Bulletin du Service Géologique National
Vol. **20**, n°**2**, pp. **189 - 203**, **9** fig., **1** tabl., **2009**

PRELIMINARY STUDY OF THE ANISOTROPY OF MAGNETIC SUSCEPTIBILITY OF THE AÏN KAHLA LATE PAN-AFRICAN GRANITES (NORTH-WEST HOGGAR, ALGERIA) AND STRUCTURAL IMPLICATIONS.

Avertissement : Cette note a fait l'objet d'une communication lors du 4 ème Programme International de la Corrélation Géologique I.G.C.P. 485 - Alger - Tamanrasset du 12 au 9 Décembre 2006.

Mehdi Amine GUEMACHE*, Bernard HENRY, Hamou DJELLIT***
and Mohamed El Messaoud DERDER*

ABSTRACT

The Aïn Kahla granites are located along the N-S-trending Late Pan-African Arak major fault, which separates the Ahnet and Mouydir basins (Algerian Saharan platform, North-West Hoggar). They belong to a crystalline and phyllo-crystalline complex located between a northern segment of the Arak fault in the West (Aïn Kahla fault) and one of its satellite faults at the East (called here «Eastern fault»). We analyze in this work the evolution of the anisotropy of magnetic susceptibility (AMS) of these granites over four sampling sites (with a total of 26 core samples) on an E-W cross section. The main magnetic carrier is magnetite, with multi-domain grained size. The shape parameter evolves from east to west, from a prolate shape to an oblate shape. The mean magnetic foliation dips with a relatively low angle towards the west. It contains a W to WNW shallowly-dipping magnetic lineation. The main directions of the magnetic fabric cannot be correlated with those of the visible brittle structures (mainly regional cleavages S1 and S2), that affected the granites at solid state later, likely at the end of the Paleozoic. It would rather express structures related to the deformation acquired during magmatic to late-magmatic state of the granite, between the Pan-African and Early Paleozoic times, within a WNW-ESE to E-W regional stress field.

Key words - Aïn Kahla granites - Eastern fault - Magnetic fabric - Magmatic to late - magmatic deformation.

ETUDE PRELIMINAIRE DE L'ANISOTROPIE DE SUSCEPTIBILITE MAGNETIQUE DES GRANITES TARDI-PANAFRICAINS D'AIN KAHLA (NORD-OUEST HOGGAR, ALGERIE) ET IMPLICATIONS STRUCTURALES.

RESUME

Les granites d'Aïn Kahla sont situés le long de la faille majeure panafricaine d'Arak, qui sépare les bassins de l'Ahnet et du Mouydir (Plateforme saharienne algérienne, Nord-Ouest Hoggar). Ils appartiennent à un complexe cristallin et cristallophyllien, situé plus précisément entre un segment septentrional de la faille d'Arak à l'ouest (faille d'Aïn Kahla) et l'une de ses

*Centre de Recherche en Astronomie, Astrophysique et Géophysique (CRAAG) : BP. 63, route de l'Observatoire, Bouzaréah 16340, Algiers, Algeria. (m.guemache@craag.dz).
**Paléomagnétisme, IPGP et CNRS : 4, avenue de Neptune, 94107 Saint-Maur des Fosses cedex, France.
- *Manuscrit déposé le 27 Mai 2007, accepté après révision le 01 Juillet 2008.*

failles satellites à l'est (appelée ici Faille orientale). Nous avons étudié l'évolution de l'anisotropie de susceptibilité magnétique (ASM) de ces granites à travers quatre sites d'échantillonnage (avec un total de 26 échantillons) disposés suivant une coupe est-ouest. Le principal porteur magnétique est la magnétite, caractérisée par des grains poly-domaines. D'est en ouest, le paramètre de forme évolue d'une fabrique allongée vers une fabrique aplatie. La foliation magnétique est orientée autour de la direction N-S et plonge faiblement vers l'ouest. Elle porte une linéation magnétique peu pentée vers la même direction. Les directions principales de la fabrique magnétique ne peuvent pas être corrélées de façon simple avec celles des structures cassantes visibles sur le terrain (notamment deux principales schistosités S1 et S2), qui ont affecté les granites à l'état solide, vraisemblablement à la fin du Paléozoïque. Ces directions exprimeraient plutôt des structures liées à une déformation magmatique ou tardi-magmatique, intervenue entre le Panafricain et le début du Paléozoïque, dans un champ régional de contraintes dominé par une compression WNW-ESE à E-W.

Mots-clés - Granites d'Aïn Kahla - Faille d'Arak – Faille orientale - Fabrique magnétique - Déformation magmatique à tardi-magmatique.

1. INTRODUCTION

The magnetic susceptibility K expresses the ability of a body to acquire a magnetization M when subjected to an inducing magnetic field H. It is given by the relation K = M/H. K corresponds to a second rank tensor, whose geometric representation is an ellipsoid with tree principal magnetic susceptibility axes: K_1 (maximum magnetic susceptibility axis), K_2 (intermediate magnetic susceptibility axis) and K_3 (minimum magnetic susceptibility axis), where $K_1 \geq K_2 \geq K_3$ and the bulk susceptibility $K_m = (K_1 + K_2 + K_3)/3$ (Jelinek, 1981). The magnetic anisotropy of a rock sample can be related to the lattice (crystalline) or for magnetite to shape-preferred orientations of the minerals. Often Fe-oxides or Fe-sulfides have the dominant role in the anisotropy of magnetic susceptibility (AMS). Depending on the studied material, the magnetic fabric reflects the mode of rock formation (sedimentation planes, paleocurrents, etc.) or deformation (compaction, magmatic flow, shape of the finite deformation ellipsoid, etc.). In the case of deformation, the orientation of anisotropy axes coincides often with the principal deformation directions (Hrouda, 1982; Henry and Hrouda, 1989; Borradaile and Henry, 1997), making the AMS a reliable tool for structural analyses. This tool can be applied to geological environments either strongly deformed or weakly deformed, especially when visible tectonic markers are lacking. This is referred to a structural magnetism, and it was early used for structural geological studies (Graham, 1954). When applied to granite body, the AMS reveals generally deformation that the granitic magma underwent before complete crystallization. It can reveal also subsequent tectonic deformation of the granite at its solid state. We aim precisely in this work using the AMS method in order to point out the potential structural relations existing between the Aïn Kahla granites and the activity of nearby major faults, during and after the granites emplacement.

2. GEOLOGICAL SETTING

The Ahnet and Mouydir Paleozoic basins are located North-West of the Hoggar (fig. 1). The two basins are separated by the N-S trending Arak fault (Beuf et *al.*, 1971; Haddoum et *al.*, 2001), which corresponds to a set of important generally vertical faults. Arak fault itself constitutes the northern prolongation of both the East-Ouzzalian fault and the Adrar fault, which are N-S-trending and cross the Hoggar from south of the study area to the Iforas area, located south-west of the Tuareg shield. Both faults join south of the study area into the Arak fault. The East-Ouzzalian fault separates the In Ouzzal granulitic terrane in the East, which corresponds to an Archaean crust remobilized during the Eburnean tectono-metamorphic event (2 Ga) that occurred in the granulites facies (Haddoum et *al.*, 1994), from the Tirek terrane in the West, composed of highly deformed and metamorphized rocks (amphibolite facies of high grade), comprising gneisses with alumina silicates (sillimanite, cordierite), garnets, amphiboles... Eastward, a batholith of deformed granites outcrops, limited eastwards by the Adrar fault, east of which the terrains are dominated by low grade Neoproterozoic volcanic and volcanoclastic rocks injected by granitoids. These major faults have been created during the Pan-African Orogeny, with the other major north-south shear zones of the Hoggar (e.g. 4°50 and 8°30 mega-shear zones), when the West African Craton collided with the Saharan Metacraton (Abdessalam et al., 2002), between 650 and 550 Ma (Bertrand and Caby, 1978; Black et *al.*, 1979; Caby et *al.*, 1981; Liégeois et *al.*, 1987), and was afterwards rejuvenated during the Paleozoic, influencing the sedimentological and structural evolution of the Ahnet and Mouydir basins (Beuf et *al.*, 1971; BEICIP, 1972a; Conrad, 1984).

