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A REVIEW OF THE HOGGAR ECLOGITES (SOUTH ALGERIA)

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ABSTRACT

The high-pressure eclogites of the Hoggar massif (Central and Western Hoggar, Algeria) record a complex Neoproterozoic tectono-metamorphic history tied to the Pan-African orogeny. These eclogites occur as lenses within diverse host rocks across several terranes (Egéré-Aleksod, Tighsi, Tassendjanet, Sérouenout), and preserve peak eclogite-facies mineral assemblages dominated by garnet, omphacite, quartz and rutile, with retrograde symplectites marking subsequent decompression and hydration events. Thermobarometric and pseudosection analyses indicate peak conditions commonly in the range of ~19–22 kbar and ~650–750 °C, reached along a generally clockwise P–T path with near-isothermal decompression during exhumation, consistent with subduction of both oceanic and continental rift-related mafic crust followed by rapid uplift and transpression during continental collision. Geochemical signatures suggest basaltic protoliths derived from rift-shoulder settings during late Neoproterozoic extension, while isotopic and U–Pb zircon ages cluster around 680–620 Ma, recording eclogite-facies crystallization and syn-collisional exhumation. Field relationships and structural data highlight these eclogitic rocks as markers of deep crustal processes within the Tuareg Shield, representing remnants of subducted lithosphere that were later overprinted by high-temperature metamorphism and tectonic reworking. The recently obtained dataset underscores the role of the Hoggar eclogites in deciphering the dynamics of Pan-African subduction-collision cycles and Gondwana assembly in northern Africa.

Keywords - Hoggar - Eclogites - P-T-t path - Geochemistry - U-Pb zircon ages.

SYNTHÈSE SUR LES ÉCLOGITES DU HOGGAR (SUD DE L'ALGÉRIE)

RÉSUMÉ

Les éclogites de haute pression du Hoggar (Hoggar central et occidental, Algérie) témoignent d'une histoire tectono-métamorphique néoprotérozoïque complexe liée à l'orogenèse pan-africaine. Ces éclogites se présentent sous forme de lentilles au sein de roches hôtes diverses, réparties sur plusieurs terranes (Egéré-Aleksod, Tighsi, Tassendjanet, Sérouenout), et conservent des assemblages minéraux caractéristiques du pic du faciès éclogitique, do-

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minés par le grenat, l'omphacite, le quartz et le rutile, avec des symplectites rétrogrades témoignant d'événements ultérieurs de décompression et d'hydratation. Les analyses thermobarométriques et de pseudosections indiquent que les conditions de haute pression se situent généralement dans une fourchette d'environ 19–22 kbar et 650–750 °C, atteintes le long d'une trajectoire P–T généralement dans le sens des aiguilles d'une montre, avec une décompression quasi isothermique lors de l'exhumation, ce qui concorde avec la subduction d'une croûte mafique à la fois océanique et continentale liée au rift, suivie d'un soulèvement rapide et d'une transpression lors de la collision continentale. Les signatures géochimiques suggèrent des protolithes basaltiques issus d'environnements de flanc de rift lors de l'extension du Néoprotérozoïque tardif, tandis que les âges isotopiques et U–Pb des zircons se situent entre 680 et 620 Ma, témoignant d'une cristallisation en faciès éclogitique et d'une exhumation syn-collisionnelle. Les relations sur le terrain et les données structurales mettent en évidence que ces roches éclogitiques constituent des témoins des processus crustaux profonds au sein du bouclier Touareg, représentant des vestiges de la lithosphère subductée qui ont ensuite été modifiés par un métamorphisme à haute température et un remaniement tectonique. L'ensemble de données récemment obtenu souligne le rôle des éclogites du Hoggar dans la compréhension de la dynamique des cycles de subduction-collision Pan-Africains et de l'assemblage du Gondwana en Afrique du Nord.

Mots-clés - Hoggar - Éclogites -Trajectoire P-T-t - Géochimie - Âges U-Pb du zircon.

I- INTRODUCTION

Despite numerous studies of eclogites in the 20th century, a debate has long persisted regarding their magmatic or metamorphic origin. Initially, metamorphism was associated with temperature and fluids, whereas pressure was linked only to deformation. The presence of foliations led some authors to consider them metamorphic, while others thought they were magmatic due to confusion with garnet pyroxenites. Eskola (1921), initially in agreement with the magmatic origin, finally recognized their metamorphic nature. In the 1970s-1980s, mafic eclogites were widely accepted as resulting from the metamorphism of gabbro or basalt, supported by geochemical data and laboratory experiments.

The occurrence of eclogites in different geological environments, in addition to their varied mineralogical characteristics, indicates that eclogites were formed under a wide range of pressure and temperature conditions. Thus, during the evolution of eclogites investigations, several hypotheses have been advanced to explain the geodynamics of eclogite formation. Eskola's (1921) classification was based on the occurrence of eclogites in four different geological settings: xenoliths in kimberlites, lenses in peridotites, in migmatitic gneisses and in blue schist. In more recent classifications (Coleman *et al.*, 1965; Smulikowski, 1968), eclogites are distinguished on the basis of their modes of occurrence, mineralogical and chemical compositions, and also in relation to their geodynamic settings. These two classifications are almost identical, and the three groups proposed are very different in terms of geodynamic context: mantle-derived eclogites, ophiolitic eclogites, and eclogites in gneisses.

After the huge success of plate tectonic theory in 1970, the mechanism of eclogite formation was more or less understood. Following the discovery of coesite (a high-pressure polymorph of quartz) and also microdiamonds in eclogites (Sobolev and Shatsky, 1987; Xu *et al.*, 1991; Dobrzhinetskaya *et al.*, 1995; Godard, 2001), the notion of ultrahigh pressure (UHP) metamorphism emerged, with eclogites reaching depths of the order of 90 to 110 km (corresponding to 30–33 kbar), which was difficult to explain. The problems encountered concern the density between the mantle and the buried rocks and the melting

temperatures of these eclogites. The exhumation of these rocks also poses many challenges and various models have been proposed.

Thermodynamic modelling of eclogites, integrating a large number of constituents that more closely approximate the actual composition of the rocks, and advances in thermodynamic databases, in particular a better understanding of minerals such as omphacite, garnet and amphibole, have made it possible in recent years to constrain the pressure-temperature trajectories of high-pressure domains. The geodynamic mechanisms responsible for the appearance of high-pressure paragenesis in omphacite-garnet-rutile-quartz eclogites continue to attract the interest of specialists in an attempt to explain the anomalous geothermal gradients they have undergone. The mineral parageneses exposed by these high-pressure rocks, the mineral reactions they display and the chemical variations of the minerals they possess, make it possible, in successive stages, to reconstruct this complex history, which is fundamental to understanding the geological evolution of the region.

II- GEOLOGICAL SETTING

The Hoggar is part of a large Neoproterozoic orogenic belt known as the "West Gondwana Orogen" (fig. 1a), a linear belt over 4000 km long stretching from northeastern Africa to central Brazil (Caby, 1989; Cordani *et al.*, 2013). All hypotheses suggest that this chain resulted from a continent-continent collision between the Amazon craton and the West African craton on the one hand, and the Saharan metacraton and the São Francisco-Congo metacraton on the other hand (fig. 1a). The orogeny spanned 400 Ma, from the onset of juvenile oceanic arc magmatism at around850 Ma to the end of continental collision at 615–610 Ma and the emplacement of post-collisional granites at around 580–500 Ma (Caby, 1989, 2003).

This belt is characterized by the occurrence of several mafic massifs containing relics of high- and ultra-high-pressure metamorphism (Jahn *et al.*, 2001; Agbossoumondè *et al.*, 2001; Berger *et al.*, 2014). The work of Ganade *et al.* (2014) on eclogites from Mali, Togo, and NE Brazil demonstrated that eclogites from Mali and Togo are intercalated with UHP/HP quartzites (Jahn *et al.*, 2001; Agbossoumondè *et al.*, 2001). They show a well-preserved pressure-peak paragenesis (garnet, omphacite, phengite, and coesite/quartz). Peak P-T conditions for the Gourma region (Mali) have been estimated at 30–33 ±3 kbar and 690–705 ±65°C. These conditions are consistent with the rare occurrence of coesite in old orogens and testify to subduction of the passive Gourma margin at depths of the order of 100 km (Kylander-Clark *et al*., 2012). U-Pb zircon dating of these eclogites yielded a metamorphic age of 611.3 ±3.6 Ma and a protolith with an age greater than 1000 Ma (Ganade *et al.*, 2014).

