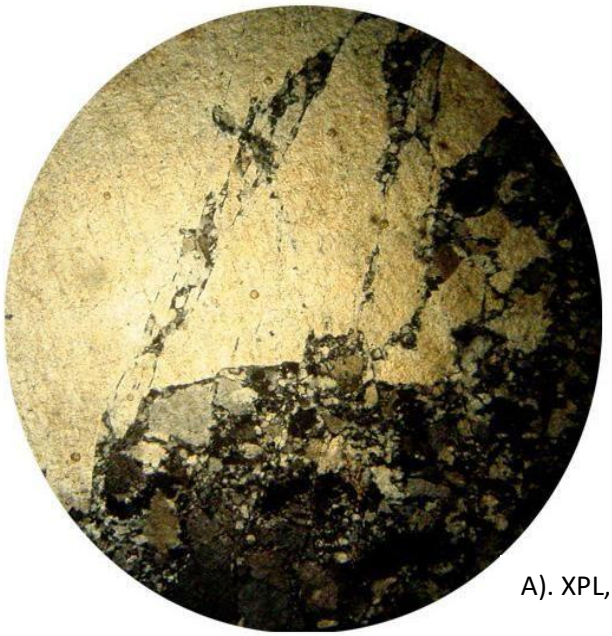


B).Microcrystalline quartz veinlets, phyllites, and opaque minerals cutting across the quartzitic facies. (XPL, 10x)

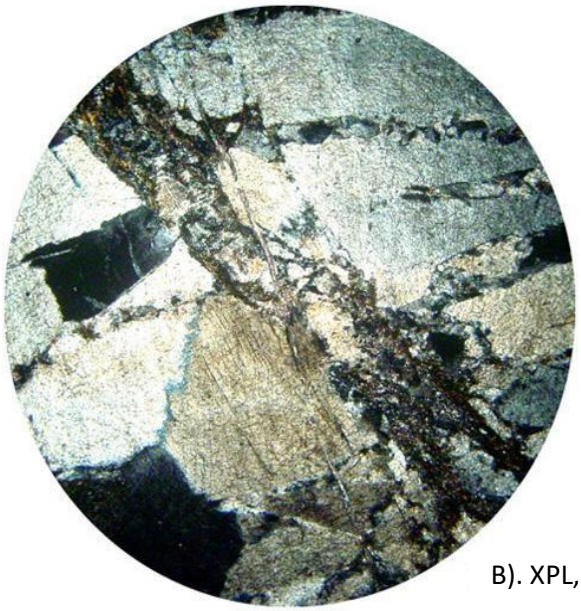


C). Microcrystalline quartz with infillings of opaque minerals and iron oxides. (XPL, 5x)

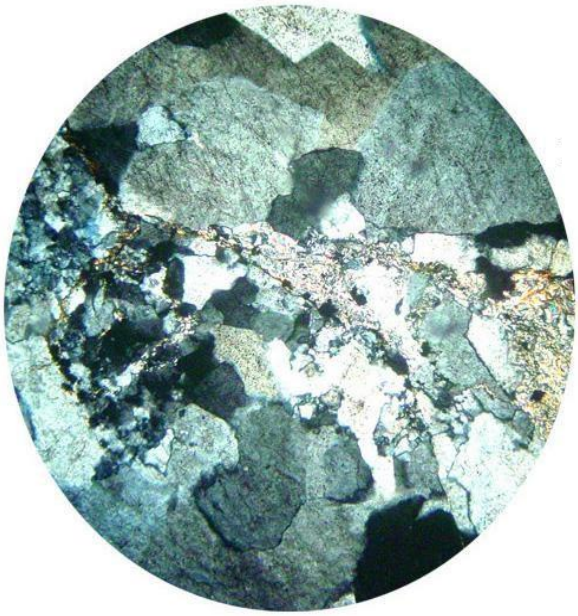
Plate 01: Opaque minerals are localized along schistosity planes and as fillings in veinlets and small veins; facies with quartzites and gravelites of the Yetti Series. (Benramdane, 2007)



A). XPL, 10x

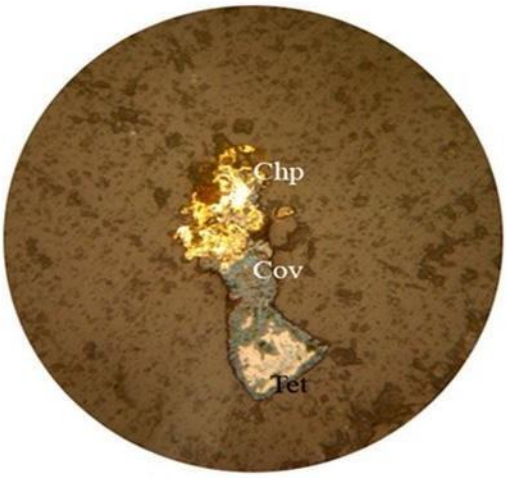


B). XPL, 5x

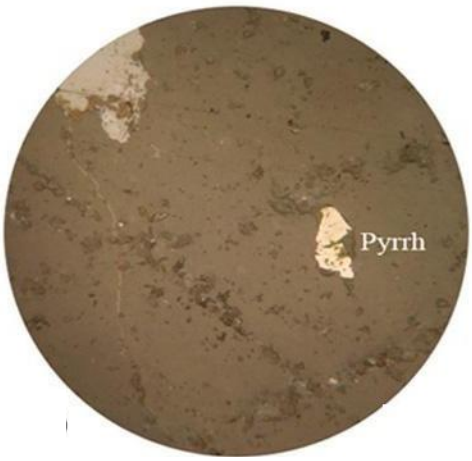


C). Opaque minerals associated with microcrystalline quartz and calcite fill veinlets and small veins, which are themselves hosted within veins containing coarse quartz crystals. (XPL, 5x)

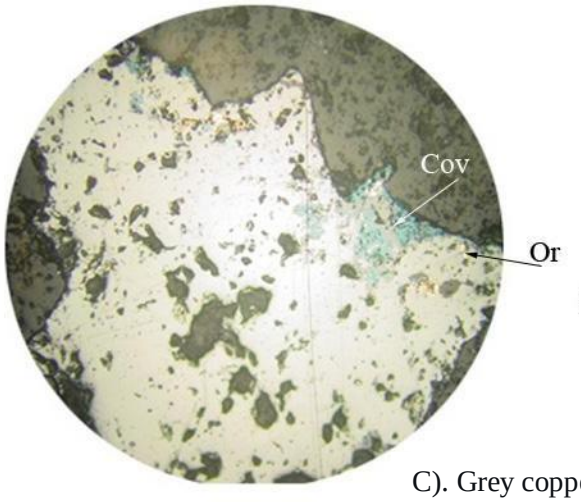
Plate 2: Opaque minerals associated with microcrystalline quartz and calcite fill veinlets and small veins, which are themselves hosted within veins containing coarse quartz crystals. (Benramdane, 2007)

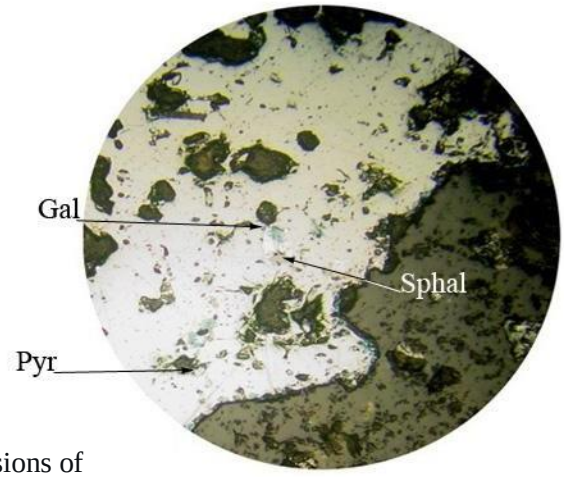


A).Chalcopyrite, the main sulfide observed. (PPL, 20x)



B).Slightly altered pyrrhotite aggregate with concentric structure. (PPL, 20x)





C). Grey copper with inclusions of sphalerite, galena, pyrite, and gold. (PPL, 20x)

Plate 3: Nature of the intermineral relationships observed in the vein-type mineralization. (Benramdane, 2007)

3.2.2 Paragenetic succession

In the Akilet Deilel gold occurrence within the Yetti-Eglab shear zone (ZCY-E), the paragenetic succession is characterized by a well-defined sequence based on macroscopic and microscopic observations. The succession includes (Benramdane, 2007) (Table 01):

- Early barren stage: Deposition of coarse-grained, sterile quartz (QI) following initial fracturing.

