A major Pan-African crustal decoupling zone in the Timgaouine area (Western Hoggar, Algeria)

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Abstract—In the Timgaouine area, the granite-gneisses and medium-grade metasediments of the Aoullene domain, situated to the east of the area studied and separated from the Timgaouine domain by a high-strain zone the Tim Dl-Tin Efene lineament, do not correspond to a simple pre-Pan-African basement The Timgaouine domain is constituted by two unconformable formations, the older Pharusian I cycle which ended 840 Ma ago with the emplacement of post-tectonic high-K granites and syenites, while the Pharusian II constitutes a volcanoclastic unconformable cover Both units have been slightly deformed and metamorphosed under greenschist-facies conditions and large late-tectonic batholithic complexes (Imezzarene pluton) were emplaced The contrast is sharp with the highly deformed, medium-grade Aoullene domain where, however, Pharusian II equivalents have been recognized A study of the deformation in the Tim Dl-Tin Efene lineament and in the Aoullene domain (which are characterized by a strong often mylonitic and flat-lying foliation and a conspicuous NE trending stretching lineation) shows that it corresponds to a complex association of thrusting and strike-slip mechanisms This feature is interpreted as the result of a major intracrustal decoupling zone separating a deeply reactivated underlying basement and cover unit from a high-level unreactivated crustal 'pop-up' U/Pb geochronological results confirm this interpretation and fix the age of the main tangential tectonics in the range 629–614 Ma Ages and tectonic evolution of the Aoullene domain are thus very similar to what is known in the neighbouring Central Hoggar The late-tectonic Imezzarene pluton has been dated by the same method at 583 Ma

INTRODUCTION

During the Pan-African orogeny, 600 Ma ago, a wide mobile belt was formed in the Hoggar area to the east of the West African craton, which remained stable during the Middle and Upper Proterozoic From convergent evidence, a complete Wilson cycle was proposed, initiated ca 800 Ma ago, it ended ca 600 Ma ago with the building of a collisional orogen (Bertrand and Caby 1978, Black et al 1979, Caby et al 1981)

The most prominent structural features are N–S trending folds, and mega shear-zones which acted as thrusts or strike-slip faults Three structural domains have been defined, separated by major lineaments (Bertrand and Caby 1978) They are, from west to east the Pharusian belt, the Central Hoggar, the Eastern Hoggar The Timgaouine area belongs to the eastern branch of the Pharusian belt (Fig 1)

GEOLOGICAL SETTING OF THE TIMGAOUINE AREA

The Pharusian belt is separated into two branches by the In Ouzzal and the Iforas granulitic units interpreted as representing basement nappes (Boullier 1979) Except for these units, most of the belt is constituted by Middle to Upper Proterozoic formations (Caby 1970) In the eastern branch, two tectonometamorphic cycles have been demonstrated (Bertrand et al 1966, Gravelle 1969) Pharusian I and Pharusian II
The Pharusian I is constituted by a volcanosedimentary unit with calc-alkaline affinities (Fabries and Gravelle 1977, Chikhaoul 1981), deformed under greenschist-facies conditions between 868 Ma and 839 Ma, ages corresponding respectively to pre-tectonic and post-tectonic calc-alkaline intrusives (Caby et al. 1982).

The Pharusian II lies unconformably on the eroded terranes of the Pharusian I and is mainly composed of andesitic to rhyodacitic flows and tufts.

In this study, the two tectonic events which affect respectively the Pharusian I and the Pharusian II will be noted D1 and D2 (S1 and S2 are the corresponding foliations or schistoses).

In the Timgaouine area, a 'Saggarian horst' has been previously proposed (Bouvet and Reboul 1961), based upon the existence of high-grade gneisses and of a stratigraphic unconformity. More recently the terranes separated by the unconformity were attributed respectively to the Pharusian I and Pharusian II (Bertrand et al. 1966), but the significance of the gneissic assemblage, well represented in the eastern part of the area, was not understood.

On the field, a major NE-SW trending lineament (Tin Di–Tin Elfei), corresponding to a high-strain zone and locally to a fault, separates two domains—Aoulène to the east and Timgaouine to the west—whose structure and lithology are described in this paper (Fig. 2). The Pharusian belt is classically bordered to the east by the 4°50' mega-fault. The structural evolution of the adjacent Central Hoggar has been recently reinterpreted as composed of an Eburnean basement strongly reactivated during the Pan-African event s s (615–580 Ma). The corresponding reorientation occurred in a thrust regime under metamorphic conditions which evolved, in time, from deep amphibolite-facies to greenschist-facies (Bertrand et al. 1984, 1986).