Further south, in the Dahomey massif (Togo), eclogites and HP/UHP granulites have been described in the Lato region (Agbossoumondè *et al.*, 2001). Estimated conditions for this region are 28–30 ±0.3 kbar and 620–700 ±65°C with a metamorphic age of 608.7±5.8 Ma and a protolith of 703.2±8.1 Ma (Ganade *et al.*, 2014). These conditions are favorable for coesite stability, but to date no coesite has been found at Lato. The eclogites of NE Brazil occur as puddles with a high-temperature meta-sedimentary enclosure that shows evidence of partial melting (Santos *et al.*, 2009). They are highly retrogressed, composed of garnet, hornblende, diopside, and plagioclase, giving conditions of 17 kbar and 770°C, with ages ranging from 624.7 ± 7.0 Ma to 616.0 ± 4.0 Ma.

The Tuareg Shield, comprising the Hoggar, Aïr and Adrar des Ifoghas, is made of 25 "terranes" separated by sub-vertical shear zones or thrust fronts (fig.1b; Black *et al.*, 1979; Caby *et al.*, 1981; Bertrand *et al.*, 1986; Liégeois *et al.*, 1987; Black *et al.*, 1994; Liégeois *et al.*, 1994; Abdelsalam *et al.*, 2002; Liégeois *et al.*, 2003, 2013; Liégeois, 2019). Their construction is contemporary with the western Gondwana

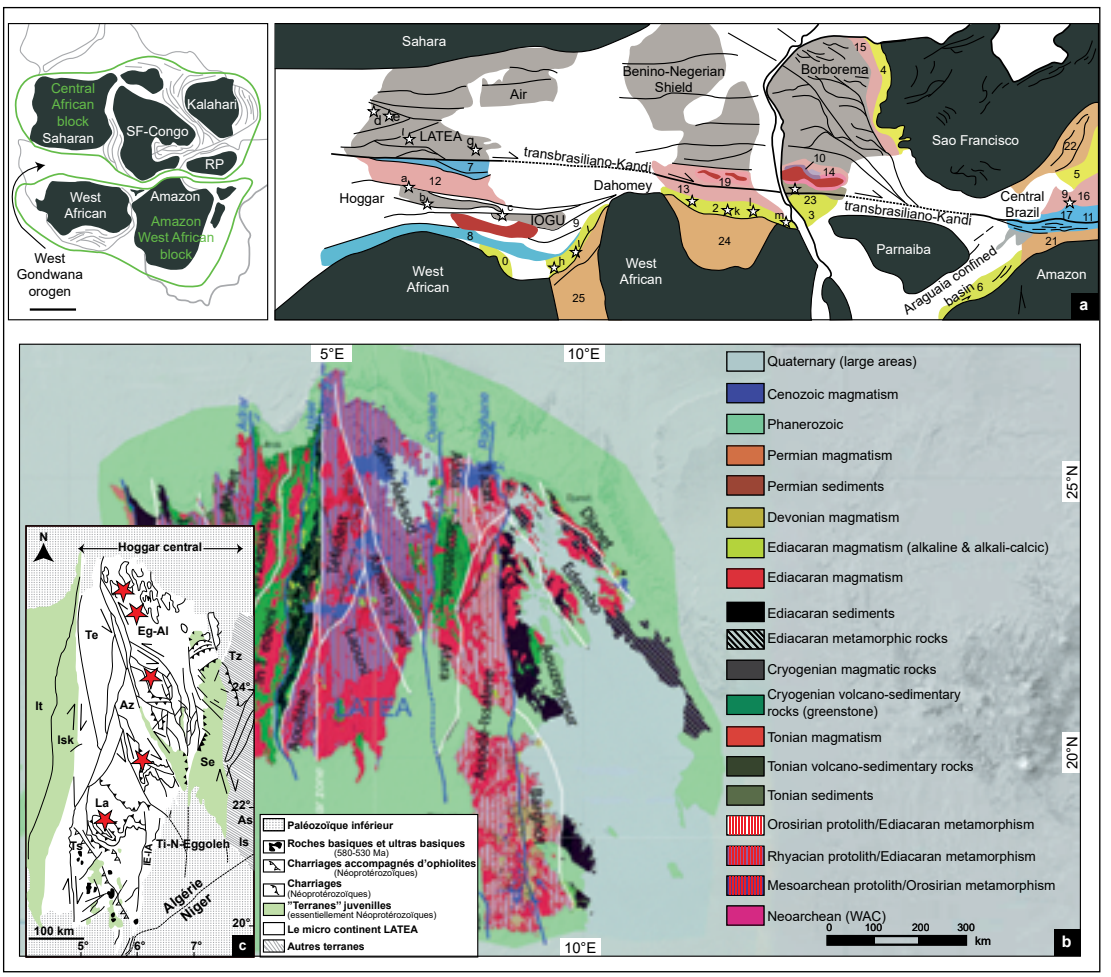


Fig. 1- Geological and tectonic context of the West Gondwana Orogen. **(a)** Cratons and blocks involved in the formation of the West Gondwana Orogen and the spatial distribution of high-pressure and ultra-high-pressure rocks. **(b)** Synthetic geological map of the Tuareg Shield showing the relationships between the different terranes and the main Pan-African shear zones after Liégeois (2019). **(c)** Zoom on the LATEA terranes after Liégeois *et al*. (2003), showing the position and distribution of Hoggar eclogites.

Contexte géologique et tectonique de l'orogenèse du Gondwana occidental. (a) Cratons et blocs impliqués dans la formation de l'orogène du Gondwana occidental et répartition spatiale des roches à haute pression et à ultra-haute pression. (b) Carte géologique synthétique du bouclier Touareg montrant les relations entre les différents terranes et les principales zones de cisaillement panafricaines (Liégeois, 2019). (c) Zoom sur les terranes LATEA (Liégeois et al., 2003) montrant la position et la répartition des éclogites du Hoggar (étoiles).

orogeny, which involved the accretion of several island arcs prior to the final collision (630–580 Ma) formed during a northward tectonic migration during the closure of the basin between the West African craton and the Saharan metacraton (Black *et al.*, 1994; Dostal *et al.*, 2002; Liégeois *et al.*, 2003, 2013). These "terranes" have different origins; they may be composed of Archean rocks or juvenile Paleoproterozoic or Neoproterozoic rocks (Caby, 2003, Liégeois *et al.*, 2003; Ouzegane *et al.*, 2003; Peucat *et al.*, 2003; Fezaa *et al.*, 2010).

The Hoggar is known for the presence of Precambrian rocks showing eclogite-facies metamorphism (Bertrand, 1974; Sautter, 1985;

Liégeois *et al.*, 2003; Zetoutou *et al.*, 2004; Bitam-Derridj *et al.*, 2010; Berger *et al.*, 2014; Doukkari *et al.*, 2014, 2015; Arab *et al.*, 2015, 2021; Ouzegane *et al.*, 2023).

Eclogites have been described in the Central Hoggar, also named LATEA, consisting of five terranes: Laouni, Azrou N'fad, Tefedest, Egéré-Aleksod and Aouilène (Liégeois *et al.*, 2003; Liégeois, 2019). This metacraton shows a very well-preserved Archean/Paleoproterozoic basement that has been partially deformed by horizontal displacements along the NS mega-shear zones and also by granitoid intrusions (Liégeois *et al.*, 2003).This Archean/Paleoproterozoic basement shows amphibolite/granulite facies metamorphism. Archean rocks have been dated at 2.7 Ga in the Gour-Oumelalen region (NE LATEA; Peucat *et al.*, 2003). Paleoproterozoic events have been dated at 2.15 Ga (migmatite protolith) and 2.06 Ga (granulite metamorphism) in the Laouni terrane (Tidjenouine region; LA-ICP-MS on zircon: Bendaoud *et al.*, 2008) and at 1.9 Ga in the Gour-Oumelalen region (Peucat *et al.*, 2003). The Aleksod terrane shows eclogites with an Archean Nd TDM model age (Bernard-Griffiths *et al.*, 1991). However, these model ages are called into question because they are based on rocks that have a 147Sm/144Nd ratio of 0.19 and 0.16. These ratios are very high for calculating reliable model ages (see Stern, 2002, and Liégeois and Stern, 2010, for discussions).

