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STRUCTURE AND U/Pb GEOCHRONOLOGY OF CENTRAL HOGGAR (ALGERIA): A REAPPRAISAL OF ITS PAN-AFRICAN EVOLUTION

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Abstract. Discovery of large-scale deep-seated thrusts in Central Hoggar, with a plurifacial evolution ranging from lower amphibolite facies to upper greenschist facies conditions and linked to a regional refoliation, has led us to reconsider the Pan-African tectonic and metamorphic history in that region. Two areas are described, and a review of other thrusts leads to an interpretative cross section of a large portion of reactivated continental crust. The age and kinematics of this structural reworking have been approached using U/Pb zircon dating in the Tamanrasset region. Despite the difficulty of estimating the age of the initiation of the assumed intracontinental A-type subduction, the results provide a time span of 30-40 m.y. between the climax of granitoid emplacement and a late retrogressive offset along the thrust planes. Some key ages were determined: (1) 2075 ± 30 Ma is the age given by granulite facies remnants which escaped from the refoliation, the corresponding lower intercept at 530 ± 70 Ma confirms the Pan-African imprint; (2) 615± 5 Ma reflecting the age of syntectonic to late-tectonic granitoids emplaced in reworked gneisses and in preserved granulites; (3) 580 Ma, the concordant age of sphenes and monazites from the same granitoids, which is interpreted as corresponding to the end of medium-grade conditions. No evidence has been found of a ~1000 Ma age: a Kibaran event does not appear to exist in Central Hoggar. The age similarity between the observed deep intracontinental evolution of Central Hoggar and the collision-related tectonics of Western Hoggar and Iforas suggests a common origin for both phenomena.

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INTRODUCTION

Since the work of Lelubre [1952], the gneisses and granites of the central part of the Hoggar have been considered to belong to the oldest stratigraphic unit of the shield. High-grade metamorphic terranes collectively called Suggarian are associated with restricted belts of low-grade schists defined as Pharusian [Kilian, 1932; Lelubre, 1952]. The high-grade gneisses from Central Hoggar have never furnished ages older than the Eburnean (about 2000 Ma [Bertrand and Lasserre, 1976; Vialette and Vitel, 1979; Latouche and Vidal, 1974]) except a Pb/Pb whole rock isochron (3480 ± 90 Ma) quoted by Latouche [1978]. Recent syntheses [Bertrand and Caby, 1978; Caby et al., 1981] have proposed a geotectonic approach, trying to recognize which structures of the Hoggar shield are correlated with the Pan-African Wilson cycle and the well-defined collision along the eastern margin of the West African craton. Recent field observations and geochronological data in the "polycyclic Central Hoggar" have led to a reappraisal of its geotectonic evolution [Boullier and Bertrand, 1981; Bertrand et al., 1984].

GEOLOGICAL SETTING OF THE CENTRAL HOGGAR

As shown in Figure 1, three main lithologic associations may be defined in Central Hoggar, irrespective of their presumed age: (1) quartzo -

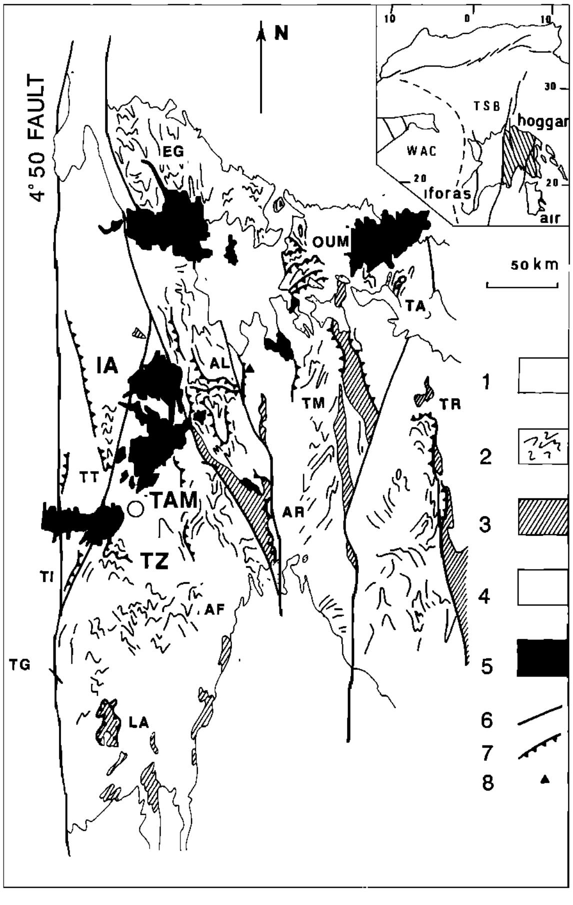

Fig. 1. Sketch map of Central Hoggar (see inset for location). 1, Granites and quartzofeldspathic gneisses; 2, high-grade metasediments; 3, low-grade schist belts; 4, Ordovician to Quaternary sediments; 5, Phanerozoic lavas; 6, major wrench faults; 7, thrusts; 8, eclogites. WAC, West African craton; TSB, Transaharan belt. Localities quoted in the text: TAM, Tamanrasset; TZ, Tin Amzi; IA, In Amguel; AL, Aleksod; OUM, Oumelalen; TA, Tazat; TI, Tinef; TT, Tin Teganet; TM, Temasint; EG, Egere; TR, Tiririne; AF, Afedafeda; AR, Arefsa; TG, Timgaouine; LA, Laouni.

feldspathic gneisses and granites, (2) banded high-grade metasediments including quartzites, marbles, and metapelites, and (3) low-grade metavolcanics and graywackes. The latter association, still undated, is known as "Pharusian" and forms linear belts or small basins presumed to be upper Proterozoic in age. In all three lithologic associations the main metamorphic foliation is more or less gently dipping, often horizontal, and often associated with polyphased recumbent folds [Bertrand, 1974; Latouche, 1978; Vitel, 1979], except in the vicinity of the late wrench faults and in some linear belts of upright north-south trending folds.

Amongst the metasediments two groups have been defined: (1) those intimately associated with the quartzofeldspathic gneisses , the Arechchoum series, and (2) the Aleksod series which lies in structural unconformity upon group 1 and shows a simpler structural history suggesting a younger age.

The two groups are very similar in lithology, but in the Aleksod area a set of basic dykes allows the clear separation of the two groups [Bertrand, 1974]. In places, stratigraphic unconformities are preserved, for example, in the Toukmatine series in the Oumelalen area [Latouche, 1978] and the Tazat area [Blaise, 1967; Bertrand et al., 1968], but tectonic contacts are more usual. It was from the distinction of two groups of metasediments and from the noncritical acceptance of the "classical" Pharusian unconformity, which was considered as giving a lower limit for the upper Proterozoic, that the existence of a Kibaran event at about 1000 Ma was previously proposed in Central Hoggar [Bertrand, 1974]. Some geochronological results seemed at that time to support this assumption [Bertrand and Lasserre, 1976], but they were discussed using data from other regions [La Boisse and Lancelot, 1977]. In fact, recent structural investigations in the schist belts have shown the tectonic nature of the "classical" unconformity (M. Briedj and J. M. Bertrand, unpublished observations, 1980).

Two major events have been recognized in Central Hoggar using available geochronological data [Pic - ciotto et al., 1965; Latouche and Vidal, 1974; Bertrand and Lasserre, 1976; Bertrand et al., 1978, and 1984; Vialette and Vitel, 1979; Latouche and Vidal, 1974]: (1) the Eburnean event at about 2000 Ma is defined from quartzofeldspathic gneisses, including orthogneisses and charnockites, and from the older metasediments and (2) the Pan-African event at about 600 Ma.

The metamorphic evolution of Central Hoggar reflects the dual influences of the history of the Suggaran (Eburnean) basement and of the Pan-African imprint. From their structure and radiometric age, the granulitic assemblages and the prebasic dyke gneisses are attributed to the Suggaran event [Latouche, 1978; Vitel, 1979; Ouzegane, 1981]. The tendency, in recent papers and theses, is to attribute the intermediate pressure metamorphism, often corresponding to the most conspicuous foliation, to a Kibaran event, and the low-pressure metamorphism to a thermal effect related to granite emplacement during the Pan-African, the low-grade retrogression being the result of late wrench faults and/or associated upright north-south folding. From the point of view of the plutonic evolution, no Kibaran age has ever been found in any granitic body. In the In Amguel region, Vitel [1979] has proposed a classification of the Pan-African granitoids dated by the Rb/Sr isochron method [Vialette and Vitel, 1979] from 670 ± 20 Ma to 514 ± 20 Ma.

