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Preface

The Precambrian of Hoggar, Tuareg shield: history and perspective

The Hoggar is located in southern Algeria and constitutes the major part of the Tuareg shield, which comprises also the Adrar des Iforas in Mali to the SW and the Aïr in Niger to the SE.

The first geological observations were made during the great geographical explorations of the 19th century, especially after 1850: Barth (1863) in Eastern Hoggar, Duveyrier (1864) on the Atakor volcanic massif, contributed important information. The Foureau–Lamy expedition of 1898–1900 recognised the presence of a crystalline basement under sandstone formations (Foureau, 1898; the samples were studied by Gentil (1909)). From about 1900 until the First World War, the geological explorations followed the axes of the French military progression. In 1909, Chudeau published his memoir on the "Sahara soudanais" (Sudanese Sahara), in which he considered the "highly recrystallized" (= highly metamorphic) gneisses as Archaean but the micaschists as Silurian. In 1911, Flamand, in his publication entitled "Recherches géologiques et géographiques sur le haut pays de l'Oranie et du Sahara" grouped all the metamorphic rocks in one basement, estimating that the youngest could be Cambrian.

After the First World War, the pace of geological studies in Hoggar quickened. Bütler's memoir (1922, 1924) is the first really precise description of Hoggar geology. Between 1921 and 1932, Kilian introduced fundamental clarifications in the understanding of the central Saharan structure and thus opened the way for systematic research (e.g. Kilian, 1931). He defined the Tassilian unconformity separating the basement from the unmetamorphosed Phanerozoic sedimentary rocks, and he subsequently proposed a major structural subdivision of the Hoggar by dividing the basement into two terms: the younger slightly metamorphic Pharusian "series" and the older strongly metamorphic Suggarian series (Kilian, 1932). Bourcart, alone in 1923 and with Monod in 1929–1930, extended the concept of a Tassilian unconformity to the western Hoggar. They published jointly in 1932 a description of the Adrar Ahnet area. Denaeyer (1923a,b, 1925), a Belgian geologist, provided the first detailed petrographical descriptions of the Precambrian rocks of the Tuareg shield. Bourcart also described the Atakor volcanic massif, later to be investigated in more detail by Bordet (1954). All these pioneering works were synthesized in 1937 in the sheet no. 1 of the international geological map at the scale of 1/5,000,000, whose explanation booklet was mainly written by Kilian (1937).

In 1938, Lelubre began his research work in Hoggar, which lasted until the presentation of his thesis in 1952. Lelubre built a synthesis in two volumes of the Western and Central Hoggar, which constituted the basis of the following geological studies in the region. Lelubre can be regarded as having initiated the modern geological studies in Hoggar. He considered that the Suggarian and the Pharusian "series" belonged to two distinct orogenic cycles. He distinguished moreover two groups within the Suggarian: an old basement (Arechchoum gneisses) being covered by a mainly metasedimentary series (Egéré "series"). At the same time in the Adrar des Iforas in Mali, Roman Karpoff applied the same concepts and defined in addition the *Nigritian* "Series", which he believed to represent a distinct geological cycle, but which is actually the youngest Precambrian series made of molasse sedimentary and volcanic rocks, the whole being described in his thesis (Karpoff, 1958). The work of Lelubre was remarkably highlighted during the International Geological Congress in Algiers in 1952.

During the fifties, the great period of geological mapping (made at the scale of 1/200,000 and published at the 1/500,000 scale) and of mining exploration began within the framework of the BRMA (Bureau de Recherches Minières de l'Algérie). Nearly all the Hoggar was mapped and numerous unpublished reports were written. This is the period of geologists such as Arène, Blaise, Byramjee, Guérangé, or Vialon. These root works, although mainly unpublished, constituted the basis of further works.