The Egéré eclogites outcrop in several regions, including Gara-Tighsi, Adrar Izzilatène, Gara Aoular, and Tin Hamane. This terrane has some of the best-preserved eclogites in the Hoggar (Doukkari *et al.*, 2014, 2015; Ouzegane *et al.*, 2023). The eclogites in this terrane were interpreted by Latouche (1985) as exotic tectonic units underlining large overlaps that separate them from their enclosing metasediments of lower metamorphic grade. However, recent work has shown that high-pressure mineralogical assemblages are also found in marbles and metapelites associated with eclogites (Arab *et al.*, 2015, 2021; Ouzegane *et al.*, 2023). Eclogite outcrops in the Adrar Izzilatène occur as well-preserved lenses from 1 to 500 m long and can follow each other cartographically for several kilometers. The Gara Tighsi region lies in the northwestern part of the Egéré terrane. In this region, the eclogites are smaller than at Adrar Izzilatène and show stretched boudins parallel to the foliation (Doukkari *et al.*, 2014, 2015; Ouzegane *et al.*, 2023).

In the Aleksod domain, in the northern Serkout area, eclogites were first described by Bertrand (1974) and later studied by Sautter (1985). The eclogite pods are found within early Pan-African mylonitic zones, beneath the contact between metasedimentary and orthogneissic rocks. These basic pods, ranging in length from 0.2 to 500 m, are distinct from interbedded amphibolites which also contain eclogite relics. Pods longer than 3 meters typically display two concentric zones: a central eclogite core – variably preserved depending on boudin size – surrounded by a darker, amphibolitized margin. This margin itself consists of an inner zone of garnet amphibolite and an outer zone of foliated amphibolite. The most common mineral assemblage includes garnet + omphacite + quartz + zoisite ± amphibole, with rutile, zircon, and apatite as accessory phases.

In the Tin-Begane region of the Laouni Terrane (Central Hoggar), high-grade metabasites have attracted considerable attention since the pioneering work of Boughrara (1999), primarily due to their limited occurrence and association with migmatitic rocks. Recent investigations by Arab *et al.* (2025) have further clarified the nature of these mafic lithologies, which exhibit prominent reaction textures – most notably symplectites. Previously identified as eclogites by Boughrara (1999) and Liégeois *et al.* (2003), these rocks are now recognized as garnet–clinopyroxene–amphibole–plagioclase

–quartz–titanite–ilmenite-bearing granulitic metabasites. The mineral assemblages and reaction textures within these rocks reflect a metamorphic evolution that began under intermediate-pressure granulite-facies conditions of 13–15 kbar and 750 ± 50 °C followed by overprinting at lower-pressure conditions 7–4.5 kbar. All lithologies exhibit clear evidence of high- temperature decompression overprints (Latouche, 1985; Boughrara, 1999; Liégeois *et al.*, 2003).

The Ti-N-Eggoleh area, located within the Sérouenout Terrane, is predominantly composed of high-pressure metamorphic rocks, including granulitized eclogites associated with talc–kyanite–quartz white schists, chlorite schists, marbles, sulphide ores and serpentinized peridotites. These assemblages represent components of an ophiolitic material metamorphosed under eclogite-facies conditions (Adjerid *et al.*, 2012, 2015). The primary high-pressure paragenesis– comprising omphacite, garnet, and quartz – has been partially replaced by orthopyroxene–hornblende–clinopyroxene–plagioclase symplectites, indicating overprinting under lower-pressure, high-temperature granulite-facies conditions (Bitam-Derridj *et al.*, 2010).

In the Azrou N'Fad, eclogites occur in meter-to-decameter-sized elongated lenses. They are preserved only in the cores of large lenses within shear zones, while their margins have fully transformed into amphibolite. These eclogites are intensely deformed and consistently delineate shear zones, as evidenced by the mylonitic fabric of the surrounding migmatitic gneisses. These low-angle shear zones are interpreted as nappe soles formed during the Pan-African orogeny (Zetoutou *et al.*, 2004).

The Neoproterozoic eclogites from the Tassendjanet-Tidéridjaouine terrane in the Pan-African Western Hoggar (Tuareg shield, Southern Algeria) form lenses enclosed in 1.8 Ga subalkaline Paleoproterozoic orthogneisses (Berger *et al.*, 2014). They lie along a major sinistral shear zone marking the boundary with the Archean/Paleoproterozoic granulite-facies In Ouzzal terrane and are associated with high-pressure metasediments (Berger *et al.*, 2014).

III- PETROLOGY AND MINERAL CHEMISTRY

The petrology and mineral chemistry of the Hoggar eclogites are essential for reconstructing the pressure–temperature–time (P–T–t) history of subducted oceanic and continental crusts in this orogenic belt. Their mineral assemblages, chemical zoning, and phase relationships provide key insights into metamorphic conditions, fluid interactions, and tectonic processes such as subduction, exhumation, and crustal recycling.

3.1- Several contributions on the Egéré domain have concerned these mafic eclogites (Doukkari *et al.*, 2014, 2015; Ouzegane *et al.*, 2023). Eclogite samples revealed complex textures as a result of the extremely heterogeneous mineral associations that developed in closely spaced domains during the various metamorphic stages. The high-pressure primary paragenesis consists of omphacite-garnet-rutile-quartz and epidote, where omphacite contains epidote, rutile and quartz inclusions. Three distinct metamorphic parageneses have been recognized in these eclogites: (i) the pre-peak paragenesis (M1), characterized by garnet, amphibole, epidote, quartz and rutile; (ii) the peak eclogite-facies assemblage (M2), consisting of omphacite, garnet, high Mg-edenite, epidote, quartz and rutile; and (iii) the retrograde paragenesis (M3), characterized by the development of plagioclase-pargasite-diopside-ilmenite symplectites at the expense of omphacite, garnet, quartz and rutile. Due to decompression, omphacite was the first mineral destabilized into very thin symplectites of

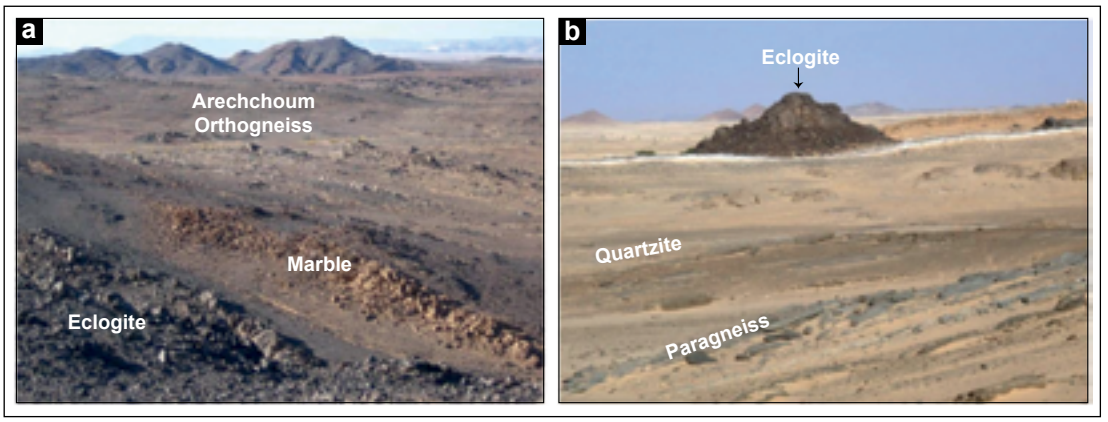


Fig. 2- Outcrop photographs of some eclogite lenses from the Egéré Terrane.

Photographies d'affleurements de quelques lentilles d'éclogites provenant du terrane de l'Egéré.

plagioclase and jadeite-poorer clinopyroxene. The paragenesis of the lower pressure conditions is represented by kelyphites and symplectites of amphibole-plagioclase separating garnet from omphacite and quartz. During this retrograde evolution, rutile was replaced by ilmenite.

The mineralogical composition of these eclogites includes garnet, clinopyroxene, amphibole, plagioclase, and accessory minerals, reflecting complex metamorphic histories.

The rock contains two types of garnet: common large porphyroblasts (1.5–4.0 mm) with amphibole–plagioclase (kelyphite) coronas and rare fine-grained crystals (20–40 μm) within kelyphite zones. Coarse garnets are almandine-dominated, zoning from 55 to 61 mol% almandine with decreasing pyrope and grossular contents towards the rim, and contain inclusions of epidote, quartz, amphibole, and rutile mainly in their cores. Clinopyroxene occurs as large omphacite porphyroblasts often partially replaced by diopsidic clinopyroxene–plagioclase symplectites; primary omphacite has higher jadeite content (up to 36 mol.%) compared to the more diopsidic replacement 3–23 mol%. Amphibole phases are Ca–Na types (mainly pargasite and edenite) showing complex zoning with porphyroblasts with blue-green cores and brown-green rims; later amphiboles occur as Fe-rich pargasite in symplectites or coronas around garnet and omphacite. Plagioclase is always secondary, varying from oligoclase in symplectites after omphacite to andesine in kelyphites around garnet and anorthite in coronas around epidote. Accessory minerals include epidote (as inclusions and matrix grains often rimmed by plagioclase) and rutile (inclusions in garnet and matrix), with minor ilmenite.