- Pre-mineralization stage: Continued fracturing leads to deposition of microcrystalline quartz and chalcedony.

- Main mineralization stage: Deposition of sulfides including pyrrhotite, pyrite, and arsenopyrite (mispickel). Subsequent tectonic fracturing brecciated these early sulfides.

- Late gold stage: Native gold fills microfractures within brecciated arsenopyrite and galena and is also observed as inclusions in chalcopyrite and galena, indicating a late timing for gold precipitation relative to the main sulfide assemblage.

- Supergene stage: Well-developed supergene alteration produced iron and copper hydroxides (goethite, hematite, malachite, covellite), with gold observed in association with these secondary oxides, suggesting secondary supergene gold enrichment.

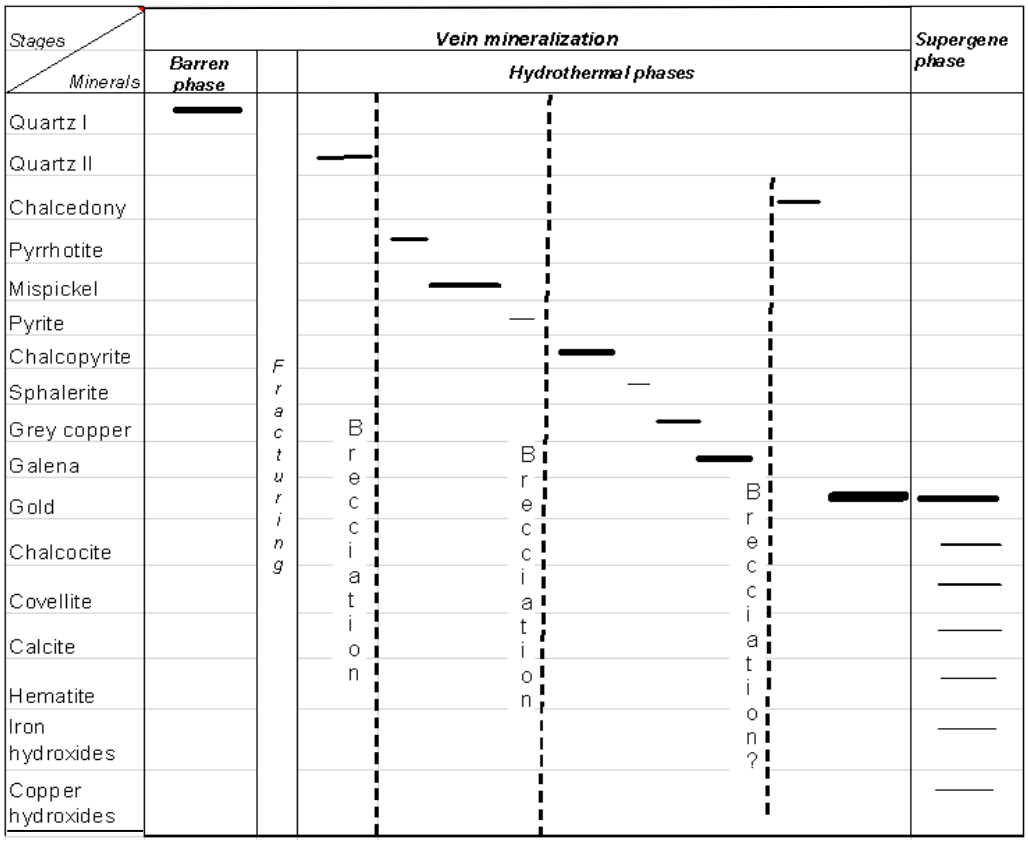


Table 01: Probable paragenetic succession of the vein-type mineralization of the Akilet Deilel occurrence (in Benremdane, 2007)

Gold grades range from 0.4 to 74 g/t Au in surface samples, with a maximum of 311 g/t Au in quartz veins, decreasing to approximately 1.5 g/t Au at depth, suggesting significant supergene enrichment (Benramdane, 2007).

According to ORGM datas (2002), the grades on quartz are greater than 5 g/t Au, while the immediate pyroclastic host rock with quartz veinlets yields low grades of about 1.2 g/t (exceptionally 2 g/t). At depth, grades vary from 1 to 5 g/t in quartz and are less than 0.6 g/t in the host rock (in. Benramdane, 2007).

3.3 Petrographic Study

Our microscopic study was carried out on several thin sections to identify and describe the minerals and also to try to highlight the petrology of the different facies present in our study area. We identified three facies: conglomerate (metagreywacke), quartzite (metaquartzite)and epiclastites , and metasomatite.

3.3.1 Conglomerate facies:

The conglomerate exhibits dark and light gray colors. It contains black grains with alteration products (pyrite, hematite) and metallic luster grains that are subrounded. A large crack filled with gray minerals is also observed.

There are two types of metaquartzite. The rock contains xenomorphic mineral grains, as well as others that are sub-automorphic, with jointed (interlocking) grain boundaries. The cement is argillaceous. Plagioclase mineral grains of heterogeneous size are observed.

Regarding opaque minerals, isolated grains and sometimes aggregates are observed. Rock fragments (metagreywacke) and mineral grains (quartz and plagioclase) are more or less altered.

For the first type of opaque minerals, they are isolated, subrounded in shape, and jointed with other minerals, cross-cut by Vein 1 and Vein 2.

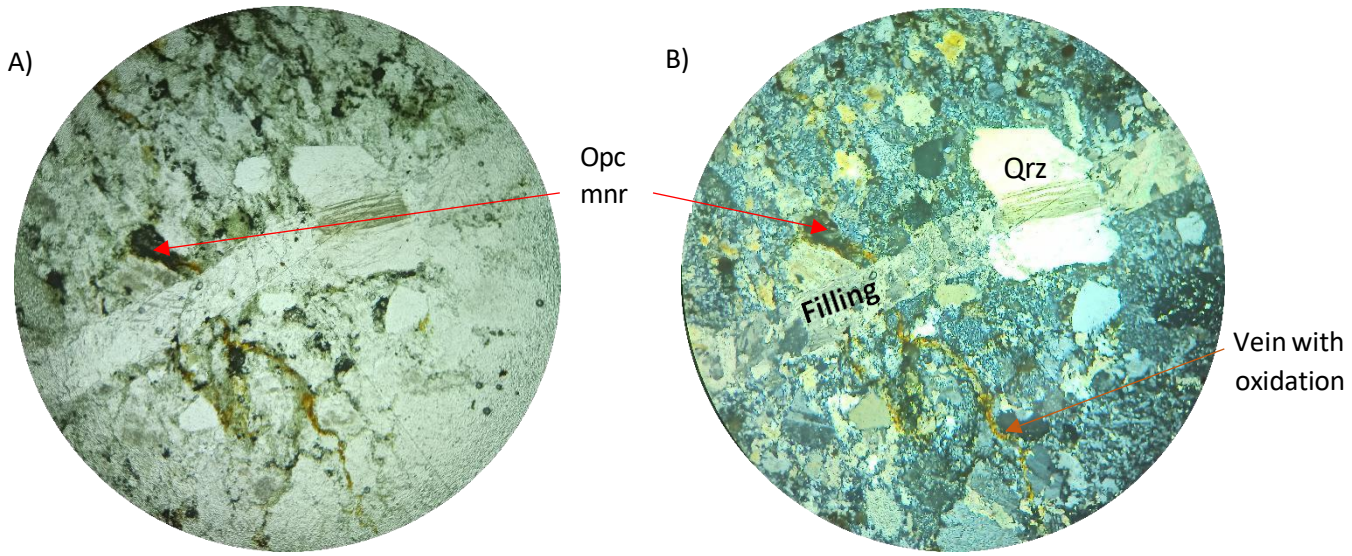


Fig.15:Sample (Y5) PPL (A) and XPL (B) , Mag : X10 : It shows a carbonate filling cross-cutting quartz grains, with varying quartz grain sizes and vein contain oxidation with red color.