THE TIMGAOUINE DOMAIN

Pharusian I series, rock types and structures

The Pharusian I terranes are composed of interbedded sedimentary and volcanic terms. The lithology is not uniform and the sedimentary terms are more abundant to the east of the domain. To the west, the basaltic terms and associated greywackes become dominant, but still contain some interbedded marbles and microconglomerates. The shelf sediments and lavas are cross-cut by pre-tectonic ultrabasic and gabbroic to dioritic rocks forming sills or small plutons. The basement of the series is rarely exposed but can be observed near the EREM Abankor base, where a small anticline exhibits the unconformity of the Pharusian I on older gneissic rocks.
In that place, the Pharusian I sequence starts with quartzites and conglomerates followed by Conophyton marbles (Gravelle and Lelubre 1957, Gravelle 1969), which may be equivalent to those of the Stromatolite series of the NW Hoggar (Caby 1970).

The whole complex was deformed during the D1 event under lower greenschist-facies conditions, and locally amphibolite facies conditions, producing a strong foliation in the lavas, sills and sediments, but often unaffected in the core of the gabbroic plutons. The D1 folds are recumbent isoclinal folds, latterly locally disturbed during D2. Early isoclinal folds are sometimes preserved but the lineation is weak except in dioritic gneisses poorly affected by D2 which exhibit a W-E to NW-SE trending stretching lineation representing the movement direction during D1.

Two groups have been defined in the plutonic rocks. The older one, generally the most deformed, predates the D1 event. It is composed of granodiorites and quartz-diorites foliated and retrogressed in greenschist-facies conditions. Dioritic rocks, spatially associated with the gabbroic bodies, are often tectonically interleaved with the lavas. The younger, more granitic, one intrudes the granodiorites of the first group and has only been affected by a weak N-S trending cleavage of the D2 event.

Pharusian II series, rock types and structures

An important Pharusian II volcanosedimentary basin outcrops in the eastern part of the domain. West of the alkaline granite of Abankor, the basal unconformity is marked by a thin and discontinuous conglomerate horizon (Bertrand et al. 1966). It is overlain by grits and pelites which exhibit numerous sedimentary structures (interpreted as flysch-type structures by Haddoum 1984), and it is intruded by basaltic and andesitic dykes. At the top of the series, acid volcanites become dominant. They are composed of pyroclastics (brecias to tufts), ignimbrites and rhodacitic flows. Some gabbroic dykes cross-cut the rhyolites. The thickness of this volcanosedimentary series is estimated to be about 4 km (Haddoum 1984).

The D2 event is responsible for N-S to N20°E trending upright open folds and for a more or less penetrative axial-plane cleavage formed under upper greenschist-facies conditions.

To the west, the sequence is less well developed and polygenic conglomerates outcrop in N-S trending elongate ‘spoon-shaped’ structures affected by D2 open folds. Further west, metamorphic gneisses locally associated with polygenic conglomerates (‘gresco-pelitic’ formation of Gravelle 1969) are the host-rock of the Imezzarene pluton. They exhibit a dynamic contact metamorphism, and in places migmatization. There is no detailed mapping of the Pharusian II rock types, but there should be an east–west gradation from a volcanic (Abankor, Tin Ds–Tin Eifie) to a clastic facies where the grits could represent the most evolved terms.

The main post-tectonic plutonism is represented by the Imezzarene pluton which largely outcrops to the west of the Timgaouine domain and also extends southwards (In Tedenni) and northwards (Silet). It is a complex pluton, composed of late to post-tectonic units, and whose detailed study remains to be done.

THE TIN DI-TIN EIFEI LINEAMENT (Fig. 3a)

This high-strain zone contrasts sharply with the weak development of S2 in the Timgaouine domain, it follows closely a narrow Pharusian II volcanosedimentary basin, which shows a unique phase of deformation D2. The stratigraphic unconformity of volcanoclastics on the marbles and granodioritic gneisses of the Pharusian I was observed along the western border and the southern end of the basin. The Pharusian II is similar to the sequence defined in Timgaouine but numerous rock type repetitions occur either due to a primary volcanic alternate or to the intense D2 deformation. It is then not possible to determine the initial thickness and the subsequent shortening.