The study area occupies the northern extremity of the Arak fault. At this place, two important sub-parallel segments of the Arak fault exist, namely the Aïn Kahla fault at the West and the In Nahas fault at the East (Guemache, 2005) (fig. 1a). The Paleozoic series ranges from the Cambrian-Ordovician, which can be observed at the core of NW-SE to N-S trending anticlines (e.g. Djebel Azaz, Djebel Idjerane), to the Carboniferous, drawing large synclines. Northwards, Paleozoic series are covered in unconformity by Meso-Cenozoic deposits. The Paleozoic series were structured during the main Hercynian tectonic phases at Late Carboniferous (BEICIP, 1972a; Conrad, 1984; Haddoum et *al.*, 2001), during which N-S right-lateral strike-slip faults created N160° drag-folds (BEICIP, 1972a; Conrad, 1984). Between the Upper Jurassic and the Lower Cretaceous, left-lateral movements along the N-S strike-slip faults superimposed N020° drag-folds (BEICIP, 1972a; Conrad, 1984), with a comparable intensity (Smith et *al.*, 2006).

At the location 27°31'N and 3°24'E (fig. 1a), along the Aïn Kahla fault, granites outcrop (Bennaceur and Airèche, 1995; Guemache, 2005) within a highly deformed basement, composed of thick series of schist, quartzite, etc. (BEICIP, 1972a,b), related to the Pharusian series of the Hoggar (Kilian, 1932), and of dolerites. Rocks looking like rhyolite outcrop also around the granites (Guemache, 2005). The surface area is of about 2.5 km². The basement complex is limited to the West by the Aïn Kahla fault and to the East by an important fault, called here «Eastern fault», which would connect southwards to the Aïn Kahla fault (fig. 1a).

The magmatic rocks emplaced likely between the Pan-African and Lower Paleozoic. Indeed, at the East, the basement is unconformably covered by the Tamadjert formation of Ordovician age (fig. 2a and 2b), which is composed of detrital glacial deposits, and there are no magmatic rocks observed into these deposits. The magmatic rocks observed in the study area are then Pre-Ordovician. On the other hand, the magmatic rocks are only slightly deformed but are within a strongly deformed series. Therefore, they emplaced after the main defor-mation that occurred during Pan-African times.

Besides, this means that the first tectonic exhumation/erosion phenomon affected the complex prior to the Upper Ordovician, likely during the Taconic phase of the Caradocian (Beuf et *al.*, 1971). It was then likely buried under Upper Ordovician-to-Carboniferous series, and finally exhumed again by the major tectonic events at the end of the Carboniferous and the Jurassic-Cretaceous boundary. Indeed, the «Eastern Fault» also affects the unconformably overlying Ordovician formations (fig. 1a, 2a and 2b).

The Aïn Kahla granites are middle-grained and consist of anhedral quartz with rolling extinction, K-feldspar (orthoclase), plagioclase (An_{30-50}), Mg-rich amphibole (magnesio-hornblende; Leake et *al.*, 1997), biotite, chlorite and accessory minerals, such as sphene and opaque minerals (Guemache, 2005; Guemache et *al.*, 2006). The geothermobarometry shows that the granites crystallized approximately at a temperature of 750°C, a pressure of 3 kbars and at about 11 km of depth (Guemache, 2005; Guemache et *al.*, 2006).

Outcrop conditions are somewhat bad, showing difficult *in situ* structural investigations. Indeed, granites, although clearly in place, outcrop as blocks of some decimeters, wide forming the top of small hills, around which little fine-grained blocks lay concentrically (fig. 2a). Nevertheless, the sampled granites present slight preferred orientation. They are also affected by poorly expressed S/C structures. Two main regional cleavages, S1 and S2, were also observed and trend statistically respectively N160°-75°W and N070°-90°. Geometrical ratios between the two cleavages indicate that S1 is prior to S2. We have also seen at one place a shallowly-dipping fault affecting the granite. This quasi-horizontal fault trends N150°-10°W and evokes a local thrusting movement. However, the bad outcrop conditions did not allow us to see any slickenlines. This fault overlies the cleavage S2. Therefore, its movement is subsequent to both S1 and S2 cleavages.

Fig.1: (a) Geological map of the Aïn Kahla area (modified and completed from the 1/200 000 geological map of Ers Oum el Lil; BEICIP, 1972b), showing the location of the crystalline and phyllo-crystalline outcrop, to which belong the studied granites, according to the Aïn Kahla fault ***(Carte géologique de la région d'Aïn Kahla (modifiée et complétée d'après la carte géologique de Ers Oum el Lil au 1/200 000; BEICIP, 1972b), montrant la localisation de l'affleurement du complexe cristallophyllien, auquel appartiennent les granites étudiés, par rapport à la faille d'Aïn Kahla)***.

1: Quaternary ***(Quaternaire)***; **2:** Cenozoic ***(Cénozoïque)***; **3:** Cretaceous ***(Crétacé)***; **4:** Carboniferous ***(Carbonifère)***; **5:** Upper Devonian ***(Dévonien supérieur)***; **6:** Middle Devonian ***(Dévonien moyen)***; **7:** Lower Devonian ***(Dévonien inférieur)***; **8:** Silurian ***(Silurien)***; **9:** Ordovician ***(Ordovicien)***; **10:** Pan-African crystalline and phyllo-crystalline complex ***(Complexe cristallophyllien panafricain)***.

(b) Location of the area within the actual general geological context of North Africa ***(Situation de la région d'étude dans le contexte géologique général actuel d'Afrique du Nord)***.

1: Archean units ***(Unités archéennes)***, **2:** Proterozoic series ***(Séries protérozoïques)***, **3:** Pan-African orogeny material ***(Séries du Panafricain)***, **4:** Palaeozoic series (North of the Hoggar) ***(Séries paléozoïques (au nord du Hoggar))***, **5:** Meso-Cenozoic series ***(Séries méso-cénozoïques)***.

For western Hoggar ***(Pour le Hoggar Occidental)***: **AH:** Ahnet basin ***(Bassin de l'Ahnet)***, **MY:** Mouydir basin ***(Bassin du Mouydir)***, **AF:** Arak Fault ***(Faille d'Arak)***, **EOF:** East-Ouzzalian Fault ***(Faille est-ouzzalienne)***, **EPB:** East Pharusian branch ***(Branche pharusienne est)***, **WPB:** West Pharusian branch ***(Branche pharusienne ouest)***, **IO:** In Ouzzal Archean unit ***(Unité archéenne de l'In Ouzzal)***.

(c) Satellite view (Google Earth) of the study area ***(Image satellitaire (Google Earth) du secteur d'étude)***.