To summarize, a polycyclic evolution has been recognized in Central Hoggar, but with the exception

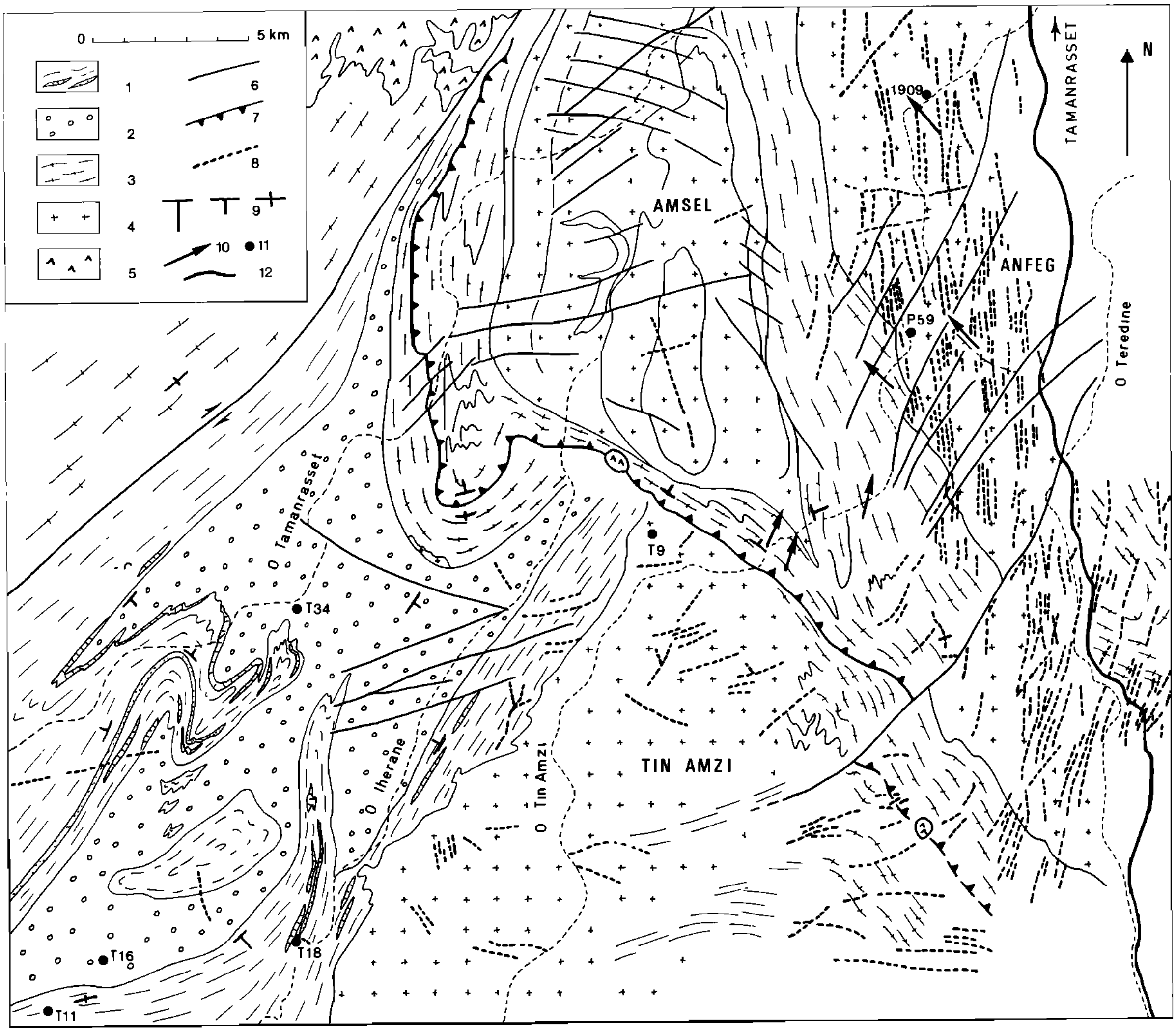

Fig. 2. Sketch map of the Tin Amzi area. 1, Iherane gneisses and granulites (with marbles and quartzites); 2, migmatitic granite; 3, refoliated gneisses; 4, granites; 5, recent volcanism; 6, fault; 7, thrust; 8, dyke; 9, foliation dip < 40°, 40°-60°, > 60°; 10, stretching lineation; 11, sample; 12, Transaharan road.

of the granitoid emplacement and associated low pressure metamorphism of evidently Pan-African age, most of the tectonic and metamorphic evolution was considered as older, belonging either to an Eburnean or a hypothetical Kibaran event. The new observations and data presented in the following sections were initiated after the discovery of flat-lying retrogressive mylonites contrasting with zones where older structures are preserved [Boullier and Bertrand, 1981].

THRUST TECTONICS IN CENTRAL HOGGAR

North Tin Amzi Area

Situated 50 km south of Tamanrasset (Figure 1), this area is characterized by a strong contrast between two completely different tectonic units separated by a mylonite belt dipping gently toward the NE (Figure 2). The tectonic units are as follows.

Lower tectonic unit: the Iherane gneisses and migmatites. The lower tectonic unit comprises granulite facies metasediments which are invaded by migmatites and nebulitic granites with numerous xenoliths and patches of garnet + cordierite restite. Two successive metamorphic assemblages have been defined by Ouzegane [1981] and correspond to the following PT conditions: M1 = more than 8 kbar and 800°C; M2 = 5 ± 1.5 kbar and 600° ± 50°C. M2 associated migmatites and migmatitic granites are related to or slighly postdate large-scale recumbent isoclinal folds, the axes of which trend approximately east-west; they are in turn refolded by NE trending upright open folds. No mineral or stretching lineations have been observed in the Iherane gneisses where the textures are always granoblastic and the Se foliation, presumed Eburnean in age, is actually a metamorphic banding. Together with a slight deformation of quartz grains (undulatory extinction, subgrains), a third, retrogressive assemblage is observed in some samples, especially those from near the mylonite belt: cordierite is replaced by muscovite and by small flakes of pale red biotite.

The Iherane gneisses and migmatites are crosscut by the Tin Amzi plutonic complex, an association of heterogeneous granites and granodiorites with some dioritic xenoliths. Along the contact, numerous dykes of granodiorite and porphyritic granite showing granophyric textures are intruded into the gneisses. The Tin Amzi complex was deformed under relatively low-temperature conditions near the mylonite belt.

Upper tectonic unit. In the upper tectonic unit all the gneisses have an intense gently NE dipping foliation and show a conspicuous stretching lineation well marked by minerals such as biotite and sillimanite, the latter being broken into pieces sealed by recrystallized sillimanite (Figure 3). This foliation, Sp1 because it is considered as the older Pan-African foliation, thus occurred under deep amphibolite facies conditions and corresponds to a complete tectonic and metamorphic reworking of ancient gneisses similar to the Iherane granulitic gneisses which are recognizable as remnants even in this highly deformed unit. Toward the NE, tight overturned, postfoliation folds with NW trending axes perpendicular to the stretching lineation develop locally a new axial planar cleavage (Sp2) formed at lower metamorphic grades (greenschist to epidote-amphibolite facies) at a very low angle from Sp1. The Anfeg and Amsel plutons crosscut Sp1 but are deformed later, and the Sp2 foliation affects their outer zone.

Mylonitic belt. A mylonitic belt sharply separates the two tectonic units described above and is 50-100 m thick. The mylonitic surface (Figure 3) is parallel to Sp2 and reflects epidote-amphibolite facies conditions; it is characterized by fine-grained recrystallized quartz and biotite; some boudins of refoliated gneisses (Sp1) persist in an anastomosed mylonitic net.

The mylonitic foliation bears a stretching lineation orientated 30°N and shows shear sense criteria such as rotated porphyroclasts, shape fabric of quartz grains, preferred orientation of quartz C axes, mica-fishes, and C-S structures [Simpson and Schmid, 1983; Bouchez et al., 1983], which indicate a NNE sense of movement of the upper unit. The overall parallelism between Sp1, Sp2 and the mylonitic foliation suggests a continuum between these deformations: they are interpreted as the result of a progressive tangential strain occurring while metamorphic conditions were vaning (Figure 4). Finally, the thrust itself was folded by NS to NE-SW trending open folds (Fp3), which do not develop a new cleavage in that area.

The mylonite belt could be interpreted in two ways: (1) it is a normal fault (NE dip, NNE direction of movement of the upper unit), or (2) it is a thrust, originally subhorizontal or SW dipping, the dip of which has been inverted by later large wavelength doming; the vergence of the thrust is then toward the NNE.

This latter interpretation is preferred for the following reasons: a southerly dipping mylonitic belt, structurally equivalent to the North Tin Amzi mylonite has been observed in the North Laouni region by Latouche [1985] and also shows a NNE movement direction; and at Pan-African times the deepest level corresponds to the upper tectonic unit (biotite-sillimanite bearing Sp1). This is confirmed by the different emplacement levels of the Anfeg and Tin Amzi plutons (syntectonic granite versus crosscutting dykes).

Such features are actually incompatible with normal faulting and favor the thrust interpretation. As the Anfeg pluton has long been considered to be Pan-African in age (U/Pb dating by Picciotto et al. [1965]) and is bracketed by the progressive Sp1-Sp2 deformation, this main refoliation event and the thrusting event are also Pan-African in age.

Very close to the Tin Amzi area, the Tinef area shows a similar structure but the refoliation is more widespread and more retrogressive (Figure 5). The main horizontal mylonitic foliation (S1 from Boullier and Bertrand [1981]) affects a unit of fine-grained felsic gneisses, the so-called Tinef series [Gravelle, 1969]. These gneisses grade into augen ortho-gneisses, showing preserved intrusive contacts with the In Azarou gneisses where granulite remnants are also observed. Accordingly, the Tinef orthogneisses may be broadly equivalent to the Anfeg granite.