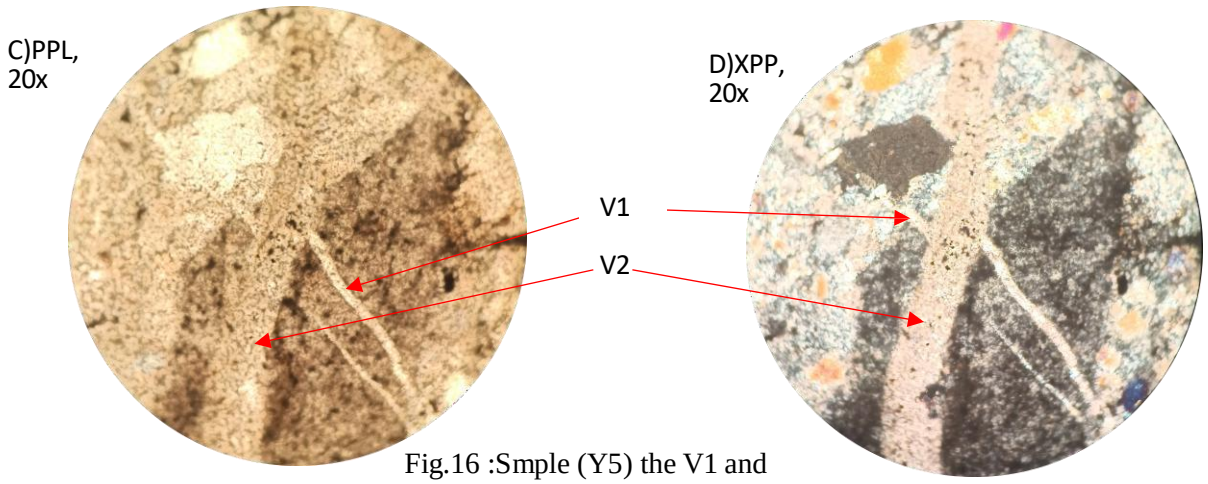


Fig.16 :Smple (Y5) the V1 and V2 are well identified in (C) and (D)

The second type of opaque minerals occurs within the veinlets. There are two types of veinlets:

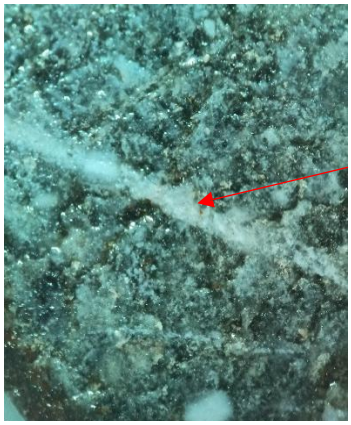
- V1: Carbonate veinlet, crystallized, with opaque minerals that are sometimes automorphic in size.
- V2: Veinlet filling with very small opaque crystals. V2 cross-cuts V1.

Regarding hydrothermal alteration, carbonatization and sericitization are visible within the veinlet fillings.

Another type of samples consists of epiclastic samples, with rock fragments (schist, quartzite, and trachyte) and debris of very angular minerals, including microcline, orthoclase, and opaque minerals (pyrite, chalcopyrite). The sample contains transparent quartz with a rose color, probably feldspar. Chalcopyrite (yellow white) and pyrite (more or less altered) are present. Soluble metallic minerals are observed within the matrix.

The conglomerate exhibits dark and light gray colors. It contains black grains with alteration products (pyrite, hematite) and metallic luster grains that are subrounded. A large crack filled with gray minerals is also observed.





A fracture that cross-cuts filling of Quartz

Fig. 17: showing different type of filling veins from sample Y5

The rock is mostly similar to Y5 but with less fracturation and vein filling. The sample contains transparent quartz with a rose color, probably feldspar. Chalcopyrite (white) and pyrite (more or less altered) are present. Soluble metallic minerals are observed within the matrix.



Fig.18: Binocular, chalcopyrite is observed, associated with malachite and oxidation. The rock contains rock grains black and white.
The cement contains different minerals like chlorite, epidots and calcite associated with iron oxidation.

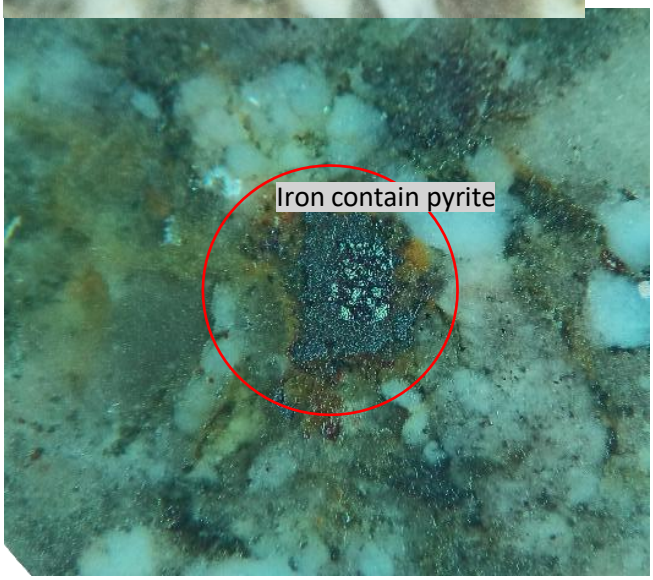
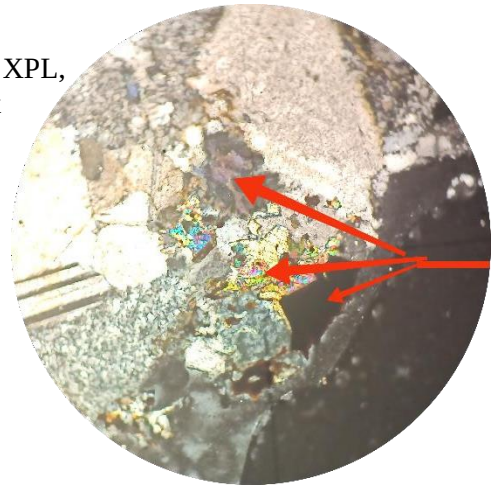


Fig.19: Binocular photo from sample 103

However, this sample contains epidote and very strong chloritization, with chlorite sometimes forming aggregates. Opaque minerals are associated with chlorite, not in fractures this time. This sample also contains a lot of plagioclase feldspaths and rock fragments that contain quartz. The presence of the feldsphar probably indicates an potassic sodic hydrothermal alteration but its still not enough to say that. Some sericite is present inside quartz grains.

A). XPL, 20x



B). PPL, 20x

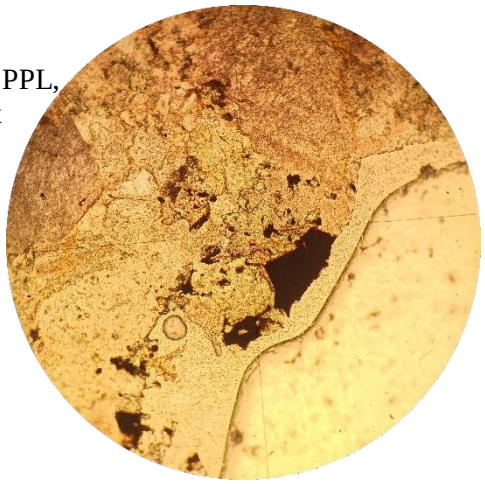


Fig.20 : From the sample 103 automorphic opaque minerals associated with epidote showing bright colors in XPL. Elongated aggregates of chlorite are also observed.