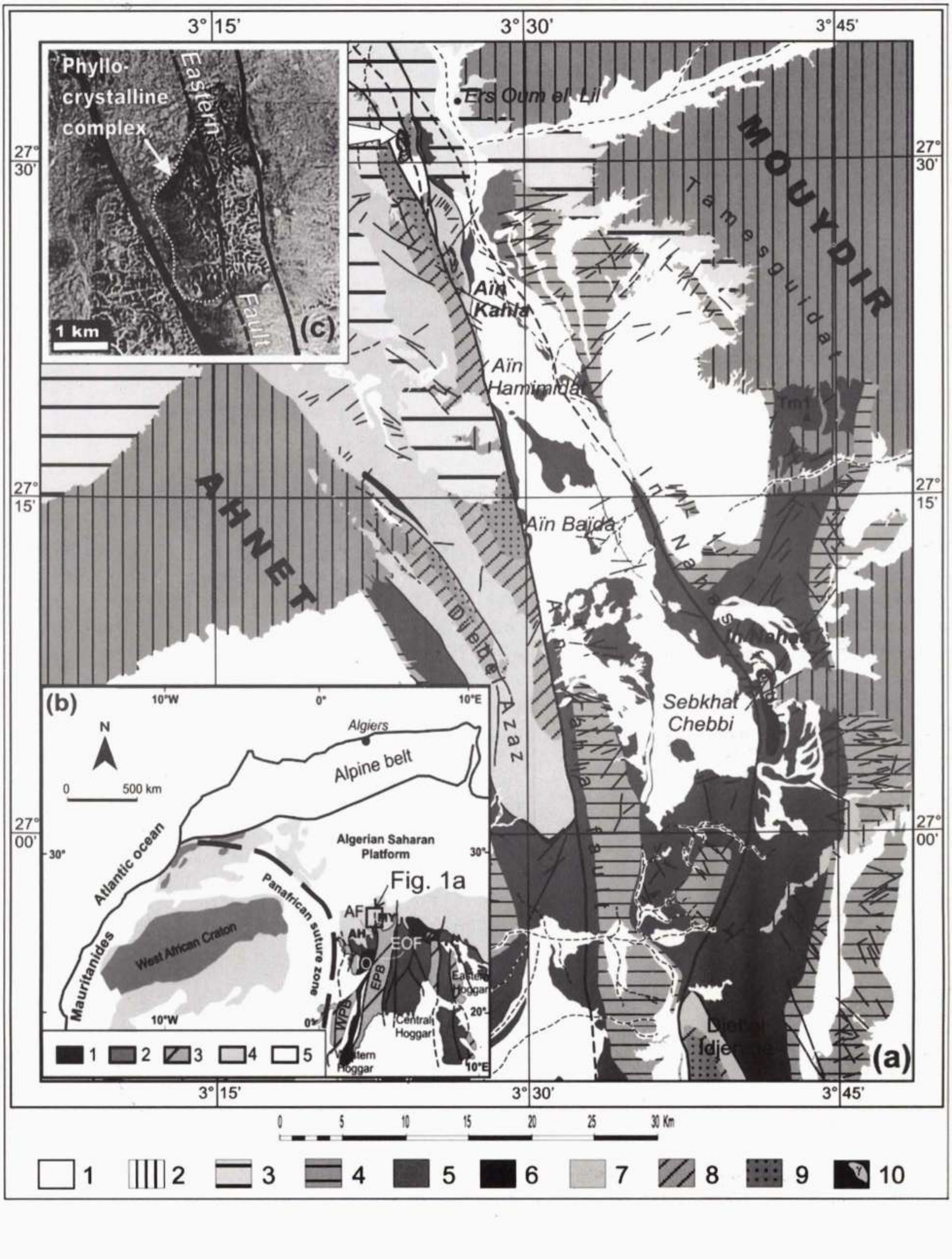
3° 15'
3° 30'
3° 45'
27° 30'
27° 15'
27° 00'
Phyllo-crystalline complex
Eastern Fault
1 km
(c)
Ers Oum el Lil
MOUYDIR
Tamesguidat
Aïn Kahla
Aïn Hamimidat
Tm1
AHNET
Aïn Baïda
In Nahes
Djebel Azaz
Sebkhat Chebbi
Djebel Idjerane
(a)
(b)
10°W
0°
10°E
N
0
500 km
Algiers
Alpine belt
Atlantic ocean
Algerian Saharan Platform
30°
Fig. 1a
Panafrican suture zone
AF
MY
AH
EOF
IO
EPB
WPB
West African Craton
Mauritanides
Eastern Hoggar
Central Hoggar
Western Hoggar
20°
0°
1
2
3
4
5
0
5
10
15
20
25
30 Km
1
2
3
4
5
6
7
8
9
10

Fig. 2 - (a) Photography of the first site of sampling (site 1).

Photographie du premier site d'échantillonnage (site 1).

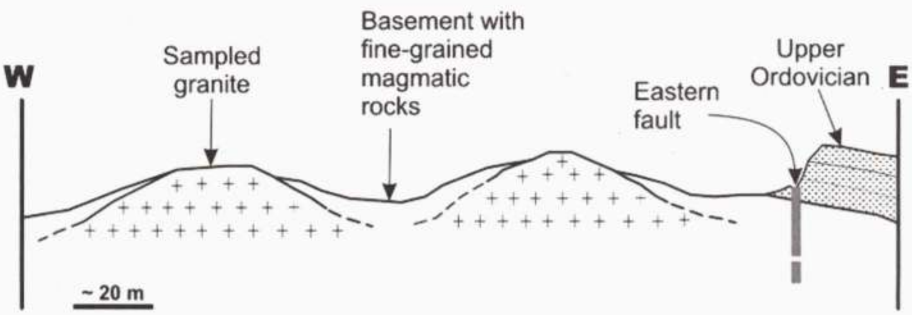

Fig. 2 - (b) Representative geological cross section showing the relationship between the granites and the host-rock.

Coupe géologique représentative montrant la relation entre les granites et l'encaissant.

Some 26 oriented core samples were taken over four sites (1 to 4) (table I), concentrated along an E-W cross section, perpendicular to the nearby «Eastern Fault» (fig. 3). The sites are distant one to each other of about 60 meters. In that way, we can study the variation of the magnetic fabric, then that of the finite deformation (Hrouda, 1982; Henry and Daly, 1983; Henry and Hrouda, 1989; Borradaile and Henry, 1997). This will allow checking if the magnetic fabric is related to (1) a late deformation that affected granites at solid state in relation with the tectonic activity of the «Eastern fault» or (2) rather to a deformation acquired before the entire solidification of granites, i.e. at magmatic or late-magmatic states.

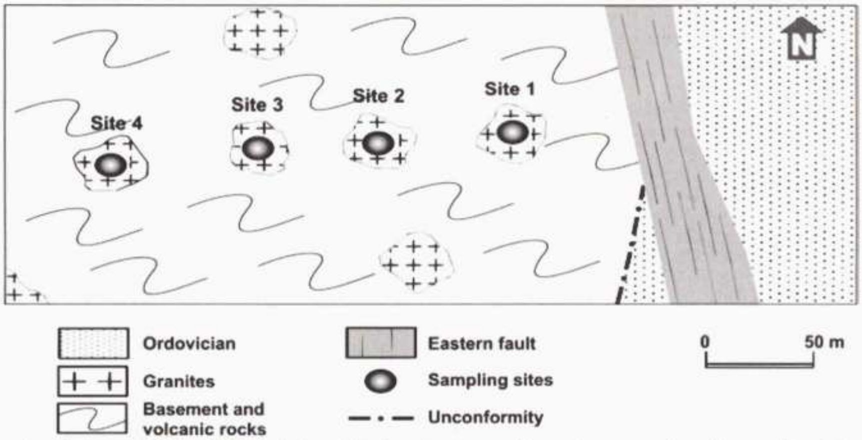

Fig. 3 - Example of unreliable AMS data obtained on sedimentary rocks (here the Givetian, which outcrops west of the «Eastern Fault»). Lower hemisphere equal-area projection with confidence zones at 95% (Henry and Le Goff, 1995).