In Amguel Area

The area is known as the "In Amguel mylonite belt" and was interpreted as a major vertical transcurrent shear zone in the Hoggar shield [Vitel, 1979]. Some of the mylonites actually correspond to an early tangential event and were offset during late open folding and shearing [Boullier and Bertrand, 1981] (Figure 6); a similar interpretation was previously proposed by Fauré [1967]. The lithologies are quite different on both sides of the mylonite belt, but the structural sequences in the two domains are similar, as shown below.

Western domain. The western domain is mainly composed of granite gneisses and migmatites (the Arechchoum gneisses). An Sm migmatitic banding appears as relics in a nonpenetrative flat-lying secondary foliation Sm1 which is in turn folded by open dissymetric folds. As these folds become more and more tightened on approaching the mylonite belt, a third foliation Sm2 appears. The constant dissymetry of the 350°N trending Fm2 folds and the fanning displayed by Sm2 suggest that the "mylonite

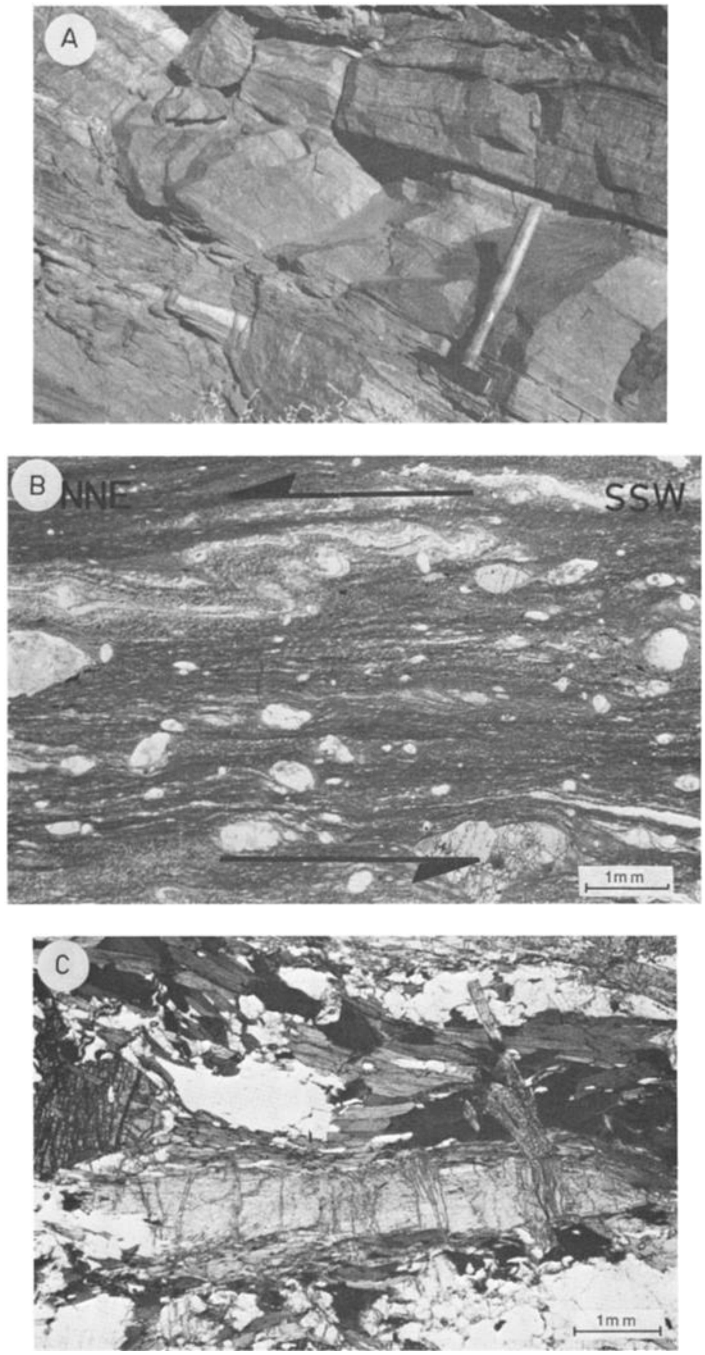

Fig. 3. Some aspects of the Tin Amzi thrust. (a) Banded mylonite; dark layers are ultramylonites. (b) Ultramylonite in XZ section showing the movement direction; clasts are feldspars, garnet, and sillimanite. (c) Refoliated gneiss of the upper tectonic unit showing fractures in a sillimanite clast sealed by new transverse sillimanite.

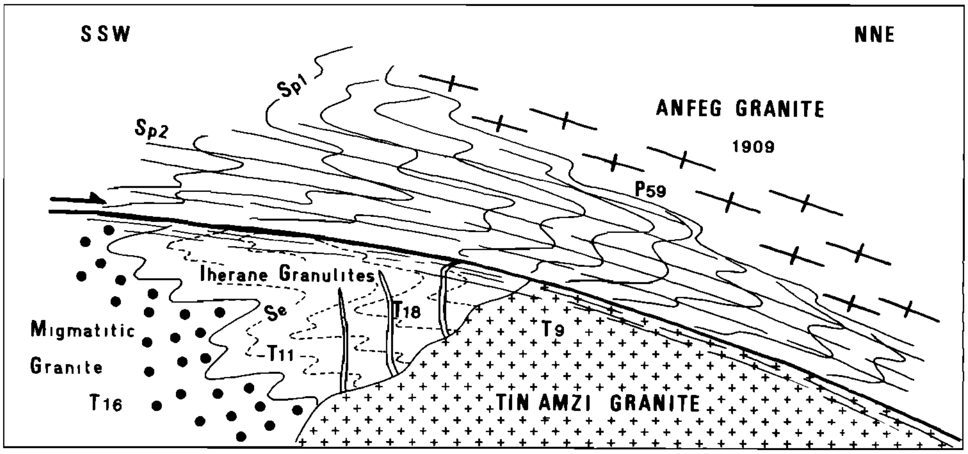

Fig. 4. The tectonic evolution of the Tin Amzi area. Se is the Eburnean foliation in the granulites; Sp1 is the main refoliation in the gneisses; and Sp2 is the superimposed lower-grade foliation parallel to the mylonites.

belt" actually represents the core of a large anticlinorium disrupted by a late sinistral strike-slip fault corresponding to retrogressive greenschist facies conditions. Even when Sm1 is still recognizable, a conspicuous Lm2 horizontal stretching lineation is developed on vertical Sm2 foliation.

Eastern domain. In the Eastern domain the Amsinassene Formation [Vitel, 1979] consists of metapelitic gneisses, marbles, and some quartzites with minor plagioclasic gneisses. Some granulitic remnants have also been described by Vitel [1979]. An Sn migmatitic banding is refolded and transposed in most cases into a Sn1 subhorizontal foliation, a transposition which occurred under amphibolite facies conditions. This formation is intruded parallel to the Sn1 foliation by a heterogeneous, often migmatitic, monazite-rich porphyritic granite (Aou Zebaouene granite [Vitel, 1979]). Fold axes and mineral lineations on the Sn1 foliation are erratic (from 30°N to 150°N) probably as a result of an Fn2 open folding, which becomes more and more tighter as the "mylonite belt" is approached.

Assuming the identity of Sm1 and Sn1, the In Amguel "mylonite belt" appears as a large anticlinorium, the core of which is invaded by post-Sm1 pink granites and characterized by high strain corresponding to a later shear zone. The Sn1 and Sm1 surfaces exhibit many similarities with the Sp1 surface defined in the Tin Amzi area except for the less marked stretching lineation in the former. Furthermore, in the Tin Teganet area, 80 km south of the Amsinassene region, an antiformal structure was recognized whose upper layers consist of refoliated high-grade gneisses and whose core is composed of greenschist facies phyllonites with a 230°N stretching lineation. Thus a thrust zone similar to the Tin Amzi thrust may exist in the In Amguel area, hidden by the widespread occurrence of post-Sm1 intrusives and by the late high-strain strike-slip shear zone.

Other Thrusts in Central Hoggar

Other thrusts seen in the Central Hoggar region, are described below.

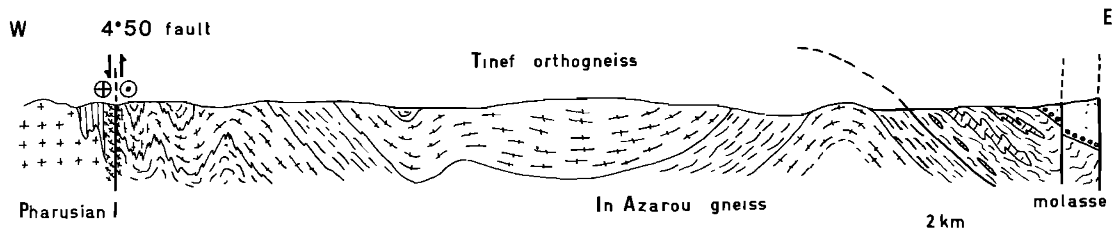

Fig. 5. Cross section of the Tinef area (Tinef well 22°20'N, from Gravelle [1969] and Boullier and Bertrand [1981]). A major thrust separates two refoliated tectonic units in this region. The upper unit, with numerous marbles, is very similar, except for the retromorphic foliation, to the Iherane granulites.