3.2- The mineral compositions of eclogites from the Aleksod reveal distinct variations reflecting both metamorphic conditions and deformation processes. Garnet shows compositional zoning, ranging from Fe-rich types (Alm42-Prp28.5) in coarse-grained horizons to Mg-rich types (Alm36-Prp38) in fine-grained layers. In sheared eclogites, garnet compositions are more homogeneous and intermediate (Alm39-Prp33), likely due to deformation-induced chemical re-equilibration. While Ca content remains constant in banded eclogites, it decreases

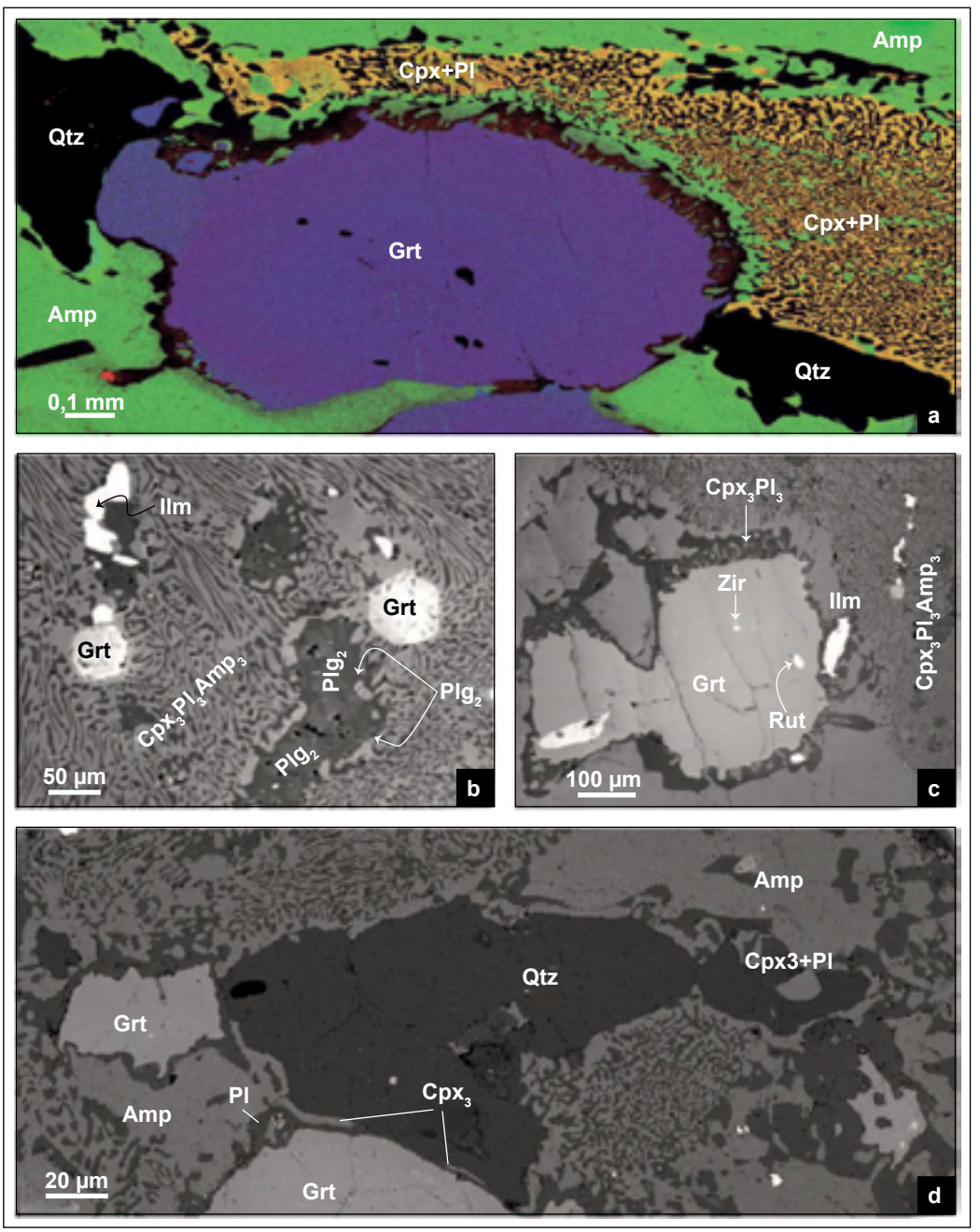


Fig. 3- RBSE and RGB backscattered SEM images showing mineral assemblages and general microtextures of selected eclogites. **(a–d)** Coarse-grained crystals of garnet, amphibole, and quartz associated with very fine-grained clinopyroxene + plagioclase symplectites that pseudomorph original omphacite. Mineral abbreviations after Kretz (1983): Grt = garnet; Qz = quartz; Amp = amphibole; Pl = plagioclase; Cpx = clinopyroxene; Rt = rutile; Ilm = ilmenite; Ep = epidote.

Images MEB à rétrodiffusion BSE et RVB (R : rouge, V : vert, B : bleu) montrant les assemblages minéraux et les microtextures générales de certaines éclogites. (a-d) Cristaux à gros grains de grenat, d'amphibole et de quartz associés à des symplectites à grains très fins de clinopyroxène et de plagioclase, pseudomorphes d'omphacite d'origine. Toutes les abréviations minérales sont d'après Kretz (1983) : Grt, grenat ; Qz, quartz ; Amp, amphibole ; Pl, plagioclase ; Cpx, clinopyroxène ; Rt, rutile ; Ilm, ilménite ; Ep, épidote.

from core to rim in garnet porphyroblasts within sheared types. Pyroxenes exhibit consistent compositions across all eclogite types, characterized by high magnesium content (XMg≈ 0.85) and negligible Fe^{3+}.

Their jadeitic content (26–29 mol%) places them within the omphacite compositional field. Amphiboles belong to the edenite group, with high magnesium content (XMg≈ 0.80) and slight glaucophane substitution. Matrix amphiboles tend toward magnésio-hornblende compositions, whereas those included in garnet and zoisite correspond to the barroisite group.

3.3- Based on textural observations, five metamorphic stages have been recognized in the Tin-Eggoleh area: (i) a pre-eclogitic stage characterized by inclusions of clinozoisite, rutile, and quartz in garnet; (ii) an eclogitic stage with assemblages of omphacite, garnet (Alm_{49-56} Prp_{25-22} Grs_{25-21}), quartz, and ilmenite, (iii) an amphibolite-facies stage appeared during decompression. The presence of large hornblende associated with plagioclase is interpreted as the result of the amphibolization; omphacite (Jd_{30}) of stage. The presence of large hornblendes associated with plagioclases is interpreted as the result of the destabilization of garnet in contact with omphacite; (iv) a granulitic stage during which orthopyroxene (En37) and plagioclase (Ab_{39-65}) develop into symplectites and crowns according to the following reactions: garnet + quartz → Opx + plagioclase; amphibole + quartz → Cpx + Opx + plagioclase + H_2O; the last reaction is symptomatic of high-grade dehydration after amphibolization of the eclogite. (v) a final stage characterized by the development of fine intergrowths of chlorite + plagioclase around the amphibole, resulting from the reaction amphibole → chlorite + plagioclase + H_2O (Bitam-Derridj *et al.*, 2010).

3.4- The Azrou N'Fad terrane is remarkable by the presence of eclogites (Zetoutou *et al.*, 2004) that are particularly rich in magnesium, as reflected in the composition of the primary phases such as garnet (44.3 mol% pyrope). The breakdown of primary omphacitic clinopyroxene causes a gradual loss of jadeite and sequential formation of plagioclase types, starting with the most sodic. Concurrently, garnet becomes increasingly iron-rich and breaks down into symplectites composed of hornblende and plagioclase or clinopyroxene, plagioclase, and hornblende at contacts with primary clinopyroxene and quartz. Both high-Mg and low-Mg eclogites have similar mineral compositions, mainly garnet, clinopyroxene, quartz, secondary amphibole, and plagioclase, with rutile and ilmenite as minor phases.

They show granoblastic textures with reaction microstructures. High-pressure minerals (garnet, primary clinopyroxene, rutile, quartz) are surrounded by coronas and symplectites – plagioclase intergrown with secondary clinopyroxene or plagioclase-bearing kelyphites with hornblende and ilmenite, reflecting retrograde metamorphism. Garnets (2-5 mm) contain inclusions and fractured rims of kelyphite formed via the breakdown of garnet, clinopyroxene, and quartz into plagioclase and hornblende. Primary clinopyroxene grains include rutile and quartz inclusions that react to form secondary clinopyroxene, plagioclase, amphibole, and ilmenite. Plagioclase is always secondary, either in symplectites or kelyphite rims. Quartz occurs as inclusions and matrix grains, while rutile and ilmenite are abundant with rutile often rimmed by ilmenite.