The third type of rock studied is compose of white quartz with subrounded grains. Some of these grains show different colors, such as white and brown (probably feldspar). Some grains have a metallic luster and are also subrounded. Some grains are located within cracks, while other cracks remain empty.



Photo.21 :the quartz fracture is typically conchoidal with smooth surfaces.



Fig.22:sample PW21-5 showing quartz grains

In the greywacke, the quartz veins are present. Under microscopic examination, the greywacke exhibits a polygenic texture with very tightly cemented grains. The intergranular spaces are filled with opaque minerals and iron oxides. Fractures observed in the rock show various infillings: some palissadic quartz Q1, others with calcite, and still others with (microcrystalline quartz Q2/chalcedony Q3).

The grain size is fine to medium, and the rock is relatively homogeneous. The main characteristic is the presence of microcrystalline quartz, which is elongated and interlocking. Quartz itself serves as both the main mineral and the cement. (Fig.23)

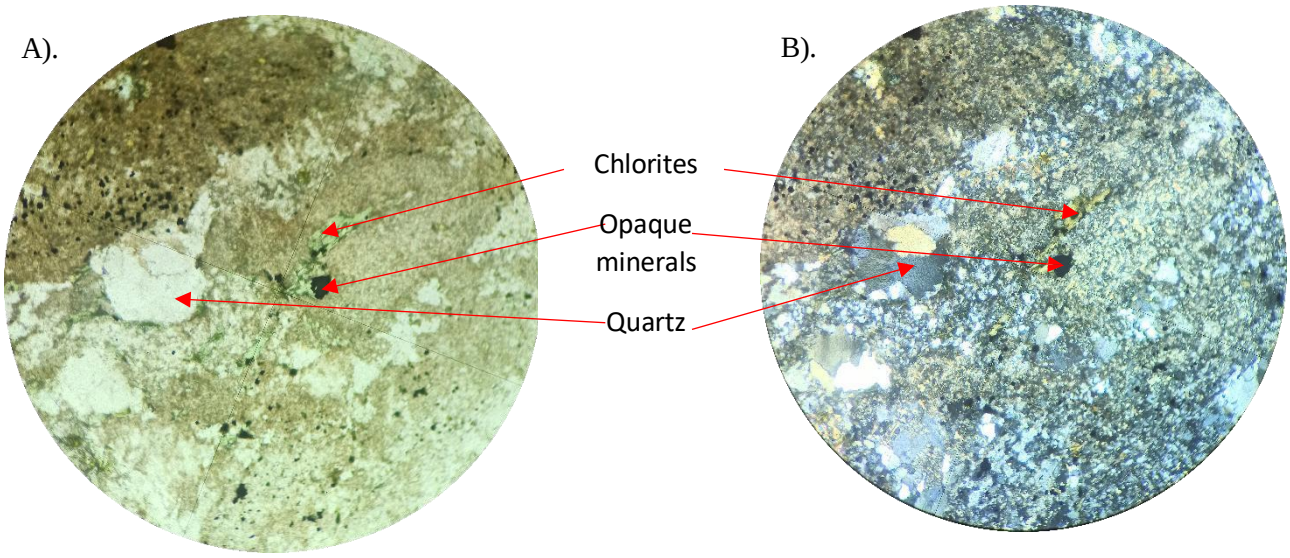


Fig.23 : Sample P21-5 in PPL (A) and XPL (B) with M: 10x

Opaque minerals are small and generally jointed (interlocked) with rock fragments and quartz grains. The cement is fine, automorphic silica, sometimes forming aggregates, with a weak concentration of chloritization, occasionally associated with opaque minerals.

3.3.3 Quartz vein gold facies:

The rock is composed of white quartz, sometimes appearing brown due to water movement. This quartz contains microcracks; some of them are filled with black grains, while others are brown due to the oxidation of metallic elements. Some cracks contain small amounts of gold grains. Several of these cracks cut across each other in different patterns. (Fig.24)

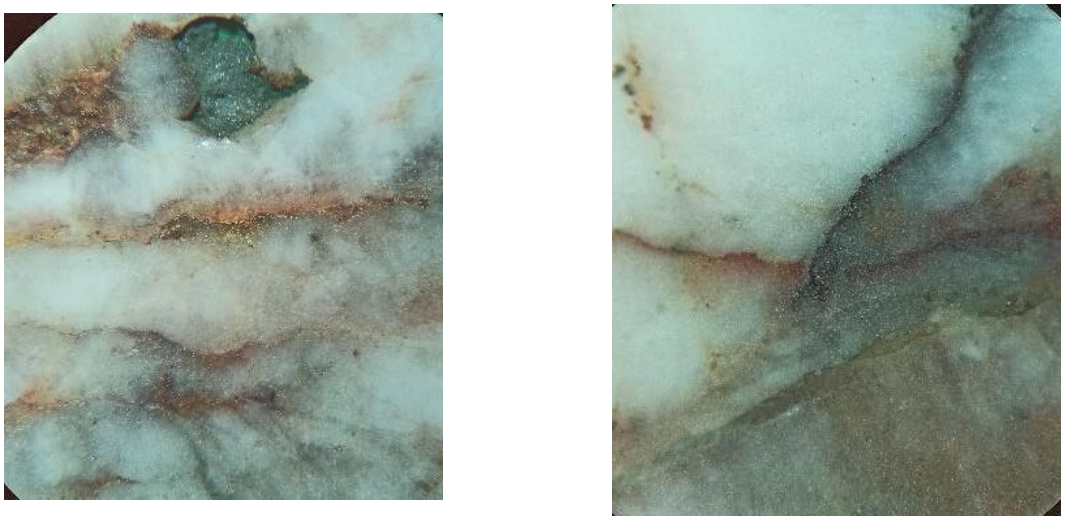


Fig. 24: Sample P35-4 showing quartz with micro fractures contain some gold grain and some copper in cavity (M: 2x)

The sample is composed of white quartz with metallic luster grains. Some cracks are filled with oxidation. One crack cuts across the fault and cavities. Some cavities are filled with grains of metallic luster, while others are empty. (Fig.25)

Under the metallographic microscope, chalcopyrite is observed to be replaced by covellite and chalcocite.

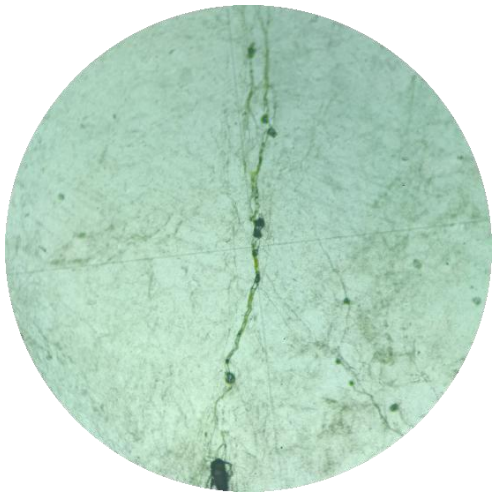




Fig. 25: Sample P7 shows quartz with some gold grains (M :2x)

In the microscope observation the texture is microcrystalline, with quartz grain size ranging from medium to coarse, and there are microfractures filled by dark minerals. Regarding the cement, quartz is both the main mineral and the cement. For alteration, there is silicification and traces of sericite.

A). PPL, 5x



B). XPL, 5x

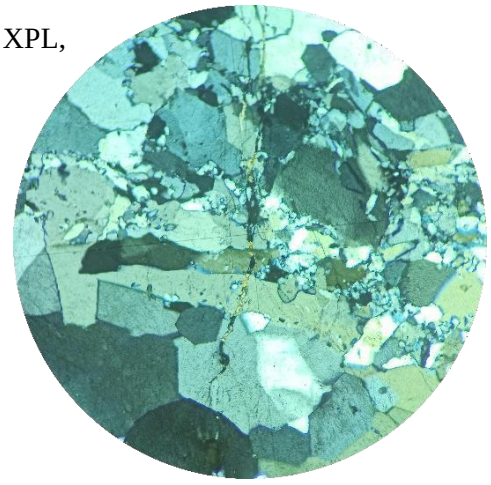


Fig.26 : Sample P-7 micro fractures filled by dark minerals; Q1→Q2→Q3 with opaque-filled spaces (A) with brecciated texture; angular fragments cemented by recrystallized quartz (B)

Sample P7 shows automorphic pyrite crystals and galena corroded by sericite, with gold and quartz filling the fractures. There may be quartz minerals that accumulated in the same position; they might be different from each other (three different types): Q1, then Q2, then Q3, which are associated with opaque minerals that fill the space (Fig.26). Opaque minerals are large in the fractures and small in other places, with xenomorphic shapes and this might indicate there is 2 types of opaques.