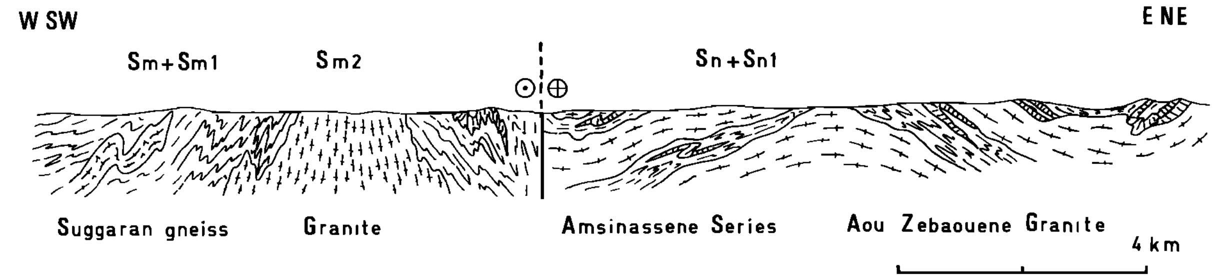

Fig. 6. Cross section of the In Amguel area (O.Tekchouli 23°30'N, from Vitel [1979] and Boullier and Bertrand [1981]). The late brittle fault is situated in the eatern domain, to the east of the main "mylonite" belt. The post-Sm1, pre-Sm2 K-granite is emplaced at the suspected position of the main thrust recognized farther south.

Aleksod. In the Aleksod mountains [Bertrand, 1974] two types of thrust have been described.

1. The oldest thrusts are parallel to the main S1 foliation and correspond to mapped disconformities accompanied by a strain increase but without a metamorphic break. The "Ouadenki unconformity," previously interpreted as having a partly stratigraphic origin, corresponds to one of these early thrusts; it marks the contact between the Aleksod Formation where S1 is the main and seems the first, foliation, and the Arechchoum gneisses where S1 is superimposed upon Eburnean structures [Bertrand and Lasserre, 1976]. Contrasting with the Tin Amzi thrust, the Aleksod ones are in metamorphic equilibrium and are refolded by isoclinal, postfoliation recumbent folds accompanied by the recrystallization of the same metamorphic assemblage (Bi, Mu, Ky, Gt) (Figure 7). Very often the thrusts appear as wide belts of high strain submylonitic gneisses and phyllonites. One of these belts contains tectonic lenses of eclogites [Sautter, 1985].

2. The younger thrusts, the most obvious on the map, were formed, unlike the older thrusts, under retrogressive conditions and crosscut all the folds. As they merge gradually with the vertical srike-slip faults, they were interpreted as a consequence of the late wrench-fault tectonics [Bertrand, 1974].

Oumelalen. In the Oumelalen region, Latouche [1979] described several thrust sheets predating the late F3 upright folding. The thrusts are related to a SW trending recumbent folding, which occurred under amphibolite facies conditions. They postdate a granulite facies assemblage dated at 2000 Ma [Latouche and Vidal, 1974]. Towards the south in the Temasint area, some of the unconformities described by Guérangé [1966] may actually be thrusts (B. Guérangé, personal communication, 1984; J.M.L. Bertrand, unpublished field observations, 1975).

Tazat. In the Tazat mountains, Blaise [1967] described a large synform deforming a basement and a sedimentary cover characterized by numerous intraformational unconformities. Bertrand et al. [1968] confirmed the existence of one major stratigraphic unconformity corresponding either to the bottom of the middle or upper Proterozoic, but they interpreted one of Blaise's unconformities as a thrust on the basis of structural and metamorphic breaks.

Tiririne. The Tiririne thrust forms the eastern boundary of Central Hoggar. The high-grade Issalane Formation is thrust over the late Proterozoic molassic and arenaceous sediments of the Tiririne Formation [Bertrand et al., 1978]. The thrust grades toward the south into the 8°30' wrench fault but a thrusting component probably reappears along the eastern edge of the Air mountains in Niger [Black et al., 1967].

Other areas. Other large-scale thrusts were not surveyed in detail. Their interpretation as thrusts is based upon recent reconnaissance cross sections. For example,in the Egere region [Duplan, 1972], early thrusts are outlined by eclogite lenses, and from a crude restoration, a 100-km shortening estimate is proposed by Latouche [1985]. In the Arefsa and Afedafeda regions, the basal layers of the so-called Pharusian basins must be reinterpreted as mylonites and the classical stratigraphic unconformity is highly dubious in most places [Latouche, 1985; M.Briedj et al., unpublished results, 1980]. In the Timgaouine area [Lapique et al., 1986] high-grade granite gneisses and metasediments are in complex tectonic contact (wrench fault grading to thrust) with the overlying Pharusian low-grade metavolcanics. The age of this tectonic event is bracketed between 629 Ma and 614 Ma (zircon and sphene U/Pb dating of a pretectonic granodiorite [Bertrand et al ., 1986]).

Figure 8 summarizes the thrusts discussed in this section with their sense of movement as determined by microstructural criteria.

An Interpretative Cross Section of Central Hoggar

The cross section presented here (Figure 9) is very different from previously published sections [Bertrand and Caby, 1978]. Vertical structures have been attenuated on purpose, just keeping the envelopes of the large synclinoria and anticlinoria. Almost all the

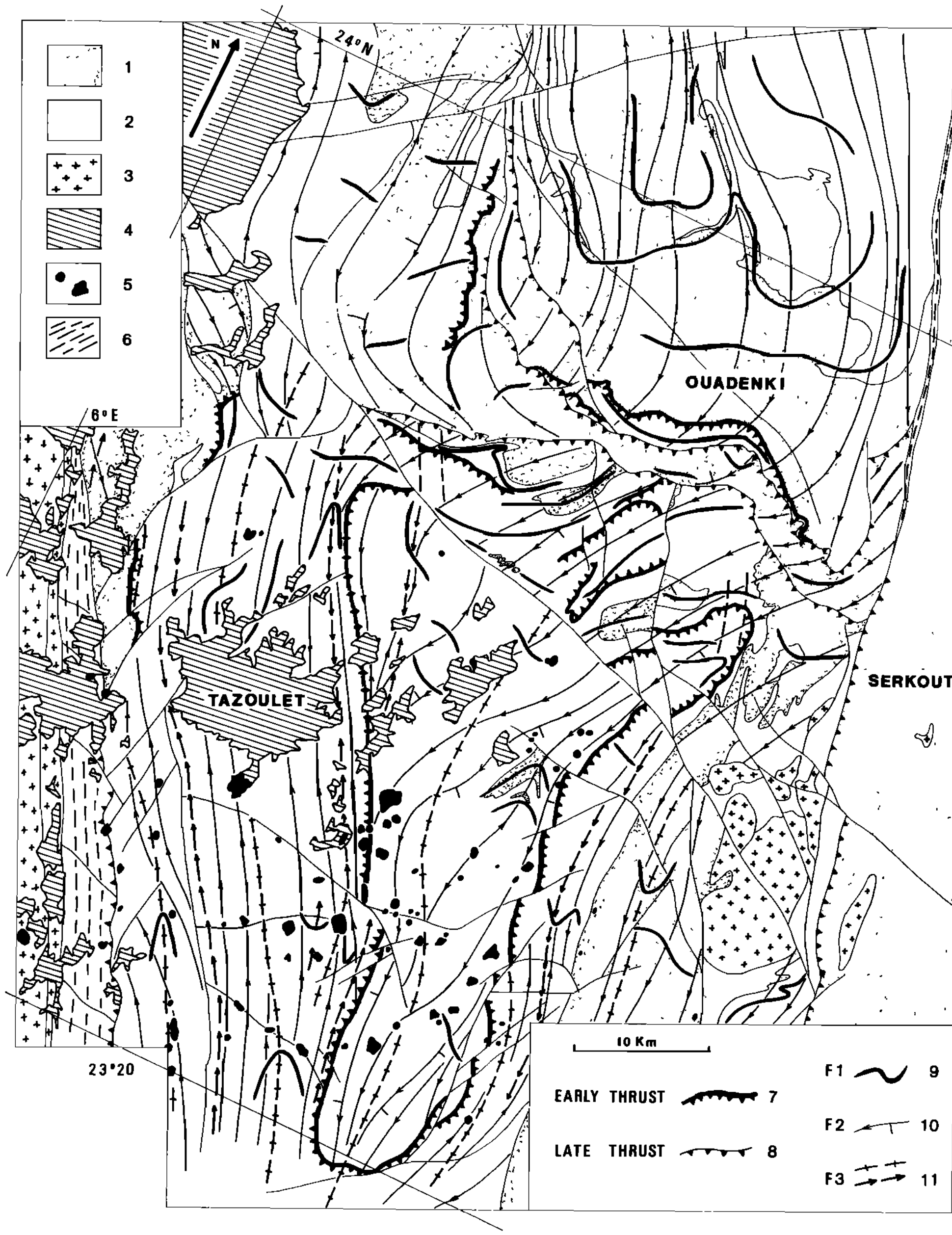

Fig. 7. Structural map of the Aleksod area [from Bertrand, 1974]. 1, Arechchoum gneisses, lower Proterozoic; 2, Aleksod series, middle Proterozoic (?); 3, granite; 4, recent plateau basalt; 5, recent trachyte or phonolite; 6, mylonite; 7, early thrust; 8, late retogressive thrust; 9, map projection of F1 axial plane; 10, trajectory and dip of L2 lineation with correspending dip; 11, F3 antiform and synform (arrow); 12, early high-grade thrust; 13, late retrogressive thrust.

observations converge to define a N to NE movement direction, except in the Tinef and Egere areas [Duplan, 1972; Latouche, 1985], and in many cases, thrusts may evolve gradually to wrench faults (e.g., Tiririne and Timgaouine).