Exemple de données d'ASM peu fiables, obtenues sur des roches sédimentaires (ici dans le Givétien affleurant à l'ouest de la «Faille orientale»). Projection à égale surface sur l'hémisphère inférieur avec les zones de confiance à 95% (Henry et Le Goff, 1995).

Table I: Number of measured samples N, mean susceptibility K_m (10^{-2} SI), declination D and inclination I (in degrees) respectively for maximum (K_1) and minimum (K_3) magnetic susceptibility axes, corrected degree of anisotropy P' and shape parameter T.

Nombre d'échantillons mesurés N, susceptibilité magnétique moyenne K_m (10^{-2} SI), déclinaison D et inclinaison I (en degrés) pour les axes de susceptibilité magnétique maximum (K1) et minimum (K3), degré d'anisotropie corrigé P' et paramètre de forme T.

Site	N	K_m	K_1		K_3		P'	T
			D	*I*	*D*	*I*		
1	8	2,15	275	10	130	77	1,319	- 0,404
2	5	2,17	298	10	72	76	1,304	- 0,323
3	7	1,84	293	32	62	45	1,222	- 0,201
4	6	1,81	294	19	77	66	1,197	0,156

One should note that, in addition to samples taken in granites, the sedimentary terrains situated around both the Aïn Kahla and the «Eastern Fault» were also sampled (26 sampling sites totalizing 304 core samples). However, magnetic susceptibilities were too weak and AMS data unreliable (fig. 4) to be used for structural geological interpretations.

3. ROCK MAGNETIC DATA

Thermomagnetic analyses (low field magnetic susceptibility as a function of temperature) were performed for each site on Agico KLY3 susceptibility Kappabridge with high temperatures attachments (fig. 5a-d). For all sites, curves show mainly a sharp decrease of magnetic susceptibility at 580°C, which is the Curie tempe-

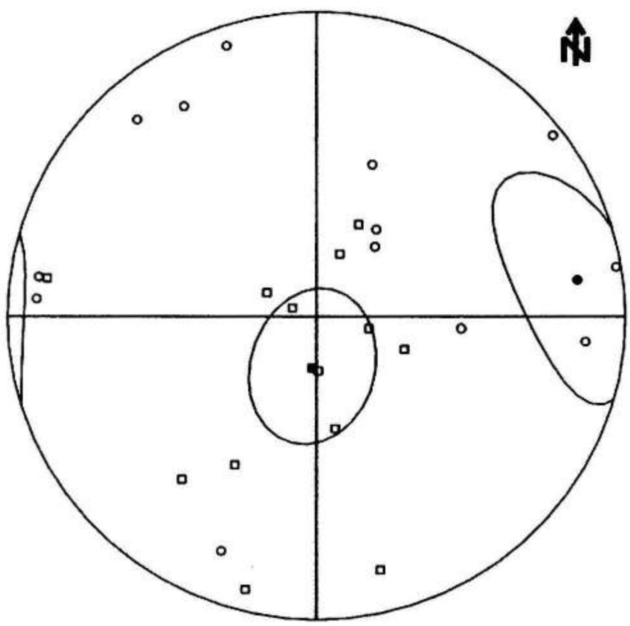

Fig. 4 - Configuration of the area where outcrop the sampled granites.

Configuration du secteur où affleurent les granites échantillonnés.

1: Ordovician ***(Ordovicien)***; **2:** Granites ***(Granites)***; **3:** Basement with fine-grained magmatic rocks ***(Socle et autres roches magmatiques)***; **4:** Eastern Fault ***(Faille orientale)***; **5:** Sampling sites ***(Sites d'échantillonnage)***; **6:** Unconformity ***(Discordance)***. The scale is approximate ***(L'échelle est approximative)***.

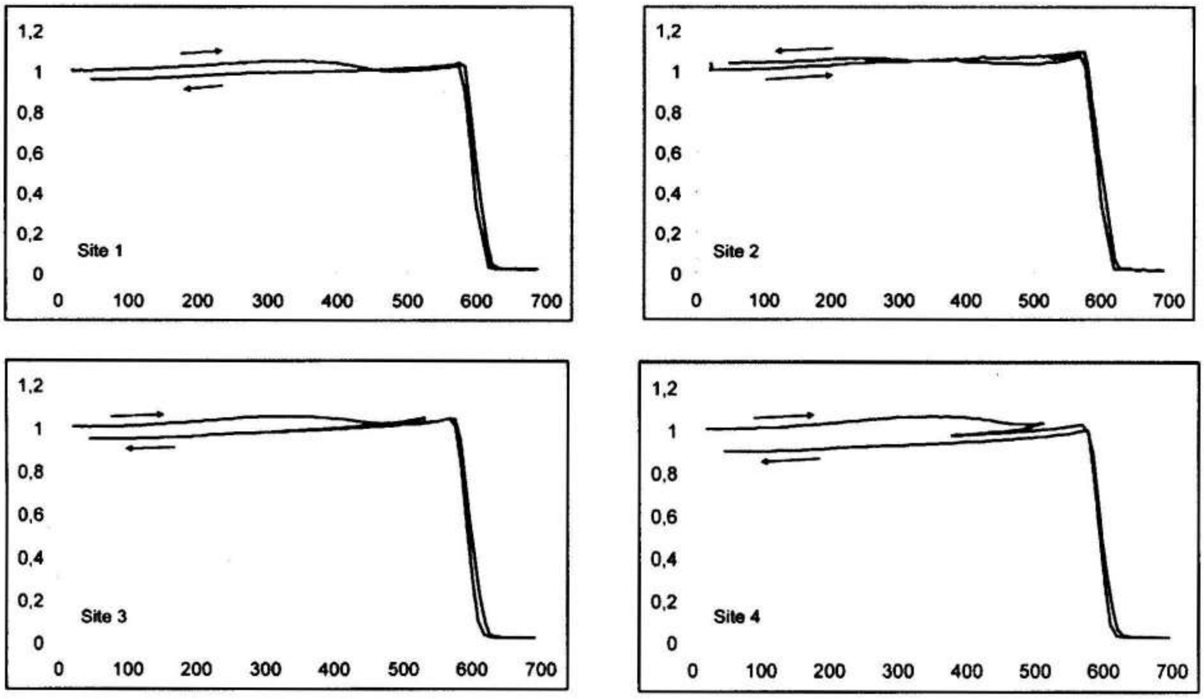

Fig. 5 - Thermomagnetic curves (normalized magnetic susceptibility K/Ko vs. temperature T) for the four sites.

Courbes thermomagnétiques (susceptibilité magnétique normalisée K/Ko en fonction de la température T) pour les quatre sites.

rature of magnetite. A weak irreversible susceptibility decrease around 400°C corresponds to a slight mineralogical alteration (probably transformation of maghemite to hematite). On the other hand, the characteristic rectangular shape of the thermomagnetic curves, due to the brutal variation of magnetic susceptibility at 580°C, and the lack of clear Hopkinson peaks (thermal enhancement of magnetic susceptibility near the Curie temperature occurring for particular grain sizes of ferromagnetic minerals) suggest that the magnetite is of a large multi-domain size.

