AUFSÄTZE

Geodynamic Evolution of the Pan-African Orogenic Belt: A new interpretation of the Hoggar Shield (Algerian Sahara)

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With 8 figures

Zusammenfassung

Der panafrikanische Orogen-Gürtel des Hoggar-Gebirges in Südalgerien erstreckt sich über eine Breite von ca. 800 km und entspricht einer extrem eingeengten, aus komplexen geologischen Einheiten aufgebauten mobilen Zone. In seinem westlichen Teil zeugen bereits die untersten mächtigen metasedimentären Ablagerungen sowie die alkalischen und hyperalkalischen Intrusionen des mittleren Proterozoikums von der frühen Mobilität eines N—S streichenden ensialischen Bereiches. Vor ca. 800 M. J. wurden die etwa 800—1000 M. J. alten Kratonsedimente von großen Mengen basischen und ultrabasischen Materials aus dem oberen Erdmantel intrudiert. Volumenmäßig noch bedeutender sind Vulkanite und Vulkanoklastite von andesitischer bis rhyodazitischer Zusammensetzung sowie zahlreiche batholitische Intrusivkörper kalkalkalischer Natur. Als Ursprung dieser Gesteine wird eine Zone vom Typus Inselbogen auf basischer (ozeanischer) Kruste sowie ein Orogen vom andinen Typus auf granulitischem Untergrund in Betracht gezogen. Dieses der Kruste vor ca. 650—800 M. J. neu zugeführte Material steht möglicherweise in Zusammenhang mit nach Osten einfallenden Subduktionszonen, und wir nehmen daher die Existenz einer tief abgetragenen Sutur am Ostrand des westafrikanischen Kratons an.

Der zentrale Hoggar besteht hauptsächlich aus prä-panafrikanischen Gneisen, die dem eburnischen und teilweise auch dem kibaridischen Zyklus angehören; ferner enthält er schmale ensialische, mit spätproterozoischen Schiefern aufgefüllte Grabenzonen. Diese verschiedenen Elemente werden in unterschiedlichem Maße von der panafrikanischen Tektogenese und Metamorphose beansprucht.

Der östliche Hoggar besteht ebenfalls aus Gneisen und Graniten prä-panafrikanischen Alters, wogegen die schmale Kette des Tiririne-Gebirges während der Endphase der panafrikanischen Faltung entlang einer N—S streichenden bedeutenden Scherzone gebildet wurde.

Deckentektonik, liegende Falten, Anatexis sowie ca. 650 M. J. alte syntektonische Granitoide charakterisieren die frühe Phase der panafrikanischen Orogenese im Hoggar und können als Resultat von Krustenverdickung und Krustenaufschmelzung infolge von Plattenkollision interpretiert werden. Die spät-panafrikanische Tektonik beruht auf einer O—W gerichteten Einengung der gesamten Hoggar-Gebirgskette, wodurch N—S streichende Falten entstanden, die geometrisch mit einem Mega-System von Scherzonen und Brüchen in Verbindung stehen. Dabei wurden die alten Massive in langgestreckte N—S orientierte Blöcke zerschnitten, bei denen seitliche Verschiebungen bis zu mehreren hundert km vorkommen. Dieses Strukturbild ist das Ergebnis eines äußerst starken O—W gerichteten Zusammenschubs der mobilen Zone zwischen zwei starren Platten: dem westafrikanischen Kraton und dem Ostsahara-Kraton, die unter Linksdrehung aufeinander stießen. Während dieser Phase (550—600 M. J.) trat ferner eine quantitativ noch nicht abschätzbare O—W-Verkürzung der Gebirgskette ein, die mög-

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licherweise durch seitliche Verschiebung entlang konjugierter Scherzonen mit dominierender Linkskomponente absorbiert wurde. Mineralalter sowie Diagenese-Alter der panafrikanischen Molasseablagerungen stellen die letzte post-orogene Hebung im Hoggar deutlich in das Post-Kambrium.

Abstract

The Pan-African orogenic belt of Hoggar, 800 km wide, represents an extremely tightened complex and composite mobile zone. In the western part, the earlier thick meta-sedimentary units and alkaline-peralkaline intrusives, both of middle Proterozoic age, account for the early mobility of a N—S trending ensialic domain. Later, large scale upper-mantle contribution was responsible for many magmatic complexes of basic to ultrabasic rocks intruded at c. a. 800 m. y. in cratonic platform sediments 1000 to 800 m. y. old. A very important volume of volcanoclastic deposits, andesites to dacites, and widespread calc-alkaline batholiths are supposed to derive from two assemblages of island-arc type upon basic crust and of Andean type upon granulite basement and this newly accreted material 800 to 650 m. y. old, may be related to subduction zones dipping East. A cryptic suture ist postulated along the margin of the West African craton. The central Hoggar is mainly composed of pre-Pan-African gneisses belonging to the Eburnean cycle and *pro parte* formed during a "Kibaran" cycle, and ensialic upper Proterozoic schist belts, which were subjected at varying degrees to the Pan-African deformation and metamorphism. Eastern Hoggar includes also pre-Pan-African gneisses and granites, and the narrow ensialic upper Proterozoic Tiririne belt formed during the late Pan-African along a N—S trending major shear zone. High structural level nappes, recumbent folding, anatexis and syn-kinematic granites emplaced at c. a. 650 m. y. define the early Pan-African, related to crustal thickening and crustal melting during the early stage of a continental collision. The late Pan-African E—W compression produced in the whole shield N—S trending folds geometrically linked to a mega-system of shear belts and strike-slip faults, which dissect the earlier edifices into N—S trending branches and blocks of many hundred kilometres lateral displacement. This pattern is the result of an extreme E—W tightening of the belt between two rigid plates: the West African craton and the East Saharian craton colliding with a sinistral confrontation. During this stage (600—550 m. y.) an unquantified E—W shortening may have been absorbed by lateral movements along conjugate shear zones with a main sinistral component. Mineral ages and diagenesis of molassic deposits point out to a post-Cambrian uplift of the belt.