In 1962 Algeria become independent and the geological studies, including mapping and mining, were organised following three axes: (1) the university cooperation allowed the nomination of cooperant professors in the newly created universities; Fabre and Fabriès

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played an important role; (2) in France, the CRZA (Centre de Recherches des Zones Arides) is largely developed and is at the origin of the first multidisciplinary research (including geology) in Hoggar. This is the period of the major theses of the "Saharan" French geologists, Gravelle (1969), Boissonnas (1973), these two were actually being initiated in the days of BRMA, Caby (1970), Bertrand (1974), Latouche (1978) and Vitel (1979), all of them combined extensive field work (leading to a geological map) and laboratory work. With the exception of eastern Hoggar, these theses covered nearly all the Precambrian of Hoggar and resulted many international publications; (3) in Algeria, the SONAREM (Société Nationale de la Recherche Minière) was created. It developed, in cooperation with the universities, the CRZA and USSR, its own programs turned towards mining exploration.

All these works converged in 1977 to a fundamental synthesis, the geological map of the Hoggar at the 1/1,000,000 scale, which is still in use. The main contributors to this map were Caby, Bertrand and the SONAREM. This map gave for the first time a homogeneous view of the whole Hoggar with a subdivision based on time, distinguishing Archaean and four Proterozoic units (Pr1, Pr2, Pr3 and Pr4). It was accompanied by a remarkable description of the main lithological units identified. As in many areas, the initial subdivision in Suggarian and Pharusian based on the grade of metamorphism was questioned by the first geochronological measurements (U-Pb on zircon) performed on Hoggar rocks by Picciotto et al. (1965): for instance, the "Pharusian" Ouallen granite gave an age of approximately 1900 Ma and the "Suggarian" granites in the Tamanrasset area gave ages in the range 650–600 Ma, thus prompting the idea that measured ages reflected extensive rejuvenation at the end of Precambrian times. The concept that developed later was to consider the Suggarian as the equivalent of the Eburnian ($\approx$2 Ga orogeny) or of the middle Palaeoproterozoic (2.2–1.8 Ga) and the Pharusian as the equivalent of the Pan-African ($\approx$0.6 Ga orogeny) i.e. related to the Neoproterozoic.

The 1977 geological map (Sonarem et al., 1977) displays remarkably the existence of N–S oriented mega-shear zones. The two most important extend respectively along the 4°50′ and 8°30′ meridians, that gave them their name. They were considered as separating the Western Hoggar (mainly "Pharusian"), the Central Hoggar (mainly "Suggarian") and the Eastern Hoggar. This subdivision constituted the basis of further studies at least for 15 years.

During the eighties, the cooperation between Algeria and France became more formal through the initiation of "Accord-Programmes" between universities and ORGM (formerly SONAREM). The Hoggar became better known but always within the homogeneous framework of the 1977 geological map. During this period, independent efforts were oriented towards: (1) the Adrar des Iforas in Mali where a geological map was established by the CGG (Centre Géologique et Géophysique, evolution of the CRZA) of Montpellier in 1981 and where Late Precambrian plate tectonics was demonstrated (Black et al., 1979); (2) the Aïr, in Niger, initially mapped by Black et al. (1967) and where terrane geodynamics were introduced by Liégeois et al. (1994). This led to a strong rupture in 1994 in the global interpretation of the Hoggar geology. Based on the Aïr work and on the whole Hoggar knowledge, including BRMA reports, Black et al. (1994) suggested that the Tuareg shield (550,000 km^2) corresponds to the amalgamation of more than 20 terranes during the Pan-African orogeny. These terranes were shown to be contrasted, comprising juvenile oceanic Neoproterozoic terranes, remobilized or well-preserved Archaean and Palaeoproterozoic terranes. The Mesoproterozoic (1600–1000 Ma) is remarkably absent. These terranes are N–S elongated, their main relative movements having resulted from a northern transpressional tectonic escape due to their squeezing between the West African craton to the west and the East Saharan craton (now Saharan metacraton) to the east. This model explained a series of major Hoggar features such as the difficulties of E–W correlations, but gave rise to new major questions including the way along which the Hoggar terrane amalgamation occurred and the origin of the various Hoggar terranes.

