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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 Aouilene domain, situated to the east of the area studied and separated from the Timgaouine domain by a high-strain zone the Tin Di–Tin Eifei lineament, do not correspond to a simple pre-Pan-African basement The Timgaouine domain is constituted by two inconformable 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 batholitic complexes (Imezzarene pluton) were emplaced The contrast is sharp with the highly deformed, medium-grade Aouilene domain where, however, Pharusian II equivalents have been recognized A study of the deformation in the Tin Di–Tin Eifei lineament and in the Aouilene 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 Aouilene 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

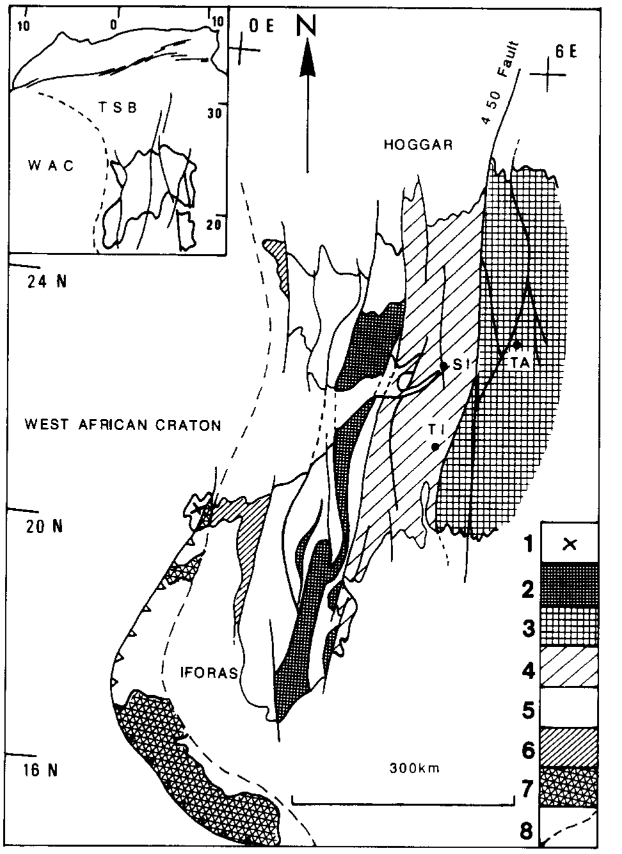

Fig 1 Simplified geological map of the western part of the Tuareg shield 1, West African craton 2, Eburnean granulites (Iforas and In Ouzzal) 3, Central Hoggar 4, Eastern branch of the Pharusian belt 5 Western branch of the Pharusian belt 6, Tilemsi accretion domain 7, Gourma and Timetrine nappes 8 Suture zone SI Silet TA, Tamanrasset TI, Timgaouine W A C , West African craton T S B , Trans-Saharan belt