Second studied with the naked eye, the sample shows quartz with disseminated gold grains and iron oxides. The sample is a fine, compact quartz vein filled with opaque minerals or metallic oxidation. These are likely to represent different generations, which can be confirmed later.



Fig.27:The rock is composed of fine compact quartz, cross-cut by veins. One vein is filled with iron, showing a red color, and another vein has a different filling.

The texture is brecciated with coarse, automorphic crystals. There are angular rock fragments embedded in finer material. The grain size is very heterogeneous, and the fragments vary in size. There are microveins that cut across the rock that indicates that the rock was crushed by a fault or shear zone

Zones of recrystallized quartz are observed, which contrast with the darker alteration zones. The cement is a mixture of crushed rock fragments and quartz minerals that cemented the fragments after the fracture event. The small quartz crystals are chalcedony, associated with veinlets filled with opaque minerals and clay minerals.

A). PPL, 20x

B). XPL, 20x

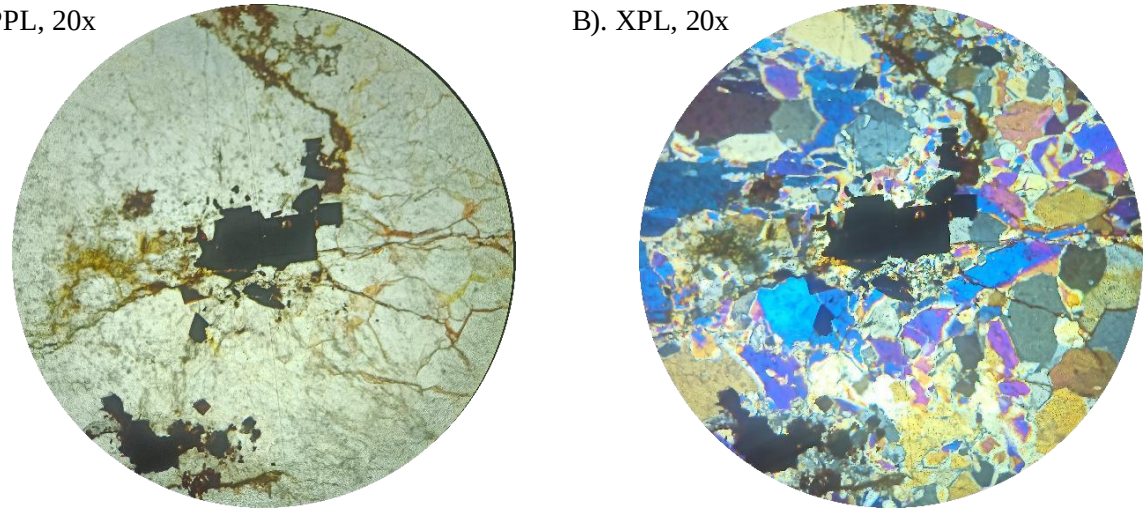


Fig.28 : Sample P-7 shown a different type of quartz with different opaque minerals forming an aggregate

In thin section, this mineral is associated with chlorite and sericite, which indicates silicification and propylitic or sericitic alteration types**.**Sericite is present, sometimes jointed (interlocked) with opaque minerals or within the fractures. Opaque minerals are jointed with quartz minerals or occur within veinlets, sometimes showing oxidation.

The large (Q1) crystals are crosscut by microfractures filled with microcrystalline quartz (Q2), while others are filled with calcite and opaque minerals.

Another studied the sample is composed of detrital quartz with a white color and subrounded form. Small cracks are present; some of them are filled with sodic feldspar (albite) and gray copper with carbonate. There is also a pyrite crystal with a lustrous grain.

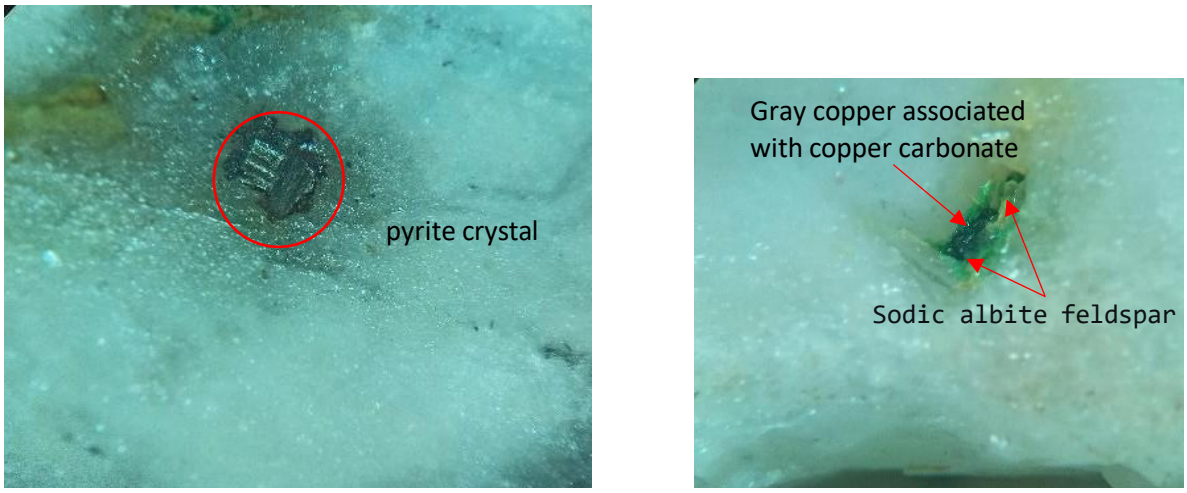


Fig.29 : Sample 21-3 shows white quartz with pyrite cristal and and some gray copper associated with copper carbonate and sodic albite feldspar (M:4)

In microscope there are large, xenomorphic quartz crystals. The cement is quartz, which is the major constituent. There is filling of chalcedony or epidote. Hydrothermal alteration is characterized by intense silicification and sodic alteration, accompanied by minor epidote mineralization. The epidote occurs as brightly colored crystals within the interstitial spaces of certain quartz grains. There are three types of quartz and one type of fracture:

- **Q1:** Large, xenomorphic crystals with undulatory extinction.
- **Q2:** Crystals, sometimes large, automorphic.
- **F:** Fracture with fine
- **Q3:** Microcrystals (chalcedony) that cement the fractures.

Opaque minerals are sometimes rounded and sometimes appear as spots. There are also other green spots, probably malachite issue from copper sulphide , sometimes associated with opaque minerals in the form of spots.

3.3.4 Metasomatite facies:

The rock is brown-yellow in color, with black and white quartz grains trapped within microcracks.