Geochemical analyses carried out on opaque minerals of the Aïn Kahla granites (Guemache, 2005) show that the dominant ferromagnetic mineral is a Ti-poor iron oxide ($TiO_2 < 0.06$ %), containing on average 31 % of FeO and 68 % of Fe_2O_3, which corresponds in the TiO_2 - FeO - Fe_2O_3 diagram (Thompson and Oldfield, 1986; Dunlop and ضzdemir, 1997) to an almost pure magnetite. Magnetite is the single ferromagnetic mineral, well represented in nature, whose shape anisotropy has a direct influence on the rock magnetic fabric (Uyeda et *al.*, 1963). Crystallizing in the cubic system, magnetite has negligible magneto-crystalline fabric, and its anisotropy of magnetic susceptibility corresponds to shape anisotropy. The fact that magnetite grains are large multi-domain excludes an inverse magnetic anisotropy (O'Reilly, 1984; Rochette, 1988). Hence, magnetic anisotropy depends here essentially on deformation conditions of magnetite (see Souque, 2002).

4. ANISOTROPY OF MAGNETIC SUSCEPTIBILITY DATA

Anisotropy of magnetic susceptibility was measured in a low magnetic field using the AGICO KLY3 Kappabridge. K_m values are on the order of some 10^{-2} SI (table 1). The measured values for the principal orthogonal axes of the AMS ellipsoid (K_1, K_2 and K_3) were used to calculate the Jelinek (1981) parameters P' and T, using the Jelinek (1978) statistics (table 1). These parameters (P' and T) were used to describe the magnetic fabric and its spatial evolution (fig. 6).

Data from sites 1 and 2 correspond to prolate ellipsoid. The relative importance of P' (about 1.3) marks a strongly anisotropic ellipsoid and reflects a relatively significant rate of preferential orientation. The fabric is clearly prolate here. Data from site 3 are more dispersed than in sites 1 and 2, and the rate of preferential orientation is variable. Mainly distributed in the zone of prolate ellipsoid, they are very close to triaxial ellipsoid line. Finally, in site 4, the tendency is reversed and measurements gather in their majority in the zone of oblate ellipsoids, but still close to the triaxial ellipsoid line. The rate of preferential orientation of the ellipsoid is less important than in sites 1 and 2 (P' = 1.2). Thus, the shape of the AMS ellipsoid evolves from a prolate shape in the east, close to the «Eastern Fault», to an oblate shape towards the west.

The P' parameter, which represents the degree of ellipsoid anisotropy and reflects the

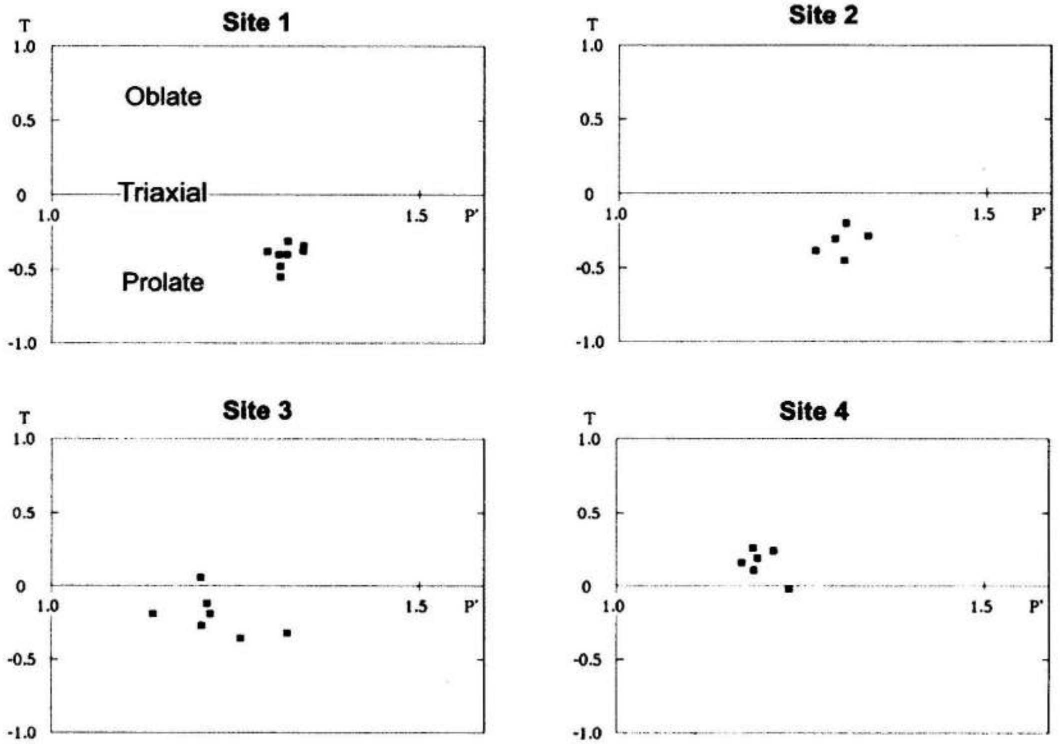

Fig. 6 - T vs. P' diagram.

Diagramme T – P'.

«intensity» of the fabric, also evolves and becomes less important towards the west, far from the «Eastern Fault» (fig. 7). However, the values of this parameter can also depend on those of mean susceptibility K_m (Henry, 1980). The P' vs. K_m diagram (fig. 8) highlights in each site such a relation, but it also shows that, for close values of magnetic susceptibility, the values of P' decrease towards the west, as it moves away from the «Eastern Fault».

The directions of the principal axes of magnetic susceptibility (K_1, K_2 and K_3) in each site were plotted (fig. 9) and the mean orientations of magnetic foliation and lineation were deduced from the values of the mean tensor. The four stereographic diagrams show good clustering for the three principal axes, in agreement with ellipsoids of triaxial shape (Tarling and Hrouda, 1993). This corresponds indeed to the observed shape parameters (fig. 6). The

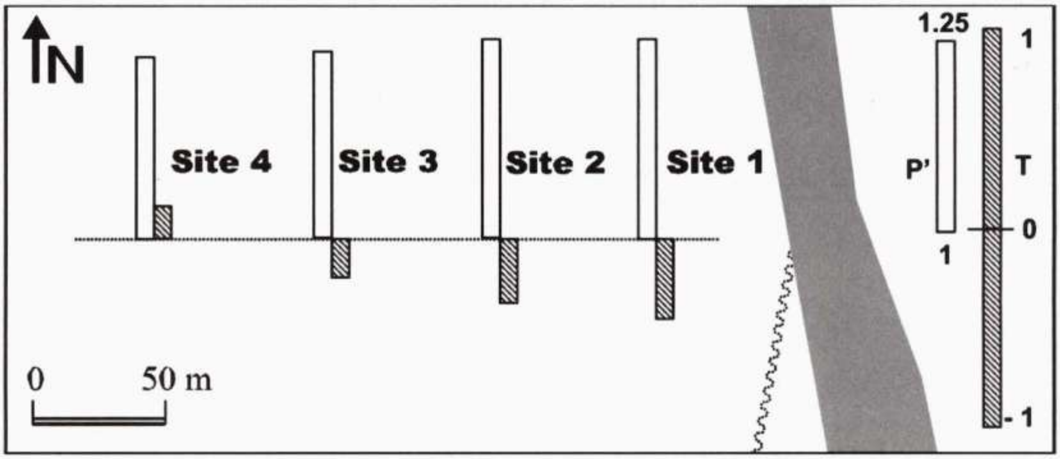

Fig. 7 - Distribution of P' and T values.

Distribution des valeurs de P' et T.