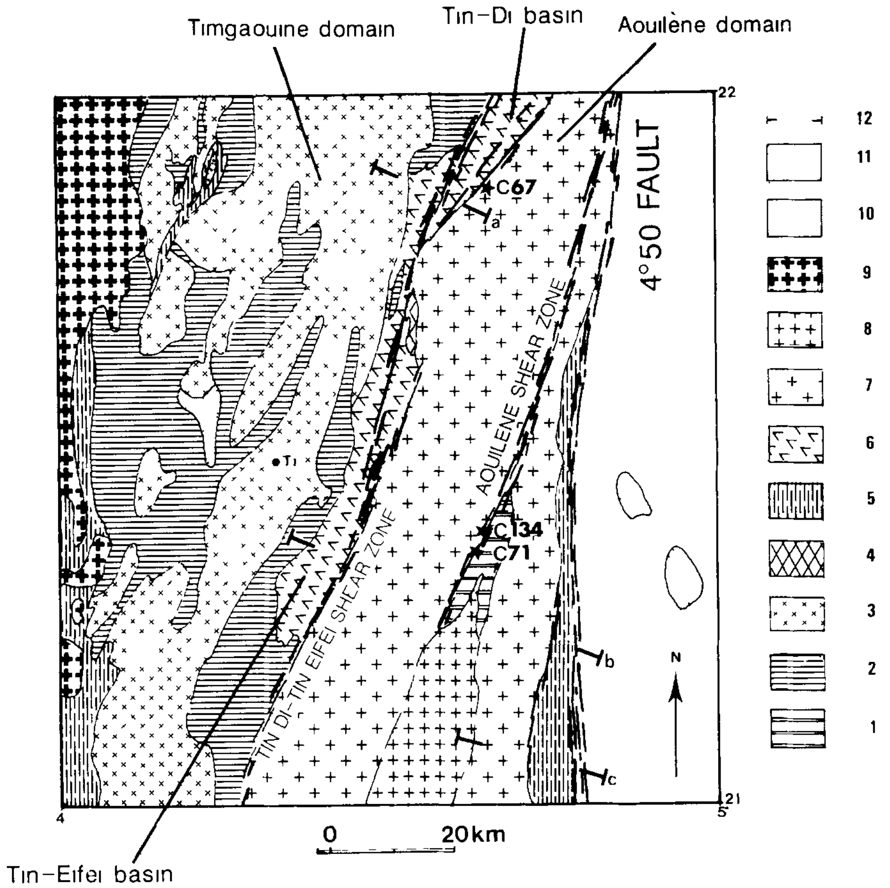

Fig 2 Timgaouine area geological map (from Reboul and Bouvet 1959 and E R E M unpublished mapping) 1, Quartzites, marbles, pyroxenites (Pharusian I?) 2, Pharusian I volcano sedimentary 3, Pharusian I granitoids 4, Abankor pre-tectonic alkaline granite 5 Pharusian II (detritic) 6 Pharusian II (rhyolitic) 7 West Aouilene granite-gneisses 8 Post-tectonic granite 9 Imezzarene post-tectonic granite 10, Taourirt granite 11, Eocambrian 12 Localization of the cross-sections described in Fig 3 TI Timgaouine

The Pharusian I is constituted by a volcanosedimentary unit with calc-alkaline affinities (Fabries and Gravelle 1977, Chikhaoui 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 tuffs

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 schistosities)

In the Timgaouine area, a 'Suggarian 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 Eifei), corresponding to a high-strain zone and locally to a fault, separates two domains—Aouilene 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 refoliation 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 unaffecting 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 retromorphosed under greenschist-facies conditions Dioritic rocks, spatially associated with the gabbroic bodies, are often tectonically interleaved with the lavas The younger, more granitic group, 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 flysh-type structures by Haddoum 1984), and is intruded by basaltic and andesitic dykes At the top of the series, acid volcanites become dominant They are composed of pyroclastites (breccias to tuffs), ignimbrites and rhyodacitic 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 grits locally associated with polygenic conglomerates ('greso-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 Di–Tin Eifei) 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 Tedeini) 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 Eifei basin, which forms a large open syncline where the basal unconformity is preserved, to the Tin Di 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 Eifei 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 Eifei lineament, this mainly granitic and gneissic domain is strongly deformed The older granitoids are clearly pretectonic They are alkaline granites forming discontinuous alignments along the edge of the Tin Di–Tin Eifei basin (as the riebeckite-bearing granite of Abankor), or preserved as remnants in the pre-tectonic granite-gneisses representing the more abundant rock type

The West Aouilene granite-gneiss is a porphyritic monzonitic granite with biotite and hornblende Its highly heterogeneous deformation corresponds to plas-