A short deformation gradient characterizes the lineament and within about a 100 m from west to east, the deformation becomes very penetrative and gives rise to a vertical N30°-N40°E trending foliation bearing a strong stretching lineation, subhorizontal or plunging about 40° to the north. Microgranites and pegmatites cross-cut the rhyolites and are affected by synfoliation folds, whose hinges are parallel to the stretching lineation. In the tuffs, sheath-like folds (Cobbold and Quinquis 1980) with NE-SW horizontal axes have been observed. Another slight deformation gradient is also observed from south to north from the southern part of the Tin Eifie basin, which forms a large open syncline where the basal unconformity is preserved, to the Tin Dios basin where the deformation is maximum.

The measurement of quartz (c) fabrics does not provide a good determination of the shear sense because of the widespread post-kinematic recrystallization of the rocks. However, some field microstructural criteria indicate a sinistral shear along the eastern border of the Tin Eifie lineament. Haddoum (1984) also reported a sinistral shear for a N20°E trending wrench fault along the Abankor alkaline granite.

THE AOUILENE DOMAIN (Figs. 3a and b)

Bordered to the west by the Tin Di–Tin Eifie lineament, this domain is strongly deformed. The older granitoids are clearly pre-tectonic. They are alkaline granites forming discontinuous alignments along the edge of the Tin Di–Tin Eifie basin (as the rebeckite-bearing granite of Abankor), or preserved as remnants in the pre-tectonic granitoid gneisses representing the more abundant rock type.

The West Aouilene granite-gneiss is a porphyritic monzonic granite with biotite and hornblende. Its highly heterogeneous deformation corresponds to plas-
Fig 3 Cross-sections located in Fig 2. 1, Quartzites, marbles (Pharaohian I), 2, Pharaohian I granitoids, 3, Pre-tectonic granodiorites, 4, Ultrabasic rocks, 5, Amphibolites and rhyolites (Pharaohian II), 6, Conglomerates (Pharaohian II), 7, West Aouline granite-gneisses, 8, Post-tectonic granites, 9, Thrusts.
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very strong heterogeneous deformation leads locally to biotite-bearing mylonites. The quartz shows very elongate ribbons, and, according to the intensity, the feldspar megacrystals are more or less rounded and exhibit a microcrystalline rim of quartz and feldspar. Dissymmetric microstructures are uncommon. Numerous deformed pegmatites, some of which are mylonitized, are associated with the Aouilene granite-gneisses.

The structure appears monophased in this domain if one excludes later N-S trending large wave-length open folds. The dip of schistosity varies from horizontal to vertical, but with a constant N30-N40°E azimuth. This foliation, often mylonitic, and produced under lower greenschist-facies conditions (locally amphibolite-facies), is broadly subhorizontal in the centre of the dome and becomes progressively vertical to the west at the contact with the Tin D1-Tin Eifel basin.

In the northern part of the basin, the granite-gneisses are tectonically interbedded with Pharusian II metavolcanics. The flat-lying mylonitic foliation which affects the granite-gneisses together with the quartzites, metahyolites and amphibolite greywackes (Pharusian II more metamorphic equivalents), becomes progressively vertical in 100 m when approaching the Tin D1-Tin Eifel lineament. Whatever the dip of this foliation, it is always associated with a N40°E trending stretching lineation, similar to the lineation observed in the Tin Eifel metahyolites. The similarity in direction and deformation type between the Pharusian II basin of Tin Eifel and the Aouilene granite-gneisses suggests that both have been deformed during the D2 event.

Close to the Tin Eifel lineament, the subvertical foliation may be affected by a slightly retrograde cleavage S'2, but always with the same stretching lineation. Although obscured by a strong recrystallization due to later heating, the quartz (c) fabric analysis performed on a sample (C 67, Fig. 5b) in the NW part of the domain indicates a movement towards the NE in the flat-lying foliation of the granite-gneisses.

North of Tin D1 (Fig. 4), the geometry of the shear-zone is disturbed by the strength of the Pharusian I mole, and is similar to what was described at frontal and lateral tips of shear-zones (Coward and Potts 1983). West of the shear-zone, the D2 deformation in the Pharusian I formations shows

—very deformed marbles, showing NE trending sheath-like folds, and boudinage giving a NE trending extension,

—strongly deformed volcano-plutonic complex made up of amphibolites intruded by gabbrics and dioritic gneisses, which often exhibits an E-W to NW-SE trending lineation. In that region, the Pharusian I rocks are cross-cut by a less deformed granite, post-D1 ante-D2.