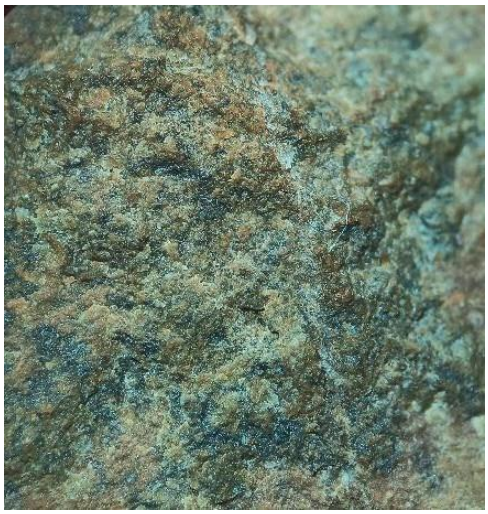
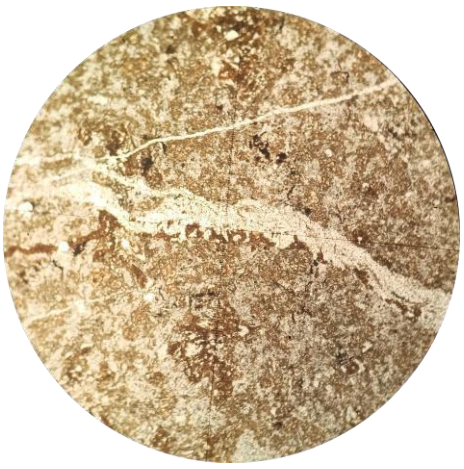


Fig.30: There are opaque minerals in patches, probably sericite, and green spots with opaque minerals forming aggregates or isolated grains, in square or sub-square shapes, of small size.

A). PPL, 20x



B). XPL, 20x

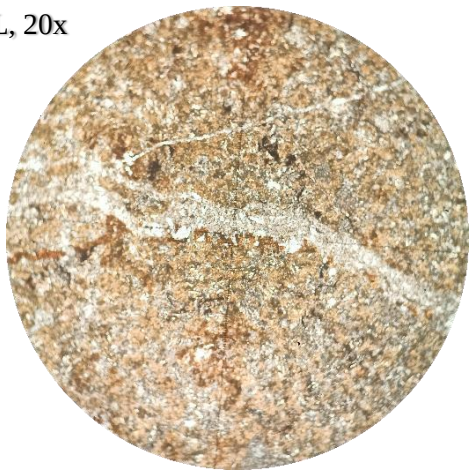


Fig.31 : 2 different veins one contain carbonates and cross-cut another vein contain opaque minerals .

CHAPTER 04: Hydrothermal alteration

4.1 Introduction

The main objective is trying to characterize the hydrothermal alteration associated to orogenic-type gold mineralization. Our work in mineralogy involves the study of the ore mineralogical composition (sulphides and gold) and associated alteration minerals. Why? Because hydrothermal alteration is a direct guide in prospecting. Therefore, it helps to guide exploration work.

Hydrothermal alteration is a change in the mineralogy of a rock resulting from the interaction of the rock with hot water fluids, called "hydrothermal fluids". These fluids carry metals in solution, either from a nearby igneous source or from leaching of surrounding rocks. The old minerals are replaced by new ones due to changes in temperature, pressure, or chemical conditions, or any combination of these factors .

Hydrothermal alteration is a common phenomenon in a wide variety of geologic environments, including fault zones and volcanic structures. The fluids cause alteration by passing through rocks and changing their composition by adding, removing, or redistributing components. Temperatures can range from weakly elevated to boiling. Fluid composition is extremely variable and may contain various gases, salts, water, and metals. The metals are carried as different complexes, primarily involving sulfur and chlorine.

There are three main sources of hydrothermal fluids:

1. **Magmatic rocks** – Water (called "juvenile" water) is released during the final stages of cooling.
2. **Metamorphic terrains** – Dehydration reactions during metamorphism release water that circulates and transports metals.
3. **Near-surface groundwater** – "Meteoric" water may mix with juvenile or metamorphic waters during late stages of mineralization .

Hydrothermal fluids in plutonic settings circulate along large-scale convective paths, similar to a pot of boiling water: hottest water rises above the heat source (ex: magma), changes to horizontal flow at the surface, and then descends along the sides. Fluids also circulate along fractures and faults, which serve as excellent pathways for mineralization. Fault zones, in particular, are ideal for fluid circulation and precipitation of minerals.

In gold case, the ore-forming fluids with gold mainly transported in solution as Au-Cl and Au-S complexes (Phillips & Powell, 2010). Changes in physicochemical conditions such as temperature, pressure, oxygen fugacity, and sulfur fugacity serve as effective mechanisms for gold precipitation (Robert & Brown, 1986).

4.2 Alteration types and their Characteristics

Hydrothermal alteration assemblages vary depending on the deposit type and the nature of the host rocks. The mineral assemblages formed during hydrothermal alteration reflect the geochemical composition of the ore-forming fluids. The most commonly described alteration types include the following.

- ✓ **Propylitic alteration** is characterized by the formation of chlorite, epidote, and actinolite, typically turning rocks green. This alteration results from the decomposition of iron-magnesium minerals and generally occurs at relatively low temperatures in distal settings away from the main fluid conduit.
- ✓ **Sericitic alteration** consists of fine-grained white mica (sericite) that forms through the decomposition of feldspars under low pH acidic conditions. Rocks affected by this alteration type become soft and easily scratchable.
- ✓ **Potassic alteration** is a high-temperature alteration type characterized by biotite, potassium feldspar, and adularia. It results from potassium enrichment and can occur in both deep plutonic and shallow volcanic environments.
- ✓ **Silicification** involves the addition of secondary silica in the form of quartz, microcrystalline quartz, or chalcedony. This alteration manifests as silica flooding or stockwork veining and can develop over a wide temperature range.
- ✓ **Carbonatization** is marked by the addition of carbonate minerals such as calcite, ankerite, and dolomite. This alteration type is often associated with talc, chlorite, sericite, and albite.

Oxidation occurs in surface or near-surface environments where atmospheric oxygen is readily available. It is characterized by hematite and limonite (iron oxides) and results from the oxidation and replacement of sulphides by iron oxides.

Alteration zoning can occur in many geometric forms, ranging from concentric shells to linear forms to irregular patterns.

The first form is in porphyry copper deposits characterized by concentric shell-shaped zones:

- **Core:** Potassic alteration (K-feldspar, biotite)
- **Intermediate:** Phyllitic alteration (quartz, sericite, pyrite)
- **Outer:** Propylitic alteration (chlorite, epidote, carbonate)

The second form is vein mineralization deposits associated with faults and fractures have linear zones parallel to the structure.

Alteration can be mapped graphically using patterns or colors. The primary characteristics to note are:

- **Alteration mineralogy** – the minerals present based on research microscopic and chemical analyses (Identification of mineral progenies => alteration types (look at the table above)
- **Style** – disseminated, massive, or veinlet-controlled
- **Intensity** – incipient (weak) to pervasive (strong)

Alteration mapping serves as a valuable tool for identifying prospective mineralized zones and directing exploration efforts, through comparison with established alteration zoning patterns of known deposits.

For orogenic gold type, there is 3 types hydrothermal alteration that well known :

- Carbonatization
- Potassic alteration
- Sodic alteration

4.3 Hydrothermal Alteration in the Studied Samples

Based on integrated macroscopic and microscopic observations of samples from the Akilet Deilel occurrence, three main facies were identified: **conglomerate (metagreywacke), quartz veins, and metasomatite**. These facies record a complex, multi-stage hydrothermal history structurally controlled by the Yetti-Eglab Shear Zone.

1.1 Alteration Assemblages by Facies

4.3.1 Conglomerate Facies (Samples Y5, 103, 21/5)

Macroscopically, this facies shows dark to light gray colors with subrounded metallic-luster grains and black alteration products (pyrite, hematite). Large cracks are filled with gray minerals. Microscopically, the rock displays xenomorphic to sub-automorphic mineral grains with interlocking boundaries and argillaceous cement. Plagioclase grains are of heterogeneous size and partially altered.

The alteration features include: **1. sericitization** of plagioclase; **2. chloritization**, locally intense with aggregate formation (particularly in Sample 103); **3. carbonatization** represented by V1 carbonate veinlets containing crystallized opaque minerals; and **4. epidotization** associated with chlorite (Sample 103). Two veinlet generations are distinguished: V1 (carbonate-rich with automorphic opaque minerals) and V2 (finer-grained, cross-cutting V1), indicating successive hydrothermal pulses. Sericite is also observed inside quartz veins.

4.3.2 Quartz Veins Facies (Samples P7, 21/3, 27/5)

This facies consists predominantly of white quartz with subrounded grains, some showing brown coloration due to oxidation. Metallic-luster grains are present within cracks, while other cracks remain empty. Conchoidal fracture surfaces are observed.