Garnet in high-Mg eclogite (type 1) forms a solid solution between pyrope (44.3% cores to 33.0 mol% rims) and almandine (26.1% cores to 38.3 mol% rims), with notable grossular and low spessartine contents; XFe increases from core to rim. Low-Mg eclogite (type 2) garnet is mainly almandine (38.2–50.5%), lower in pyrope, with similar grossular and low spessartine. Calcium slightly decreases from core to rim, especially near plagioclase, which

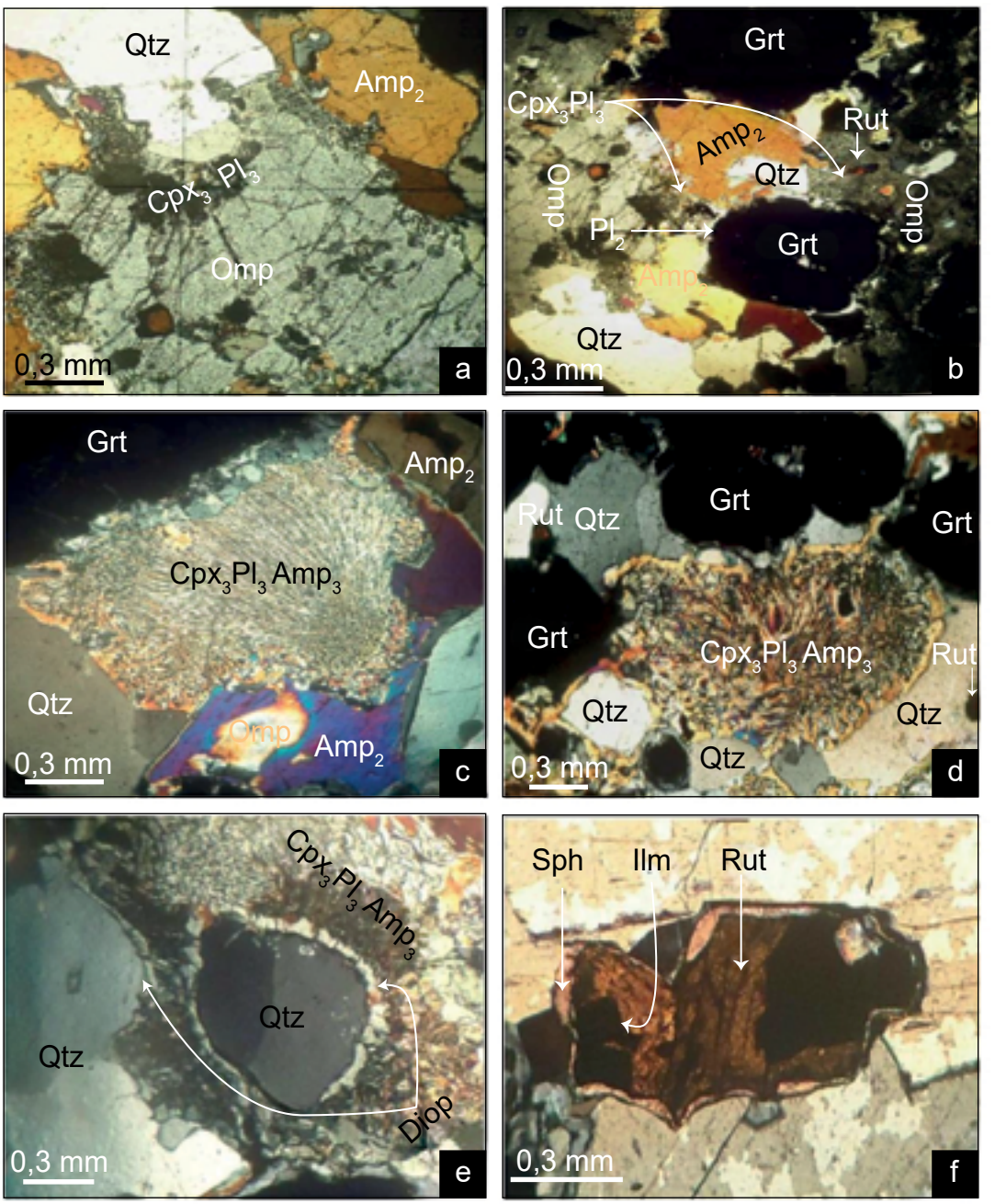


Fig. 4- Plane-polarized and cross-polarized light images showing mineral assemblages and general microtextures of selected eclogites. **(a–f)** Coarse-grained crystals of garnet, amphibole, and quartz associated with very fine-grained clinopyroxene + plagioclase symplectites that pseudomorph original omphacite.

Images obtenues par lumière polarisée et lumière naturelle montrant les assemblages minéraux et les microtextures de certaines éclogites. (a-f) Cristaux à gros grains de grenat-amphibole-quartz associés à des symplectites à grains très fins de clinopyroxène-plagioclase, pseudomorphes d'ancienne omphacite.

shows increasing anorthite. Primary clinopyroxene in type 1 is highly magnesian diopside with moderate jadeite (13.7–16.3 mol%), less sodic than type 2 clinopyroxene. Secondary clinopyroxene in plagioclase-clinopyroxene symplectites has low jadeite content in both types (6–8 mol%), with a slight zoning from core to rim that reflects jadeite loss. Plagioclase varies widely: type 1 is bytownite ($An_{78–87}$) in symplectites with amphibole; type 2 shows less anorthitic plagioclase (~An_{25}). Exsolution plagioclase from clinopyroxene breakdown is andesine (An_{32}) in both.

Amphibole is magnesio-hornblende in both types, while rutile and ilmenite are nearly pure accessory phases. These mineral compositional zonings indicate retrograde metamorphic reactions and destabilization of primary minerals in both eclogite types.

3.5-The eclogites from the Tileouine (Tassendjanet Terrane: Berger *et al*., 2014) are composed of approximately 40% polyhedral omphacite, 55% rounded garnet, and 5% rutile and ilmenite. The omphacite grains (~500 μm) are well preserved but have relatively low jadeite content (12–20 mol%; Na2O ~3.1 wt%) and high Mg# (77–86).

The Na-rich pyroxenes occur as small inclusions within garnet. Garnet grains are xenoblastic to idioblastic, 0.5–1 mm in size, with homogeneous core compositions (Alm49-50 Prp27-28 Grs20-21 Sps1-2). The core inclusions include omphacite, rutile, apatite, zircon (up to 40 μm), and quartz. Garnet zoning shows a slight increase of Fe (up to 52% almandine) and a decrease of Ca (down to 16% grossular) toward the rim, with the outermost rim richer in Mg and poorer in Fe. Retrograde metamorphism is minor (<3 vol.%) and expressed as hornblende (Mg# 69–77, Si 6.3–6.6 a.p.f.u.) and plagioclase (An33–45) coronas surrounding garnet grains.

IV- MINERAL EQUILIBRIA MODELING

Although the metamorphic evolution of eclogites in the Hoggar has been described in general terms, many details of their evolution, especially the characterization of their prograde path, remain to be determined. One of the reasons for this is that most of the P-T estimates were determined using traditional geothermobarometric methods. However, in the last decade, thermodynamic modeling has enabled to better constrain the P-T pathevolution ofeclogites from various terranes:

(i) In the Egéré Terrane, eclogites outcrop in several regions, including Gara-Tighsi, Adrar Izzilatène, Gara Aoular, and Tin Hamane. This terrane has some of the best-preserved eclogites in the Hoggar. A P-T pseudosection (Doukkari *et al.*, 2015) was modeled for 5–22 kbar and 600–900°C, at H_2O = 3 mol%. Epidote is stable at high pressure, while plagioclase appears at lower pressures; rutile is replaced by ilmenite near 9 kbar. Peak metamorphic conditions (M1) were estimated at 20.5 ± 1 kbar and 650 ± 50°C using garnet and amphibole core compositions. During decompression, omphacite destabilized into diopside–plagioclase symplectites, and peak temperature conditions (M2) reached 14 ± 1 kbar and 800 ± 50°C. The final retrograde stage (M3) occurred at 8.0 ± 1 kbar and 690 ± 50°C, marked by amphibole–plagioclase symplectites around garnet.