The importance of the NS trending wrench faults appears to have been overestimated in previous papers [Bertrand and Caby, 1978; Caby et al., 1981]. In the case of the largest fault in the Hoggar, the 4°50'E fault, it was shown [Boullier and Bertrand, 1981] that most of the mylonites belong to an earlier, tangential deformation, similar to those described in

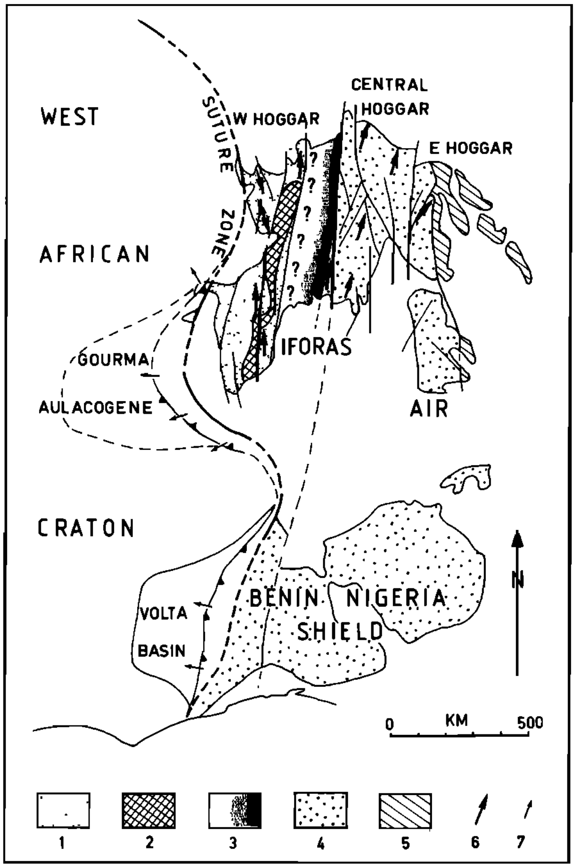

Fig. 8. Sketch map of the Transaharan belt showing the known movement directions; question marks outline the structurally unknown domain. 1, Western Pharusian belt; 2, In Ouzzal and Iforas Eburnean granulites; 3, Eastern Pharusian belt showing the known and presumed extent of the pre-840 Ma Pharusian I assemblage; 4, Central Hoggar "polycyclic" gneisses, granites, and schistbelts; 5, Eastern Hoggar; 6, direction and sense of movement of early Pan-African nappe tectonics; 7, direction and sense of movement of the late Pan-African foreland nappes.

the Tin Amzi area. The deformation related to the fault itself and, associated with an estimated dextral movement of about 100 km, is restricted to a narrow zone of retrogression in ductile conditions, followed by brittle behavior corresponding to a Phanerozoic uplift of the eastern block.

Instead of permanent, long-lived, deep vertical crustal breaks, the NS trending faults are thus interpreted as the results of the brittle behavior of the upper crust, associated perhaps with an indentation-related lateral ejection of blocks, similar to that seen in Asia during the collision process [Molnar and Tapponier, 1975; Peltzer et al., 1982]. The succes - sion of several thrusting events which are more and more retrogressive with time suggests such a continuum ending in brittle conditions with dominant lateral movement. This interpretation is in agreement with the flattening at depth of vertical structures shown by the results of deep seismic profiles (MOIST, COCORP, etc.) across comparable oro - genic belts (Appalachian and Caledonian orogens).

U/Pb GEOCHRONOLOGY

With the structural study having shown, for granitoid emplacement, the difficulties of precising a regional chronology compared to the tectono - metamorphic evolution of high-grade gneisses, the first problem to be solved by radiometric dating was to find out what stage, if any, of the structural sequence could represent a time break. For this study, both highly foliated granites parallel to the surrounding gneisses (Anfeg and Tinef) and crosscutting undeformed granitoids (Tin Amzi) were choosen. A further goal was to define the age of the initiation of the refoliation process; the syntectonic Aou Zebaouene migmatitic granite was choosen for this purpose.

Analytical Methods

Zircon fractions were separated using a com - bination of superpaner, heavy liquids and magnetic separation. Heavy mineral concentrates were purified by handpicking under a microscope to obtain

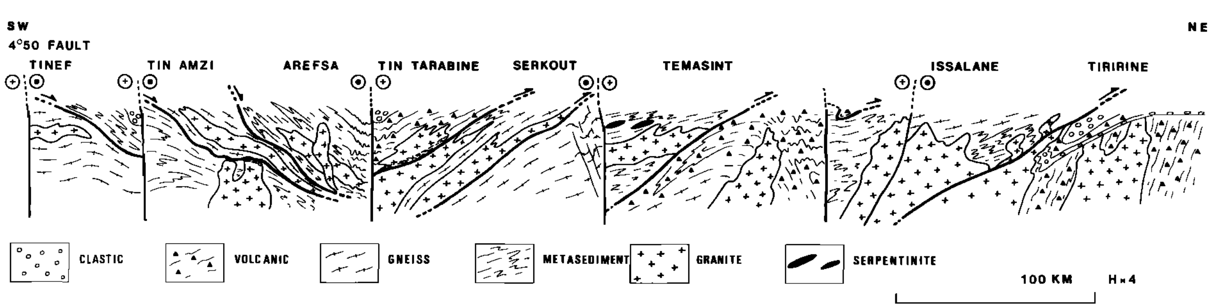

Fig. 9. Interpreted cross section from Tinef to Tiririne. The height scale is exaggerated. Granitoids are undifferentiated from pretectonic to syntectonic and posttectonic.

homogeneous fractions in size, color, morphology, and magnetism. Nonmagnetic fractions were favored for analysis, a careful study under the microscope and a SEM study having shown that in most cases the magnetic fractions are rich in small inclusions of magnetic minerals. The external and internal morphology of the zircons was studied using a Cambridge SEM.

Analyses were carried out using a variant of the technique described by Mahnes et al. [1978]. A mixed $^{208}Pb/^{235}U$ spike was added to the small teflon bombs before the HF attack. Pb and U were separated on anionic resin columns. Pb was loaded with H_3PO_4 and silica gel on a single Re filament. U was run as U_2O_3 on a single W filament with Ta and H_3PO_4. Isotopic composition was determined using a CAMECA mass spectrometer. Total lead processing blanks are smaller than 1 ng. Calculation of ages and errors was achieved with the method of Minster et al. [1979].

Results

The analytical data are given in Table 1.

Iherane gneisses and migmatites. Two samples (T11, T16) were studied (see Figure 2 for location) from a restitic metasediment and a nearly homogeneous granite, respectively. The analytical results, obtained on six zircon fractions, are grouped for each sample. They are moderately discordant, especially the granitic sample, and intercept the Concordia at 2075 ± 20 Ma and 530 ± 70 Ma (Figure 10).

Tinef orthogneisses. Two samples with similar texture and composition were studied. T22 was sampled in the type area, close to the Tinef well and IC1023 (courtesy R.Caby) is from Abalessa about 100 km to the north. Three zircon fractions from the T22 sample were analyzed. They are grouped close to the Concordia curve in the vicinity of 580 Ma and do not define a good intercept (Figure 10). The three complementary fractions from the sample IC1023 are almost concordant and define a precise upper intercept at 604 +10/-6 Ma. The age calculated with the T22 points is not significantly different from this, but the error is larger due to the scatter of the points.

Tin Amzi complex. Two samples were studied. T9 is a granodiorite forming a stock within the dominantly granitic complex and situated close to the deformed zone of the NE contact. T18 is also a granodiorite but was sampled from a 10 m thick dyke which sharply crosscuts the surrounding gneisses. The T18 results are not well aligned and the age cannot be precisely defined (612 +50/-20 Ma). Furthermore, the T9 fraction does not lie on the reference line. The T9 sphene is concordant and gives an age of 578 ± 6 Ma (Figure 10).

Anfeg granite. Two samples were studied, one from the deformed margin of the pluton (P59), and the other from a heterogeneous area situated 1 km from the contact, where gneissic xenoliths are dispersed in the granite (1009). Ten zircon fractions were analyzed (Figure 10). The P59 fractions are grouped close to the Concordia curve, four of them being almost concordant between 580 Ma and 600 Ma. The 1009 fractions and three fractions of the P59 define a Discordia with a 615 ± 5 Ma upper intercept and a 27 ± 25 Ma lower intercept. We interpret the 615 ± 5 Ma age as the time of emplacement, and the concordant P59 results as the effect of metamorphism on more or less abundant tiny Ce, Th- and U-rich inclusions in the outer zones of the zircons, which are undetected by the SEM [Kosztolanyi et al., 1986]. This interpretation is suggested by the identity of the youngest of these ages with the concordant age given by the T9 sphene.