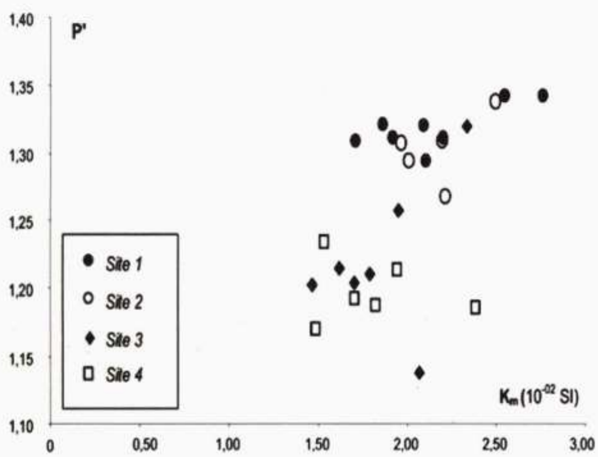

Fig. 8 - P' vs. K_m diagram.

Diagramme P' – K_m.

orientations show the existence of planes (magnetic foliation) gently dipping towards the west and bearing magnetic lineation trending E-W to WNW-ESE.

5. DISCUSSION AND CONCLUSION

A rapid examination of a map on the Tuareg shield reveals that the small outcrop of the phyllo-crystalline complex in the area of Aïn Kahla, to which belong the studied granites, is, with respect to the other similar-nature outcrops in the Hoggar, the northernmost one. It includes Precambrian basement and magmatic rocks, such as basalts, dolerites, rhyolites and granites (Bennaceur and Airèche, 1995; Guemache, 2005). It is associated to the N-S Arak major

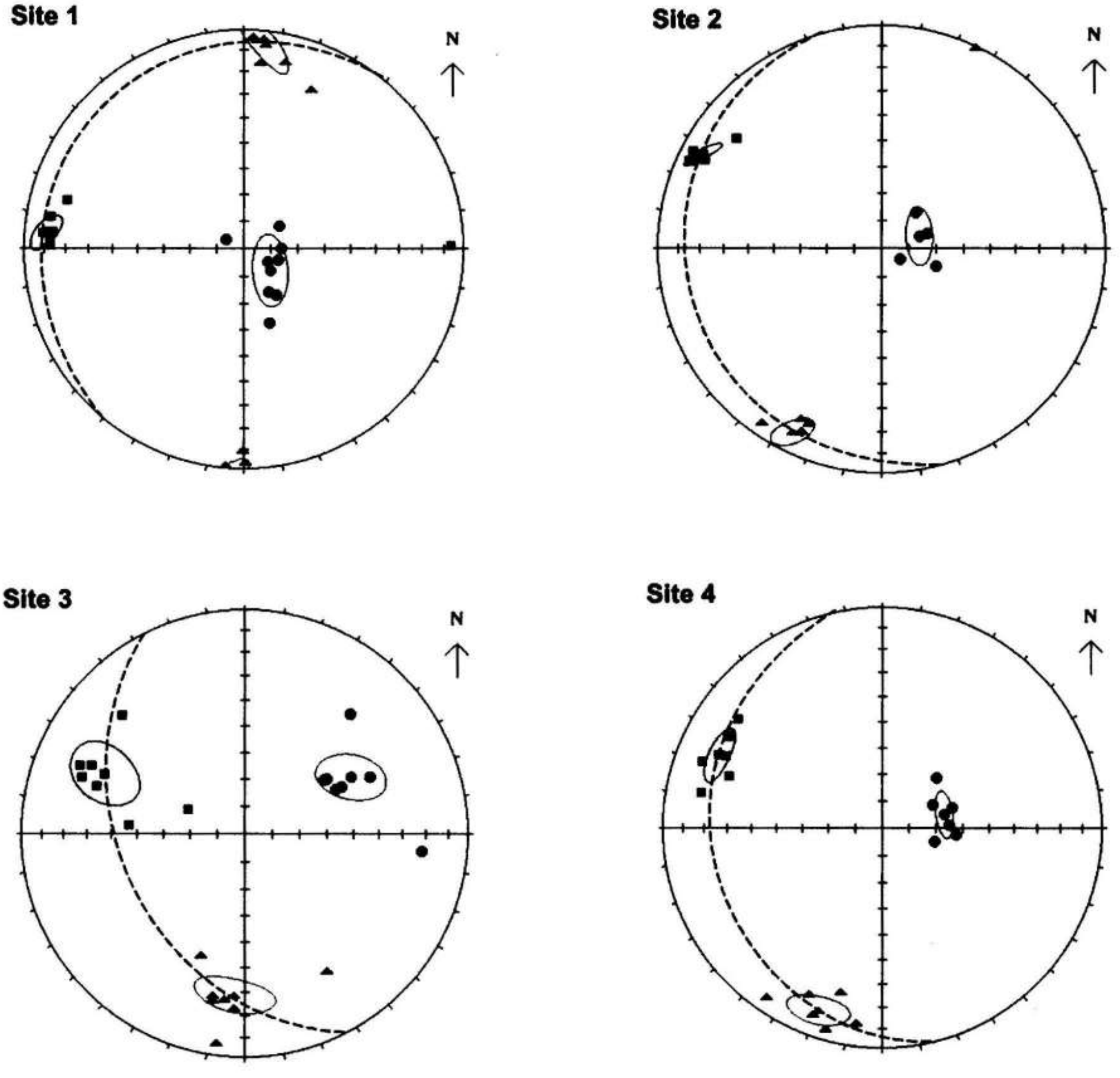

Fig. 9 - Lower hemisphere equal-area projection of magnetic anisotropy main axes with confidence zones at 95% (Hext, 1963; Jelinek, 1978). Squares: K_1 maximum axis (direction of magnetic lineation), triangles: K_2, circles: K_3 minimum axis (pole of magnetic foliation). Dashed lines: mean plane of magnetic foliation, whose pole is K_3.

Projection à égale surface sur l'hémisphère inférieur des axes principaux de l'anisotropie magnétique avec les zones de confiance à 95% (Hext, 1963 ; Jelinek, 1978). Carrés : axe maximum K_1 (direction de la linéation magnétique), triangles : K_2, cercles : K_3 (pôle de la foliation magnétique). ligne en tiretés : plan moyen de la foliation magnétique, dont le pôle est K_3.

fault, known as being of Pan-African age (Beuf et *al.*, 1971; Haddoum et *al.*, 2001) and which constitutes nowadays the structural limit between the Ahnet basin at the West and the Mouydir basin at the East.

Taking into account of (1) the unconformity existing between the Ordovician and the basement, (2) the lack of observed magmatic rocks into the Ordovician and (3) the relative weak deformation of magmatic rocks with respect to their strongly deformed Pan-African host-rocks, it is likely that the emplacement of the granites occurred during the period ranging between the end of the Precambrian and the Lower Paleozoic.

This period corresponds to the Late Pan-African period (650 - 550 Ma) (Liégeois et *al.*, 1994; Black et al., 1994) in the Central-Western Hoggar, which is characterized by N-S dextral strike-slip movements along major transcurrent shear zones, and in which local relative distension may have occurred due to the irregularity of the faults geometry (Djouadi et *al.*, 1997), allowing the emplacement of the abundant granitic plutons, and probably to which belong the studied granites.

The subsequent first exhumation of the complex occurred likely at the Upper Ordovician, during the Caradocian Taconic phase (Beuf et *al.*, 1971), before its burying under younger Paleozoic series (Upper Ordovician to Carboniferous). Then, the major tectonic movements that occurred at the end of the Carboniferous and later, and modeled the Paleozoic series at a regional scale (Beuf et *al.*, 1971, Conrad, 1984; Haddoum et *al.*, 2001; Smith et *al.*, 2006) induced likely its new exhumation, following movements along the Arak fault. The described tectonic structures and microstructures affecting the Aïn Kahla granites created probably during theose tectonic movements.