(ii) The Aleksod eclogites were first described by Bertrand (1974) and later studied by Sautter (1985), who estimated their P-T peak conditions at 750°C and >15 kbar. These estimates were obtained from the core of the eclogite pods, whereas their rims show an evolution towards hydrous amphibolite facies (T= 650 °C; P = 4.5 kbar). In the North Serkout area, thermodynamic modeling of eclogites and their evolution into garnet amphibolites (Djeddi and Badjou, 2015) shows, using garnet cores, a prograde path from14–15 kbar and 600°C to a

pressure peak of 21 kbar and 650°C. Garnet amphibolites, on the other hand, show final conditions of 9 kbar and 725°C.

(iii) In the Tin Begane region of the Laouni terrane, retrograde P-T-t paths have been proposed, implying heating during decompression from peak conditions (eclogite facies) of 15 kbar and ~790°C to garnet amphibolite facies conditions of 12 kbar and 830°C at 685 ± 19 Ma (Liégeois *et al.*, 2003). Arab *et al.* (2025) recently presented a new reconstruction of the P-T evolution for a selected sample by calculating two P-T pseudosections in the NCKFMASHTO system. The first pseudosection was based on the bulk-rock composition, while the second was derived from the overall composition of late symplectites, determined by balancing their forming reaction. Their results reveal that the metabasites underwent a clockwise P-T path, decompressing from peak conditions of approximately 13–15 kbar and 750 ±50°C to 7–4.5 kbar and 810 ± 50 °C. This clockwise path is interpreted as reflecting crustal thickening followed by exhumation, likely associated with the Pan-African orogeny.

(iv) South of the Sérouenout Terrane, granulitized eclogites are associated with talc-kyanite white schists (Bitam-Derridj *et al.*, 2010; Adjerid *et al.*, 2012, 2015). The

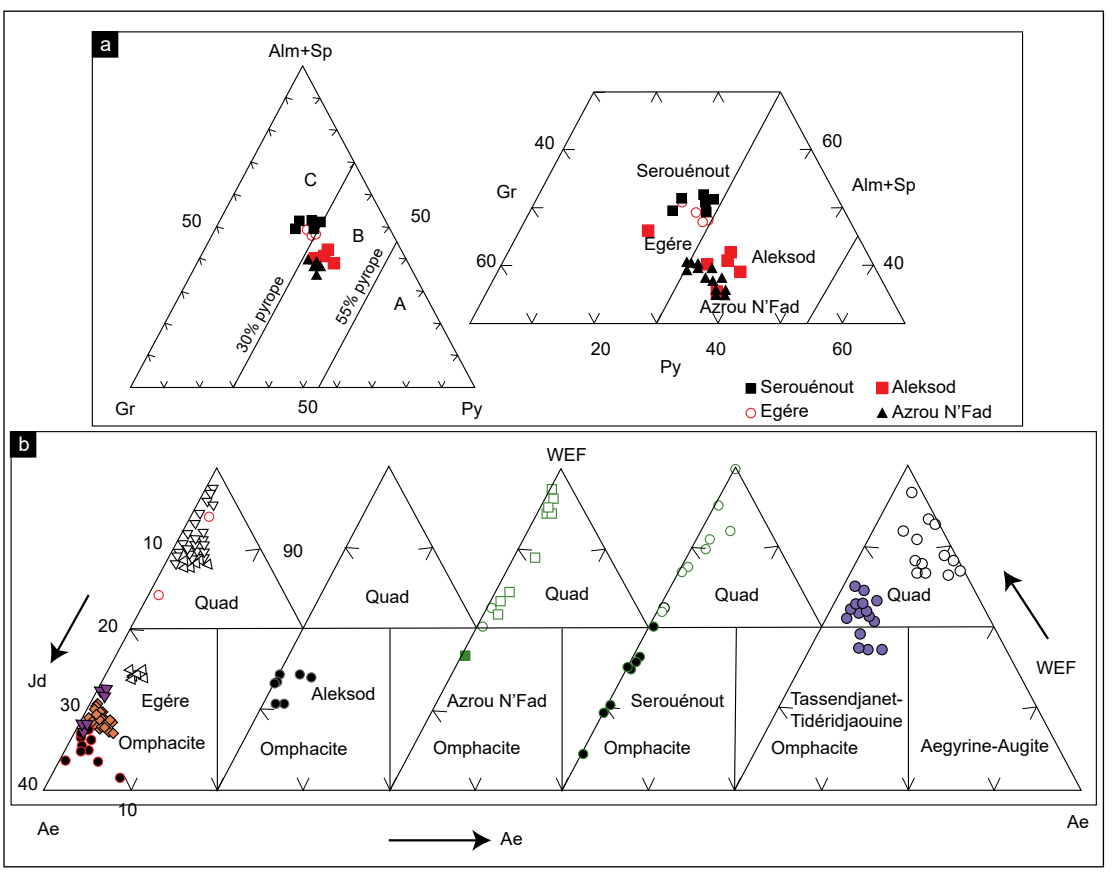


Fig. 5- Mineral compositions of garnet **(a)** and clinopyroxene **(b)** within eclogites of the various samples studied from the Hoggar Terranes (Doukkari *et al.*, 2015; Sautter, 1985; Berger *et al.*, 2014; Zetoutou *et al.*, 2004; Bitam-Derridj *et al.*, 2010).

Compositions minérales du grenat (a) et du clinopyroxène (b) dans les éclogites des différents échantillons étudiés provenant des terranes du Hoggar (Doukkari et al., 2015 ; Sautter, 1985 ; Berger et al., 2014 ; Zetoutou et al., 2004 ; Bitam-Derridj et al., 2010).

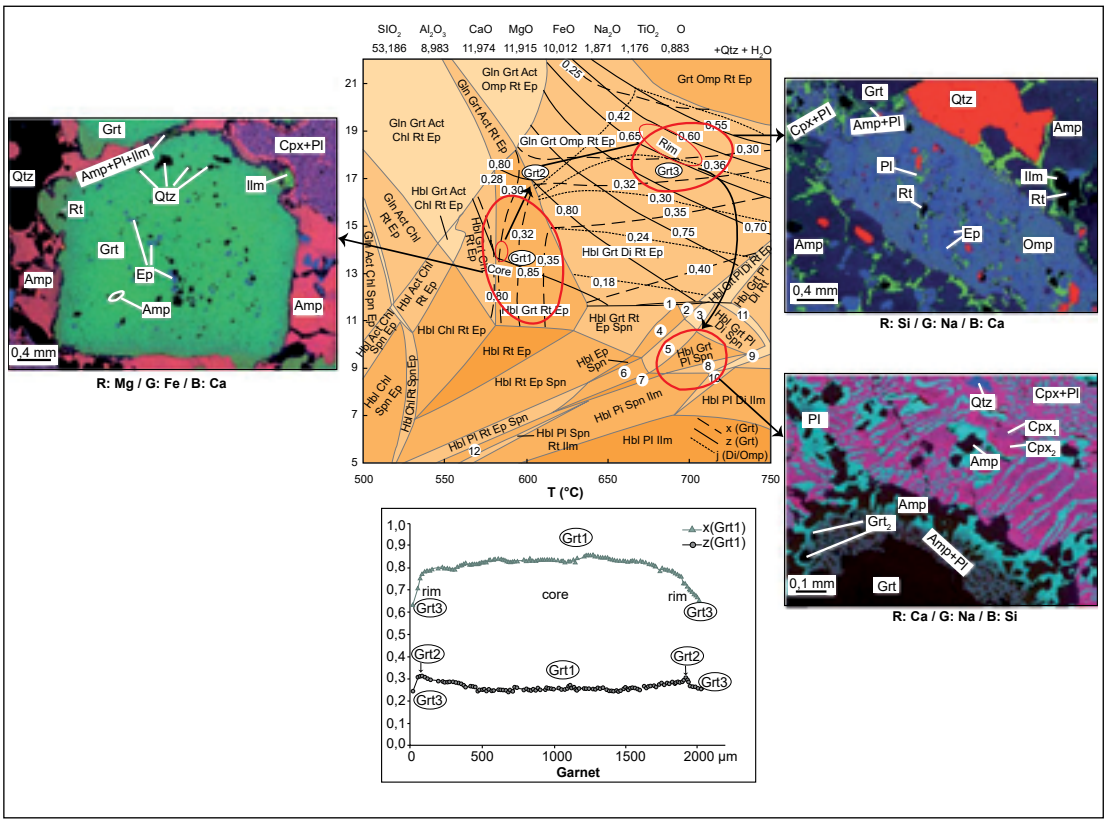


Fig. 6- P-T pseudosection showing the general clockwise P-T path of the Hoggar Terranes eclogites (Doukkari, 2016).