Microscopically, the texture is microcrystalline with medium to coarse quartz grains. Microfractures are filled by dark minerals. Quartz serves as both the main mineral and the cement. Three quartz generations are distinguished: Q1 (coarse xenomorphic crystals with undulatory extinction), Q2 (automorphic crystals), and Q3 (microcrystalline chalcedony cementing fractures). Additional features include: **1. silicification** (microcrystalline quartz, chalcedony, Q3); **2. sericitization** (traces to moderate, with sericite jointed to opaque minerals or within fractures); **3. carbonatization** (V1 veinlets); **4. sodic alteration** (albite in Sample 21/3); **5. epidotization** (Sample 21/3); and **6. supergene oxidation** of opaque minerals. Sample 27/5 shows a brecciated texture with angular fragments cemented by crushed rock and quartz, indicating post-mineralization tectonic disruption.

4.3.3 Metasomatite Facies (Sample 15/1)

This facies displays the most pervasive alteration, characterized macroscopically by brown-yellow coloration with black and white quartz grains trapped in microcracks. Microscopically, it shows opaque minerals in patches (probably sericite), green spots with opaque minerals forming aggregates or isolated grains and disseminated opaque minerals in square or sub-square shapes. The alteration types identified are: **1.** intense **sericitization**; **2. chloritization** (associated with green spots); **3. carbonatization**; and **4. epidotization**. The intensity of alteration suggests this facies represent the most hydrothermally modified rock type, likely proximal to the main fluid conduit.

4.4 Mineralogy studies

The mineralogical characterization of the samples studied was conducted through detailed microscopic examination of thin sections and polished sections. This analysis aimed to identify both transparent and opaque minerals, describe their optical properties and textural relationships, and establish the paragenetic sequence associated with hydrothermal alteration and gold mineralization.

4.4.1 Transparent minerals

Plagioclase: Heterogeneous size, partially altered and colorless in thin section with low relief and weak birefringence.

Quartz: Xenomorphic to sub-automorphic, undulatory extinction and colorless in thin section. The cleavage usually bsent with very low relief and weak birefringence.

Epidote: Present with bright colors in cross-polarized light. With perfect cleavage and high relief and moderate to strong birefringence

Chlorite: Very strong chloritization, sometimes forming aggregates. The colors are green in the thin section and in one direction parallel cleavage with fair to moderately relief and the birefringence usually weak .

Sericite: colorless to pale green in one direction cleavage weak.ry perfect and no marked relief but strong birefringence. the sericite occurs in minute shreds and is a secondary mineral formed by hydrothermal alteration of silicates especially the feldspars. In the opinion of A.F.Rogers ,it is in all probability a late hydrothermal mineral.

Chalcedony: A colorless to pale brown in thin section and often bluish reflected light with low and weak relief and birefringence. the chalcedony is a secondary mineral in the cavities fillings or lining .

4.4.2 Opaque minerals

Hematite: A steel-gray black with metallic luster in reflected light and Isolated, subrounded, jointed with other minerals, cross-cut by Vein 1 and Vein 2.

Pyrite: Within veinlets and yellow metallic luster in reflected light with square or triangular shape

Chalcopyrite: one of the most widely distributed copper minerals. it is deep brass yellow with metallic luster in reflected light. the mineral is common in vein and ore deposits.

Gold: A bright to rich yellow color , which can pale to whitish-yellow and metallic luster . Gold is frequently hidden within sulfides like Pyrite.

4.5 Paragenetic Sequence and Multi-Stage History

The alteration mineralogy and cross-cutting relationships establish a clear paragenetic sequence. The **early stage** is marked by coarse barren quartz (Q1) deposition following regional metamorphism and initial fracturing. The **pre-mineralization stage** continued with microcrystalline quartz and chalcedony (Q2–Q3) filling fractures as fluid temperatures decreased. The **main hydrothermal stage** involved sulphide deposition including pyrite, arsenopyrite, and chalcopyrite, accompanied by V1 carbonatization, sericitization, and chloritization. Tectonic brecciation disrupted these early sulphides. The **late gold stage** saw native gold precipitating in microfractures within brecciated arsenopyrite and galena, with V2 veinlets cross-cutting V1, indicating a distinct later fluid pulse. Finally, the **supergene stage** produced oxidation of sulphides to hematite, goethite, and malachite, with associated secondary gold enrichment at the surface.

The coexistence of **propylitic** (chlorite–epidote), **phyllic** (quartz–sericite), and **sodic** (albite) alteration types indicates fluctuating fluid compositions and temperatures, consistent with orogenic gold systems where distal propylitic alteration transitions to proximal phyllic and silicic assemblages.

4.6 Summary of Alteration Types

Seven alteration types were identified across the three facies. **Sericitization** is present in all facies with moderate to strong intensity, being most intense in the metasomatite. **Chloritization** occurs in the conglomerate and quartz veins with moderate intensity, reaching strong levels in Sample 103. **Carbonatization** is represented by V1 veinlets in all facies at moderate intensity. **Silicification** dominates the quartz veins facies with strong intensity, manifested as microquartz, chalcedony, and Q3 cement. **Epidotization** is weak to moderate, observed in the conglomerate (Sample 103) and quartz veins (Sample 21/3). **Sodic alteration** (albite) is weak and restricted to Sample 21/3 in the quartz veins facies. **Supergene oxidation** is strongly developed across all facies, producing iron oxides and copper carbonates.

4.6.1 Implications for Gold Mineralization

The alteration assemblages identified are diagnostic of **orogenic gold systems**. The structural control by the Yetti-Eglab Shear Zone is evident in the veinlet orientations and brecciated textures. The late timing of gold precipitation relative to sulphides, combined with strong supergene overprinting, explains the high surface gold grades (up to 311 g/t Au in quartz veins) compared to lower grades at depth (~1.5 g/t Au). The multi-stage quartz generations and cross-cutting veinlet relationships demonstrate that mineralization resulted from episodic fluid influx rather than a single event, with the shear zone acting as a long-lived permeable pathway for hydrothermal fluids.

4.7 Discussion

The hydrothermal alteration assemblages identified in the Akilet Deilel gold occurrence are characteristic of **orogenic gold systems** structurally controlled by major crustal shear zones. The distribution and intensity of alteration across the conglomerate, quartz veins, and metasomatite facies reflect a progressive evolution of hydrothermal fluids along the Yetti-Eglab Shear Zone, governed by changes in temperature, pressure, fluid chemistry, and rock permeability.

4.7.1 Alteration Zoning and Fluid Evolution

The spatial distribution of alteration types reveals a clear zonation from proximal to distal settings relative to the main fluid conduit. In the **proximal zones**, represented by the quartz veins and metasomatite facies, alteration is dominated by **silicification** with three quartz generations (Q1: coarse xenomorphic; Q2: automorphic; Q3: microcrystalline chalcedony), accompanied by **sericitization** and **sodic alteration** (albite in Sample 21/3). These assemblages indicate acidic to neutral, moderate-to-high temperature fluids enriched in SiO_2 and K^+/Na^+. The three quartz generations record episodic fluid influx with decreasing temperature and increasing fluid-rock interaction, while the brecciated texture in Sample 27/5 indicates post-mineralization tectonic reactivation of the shear zone.

In the **intermediate zones**, represented by the conglomerate facies, alteration is characterized by **chloritization**, **carbonatization** (V1 veinlets), and **epidotization**. These minerals form at lower temperatures and more neutral pH conditions, typical of propylitic alteration. The presence of both

V1 and V2 veinlets — with V2 cross-cutting V1 — confirms at least two distinct hydrothermal pulses, with V2 representing a later, finer-grained fluid event.

In the **distal to supergene environment**, pervasive **supergene oxidation** affects all facies, producing hematite, goethite, malachite, and covellite from the breakdown of primary sulphides. This oxidation explains the high surface gold grades (up to 311 g/t Au in quartz veins) compared to lower grades at depth (~1.5 g/t Au), indicating significant **supergene gold enrichment** near the surface.