Aou Zebaouene granite. One sample of porphyritic adamellite was studied (T57). Three zircon fractions and one monazite from T57 were analyzed. The experimental points of the zircon fractions are grouped despite their size difference, and their $^{207*}Pb/^{235}U$ apparent ages are sligthly older than 600 Ma (Figure 10). Including the concordant monazite in the age calculation, a lower intercept of 592 ± 6 Ma is obtained with a corresponding upper intercept of 2500 ± 400 Ma. Although no clear inherited cores have been seen in these zircons, an old component (>2000 Ma) seems to be present, as is the case in Pan-African granites from the Iforas region [Lancelot et al., 1983].

Discussion of the Results

Pan-African event. The structural data show the close links between the main tectonometamorphic evolution of the Central Hoggar and the emplacement of the large granitic plutons such as the Anfeg pluton. The 615 Ma age obtained for the emplacement of this pluton confirms previous data by Picciotto et al. [1965]: 615 and 619 Ma $^{207}Pb/^{206}Pb$ model ages as recalculated by Cahen et al. [1984]. In the light of this age, the significance of the gneissic assemblages which dominate the domain must be reconsidered. Instead of an old gneissic block of Eburnean (or older) age, affected to a limited extent by the Pan-African event [Bertrand and Caby, 1978; Latouche, 1978], it is now suggested that an almost complete tectonometamorphic reworking occurred; this reworking is, however, nonpenetrative on the crustal scale, and domains of all sizes (tectonic lenses) where older structures are still recognizable have partly escaped its effects.

In order to set up the chronology of this Pan-African reworking, the following must be pointed out:

1. The Tin Amzi and Anfeg plutons, and the Tinef orthogneisses, predate the last deformation, i.e., the last retromorphic thrusting and the upright NNE trending folding in the area.

2. The time span between the main refoliation

TABLE 1. U/Pb Analytical Data

Sample		Pb* ppm	U ppm	$^{206}Pb/^{204}Pb$	Radiogenic ratios $^{207}Pb^*/^{235}U$ [a]	Radiogenic ratios $^{206}Pb^*/^{238}U$ [b]	Radiogenic ratios $^{207}Pb^*/^{206}Pb^*$	Model ages, Ma $^{207}Pb^*/^{235}U$	Model ages, Ma $^{206}Pb^*/^{238}U$	Model ages, Ma $^{207}Pb^*/^{206}Pb^*$
T11	D	69	267	7173	4.1447	0.25385	0.11848	1665	1464	1935
	D (m)	69	245	8917	4.5496	0.27666	0.11933	1740	1580	1946
	F	73	272	5109	4.2636	0.25947	0.11924	1685	1486	1945
	F (m)	69	267	6455	4.1130	0.25212	0.11839	1657	1450	1933
T16	F	132	375	8064	5.8980	0.34151	0.12533	1963	1894	2032
	D	117	375	7692	5.2359	0.30461	0.12474	1857	1712	2026
T9	C	70	766	1960	0.7173	0.08738	0.05956	576	561	640
	Sp	23	195	491	0.7673	0.09386	0.05932	579	578	580
T18	D	51	560	2733	0.7230	0.08624	0.06084	552	533	634
	D	59	678	2570	0.7091	0.08258	0.06230	544	511	686
	F	68	717	3002	0.7531	0.08829	0.06189	570	545	670
	G	84	882	2425	0.7653	0.09091	0.06109	576	561	640
P59	F	28	270	982	0.7657	0.09395	0.05917	577	578	574
	F	33	318	656	0.7832	0.09538	0.05958	588	588	589
	G	30	298	1025	0.7586	0.09355	0.05885	576	580	562
	H	29	280	1160	0.7765	0.09362	0.06018	584	576	608
	C	27	249	761	0.8068	0.09712	0.06028	601	598	614
	E	33	326	1456	0.7717	0.09341	0.05995	581	576	602
1909	G	26	300	1097	0.6904	0.08322	0.06019	534	516	610
	E (a)	(b)	(b)	873	0.6326	0.07626	0.06019	498	474	610
	E (a)	(b)	(b)	850	0.6452	0.07806	0.05598	506	484	603
	E (a)	(b)	(b)	1510	0.6663	0.08003	0.06041	518	497	618
1023	C	30	274	1146	0.7961	0.09529	0.06059	595	587	625
	E	33	309	1451	0.7838	0.09372	0.06066	588	578	627
	G	32	281	3024	0.8065	0.09734	0.06009	601	599	607
T22	F (m)	65	826	2056	0.7538	0.09059	0.06038	571	559	617
	D (m)	66	844	2208	0.7469	0.09018	0.06010	567	557	607
	A	65	847	2225	0.7450	0.08810	0.06136	565	545	652
T57	E	22	219	2437	0.8444	0.09784	0.06259	622	602	694
	E (m)	23	227	1059	0.8360	0.09976	0.06078	617	613	632
	G	23	232	4538	0.8085	0.09629	0.06089	602	593	636
	Mz	1058	630	490	0.7799	0.09482	0.05965	585	584	591

Zircon size: A (175-125µm); B (>150µm); C (150-100µm); D (125-90µm); E (100-75µm); F (90-75µm); G (75-45µm); H (<45µm); (m) = magnetic; Sp = Sphene; Mz = Monazite; (a) brown zircon-rich fraction; (b) sample weight <1 mg: absolute concentrations not representative; Pb* = radiogenic lead. Common lead correction: $^{206}Pb/^{204}Pb = 18.60$; $^{207}Pb/^{204}Pb = 15.50$; $^{208}Pb/^{204}Pb = 38.6$.

a. Error estimated from replicate measurement of concordant zircons is 1.5%.

b. Error is 1.3%.

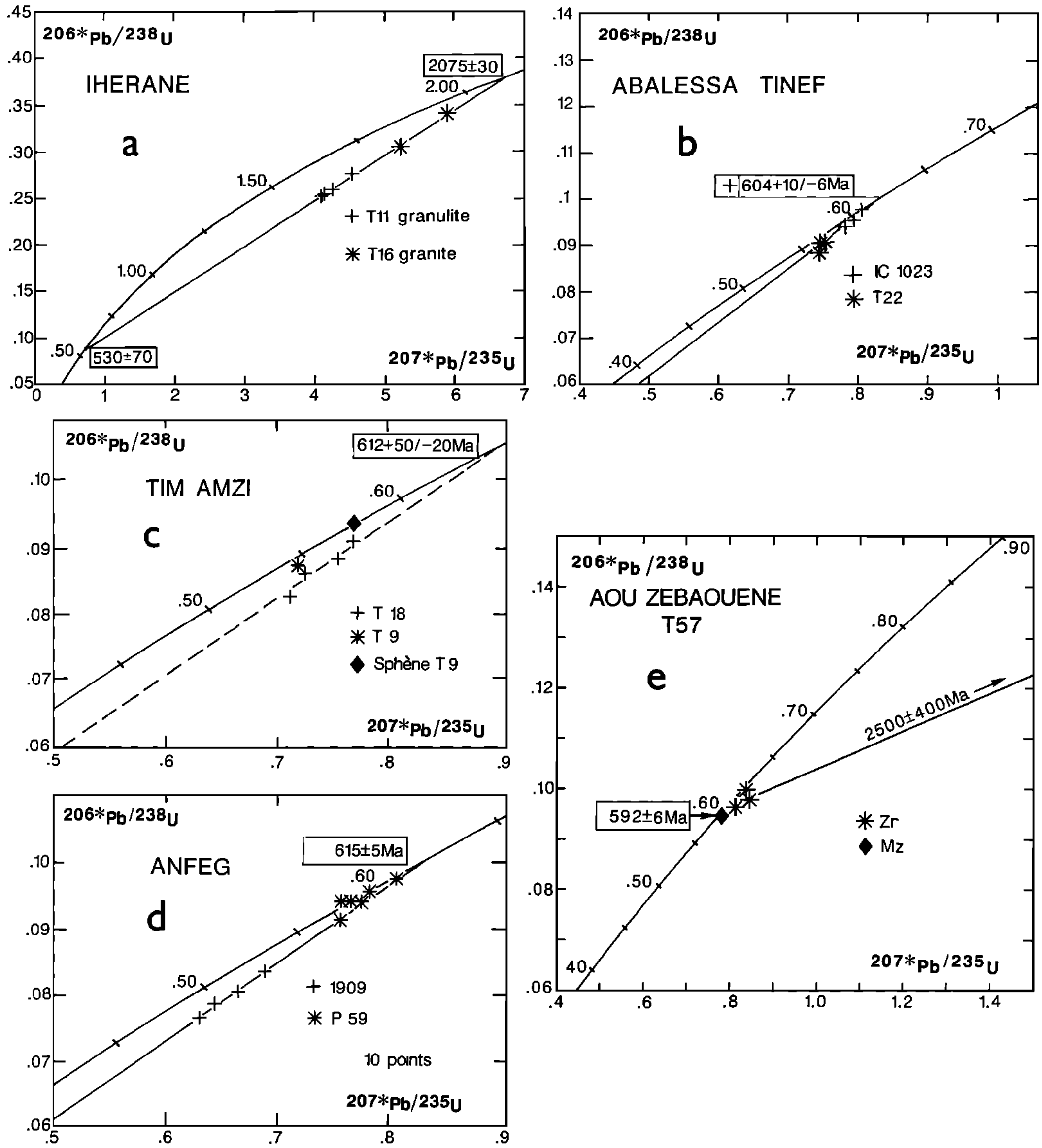

Fig. 10. Concordia diagrams. (a) Iherane granulite and migmatitic granite; (b) Tinef and Abalessa orthogneisses; (c) Tin Amzi granitic complex; (d) Anfeg granite; (e) Aou Zebaouene migmatitic granite.

event in amphibolite facies conditions (Sp1) and the emplacement of the Anfeg pluton cannot be determined precisely, but it is clear that the granite postdates this foliation. Thus the 615 Ma age given by the granite corresponds to a plutonic episode which occurred during the Sp1-Sp2 interphase. The apparently younger (604 Ma, but within the error bars) Tinef orthogneisses were probably emplaced at a higher level in the surrounding In Azarou gneisses, as they are associated with numerous deformed microgranitic rocks, and show no evidence of a peripheral migmatization.