For the last 10 years, a small group of Algerian geologists who did their PhD thesis in Hoggar during the early nineties have been educating young geologists in this region with the collaboration of European laboratories, mainly in France and in Belgium. In turn this shed new light on Hoggar geology. This Special Issue is a consequence of this new approach. It is also the final contribution of the co-operative program between the French university of Paris VII and the university of Algiers (USTHB) named "Héritage éburnéen et structuration pan-africaine du Hoggar: étude géologique et géophysique".

This Special Issue entitled "The Precambrian of Hoggar, Tuareg shield", contains 11 papers dealing with the petrology, geochemistry, geochronology, tectonics, geophysics and geodynamics of Hoggar. As it can be understood from the historical description above, the Hoggar is the result from the amalgamation of terranes during the Pan-African orogeny. However, it contains terranes that have well preserved Archaean and Palaeoproterozoic lithologies, including metamorphic parageneses. Also, in some areas, pre-amalgamation rocks such as island arc lithologies including high-pressure rocks such as eclogites have been preserved from pervasive collisional and subsequent post-collisional events. The successive collisions were responsible for the exhumation of these rocks while the final protracted post-collisional period is characterized transpressive mega-shear zones, which are the result of the amalgamation. In turn, they were the cause of the dissection of the pre-existing microcratons (metacratonization) and of the genesis and emplacement of widge range of igneous rocks. Just before its rapid peneplanation and covering by a sandstone cap, the Hoggar was subjected to transtension, generating small rift basins filled by molassic sediments and shallow-depth alkali-calcic and alkaline plutons. All these points are tackled in this Hoggar Special Issue. This volume includes three parts: (1) three papers concerning the general structure of Hoggar, from west to east; (2) four papers dealing with the preserved Archaean–Palaeoproterozoic lithologies; (3) four papers focused on the Pan-African orogeny.

1. General structure

In the first paper, **Caby** focuses on the Neoproterozoic subduction- and collision-related stages in the Western Hoggar. After reassessing available field (with several synthetic maps), geochemical and geochronological data, Caby proposes a new geodynamic scenario with several palaeosubductions zones implying an important diachronism of the Pan-African building of the Hoggar. He also provides some new information on the late molasses.

The second paper by **Liégeois et al.** shows that four terranes from the Central Hoggar belonged to one small Archaean/Palaeoproterozoic craton (LATEA) that was partly destabilized and dissected during the post-collisional stage of the Pan-African orogeny, forming a metacraton. This status implies the absence of major subduction and collisional events but the presence of preserved early Neoproterozoic oceanic thrust sheets and the intrusion of granitic batholiths along the mega-shear zones dissecting the metacraton. One oceanic thrust sheets and one granitoid body are dated and their petrology, geochemistry and isotope geochemistry studied.

The third paper by **Bournas et al.** provides an aeromagnetic map of Eastern Hoggar. The three methods used to locate major contacts and faults (Euler deconvolution, analytical signal, local wave number) allow to suggest a general structural scheme in which the eastern boundary of the Assodé-Issalane terrane is the suture zone between the Central Hoggar and the Eastern Saharan craton (= Saharan metacraton).

2. The Archaean and Palaeoproterozoic events

In the fourth paper, **Ouzegane et al.** review the Archaean and the Palaeoproterozoic evolution of the In Ouzzal granulitic terrane. This unique terrane in Hoggar hosts early Archaean (3.3–3.2 Ga) lithologies, in addition to predominant Archaean rocks in the age range 2.7–2.6, 2 Ga ultra high-temperature (more than 1000 °C) granulitic metamorphism (e.g. corundum-quartz, sapphirine-quartz, sapphirine-quartz-spinel) and 2 Ga carbonatites. A series of exceptional parageneses are reviewed and a geodynamical model is proposed where delamination and shear zones play a major role to obtain the high heat flow required.

In the fifth paper, **Peucat et al.** present TIMS and SIMS U–Pb zircon ages and Nd T_{DM} model ages on the Gour Oumelalen area (NE LATEA), marked by well-preserved Archaean lithologies. They reveal the presence of Archaean protoliths at 2.7 Ga with Nd T_{DM} at 3.0–3.2 Ga, of metasediments at 2.2 Ga and an age of 1.85 Ga for the charnockitic metamorphism (10 kbar, 850 ± 20 °C). The old Pb–Pb age of 3.5 Ga published in the seventies is not confirmed.