At its contact, the NE-trending shear-zone inverts itself eastwards and the foliations in the Pharusian I rocks undergo a sinistral rotation. Moreover, the stretching lineation of these rocks is progressively reoriented from a vertical plunge to a horizontal one (i.e., from an E-W trend to a NE-SW trend). The granite is tipped on the Pharusian I rocks and its xenolithes are strongly flattened in an E-W plane dipping to the south. These features are consistent with a NE-SW compressive lineament corresponding to a NE verging movement of the Aouilene block along the shear-zone.

In the eastern part of the Aouilene domain (Fig. 3b), a similar pattern to that of Tin Eifel was observed, with a NE-SW trending vertical foliation zone which indicates here a dextral shear. Quartz (c) fabric measurements made on a gneiss (C 134, Fig. 5a) and on a quartzite (C 71, Fig. 5c) this lineament is underlain by a metasedimentary unit composed of marbles, pyroxenites and quartzites associated with strongly deformed alkaline gneisses. The S2 foliation, also carrying a N40-N50 stretching lineation, is vertical and forms a tight anticline and syncline, and a retrogressive vertical
foliation S'2 appears. At the contact with the shear-zone, the granite-gneisses show the same structures. This association could represent a more metamorphic equivalent of the Timgaouine Pharusian I, but a similar association, also in the amphibolite-facies, is also known in the Central Hoggar where it is interpreted as Lower Proterozoic in age (Bertrand et al. 1984). The metasediments are cross-cut by pegmatites deformed in large horizontal isoclinal-folds, with boudnages on their limbs, resembling sheath-folds. All these structures indicate a NE-SW extension. Large-scale sheath-fold structures are suggested in the southern region by satellite imagery.

South of the domain (Fig. 3c), the almost flat-lying foliation affects a strongly deformed porphyritic alkaline granite, which is interlayered with a monophased sedimentary formation made of thick arkosic and pelitic layers associated with greywackes and acid metavolcanites. These terms are interpreted as Pharusian II equivalents. A NE trending stretching lineation and small parallel isoclinal folds are frequently observed, the foliation dips gently about 20-40° to the east, towards the 4°50’ mega-fault where it is latterly disturbed by a vertical mylonitic zone.

Thus, all the observed features suggest a continuum in the deformation regime between a thrust mechanism in the core of the granito-gneissic unit and a strike-slip mechanism along its margin, especially along the limit with the Timgaouine domain to the west. The tangential deformation is developed over a large domain, from the Tin Di-Tin Efei lineament to the 4°50’ mega-fault, and extends largely to the south.

Geometrically, at the map scale and in particular places, the granite-gneiss assemblage seems to plunge under the Pharusian I terranes, but no evidence has been found of an E-W early thrusting. On the contrary, the identical stretching lineation occurring in both tangential and vertical planes supports a unique, probably progressive deformation. The large-scale geometry should be an alternation of NE directed thrust and lateral ramp as the Tin Di-Tin Efei lineament.

Post-tectonic plutonism occurs in the core of the large elongated dome structure of Aouilene, where the granite-gneisses are cross-cut by an undeformed porphyritic granite which probably explains the widespread post-D2 recrystallization.

**GEOCHRONOLOGICAL RESULTS**

Two granitic complexes have been dated by the U/Pb method on zircon (Bertrand et al. 1986). From the ages obtained on the West Aouilene pre-tectonic monzogranite (respectively 629 ± 6 Ma on zircon and 614 ± 6 Ma on sphene), the age of the tangential tectonics in the Aouilene domain is well bracketed. In the Central Hoggar (Bertrand et al. 1984, 1986), the 615 Ma old Anfeg pluton post-dates an early high-grade foliation and is deformed in retrogressive conditions. The similarities in the foliation attitude and the trend of the stretching lineation point to progressive deformation, but the peak of the deformation can be estimated before 615 Ma (the Anfeg emplacement age).

Thus the deformation occurs probably at the same age in...
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the Central Hoggar and in the Aouilene domain. However, the sphene ages indicate slight differences in the thermal history, the Aouilene domain (614 Ma) cooling probably before the Central Hoggar (580 Ma). This age fixes the end of medium-grade metamorphic condition, the difference suggests a west–east younging of the main deformation and confirms the deeper and longer reworking of the Central Hoggar.