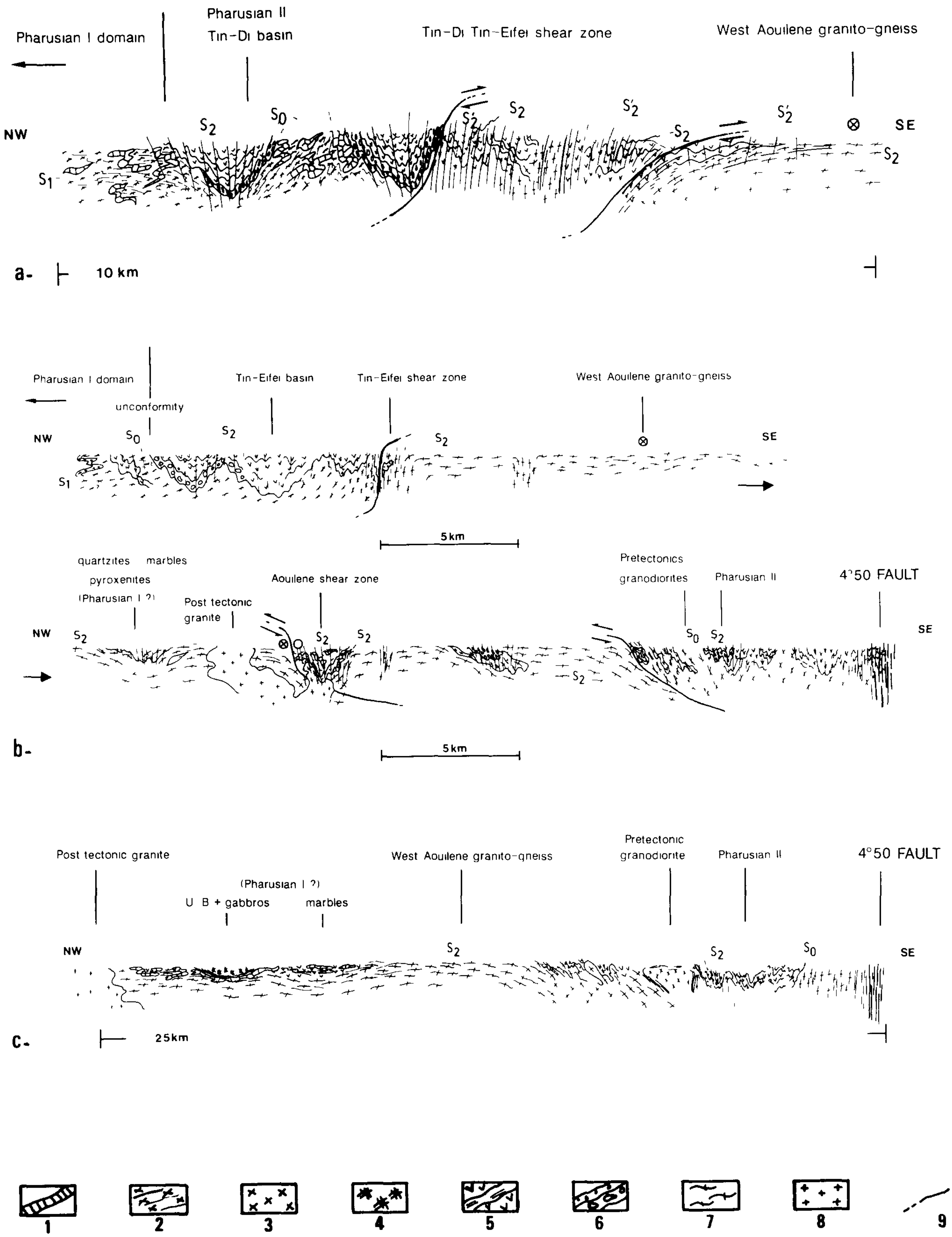

Fig 3 Cross-sections located in Fig 2 1, Quartzites, marbles (Pharusian I) 2, Pharusian I granitoids 3 Pre-tectonic granodiorites 4, Ultrabasic rocks 5, Amphibolites and rhyolites (Pharusian II) 6 Conglomerates (Pharusian II) 7, West Aouilene granite-gneisses 8, Post-tectonic granites 9, Thrusts