4.7.2 Comparison with Regional and Global Analogues

The Akilet Deilel alteration assemblages align closely with established orogenic gold deposits across the West African Craton. Comparable deposits include **Poura** in Burkina Faso, characterized by silicification, sericitization, and carbonatization along shear zones with gold associated with arsenopyrite and pyrite. **Kalana** in Mali shows similar silicification, albitization, and carbonatization in shear zone-controlled quartz veins and altered wallrock. **Ashanti** in Ghana exhibits silicification, sericitization, and chloritization along major shear zones, with gold occurring in sulphides and quartz veins. On the Reguibat Rise itself, analogous occurrences include **Florence-Khadra**, **Aguelt Nebkha**, and **Tsalabia West** in Mauritania. The consistent pattern across all these deposits — silicification and sericitization in proximal zones, propylitic alteration distally, and supergene enrichment at surface — confirms that Akilet Deilel belongs to the orogenic gold class and shares a common metallogenic heritage with the broader West African Craton.(in Benramdane, 2007)

4.7.3 Paragenetic Interpretation

The paragenetic sequence established from cross-cutting relationships indicates a five-stage evolution. The **early barren stage** involved regional metamorphism and emplacement of coarse Q1 quartz during initial fracturing. The **pre-mineralization stage** continued with deposition of microcrystalline quartz and chalcedony (Q2–Q3) as fluid temperatures decreased and fracture permeability increased. The **main sulphide stage** saw precipitation of pyrrhotite, pyrite, and arsenopyrite from reduced, sulphur-rich fluids, accompanied by V1 carbonatization, sericitization, and chloritization. Tectonic brecciation subsequently disrupted these early sulphides, creating new permeability.

The **late gold stage** involved native gold precipitating in microfractures within brecciated arsenopyrite and galena, and as inclusions in chalcopyrite, indicating gold transport as Au-S complexes and deposition during sulphide destabilization. Finally, the **supergene stage** produced surface oxidation of sulphides to iron and copper hydroxides, with secondary remobilization and enrichment of gold near the surface.

4.8 Conclusion

The hydrothermal alteration study of the Akilet Deilel gold occurrence reveals a complex, multi-stage history of fluid circulation and mineralization structurally controlled by the Yetti-Eglab Shear Zone. Three main facies — conglomerate, quartz veins, and metasomatite — show distinct but genetically related alteration assemblages reflecting varying fluid-rock ratios and distances from the main fluid conduit. Seven alteration types were identified: sericitization, chloritization, carbonatization, silicification, epidotization, sodic alteration, and supergene oxidation. These assemblages are diagnostic of orogenic gold systems and comparable to those documented at Poura, Kalana, and Ashanti in the West African Craton.

Two generations of veinlets (V1: carbonate-rich; V2: finer-grained, cross-cutting) and three quartz generations (Q1, Q2, Q3) demonstrate episodic hydrothermal activity rather than a single mineralizing event. The most intense alteration occurs in the metasomatite facies and the conglomerate facies (Sample 103), characterized by strong chloritization, epidotization, and sericitization, indicating these rocks were closest to the main fluid pathways. Supergene alteration is well developed across all facies, producing iron and copper hydroxides associated with secondary gold enrichment. This explains the high surface gold grades (up to 311 g/t Au in quartz veins) compared to lower grades at depth (~1.5 g/t Au).

Gold occurs in microfractures and cavities associated with quartz and oxidation products, confirming late-stage precipitation relative to the main sulphide assemblage, with possible secondary remobilization during supergene processes. The mineralization is interpreted as a late tardi-Eburnean metallogenic event post-dating 2.065 Ga, related to hydrothermal fluids — dominantly meteoric with possible magmatic contribution — circulating through the Yetti-Eglab Shear Zone at temperatures of 160–280°C.(in Benramdane, 2007)

This work contributes to the understanding of Paleoproterozoic gold metallogenesis in the West African Craton and supports exploration in the Eglab massif. Alteration zonation, multi-stage veins, and supergene enrichment identified here provide practical guides for targeting gold

occurrences along the Yetti-Eglab Shear Zone and similar structures in the Reguibat Shield.

This investigation contributes to the broader understanding of Paleoproterozoic gold metallogenesis in the West African Craton and provides a scientific foundation for mineral exploration targeting in the underexplored Eglab massif. The identification of alteration zonation, multi-stage vein systems, and supergene enrichment processes offers practical exploration guidelines for delineating additional gold occurrences along the Yetti-Eglab Shear Zone and analogous structures throughout the Reguibat Shield.

CHAPTER 5: GENERAL CONCLUSION

General conclusion

The Yetti-Eglab Shear Zone (Y-ESZ) exerts fundamental structural control on the distribution and localization of hydrothermal alteration and gold mineralization. This major crustal discontinuity, evolving to a mega-shear zone, served as the primary conduit for hydrothermal fluid circulation. and creating a favorable structural framework for ore deposition.

The paragenetic sequence established for the Akilet Deilel gold occurrence indicates a well-defined evolutionary path: (1) early barren quartz deposition, (2) pre-mineralization microcrystalline quartz and chalcedony, (3) main sulphide stage (pyrrhotite, pyrite, arsenopyrite), (4) late gold precipitation in microfractures within brecciated arsenopyrite and galena, and (5) supergene enrichment producing iron and copper hydroxides. Native gold occurs both as fracture fillings and as inclusions within sulphides, confirming its late-stage precipitation relative to the main sulphide assemblage.

The present study focused on the characterization of hydrothermal alteration assemblages associated with sulphide-gold mineralization in the Yetti-Eglab Junction Zone, southwestern Algeria. The Eglab massif, constituting the easternmost part of the Reguibat Shield within the West African Craton, represents a key area for understanding Paleoproterozoic metallogenesis in North Africa. Through detailed macroscopic and microscopic petrographic examination of ten samples, three main lithological facies were identified: conglomerate (metagreywacke), quartz, and metasomatite.

The hydrothermal alteration study revealed a complex, multi-stage history of fluid-rock interaction. Seven distinct alteration types were identified across the studied facies: **sericitization, chloritization, carbonatization, silicification, epidotization, sodic alteration, and supergene oxidation**. The alteration assemblages are characteristic of orogenic gold systems, consistent with deposits described elsewhere in the West African Craton.

The conglomerate facies display sericitization of plagioclase, strong chloritization with aggregate formation, carbonatization (V1 veinlets), and epidotization. The quartz facies is dominated by silicification with three generations of quartz (Q1: coarse xenomorphic, Q2: automorphic, Q3: microcrystalline chalcedony), accompanied by sericitization and carbonatization. Sodic alteration (albite) was specifically identified in one sample. The metasomatite facies exhibit the most intense alteration, characterized by pervasive sericitization, chloritization, and carbonatization.

Two generations of veinlets (V1 and V2) were distinguished, indicating multiple hydrothermal events. V1 consists of carbonate-rich, crystallized veinlets with well-formed opaque minerals, while V2 comprises finer-grained opaque crystals that cross-cut V1, representing a later, distinct fluid pulse.

The Akilet Deilel gold occurrence shares strong similarities with established orogenic gold deposits across the West African Craton. Comparable deposits include Poura (Burkina Faso), Kalana (Mali), and Ashanti (Ghana), all characterized by structurally controlled, sulphide-associated gold mineralization with similar alteration assemblages. On the Reguibat Rise itself, analogous occurrences include Florence-Khadra, Aguelt Nebkha, and Tsalabia West in Mauritania. (in Benramdane, 2007)

Finally, this study contributes to the broader understanding of Paleoproterozoic gold metallogenesis in the Eglab massif and provides a mineral researcher a basis for mineral exploration in the underexplored areas.

The characterization of hydrothermal alteration assemblages, their spatial distribution, and their relationship to structural features offers valuable exploration guidelines. The identification of multi-stage hydrothermal events (orogenic-type alteration patterns and supergene enrichment processes), and this confirms that the Yetti-Eglab Junction Zone has significant gold potential. More research is needed to fully explore this remote but promising region of southwestern Algeria.

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