The late-tectonic Imezzerene complex, which forms with similar plutons a very large volume in the Pharusian belt, has given a zircon age of 583 ± 7 Ma. This age is very close to the Rb/Sr isochron ages obtained on post-tectonic circular plutons (Taourirt granites) (Boissonnas et al. 1969, recalculated by Cahen et al. 1984). The origin of such large plutons is still in question from their gradational and migmatic contacts, they are good candidates to represent the product of crustal melting subsequent to the crustal thickening related with the tangential tectonics, but the 87Sr/86Sr initial ratios estimated from early data are low (0.701–0.705).

**DISCUSSION AND CONCLUSION**

The most striking feature of this area is the tectonic contrast between the two domains. The Timgaoume domain is dominated by old Pharusian I features (older than 840 Ma), with a weak Pharusian II vertical cleavage, while the Aouilene domain shows a strong tangential deformation affecting together gneisses and Pharusian II formations. The 630 Ma U/Pb age of the pre-tectonic West Aouilene granite-gneiss (Boissonnas et al. 1969, recalculated by Cahen et al. 1984) is the origin of such large plutons is still in question from their gradational and migmatic contacts, they are good candidates to represent the product of crustal melting subsequent to the crustal thickening related with the tangential tectonics, but the 87Sr/86Sr initial ratios estimated from early data are low (0.701–0.705).

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The existence of such crustal ‘decoupling zones’ is important for explaining the relationships between plutonism and tectonics during the Pan-African event. The existence of the Pharusian I assemblage is, from available data, strictly restricted to the eastern margin of the Pharusian belt. This terrane would seem a good candidate for an ‘allochthonous terrane’ model (Ben-Avraham et al. 1981, Nur and Ben-Avraham 1982), but unfortunately the tectonic history of the Pharusian I is poorly known, and in particular no post-Pharusian I suture can be defined. On the contrary, the lithology is not very different in the Pharusian II on both sides of the Tin Di–Tin Efei lineament.

The slight reactivation of the Timgaoume domain during the Pan-African intracontinental thrust tectonic (D2) event suggests that this domain could have been structurally isolated by a mechanism of crustal ‘pop-up’ (Fig. 6) as the one described for the Kohistan arc in the western Himalayas (Coward et al. 1986) from the model of Elliott (1981) in thin-skinned thrust zones.

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to the NE. The Tin Dr–Tin Esfer lineament is interpreted as resulting from lateral ramp formation where the lower level ‘decoupling zone’ beneath the Timgaoune domain climbed laterally to a higher and easier slip horizon

Such a structural pattern showing thrust zones, frequently associated with a NE trending lineation and limited by strike-slip faults parallel to the movement direction (with sinistral or dextral shears), has already been described in Hoggar and Mali (Bertrand et al. 1978). Boullier 1979, 1982, Latouche 1986) This implies at the shield scale that the major collisional event, which occurred in the age range 615–580 Ma, was oblique and produced heterogeneous tectonics in time and space. Looking at the geometry of the oceanic suture between the West African craton and the Hoggar mobile belt (Lesquer and Lous 1982), we see that the Benin promontory could have played the role of an indenter during the Pan-African event.

The existence of a deep-crustal ‘decoupling zone’ under the Timgaoune ‘pop-up’ could explain the emplacement of the late to post-tectonic granites west of the Tin Dr–Tin Esfer shear-zone, and especially the large Imezarrene pluton. The post-tectonic granites outcropping in the center of Aouilene could be explained in the same way by a relay to the east of another ‘decoupling zone’ situated under the Aouilene granite-grnisses.

The alkaline granites which are clearly pre-tectonic with respect to D2 could represent an early extension stage. The ones which are aligned along the eastern margin of the Timgaoune domain (e.g. Abankor) underlie the weaker zone close to the site of the future lineament. From the RIE pattern of the calc-alkaline rhyolites (Bajja 1984), which suggest an origin from crustal melting (Barbey pers comm.), and from the intense plastic deformation of these rocks (under green-schist-facies conditions) producing very stretched rhyolitic pebbles, it may be assumed that the volcanic area was not completely chilled when the D2 thrust tectonics occurred. Thus the emplacement of the Pharusian II formations may predate shortly the tectonometamorphic evolution. Moreover, it has been shown (Oxburgh 1982) that the crustal strength is lowered by earlier extension, and hence makes the following thrust tectonics easier to operate.

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