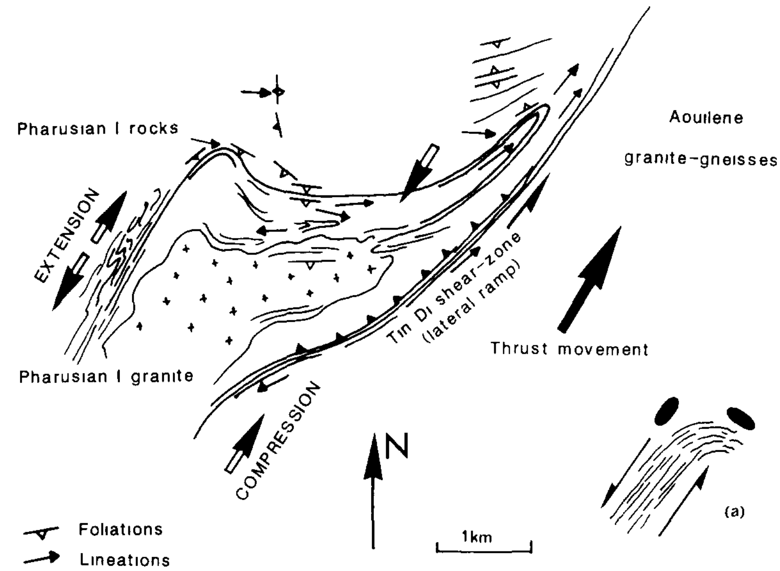

Fig 4 Sketch map in the north of the Tin Di basin showing the older Pharusian I structures reoriented by the NE verging movement of the Aouilene granite-gneisses (a) The pattern of structures is consistent with a sinistral strike-slip shear zone

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 Di–Tin Eifei basin In the northern part of the basin, the granite-gneisses are tectonically interbedded with Pharusian II metavolcanites The flat-lying mylonitic foliation which affects the granite-gneisses together with the quartzites, metarhyolites and amphibolitic greywackes (Pharusian II more metamorphic equivalents), becomes progressively vertical in 100 m when approaching the Tin Di–Tin Eifei 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 Eifei metarhyolites The similarity in direction and deformation type between the Pharusian II basin of Tin Eifei and the Aouilene granite-gneisses suggests that both have been deformed during the D2 event Close to the Tin Eifei lineament, the subvertical foliation may be affected by a slightly retromorphic 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 Di (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 gabbros 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 incurves 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 compression 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 Eifei 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 retromorphic vertical

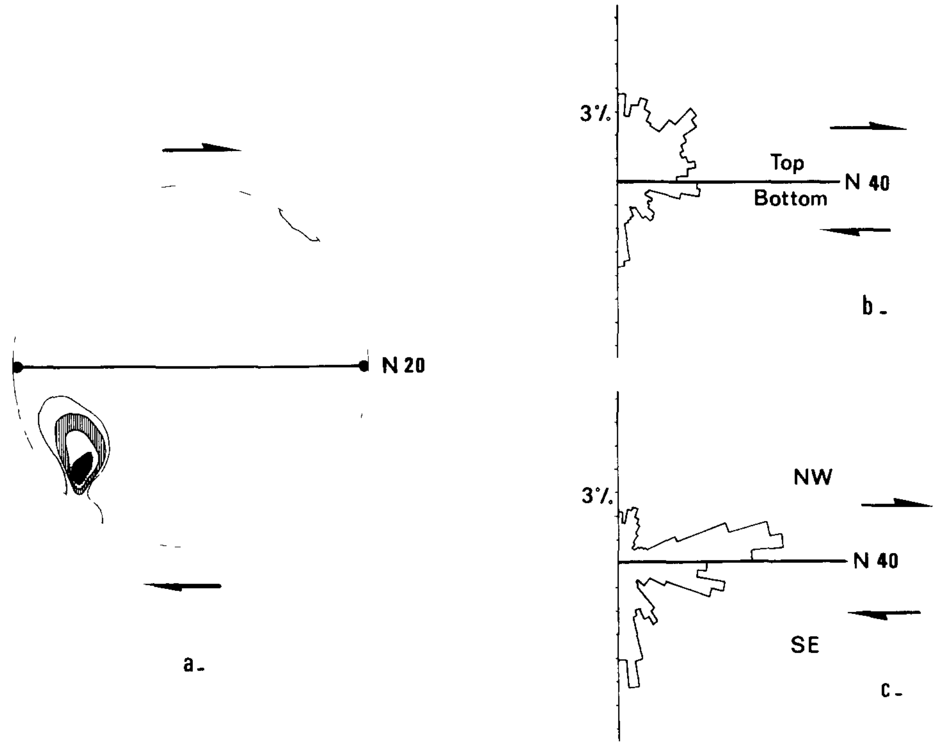

Fig 5 (a) Preferred orientation of quartz c-axes for a horizontal thin section of the sample C 134 XZ diagram Lower hemisphere equal area projection, 100 grains Contours 2, 5, 10, 15, 20, 25, max 28, measurements per 1% area (b) and (c) Diagrams of the c-axes projection in the XZ thin section plane (b) Sample C 67 250 measurements (c) Sample C 71 201 measurements Solid line is the trace of the foliation plane and for (a) the black point shows the lineation projection The samples are located in Fig 2

foliaton 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 boudinage 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 Eifei 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 Eifei 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