Pseudosection pression-température illustrant la trajectoire P-T générale, dans le sens des aiguilles d'une montre, des éclogites des terranes du Hoggar (Doukkari, 2016).

metamorphic evolution in this region is complex; the maximum jadeite component XJd of 0.30 combined with the garnet composition give eclogite-facies conditions (17 kbar and 650 ±50° C).

(v) According to Bitam-Derridj *et al.* (2010), after the first high-pressure stage, hydration of the eclogitic parageneses (omphacite, garnet, quartz, and rutile) led to the development of an amphibolite-facies paragenesis (amphibole, plagioclase) under conditions estimated at 10–11 kbar, 600 ± 40°C. This was followed by an increase in temperature with the imprinting of the granulite facies, which is characterized by the appearance of orthopyroxene-plagioclase symplectites at 10–11 kbar and 813 ± 60°C (Bitam-Derridj *et al.*, 2010; Adjerid *et al.*, 2012).

(vi) In the Azrou N'Fad Terrane, eclogites are only preserved in the lens cores, whose edges have been completely transformed into garnet amphibolites (Zetoutou *et al.*, 2004).

Pressure–temperature conditions were determined using classical geothermo-barometry. Peak metamorphism occurred at ~760 ±50°C and ~15 ± 1.5 kbar, followed by retrograde evolution marked by garnet rim re-equilibration and secondary hornblende formation at ~11.5 ± 1 kbar and 700–750°C. Retrograde assemblages record conditions of ~11.1 ± 1.6 kbar, 792 ± 54°C, and low water activity ($aH_2O \approx 0.1$), reflecting eclogite breakdown and partial

re-equilibration in the amphibolite facies (Zetoutou *et al.*, 2004).

(vii) In the Tassendjanet-Tidéridjaouine Terrane, the P–T evolution of eclogites samples was reconstructed using garnet clinopyroxene thermometry and phase diagrams. Eclogitic peak conditions were estimated at ~630–650°C and 20–22 kbar, supported by garnet-omphacite thermometry and P-T pseudosections.

Garnet zoning indicates a retrograde path with decreasing pressure and temperature, with outer rim compositions suggesting stages at ~750°C/17kbarand~650°C/12kbar. Retrogression below 14kbar led to the formation of plagioclase-bearing assemblages (e.g., garnet–plagioclase–amphibole–diopside–titanite) stable around 680 °C and 10 kbar (Berger *et al.*, 2014).

V- GEOCHRONOLOGY

Dating eclogites in orogenic belts is crucial as it provides precise timing of high-pressure metamorphic events, which helps reconstruct the P-T-t paths of crustal thickening and exhumation processes, in addition to the age of the protolith that offers powerful information regarding the emplacement geodynamic context.

This temporal information is essential for understanding the dynamics, duration, and tectonic evolution of mountain-building episodes.

(i) Within the Egéré Terrane, two samples were dated Eg18 and T96, with six zircons dated in Eg18, and four zircon grains in T96, most of which are beautiful bipyramidal crystals (Doukkari, 2016; Ouzegane *et al.*, 2023).

Sample Eg18 is a well-preserved eclogite enclosed in marble in the Adrar Izzilatène area (Doukkari *et al.*, 2015). Three datable zircon grains were extracted from this mafic rock, yielding six analytical spots (fig. 7a). Although all analyses are discordant, they define a discordia that aligns closely with data from eclogite-facies paragneisses in the Tighsi area. Additionally, four zircon grains from another sample of mafic rock provided five analyses, four of which define a Discordia line with an upper intercept age of 2118 ± 21 Ma and a lower intercept age of 613 ± 21 Ma.The upper intercept age is interpreted as the best estimate for the protolith crystallization, while the lower intercept age is attributed to Pan-African metamorphism.

The eclogite represented by sample T96 occurs as meter-scale lenses and yields a U–Pb zircon age of 1507 ± 32 Ma (MSWD = 0.02; lower intercept at 38 ± 240 Ma), interpreted as the best estimate for the emplacement age of the protolith. This Calymmian magmatic event is previously unrecorded in the Tuareg Shield and is reported here for the first time in the Egéré region. An additional zircon analysis yields a concordia age of 584 ± 20 Ma (MSWD = 0.21); this grain, characterized by a significantly lower Th/U ratio (0.12) compared to the other zircons (0.61–0.71), is interpreted as recording Pan-African metamorphism (Ouzegane *et al.*, 2023).

(ii) In the western Hoggar (Tassendjanet Terrane), eclogites show a Neoproterozoic age of 623 ±3 Ma (fig. 7c), probably corresponding to eclogitic metamorphism (Berger *et al.*, 2014). The U–Pb zircon dating from 16 spots reveals that 15 are concordant or slightly discordant (<10%), yielding a well-constrained crystallization age of 622–623 ± 5–7 Ma. Most zircons exhibit very low Th/U ratios (<0.1), consistent with metamorphic origin, and the most concordant 8 spots (<2% discordance) define a precise concordia age of 623 ± 2 Ma. The major, trace, and isotope element geochemistry of these eclogites favors the emplacement of basaltic protoliths in a rift context at 700–800 Ma. These eclogites therefore represent fragments of a continental portion that was dragged down along a sub-

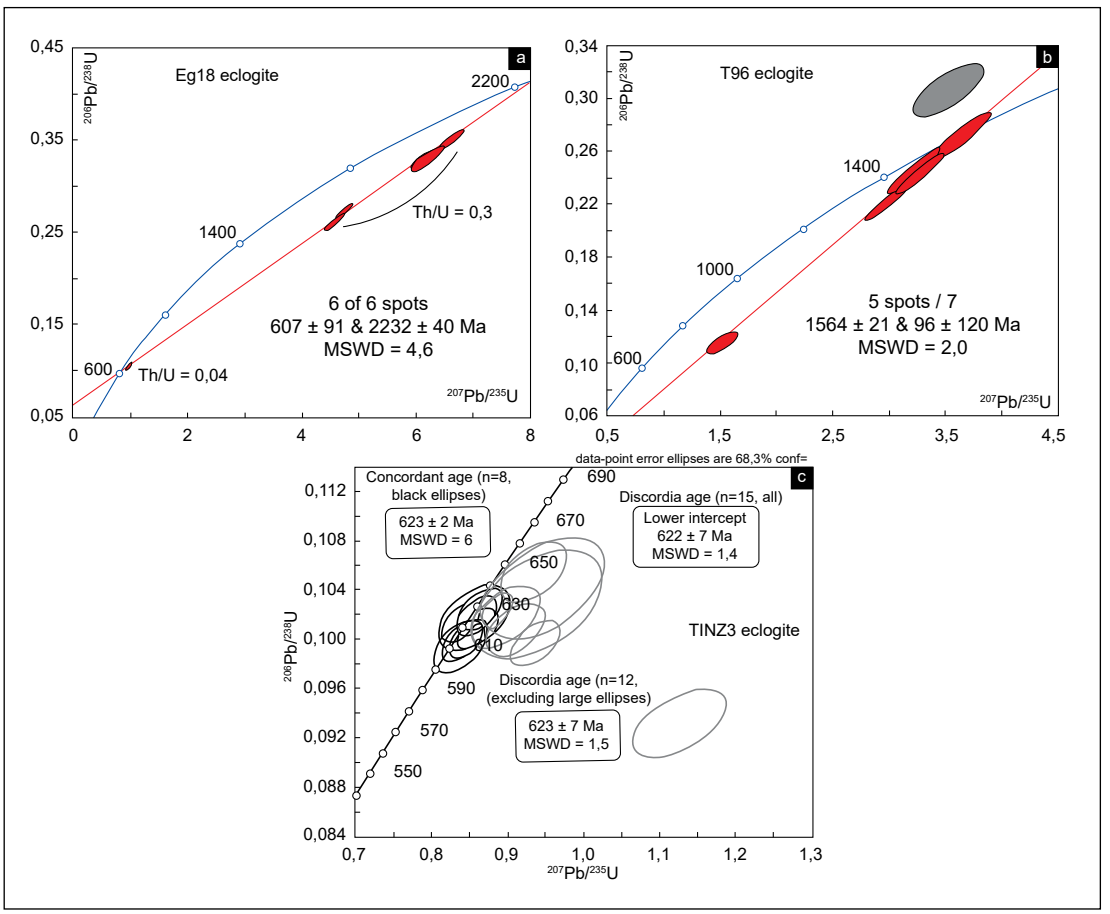


Fig. 7- Concordia plots of the eclogites zircons. **(a-b)** The Egéré eclogites (Ouzegane *et al.*, 2023). **(c)** The Tassendjanet-Tidéridjaouine eclogites (Berger *et al.*, 2014).