The LATEA metacraton comprises a series of 2.0–1.9 Ga granulitic lithologies. In the sixth paper, **Bendaoud et al.** describe ferrous granulites in the Tidjenouine area (Central LATEA) marked by the remarkable association orthoferrosilite-fayalite-quartz. This complex metamorphic history occurred from 7 to 4.9 kbar then to 3–4 kbar from 880 to 700 °C during a phase of thrust tectonics. A thrust structure can explain differences in P–T conditions observed in other nearby granulites.

In the seventh paper, **Derridj et al.** describe, in the Tin Begane area (southern LATEA), garnet pyroxenite from a high-pressure granulitic facies. The passage from a D_1 phase (13.5 kbar, 800 °C) to a D2 decompression phase (10.7–4.8 kbar, 800–700 °C in coronas and opx—pl ± hb ± sp) suggests a crustal thickening followed by an uplift. Retrogression path to greenschist facies is linked to Pan-African shear zones.

3. The Pan-African orogeny

In the eighth paper, in the light of structural, petrological and $^{39}Ar/^{40}Ar$ laser geochronological data, **Caby and Monié** re-examine the western terranes of Hoggar, which include a Palaeoproterozoic basement, an approximately 680 Ma mafic arc, a subduction-related high pressure belt (550–600 °C, 14–18 kbar) exhumed around 615–600 Ma and a low pressure granulitic belt (750–800 °C, <4.5 kbar), which cooled at a rate of 15 °C/Ma between 600 and 580 Ma, subsequently to the emplacement of late granitic plutons.

In the ninth paper, **Acef et al.** study the Anfeg granodioritic batholith intruded at approximately 608 Ma into LATEA during its metacratonization: its emplacement occurred within the 2 Ga basement along thrust planes related to the functioning of the Pan-African subvertical shear zones. Sr–Nd isotopes point to an old Rb-depleted granulitic source mixed with some mantle material. This agrees with an asthenospheric uprise provoked by a linear delamination along the mega-shear zones.

In the tenth paper, **Ait-Djafer et al.** study the Tin Zebane gabbro-anorthositic layered complex, emplaced along the western edge of the In Ouzzal metacraton together with an alkaline–peralkaline granitic dyke swarm dated at approximately 592 Ma. Late symplectites from this layered complex crystallized at 6.2 kbar for 800 °C and $aH_2O = 0.5$ to 0.6. This complex is a plagioclase-rich cumulate linked to a mantle source ($\varepsilon_{Nd} = +6$; $Sr_i = 0.7024$). This emplacement was possible because of the post-collisional transtensional movements that occurred along the rigid body of the In Ouzzal metacraton, inducing linear delamination and rapid uprise of the mantle melts.

The end of the Pan-African orogeny in Hoggar is marked by the intrusion of subcircular shallow-depth plutons called "Taourirt" in Central Hoggar. **Azzouni-Sekkal et al.**, in the last paper, redefine this expression that covers different subgroups similar by their deep source (mantle + old granulitic basement) but acquiring particularities through their interaction with their country-rocks, ranging from 2 Ga granulites to Neoproterozoic thrust island arcs assemblages. The Taourirt province is mainly alkali-calcic but can be alkaline and is linked to the late transtensive movements (≈525 Ma) along the mega-shear zones that dissected LATEA. Not a long time after, at the beginning of the Ordovician, the Hoggar was completely eroded and covered by the Tassilis sandy sedimentation.

This Special Issue shows that the Tuareg shield constitutes a fantastic area for studying a Precambrian orogen on its whole width, from a craton to another and for all disciplines. The current global model is assessed by current studies but it clearly needs refinements, which require a large panel approach from detailed geological mapping to high-tech studies. With such studies, the interpretations and conclusions obtained in Hoggar will likely be exported to other areas in the world. Also, such studies require cooperation between African countries, namely Algeria, Mali and Niger, sharing together the Tuareg shield.

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