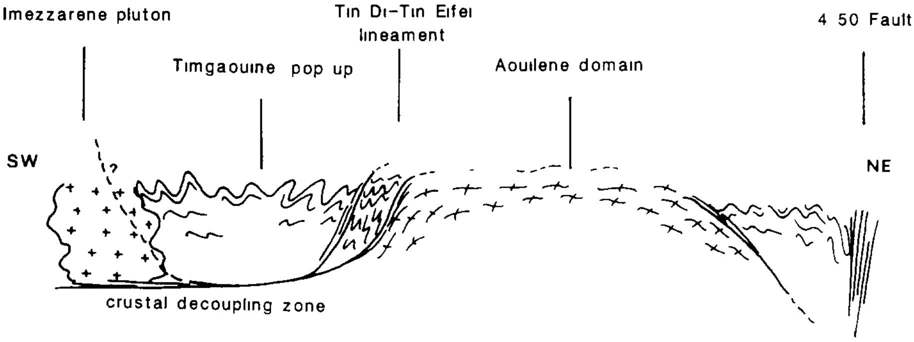

Fig 6 Stylized cross-section through the Timgaouine area showing the 'pop-up' of the Timgaouine domain and the decoupling zone between the Timgaouine and Aouilene domains

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 Imezzarene 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 migmatitic contacts, they are good candidates to represent the product of crustal melting subsequent to the crustal thickening related with the tangential tectonics, but the $^{87}Sr/^{86}Sr$ 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 Timgaouine 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 old gneisses and Pharusian II formations The 630 Ma U/Pb age of the pre-tectonic West Aouilene granite-gneiss confirms that the deformation in the Aouilene domain is related to D2 By its lithological and structural characters, the Timgaouine domain belongs to the eastern branch of the Pharusian belt, but the structural characteristics of the Aouilene domain are closer to those of the Central Hoggar, where thrust tectonics and syntectonic plutonism dated at 615 Ma have been evidenced As a consequence, the 4°50′ mega-fault cannot be further considered as the western tectonic border of the Central Hoggar, which now corresponds to the volcano–tectonic lineament of Tin Di–Tin Eifei

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 Eifei lineament

The slight reactivation of the Timgaouine 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

The existence of such crustal 'decoupling zones' is important for explaining the relationships between plutonism and tectonics during the Pan-African event s s The tectonic evolution bracketed between 629 and 614 Ma in the Aouilene domain took place preferentially along the 'decoupling zone' with vertical strike-slip movements on its borders and subhorizontal thrusting in the core of the granito-gneissic dome, in a SW–NE direction In the Aouilene granite-gneisses the deformation is clearly inhomogeneous and the sharp transitions between vertical and horizontal foliations, and sometimes lack of foliation with, however, a strong lineation, indicate that this domain cannot be interpreted in only a simple shear-zone context There is now growing evidence based upon strain analysis (Kligfield *et al* 1981, Coward and Kim 1981) that deformation in thrust sheets is a combination of simple shear and layer parallel longitudinal strain which results in a wide range of strain ellipsoid shapes from oblate to prolate The deformation probably involves different deformation rates, and hence opposed shear senses, around an approximately uniaxial prolate strain ellipsoid If the movement direction is clearly outlined by the stretching lineation, as in many ductile shear-zones (Ramsay and Graham 1970, Ramsay 1980), the sense of movement is less obvious Broadly, the granito-gneissic unit moved towards the NE on the basis of structures observed in the north of Tin Di, and interpreted as a lateral and frontal tip (Coward and Potts 1983) On a larger scale, the Aouilene domain could represent a crustal sheet verging to the NE The Tin Di–Tin Eifei lineament is interpreted as resulting from lateral ramp formation where the lower level 'decoupling zone' beneath the Timgaouine 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 Louis 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 Timgaouine 'pop-up' could explain the emplacement of the late to post-tectonic granites west of the Tin Di–Tin Eifei shear-zone, and especially the large Imezzarene 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-gneisses

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 Timgaouine domain (i e Abankor) underlie the weaker zone close to the site of the future lineament From the REE 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 greenschist-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 tectono-metamorphic 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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