The magnetic fabric of the Aïn Kahla granites is characterized by a foliation having a rather regular orientation, shallowly dipping towards the West. The magnetic lineation expresses the existence of a lineation, carried by these slightly tilted planes. As one moves away from the «Eastern Fault» (site 1 to site 4), we observe a decrease of the magnetic fabric intensity (P') and an evolution of the shape of the ellipsoid, from prolate (= constriction) to oblate (= flattening). However, because of the lack of data on magnetic susceptibility in the east of the «Eastern Fault» (into the Ordovician), we cannot conclude indisputably if that is indeed related to this structure.

However, the magnetic foliation is not parallel to the plane of the «Eastern Fault» and would undoubtedly not be related to a movement along this fault. Besides, even if an agreement exists for the strike and the plunging sense between the magnetic foliation and the cleavages (in particular S1), the difference in the plunging angle is too large (> 40°) to establish a simple relation between these structures. In addition, the magnetic lineation is not included in these planes of cleavage, and this does not represent an intersection lineation between magnetic foliation and cleavage planes. Moreover, taking into account of the significant intensity of the AMS and its homogeneity in all sites, it appears very difficult to connect the magnetic fabric with these brittle structures.

The magnetic fabric of granites is more likely related to the structural context during their magmatic or late-magmatic phases. It reflects the stress field during crystallization (or recrystallization?) of magnetite (Pignotta and Benn, 1999; Benn et *al.*, 2001; Callahan and Markley, 2003). The magma was hence submitted to the regional stress field, probably after new strike-slip movement along the Arak fault, during the Late Pan-African period (Liégeois et *al.*, 1994; Black et *al.*, 1994). The magnetic fabric of the Aïn Kahla granites suggests the existence of «thrusting» movements on planes slightly tilted towards the West. The magnetic lineation allows suggesting the direction of these movements, i.e. WNW-ESE to E-W. This last direction would reveal therefore the WNW-ESE to E-W orientation of the regional stress field during the pluton emplacement at Late Pan-African times, in agreement with the Late Pan-African E-W shortening described in the literature throughout the Tuareg shield. Similar E-W movement was recently observed using AMS in the area of In Guezzam, South-East of the Hoggar (Henry et *al.*, 2004a,b). These results are important insofar as other AMS studies carried out on plutons show that the tectonic evolution of this period is especially marked by right-lateral movements along N-S faults (Djouadi and Bouchez, 1992; Djouadi et *al.*, 1997; Henry et *al.*, 2004a,b), as also stated by many geological studies (see Bertrand and Caby, 1978; Black et *al.*, 1979; Haddoum, 1992; Haddoum et *al.*, 1994; Black et *al.*, 1994; Liégeois et *al.*, 1994).

An interesting question rises from the previous discussion: are the Aïn Kahla Pan-African granites syn, late or post-tectonic? During field investigations, we do not have seen any magmatic structures indicating that the granites are syn or late-tectonic. However, this could be due to the bad outcropping conditions, and does not mean necessarily that those structures are inexistent. Oriented magnetic fabric of the granites indicates that they emplaced within an active tectonic environment, leading to a WNW-ESE to E-W shortening. AMS studies carried out on post-tectonic plutons (e.g. Taourirt) revealed the existence of deformations inaccessible to direct observation, but well expressed into their magnetic fabrics (e.g. Djouadi et *al.*, 1997). Hence, taking into account of this «crypto-deformation» unveiled by AMS for the Aïn Kahla granites, they seem to be syn-tectonic, but we cannot answer indisputably concerning the relation with the main orogeny.

Acknowledgements : This work is supported by the PNR program N°04/04/13/99. The authors are grateful to Professor Hamid Haddoum (USTHB, Algiers, Algeria) and Professor Tahar Aïfa (university of Rennes1, France) for their detailed and insightful review of this paper. We are deeply indebted to civil and military authorities at In Salah for their constant and important help in field.

REFERENCES

ABDELSALAM, M., LIEGEOIS, J.P. AND STERN, R.J. 2002. The Saharan Metacraton. *J. Afr. Earth Sci.*, 34, pp. 119-136.

BEICIP, 1972a. Etude géologique et levés cartographiques au 1/200'000ᵉ de l'Ahnet et du Mouydir (Sahara Central). *SONATRACH unpublished report*, 89 p.

BEICIP, 1972b. 1/200 000 Geological Map of Ers Oum el Lil, ed. 1972, *Service de la Carte Géologique de l'Algérie, Algiers.*

BENN, K., PATERSON, S.R., LUND, S.P., PIGNOTTA, G.S. AND KRUSE, S. 2001. Magmatic fabrics in batholiths as markers of regional strain and plate kinematics: example of the Cretaceous Mt. Stuart Batholith. *Physics and Chemistry of the Earth, (A)*, 26, pp. 343-354.

BENNACEUR, G. ET AIRECHE, A.G. 1995. La région de Aïn Kahla (Sahara central) : une limite structurale majeure entre les domaines de l'Ahnet et du Mouydir. *Geol. Ing. Dissertation, USTHB, Algiers,* 155 p.

BERTRAND, J.M.L. AND CABY, R. 1978. Geodynamic evolution of the Pan-African orogenic belt: a new interpretation of the Hoggar shield (Algerian Sahara). *Geologische Rundschau* 67, pp. 357–388.

BEUF, S., BIJU-DUVAL, B., DE CHARPAL, O., ROGNON, P., GARIEL, O. AND BENNACEF, A. 1971. Les grès du Paléozoïque inférieur au Sahara. Sédimentation et discontinuités. Evolution structurale d'un craton. *Ed. Technip, Paris*, 464 p.

BLACK, R., CABY, R., MOUSSINE-POUCHKINE, A., BAYER, R., BERTRAND, J.M.L., BOULLIER A.M., FABRE, J. AND LESQUER, A. 1979. Evidence for late Precambrian plate tectonics in West Africa. *Nature*, 278, pp. 223–227.

BLACK, R., LATOUCHE, L., LIEGEOIS, J.P. AND BERTRAND, J.M. 1994. Pan African displaced terranes in the Tuareg shield (central Sahara). *Geology*, 22, pp. 641-644.

BORRADAILE, G. J. AND HENRY, B. 1997. Tectonic applications of magnetic susceptibility and its anisotropy. *Earth Sciences Review*, 42, pp. 49-93.

CABY, R., BERTRAND, J.M. AND BLACK, R. 1981. Pan-African closure and continental collision in the Hoggar-Iforas segment, central Sahara, in: Kr.ner, A. *(Ed.), Precambrian Plate Tectonics. Elsevier*, pp. 407–434.

CALLAHAN, C.N. AND MARKLEY, M.J. 2003. A record of crustal-scale stress; igneous foliation and lineation in the Mount Waldo Pluton, Waldo County, Maine. *Journal of Structural Geology*, 25, pp. 541-555.

CONRAD, J. 1984. Les séries carbonifères du Sahara central algérien. Stratigraphie, sédimentation, évolution structurale. *PhD thesis, univ. Marseille.*

DJOUADI, M.T. ET BOUCHEZ, J.L. 1992. Structure étrange du granite du Tesnou (Hoggar, Algérie). *C. R. Acad. Sci., Paris*, 315, II, pp. 1231-1238.

DJOUADI, M.T., GLEIZES, G., FERRE, E., BOUCHEZ, J.L., CABY, R. AND LESQUER, A. 1997. Oblique magmatic structures of two epizonal granite plutons, Hoggar, Algeria: late orogenic emplacement in a transcurrent orogen. *Tectonophysics*, 279, pp. 351-374

DUNLOP, D.J. ANDضZDEMIR, ض. 1997. Rock magnetism: Fundamentals and frontiers: Cambridge, *Cambridge University Press*, 573 p.