3. The only reason for attributing the main Sp1 refoliation to the Pan-African event is the identity of the deformation regime and movement direction before and after the granite emplacement, suggesting a progressive deformation.

On an other hand, the 580-590 Ma age yielded by the monazite and sphene (T57, T9) also supported by the sliding along the Concordia of some Anfeg zircon fractions (P59) indicates that either a cooling below 500°-450°C occurred only 30 m.y. after the granite emplacement or that some influence of later meta - morphic conditions is registered in the Sp2 mylonites.

In any case, the 580-590 Ma age corresponds to the end of medium-grade metamorphic conditions in the region and fixes an upper limit for the age of emplacement of the batholitic granites. It also corresponds to the age of the older posttectonic concentric plutons (Taourirt granites [Boissonnas, 1973]) dated in the Central Hoggar (580 ± 5 Ma [Latouche and Vidal, 1974]).

An early Pan-African or Kibaran event ? Radiometric results in the Touareg and Nigerian shields pointed to the existence of an ~1000 Ma event [Grant et al., 1972; Bertrand and Lasserre, 1976; Ogezi, 1977; Turner, 1983; Fitches et al., 1985]. One must also recall that 870-840 Ma ages have been reported from the pretectonic to late tectonic granitoids associated with the Pharusian I domain [Caby et al., 1982], a few tens of kilometers west of the area studied in this paper (Figure 8).

None of the new results point to the existence of such a Kibaran or early Pan-African event, but rather they support the idea of the strong predominance of the Pan-African orogeny. As no recent geochronological data concerning intrusive rocks in the Pan-African mobile belt of the Hoggar and Nigerian shields indicate Kibaran ages, the existence of this event is highly doubtful [Lancelot et al., 1983; Tubosun et al., 1984; Bertrand et al., 1984]. Ages of about 850-750 Ma in these regions [Caby et al., 1982; Fitches et al., 1985] show, however, that the geodynamic evolution of the upper Proterozoic is probably multistaged and would need more refinement especially in the question mark area of Figure 8.

The Suggaran event or Eburnean (see discussion by Cahen et al. 1984]). Results from the Iherane granulites confirm the previously published ages for the old gneissic and granulitic components of the Central Hoggar. The 2075 Ma age is compatible with the existence of locally preserved Suggaran assemblages. However, from the 570 ± 70 Ma lower intercept, two alternative hypotheses may be proposed concerning the significance of the granulite facies metamorphism: (1) It is of Suggaran age or (2) of Pan-African age with inherited zircons from an older stage. We favor the first hypothesis on the following arguments:

1. From structural evidence the granulites and associated migmatitic granites predate all the tangential deformations. Furthermore, the uplift indicated by the M1-M2 succession took place before the emplacement of the Tin Amzi complex and before the initiation of thrust tectonics.

2. Locally, a postgranulitic metamorphic imprint has been observed and may be attributed to the Pan-African tectonometamorphic event.

3. No evidence was found of crystal heterogeneity, or recrystallization or inherited cores, in the analyzed zircons.

4. The zircon fractions are weakly discordant, especially those from the migmatitic granite. If this granite is Pan-African, the zircon fractions would probably be located closer to the lower intercept than the fractions from the granulites.

The position of the zircon analyses on the Concordia diagram is interpreted as resulting from an episodic lead loss which occurred ~600 m.y. ago, when amphibolite facies conditions were reached. But owing to the local lack of intense deformation and corresponding pervasive fluids and considering the probable rapid emplacement of the nappe relative to the mineral reactions kinetics, recrystallization of the previous assemblages was restricted and the radiometric clocks were only sligthly affected.

CONCLUSIONS

This study presents the first comprehensive chronology of the main tectonometamorphic events in the Central Hoggar. The 615-580 m.y. time span determined by U/Pb dating on zircons, sphenes, and monazites from granitoids carefully replaced in the structural sequence requires a reinterpretation of the crustal behavior of this part of the Transaharan belt [Cahen et al., 1984]. A model for the crustal evolution during the Pan-African orogeny, involving an old crustal segment situated far behind the suture zone exposed in Mali [Black et al., 1979; Caby et al., 1981] is proposed. After emphasizing the fact that except for the dating of the Suggaran basement, no major pre-600 Ma event has been proved in Central Hoggar, three key ages may be retained from existing data:

1. From 615 to 600 Ma, emplacement of syntectonic to late tectonic granitoids (mostly S-derived?) occurred, often emplaced as large sheetlike bodies parallel to the refoliation of an older basement. This feature is the consequence of a crustal scale imbrication, which started probably not long before, and ended after, the emplacement of most of the granitoids, under metamorphic conditions decreasing with time.

2. From 590 to 580 Ma, cooling of the belt and the end of metamorphism occurred. This age also corresponds to the oldest age for the cross-cutting posttectonic Taourirt granite [Latouche and Vidal, 1974].

3. 515 Ma is the age of the youngest dated Taourirt granite [Vialette and Vitel, 1979].

There is an impressive similarity in age of plutons emplaced during the ~600 Ma major tectonic event described from the Iforas region [Liégeois et al., 1986; Bertrand and Davison, 1981], Central and Eastern Hoggar [Bertrand et al., 1978], and Central Nigeria [Fitches et al., 1985; Turner, 1984; Rahaman et al., 1983, Tubosun et al., 1984]. Close to the Pan-African suture, this event marks the occurrence of continental collision [Black et al., 1979]. It is thus tempting to interpret the tangential deformation occurring in Central Hoggar, although situated far behind the suture, as a consequence of this collision. We have shown that the result is a tectonome-

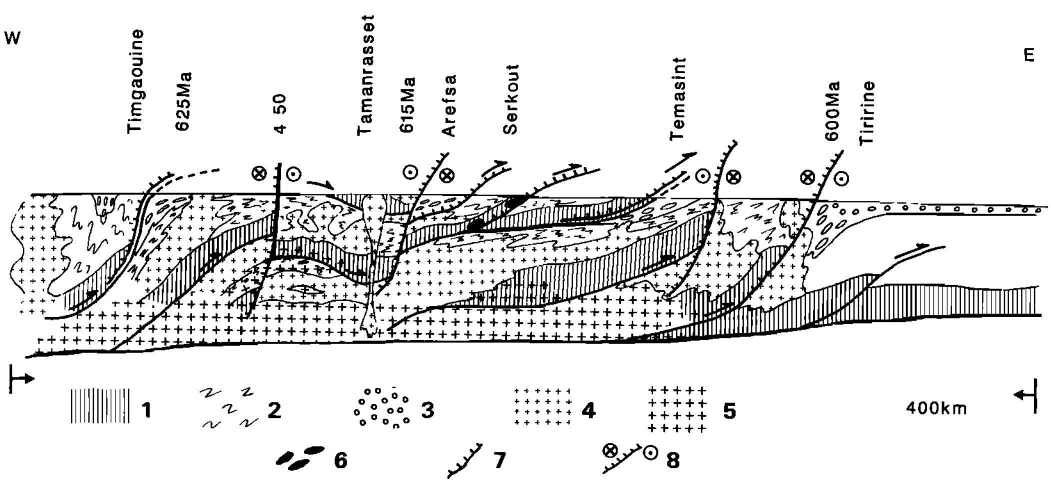

Fig. 11. Crustal evolution of the Central and Eastern Hoggar. The section represent the end of the process after isostatic readjustment. The height scale is exaggerated. 1, Lower continental crust (old granulites); 2, middle crust with metasediments; 3, clastic and volcanoclastic formations, part of them being probably syntectonic; 4, syntectonic to late tectonic granite; 5, zone of potential new granulite facies, not recorded at the surface but perhaps present in basaltic xenoliths; 6, eclogites migrating to the surface during the continuous evolution of the shear zones to more and more retrogressive conditions; 7, late retrogressive thrust, wrench fault and wrench thrust; some of them are the result of multiple offset of the primary shear zones; 8, sense of lateral movement (dextral).

tamorphic reworking, initiated under deep crustal conditions and probably including the participation of at least the crust-mantle boundary (if the Pan-African age of the Serkout eclogite is confirmed).