Diagrammes de Concordia des zircons d'éclogite. (a–b) Les éclogites d'Egéré (Ouzegane et al., 2023). (c) Les éclogites de Tassendjanet-Tidéridjaouine (Berger et al., 2014).

duction zone by the denser oceanic crust west of the In Ouzzal terrane (Berger *et al.*, 2014).

(iii) In the Laouni Terrane, the amphibolite/granulite-facies conditions (760 ± 30 °C and 11 ± 3 kbar) characteristic of the Tin Begane region have been attributed to the early Pan-African orogeny (Liégeois *et al.*, 2003), since positive εNd values, low initial Sr ratios, Neoproterozoic Nd TDM model ages, and Sm–Nd mineral isochron ages of 685± 19 Ma have been obtained for garnet amphibolites previously described as retromorphic eclogites (Boughrara, 1999; Liégeois et al., 2003).

VI- GEOCHEMICAL CHARACTERISTICS

The geochemistry of eclogites is crucial for understanding the origin, evolution, and tectonic setting of their protoliths. Major and trace element compositions, along with rare earth element (REE) patterns, help to distinguish between mid-ocean ridge, island arc, or intraplate basaltic sources. Geochemical signatures also reveal magmatic processes, such as fractional crystallization or cumulate formation, and provide insights into subduction-related fluid interactions and metamorphic overprinting.

Thus, eclogite geochemistry is a powerful tool for reconstructing crustal formation and recycling in convergent margins.

(i) The Egéré eclogites and garnet amphibolites (e.g., Eg18 dated at ~2.1 Ga) display basaltic compositions with limited variation in major elements, low Mg# (36–43), and plot as subalkaline basalts.

Their REE patterns are relatively flat with weak or absent Eu anomalies and show MORB-like trace element profiles, though enriched in Ba and K-Rb, resembling continental tholeiitic basalts such as Karoo or Giessen-South Harz types. Younger Calymmian eclogites (~1.55 Ga) from the Tighsi area are high-Fe tholeiites with similar subalkaline signatures, flat to slightly LREE-enriched patterns, weak Eu anomalies, and trace element characteristics typical of intraplate basalts, lacking a Ta-Nb negative anomaly (Ouzegane et al., 2023).

Furthermore, the Sr isotopic system in the studied rocks was reset during Pan-African metamorphism and is unreliable for older age interpretations, unlike the more robust Nd isotopes. Eclogites and garnet amphibolites/gabbros from the Lower and Upper Egéré groups exhibit high $^{147}Sm/^{144}Nd$ ratios (0.182–0.214), causing their evolution lines to run nearly parallel to the mantle array and rendering model age estimates uncertain. Despite this, Nd TDM ages range from ~1.85 to 2.2 Ga or older, suggesting that the protoliths are ancient (Paleoproterozoic to Archean) rather than juvenile Neoproterozoic material. During the Pan-African event (~600 Ma), these rocks retained an apparently juvenile isotopic signature due to their mantle-like Rb/Sr and Sm/Nd ratios, although this signature reflects a much older source (Ouzegane *et al.*, 2023).

(ii) Eclogites from Foutes (Azrou N'fad Terrane: Zetoutou *et al.*, 2004) are geochemically divided into high-Mg (Mg# 69–72) and low-Mg (Mg# 52) types. Both types exhibit island arc tholeiitic affinities and display similar, nearly flat REE patterns without significant Eu anomalies, suggesting immobile REE behavior during metamorphism and a likely cogenetic origin. Enrichment in K, Rb, and Ba further supports an island arc setting, while the high-Mg eclogites show cumulate features, such as elevated Cr content (1168–1407 ppm).

(iii) Eclogites from Tassendjanet Terrane (Berger *et al.*, 2014) are characterized by low SiO_2, Al_2O_3, and Na_2O contents, and high TiO_2 and MgO, with trace element signatures indicative of alkaline basalt. Despite this, the FeO/MgO vs. SiO_2 diagram suggests tholeiitic affinity for the broader suite. Low Sr and Cr contents, along with the absence of positive Eu anomalies, support a basaltic melt origin rather than a cumulate.

A sample is strongly enriched in incompatible elements (e.g., Zr, Nb, Th) and displays a steep REE pattern ($(La/Yb)N = 9.59$), typical of alkali basalts, with notable negative anomalies in Rb, K, Pb, and Sr.

VII- DISCUSSION AND CONCLUSIONS

The Hoggar eclogites provide important geodynamic constraints on the evolution of this domain, especially the LATEA metacraton. The protolith ages of the Hoggar eclogites are inferred to be either Archaean–Paleoproterozoic or Neoproterozoic (Bernard-Griffiths *et al.*, 1991; Liégeois *et al.*, 2003; Berger *et al.*, 2014; Ouzegane *et al.*, 2023). The interpretation of Archaean–Paleoproterozoic protolith ages is not unequivocal, and it has been argued that the high 147Sm/144Nd ratios of ~0.19 in these rocks preclude the calculation of meaningful Nd TDM model ages (see Liégeois and Stern, 2010 and Stern, 2002). For eclogite occurrences where the protoliths appear to belong to the Archaean–Paleoproterozoic basement, the eclogitic parageneses have been linked to reworking of the rocks along Pan-African structures (Saut-

ter, 1985; Sautter and Harte, 1986; Ouzegane *et al.*, 2023). Conversely, where the eclogites were derived from juvenile protoliths, such as at Tidéridjaouine (Berger *et al.*, 2014), it has been demonstrated that the rocks originated as basalts formed 700–800 Ma ago in a continental rift that evolved into an oceanic basin, before experiencing eclogite-facies metamorphism at 623 ± 3 Ma (Berger *et al.*, 2014).

The eclogites of the Egéré areas represent a very good example to study the exhumation of the high-pressure basic rocks; the conditions of 19.6 kbar - 694°C are the highest obtained in the LATEA metacraton (Doukkari *et al.*, 2014, 2015; Arab *et al.*, 2015, 2021; Ouzegane *et al.*, 2023).

The use of the thermodynamic modeling has allowed the investigation of the P–T path and the different reactions that happened during the exhumation; furthermore, the isopleths track the evolution of each mineral composition in relation to the pressure/ temperature modification. The clockwise P–T path of eclogite from the Egéré-Aleksod terrane is characteristic of a major burying of the crust during subduction or continental collision followed by exhumation which goes from 19.6 kbar - 694 °C (60 km deep) to 9.3 kbar - 695 °C revealed by a spectacular range of reaction textures, particularly amphibole, diopside, plagioclase and ilmenite symplectites that replaced the peak metamorphic mineral assemblage (garnet, omphacite, quartz, rutile) (Ouzegane *et al.*, 2023).

The Egéré lithologies underwent subduction and exhumation between ~680 and 630 Ma along a clockwise P–T–t path, reaching peak pressures of ~20 kbar at 650°C and peak temperatures of ~800°C at 14.5 kbar during slab break-off, followed by cooling to

~690°C and 8 kbar. A prolonged post-collisional transpressive phase led to further cooling to ~610°C and 6 kbar by ~580 Ma, generating Barrovian metamorphism and NW-verging thrusts due to tectonic compression from the Amadror craton. The Egéré-Aleksod terrane is distinct within the Tuareg Shield due to its abundant metasediments, early Paleoproterozoic magmatism, Pan-African eclogite record, absence of Paleoproterozoic orogenic and Pan-African magmatic events, as well as the presence of a concealed Archean craton, offering crucial insights into the region's tectonic history.

Eclogites from the Tassendjanet and Tidéridjaouine areas in Western Hoggar (Berger *et al.*, 2014) recorded peak metamorphic conditions of ~650°C and 20–22 kbar, followed by exhumation marked by a slight temperature increase to ~730°C at 14–18 kbar, then cooling to ~610 °C at 7–10 kbar. Geochemical and isotopic data suggest their igneous protoliths were Neoproterozoic rift-related basalts derived from a heterogeneous subcontinental lithospheric mantle contaminated by >1.8 Ga crustal material. While fragments of oceanic lithosphere are not yet identified, pre-metamorphic mafic-ultramafic complexes in the Tassendjanet terrane are potential remnants of oceanic lithosphere. The lack of arc-related signatures may reflect short-lived subduction. U–Pb dating of metamorphic zircon in eclogite yields an exhumation age of 623 ± 2 Ma, interpreted as related to westward transport of HP units, indicating an east-dipping subduction. Exhumation was likely followed quickly by transpressive shearing due to northward movement of the In Ouzzal terrane, with sinistral strike-slip deformation beginning around 620 Ma, although further geochronological data are needed to refine the tectonic timeline (Berger *et al.*, 2014).

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