GRAHAM, J.W. 1954. Magnetic susceptibility anisotropy, an unexploited petrofabric element. *Geol. Soc. Am. Bull.*, 65, pp.1257-1258.

GUEMACHE, M. A. 2005. Rôle du rejeu des accidents panafricains dans la structuration des séries paléozoïques au Nord-Ouest du Hoggar : cas de la bordure orientale du bassin de l'Ahnet. Implications géodynamiques et piégeage des hydrocarbures. *Magister thesis, USTHB, Algiers*, 152 p.

GUEMACHE, M.A., DJELLIT, H., LOUNI-HACINI, A., DERDER, M.E.M. AND OUABADI, A. 2006. Pétrographie, minéralogie et géothermobarométrie des granites panafricains de Aïn Kahla (Nord-Ouest Hoggar, Algérie). Implications géodynamiques. *Proc. 1er Séminaire International des Géosciences au Service du Développement Durable, Tebessa, Algeria, Nov. 2006*, pp. 109 – 114.

HADDOUM, H. 1992. Structural evolution of the In-Ouzzal archaean terranes (western Hoggar, Algeria). *Abstracts volume, 29th International Geological Congress, Kyoto, 24 August - 3 September 1992.*

HADDOUM, H., CHOUKROUNE, P. AND PEUCAT, J. J. 1994. Evolution of the Precambrian In-Ouzzal block (Central Sahara, Algeria). *Precambrian Res.*, 65 (1-4), pp. 155 – 166.

HADDOUM, H., GUIRAUD, R. AND MOUSSINE-POUCHKINE, A. 2001. Hercynian compressional deformations of the Ahnet-Mouydir Basin, Algerian Saharan platform: far-field stress effects of the Late Palaeozoic orogeny. *Terra Nova 13*, 3, pp. 220 – 226.

HENRY, B. 1980. Contribution à l'étude des propriétés magnétiques de roches magmatiques des Alpes: Conséquences structurales, régionales et générales. *PhD thesis, univ. Paris*, 528 p.

HENRY, B. AND DALY, L. 1983. From qualitative to quantitative magnetic anisotropy analysis; the prospect of finite strain calibration. *Tectonophysics*, 98, pp. 327-336.

HENRY, B. ET HROUDA, F. 1989. Analyse de la déformation finie des roches par détermination de leur anisotropie de susceptibilité magnétique. *C. R. Acad. Sci. Paris*, 308, pp. 731 – 737.

HENRY, B. ET LE GOFF, M. 1995. Application de l'extension bivariente de la statistique de Fisher aux données d'anisotopie de suceptibilité magnétique : Integration des incertitudes de mesure sur l'orientation des directions principales. *C. R. Acad. Sc. Paris*, 320, II, pp. 1037-1042.

Henry, B., Bayou, B., Derder, M.E.M., Djellit, H., Ouabadi, A., Merahi, M., Baziz, K., Khaldi, A. and Hemmi, A. 2004a. Emplacement and fabric-forming conditions of the Alous-En-Tides granite, eastern border of the Tin Seririne/Tin Mersoï basin (Algeria): magnetic and visible fabrics analysis. *J. Struct. Geol.*, 2004, 26, pp. 1647 – 1657.

Henry, B., Bayou, B., Derder, M.E.M., Djellit, H., Ouabadi, A., Merahi, M., Baziz, K., Khaldi, A. and Hemmi, A. 2004b. Emplacement and fabric-forming conditions of granites close to the borders of the Tin Seririne/Tin Mersoï basin (Algeria): magnetic and visible fabrics analysis. *20th Coll. Afric. Geol., Orléans, 2004. Abstracts volume.*

Hext, G. 1963. The estimation of second-order tensors, with related tests and designs. *Biometrika*, 50, pp. 353 – 373.

Hrouda, F. 1982. Magnetic anisotropy of rocks and its application in geology and geophysics. *Geophys. Survey*, 57, pp. 37 – 82.

Jelinek, V. 1978. Statistical processing of magnetic susceptibility measured in groups of specimens. *Studia Geophysica and Geodaetia*, 22, pp. 50 – 62.

Jelinek, V. 1981. Characterization of the magnetic fabric of rocks. *Tectonophysics*, 79, pp. 63-67.

Kilian, C. 1932. Sur les conglomérats précambriens du Sahara central, le Pharusien et le Suggarien. *Comptes Rendus Sommaires Société géologique de France*, 7, 87.

Leake, B.E., Woolley, A.R., Arps, C.E.S., Birch, W.D., Gilbert, M.C., Grice, J.D., Hawthorne, F.C., Kato, A., Kisch, H.J., Krivovichev, V.G., Linthout, K., Laird, J., Mandarino, J.A., Maresch, W.V., Nickel, E.H., Rock, N.M.S., Schumacher, J.C., Smith, D.C., Stephenson, N.C.N., Ungaretti, L., Whittaker, E.J.W. and Youzhi, G. 1997. Nomenclature of amphiboles. *American Mineralogist*, 82, pp. 1019-1037.

Liegeois, J.P., Bertrand, J.M. and Black, R. 1987. The subduction- and collision-related Pan-African composite batholith of the Adrar des Iforas (Mali): a review. In: Kinnaird, J., Bowden, *P. (Eds.), African Geology Review. John Wiley, London, pp. 185–211 and Geological Journal, 22*, 185 – 211.

Liegeois, J.P., Black, R., Navez, J. and Latouche, L. 1994. Early and Late Pan-African orogenies in the Aïr assembly of terranes (Tuareg shield, Niger). *Precambrian Research*, 67, pp. 59-66.

O'Reilly, W. 1984. Rock and mineral magnetism. *Blackie, Glasgow*, 230 p.

Pignotta, G.S. and Benne, K. 1999. Magnetic fabric of the Barrington Passage pluton. Meguma Terrane, Nova Scotia: a two-stage fabric history of syntectonic emplacement. *Tectonophysics*, 307, pp. 75-92.

Rochette, P. 1988. Relations entre déformations et métamorphismes alpins dans les schistes noirs helvétiques : l'apport de la fabrique magnétique. *Geodynamica Acta*, 2, pp. 17-24.

Smith, B., Derder, M. E. M., Henry, B., Bayou, B., Yelles, A. K., Djellit, H., Amenna, M., Garces, M., Beamud, E., Callot, J. P., Eschard, R., Chambers, A., Aifa, T., Ait Ouali, R. and Gandriche, H. 2006. Relative importance of the Hercynian and Post-Jurassic tectonic phases in the Saharan platform: a palaeomagnetic study of Jurassic sills in the Reggane Basin (Algeria). *Geophysical Journal International* 167 (1), 380–396. DOI:10.1111/j.1365-246X.2006.03105.x

Souque, C. 2002. Magnétisme structural dans les chaînes de chevauchement-plissement : Développements analytiques et exemples d'utilisation dans les Corbières. *PhD thesis, univ. Cergy-Pontoise*, 192 p.

Tarling, D. H. and Hrouda, F. 1993. The magnetic anisotropy of rocks. *Ed. Chapman and Hall, London*, 217 p.

Thompson, R. and Oldfield, F. 1986. Environmental Magnetism. *Allen and Unwin, London*, 227 p.

Uyeda, S., Fuller, M.D., Belshe, J.C. and Girdler, R.W. 1963. Anisotropy of magnetic susceptibility of rocks and minerals. *J. Geophys. Res.*, 68, pp. 279 – 291.