The tentative crustal section presented in Figure 11 assumes the existence of A-type subduction and of a major decoupling zone along the Moho to explain the scarcity of mafic and ultramafic rocks in Central Hoggar; it takes into account: (1) the high-grade refoliation of the older rocks and associated eclogite tectonic lenses; (2) the corresponding prograde Barrovian metamorphism of the younger meta - sediments (assuming that the Kibaran ages are actually artefacts or reflect some kind of depositional age); (3) the late retrogressive tangential shearing evolving in the latest stages to subvertical wrench faults and occurring during the isostatic readjusment of a previously thickened crust, the speed of the unroofing being probably larger than the speed of the still active shortening; (4) the evolution of the volcanic-bearing schist belts which are possibly broadly syntectonic and whose dominantly felsic volcanics are likely to be crustally derived; this could also be true for the post-840 Ma Pharusian II volcanoclastic formation [Caby et al., 1982] implicated in the tangential deformation of the Timgaouine and Laouni regions [Lapique et al., 1986] and of the post-725 Ma Tiririne formation [Caby et al., 1981]; and (5) the large volume of granitoids often emplaced as thick sheetlike bodies. They are suggested to have been formed during thickening of the crust, their evolution being controlled by the still active thrust tectonics. The thrusting produced an alternation of more or less ductile, more or less hydrated layers, some of them being more able both to produce and guide the granitic magmas.

The calc-alkaline 670 m.y. old pluton of In Ozzaf in Central Hoggar [Vialette and Vitel, 1981] and of Tiririne in Eastern Hoggar [Bertrand et al., 1978] may correspond to the A subduction initiation stage and thus could give an older limit for the tectogenesis. However, this model is only based upon structural and geochronological data, and geochemical cons - traints are, to date, almost absent. In the Iforas region, a D1 tectonic event consists of basement nappe emplacement with a northward vergence [Boullier et al., 1978; Davison, 1980; Wright, 1979; Boullier, 1982]. The age of this event is still doubtful; it may be older than the Oued Teggart quartz-diorite dated at 690 Ma by Caby and Andreopoulos-Renaud [1985], or it may be a continuum of deformation with the D2 tectonic event reflecting SW-NE shortening associated with the collision. It does, however, seem to be older than 617 Ma age given by a Rb/Sr biotite age on a pre-D1 metadiorite [Bertrand and Davison, 1981] and than 613 ± 29 Ma age indicated by a Rb/Sr isochron age for a post-D1 and pre-D2 monzodiorite [Liégeois et al., 1986]. A N-S thrusting event has also been described in Western Hoggar [Caby, 1970; Caby et al., 1985] and may be broadly equivalent to the thrust tectonics of the Iforas [Champenois et al. 1986].

The slight diachronism which characterizes the N-NE directed thrust tectonics across the whole Hoggar shield (more than 615 Ma in the Iforas, 630-615 Ma in the Timgaouine area, 615-600 Ma in Central Hoggar, and 600-580 Ma in Eastern Hoggar) is still not understood. The tectonic regime and the chronology of the vast area situated between the Iforas and the Central Hoggar are almost unknown (Figure 8). Is there another suture, implying the possible accretion of exotic terranes? Then Iforas granulites and Pharusian I domain would be good candidates. Whatever the age of the D1 thrust tectonics is in the Iforas region, the recognition of Pan-African S-N to SW-NE thrusting directions in that region and in Central Hoggar [Bertrand et al., 1984; Latouche, 1986] does not fit with a simple E-W collision with the West African craton. One would have to imagine either an oblique collision [Wright, 1979, and unpublished results,1979; Caby et al., 1981; Boullier, 1982; Ball and Caby, 1984], a complex multicontinental collision, or an indentation of the Hoggar shield by the elbow-shaped West African craton inducing lateral movement of blocks toward the N-NE [Boullier, 1982] to explain the structures seen. These collision models have been discussed by Lesquer and Louis [1982].

At present, the gaps in the survey of the Hoggar region limit the possibility of a complete synthesis of the structure and chronology of the northern Transaharan belt. Many questions are posed by the new set of data presented here, such as the significance and geochemistry of the volcanics from the schist belts, evolution of the granitoids, the posttectonic history of the Central Hoggar and metallogenic consequences,etc. However, the reap - praisals presented here will provide new working hypotheses for the understanding of this important orogenic belt and of the behavior of the crust in collisional orogens more generally.

APPENDIX: SAMPLE PETROGRAPHY AND ZIRCON MORPHOLOGY

All the zircons were studied under a microscope and, after grain concentration, with a Cambridge SEM (whole grains and sections) to determine their internal structure and the composition of their inclusions.

Oued Iherane

T11 is a pyrigarnite with Gt, Opx, labrador, biotite, and green spinel, whose nebulitic aspect in the field, closely association with Gt-cordierite migmatite and high iron content (23% as Fe_2O_3) suggest a restite origin. The zircons are pink to yellow and without well-defined crystal faces. Only one population was distinguished, showing no zoning and almost no inclusions. Their rounded shape is often emphasized by curved cracks subparallel to the edges of the crystals.

T16 is a heterogeneous biotite granite with pluricentimetric clusters of Gt + Cord. The garnet is also distributed as small anhedral grains amongst the Q-Biot-oligoclase granoblastic assemblage and often surrounded by cordierite rims. The zircon are yellow to pale brown in color with shapes very similar to T11, although with a tendency to show more facets. Some grains are pink bipyramids and may represent a second generation; they are in small quantity and were not used in analysis.

Tinef (T22) and Abalessa (IC1023) Orthogneisses

T22 has a submylonitic texture with clasts of microcline and plagioclase (andesine) in a matrix of completely recrystallized ribbon quartz; rare chloritized primary biotite are preserved together with a fine-grained assemblage of recrystallized biotite, chlorite, and sericite; ilmenite is fringed by sphene and large crystals of apatite, allanite, and zoned zircons occur. Zircons are rounded bipyramids and show a fine euhedral zoning and partial replacement of the core of the crystal by a Fe-Ca bearing zirconosilicate under SEM. The external shape of the crystals, although more elongate, shows some similarities to the granulitic zircons; some grains are broken and sealed by K-feldspar.

IC1023 is very similar to T22 in texture but contains large broken and chloritized dark hornblende and sphene. The zircons are more elongate than in T22 and show a fine euhedral zoning without any difference in composition. As the sphene is fragmented and rounded within the submylonitic strips, the rounded zircon shape may be attributed to a similar process.

Tin Amzi Complex.

T9 comes from a granodiorite which forms stocks within the pluton. It is composed of clinopyroxene with minor hornblende, biotite, quartz, zoned plagioclase, and some xenomorphic and poikilitic microcline. The texture is intergranular and the biotite, often poikilitic, seems to have grown late in the crystallization history. Apatite, sphene, ilmenite, and zircon are abundant. Zircon shows a very peculiar acicular shape, pyramids being absent and several crystals being joined parallel to the prism faces suggesting a quenched texture. The zircon grains are often broken, striated crystals, with numerous inclusions of apatite, plagioclase, and biotite.

T18 has an equigranular texture with quartz, zoned plagioclase, microperthitic microcline with zonal quartz inclusions, biotite, and chlorite. A micropegmatitic tendency is present in places. The rock is poor in accessory minerals; zircon is euhedral with an acicular shape and contains numerous inclusions of apatite, quartz and feldspar.

Anfeg Granite

P59 is a porphyritic adamellite where the flat lying foliation, obvious in hand specimen, is weak in thin section. It contains quartz, oligoclase, microcline, hornblende, and biotite. The feldspars appear as partly recrystallized clasts, whereas the biotite and quartz are recrystallized; myrmeckite is also present. Amongst the accessory minerals (apatite, sphene, Fe-Ti oxides) the zircon is euhedral, unzoned, and contains tiny inclusions of apatite; some of them show tiny buds or outgrowths on their crystal faces (artefacts produced at the resin-crystal interface?). In the external zone of the zircon crystals, Kosztolanyi et al. [1986] have found a restricted zone (or dots, >0.1 micron) enriched in Ce, Th, and U (thorianite or monazite).

1009 is a leucocratic granite with a granoblastic equigranular texture. It is composed of quartz, oligoclase, microcline, biotite with rare sphene, apatite, and Fe-Ti oxides. The zircons are euhedral, unzoned, and contain a few inclusions of apatite. The cores of some crystals are slightly metamict.

Aou Zebaouene Granite

T57 is composed of quartz, microcline, oligoclase, and biotite and is rich in accessory minerals (apatite, monazite, and zircon). The large porphyroblasts of microcline contain numerous inclusions of quartz, plagioclase, and biotite. The biotite aggregates form a net typical of a metamorphic texture. Zircons are present with two distinct habits: small limpid balls with many facets and large colorless to pale brown bipyramids. As the color grades in both habits from colorless to honey, they do not seem to belong to different generations. Zircons show a complex zoning with alternating dark Ce, Nd and Ca-rich zones, and light zones containing traces of Hf. The outermost zone is unconformable on the main zoning and show a normal zircon composition. No evidence of inherited cores has been observed, but irregular alteration occurs sometimes. The complex crystallization history of these zircons suggests an S-type origin for the granite.

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