Résumé

La chaine Pan-Africaine affleure sur 800 km de large au Hoggar. Elle représente une zone mobile complexe et composite extrêmement raccourcie. Dans la partie Ouest, les premiers dépôts méta-sédimentaires épais, ainsi que des intrusions alcalines et hyperalcalines d'âge Protérozoique moyen témoignent de la mobilité précoce d'un domaine sud-méridien ensialique. Plus tard vers 800 Ma, la contribution à grande échelle du manteau supérieur est remarquable sous la forme d'intrusions basiques et ultrabasiques mises en place dans des sédiments cratoniques déposés entre 1000 et 800 Ma. Plus importants encore en volume, les dépôts volcano-détritiques, les roches volcaniques allant des andésites aux rhyo-dacites et de nombreux batholites calco-alcalins peuvent provenir de zones de type arc insulaire établies sur croûte basique et de type cordillère andine sur croûte granulitique. Ce matérial témoigne d'importants phénomènes d'accrétion continentale probablement liés à des zones de subduction pentées à l'Est ayant fonctionné entre environ 800 et 650 Ma. La bordure du craton Ouest-Africain correspondrait à une suture océanique. Le Hoggar central est principalement constitué par des gneiss pré-Pan-Africains appartenant à l'Eburnéen, et en partie au cycle « Kibarien » ainsi que par d'étroits sillons ensialiques de Protérozoique supérieur. Les déformations et le métamorphisme Pan-Africain affectent ces unités de manière variable. Le Hoggar oriental comprend des gneiss et granites d'âge pré-Pan-Africain, et l'étroite chaîne de Tiririne plissée au Pan-Africain tardif est controlée par une zone majeure de cisaillement. Chevauchements, plis couchés, anatexie et granites syn-tectoniques mis en place à 650 Ma sont en relation avec les premiers stades de collision continentale pendant le Pan-Africain précoce, engendrant un épaississement crustal important et des fusions anatectiques profondes. Le Pan-Africain tardif implique une compression globale E—W de la chaîne qui a produit des plis Nord—Sud géométriquement liés à un méga-système de cisaillements et de décrochements, qui découpent les édifices antérieurs en branches et blocs longitudinaux Nord—Sud avec des déplacements latéraux de plusieurs centaines de kilomètres. Cette disposition résulte d'un serrage E—W extrême de la chaîne entre deux plaques rigides: le craton Ouest-Africain et le craton Est-Saharien qui s'affrontaient avec une composante sénestre. Au cours de ce stade (600—550 Ma) un raccourcissement E—W encore non quantifié a aussi été absorbé par le jeu de mouvements latéraux le long des zones de cisaillement conjuguées. Les âges des minéraux, et ceux de la diagenèse des dépôts molassiques soulignent l'âge post-Cambrien du dernier soulèvement de la chaîne.

Краткое содержание

Пан-африканский орогенный пояс гор Hoggar в южной части Алжира простирается в широтном направлении на 800 км и соответствует сдавленной подвижной зоне, сложенной из сложных геологических структур. Подстилающие мощные метаседиментные отложены со щелочными и ультращелочными интрузиями среднепалеозойского возраста свидетельствуют о ранней подвижности простирающегося энсиалического района западной части пояса. Примерно 800—1000 миллионов лет тому назад, во всяком случае до 800 миллионов лет тому назад, имели место интрузии больших количеств базического и ультрабазического материала верхней мантии в осадочные породы кратона. Ещё большим был объем вулканитов и вулканокластитов андезитно-риодацитового состава и многочисленных батолитных интрузивных тел щелочно-кальциевого происхождения. Высказывают предположения, что эти породы происходили из зоны типа островных дуг на базической океанической коре и орогена типа Анд на гранулитовом основании. Этот новый материал, интрудированный примерно 650—800 миллионов лет тому назад в кору, возможно связан с спадающей на восток зоной субдакции материка, поэтому предполагают существование шва на восточном крае западно-африканского кратона, сейчас уже в значительной мере снесенного.

Центральная часть гор Hoggar состоит гл. обр. из гнейсов до-панафриканского орогена, принадлежащих эбурнитскому и, частично, кибаридскому циклам; кроме того этот пояс имеет узкую, энсиалическую зону грабена, заполненного поздне-палеозойскими сланцами. Эти различные элементы подвергались в различной степени степени влиянию пан-африканского тектогенеза и метаморфизма.

Восточная часть гор Hoggar состоит также из гнейсов и гранитов до-панафриканского возраста, причем узкая цепь тирилинских гор образовалась во время заключительной фазы пан-африканского складкообразования вдоль зоны сдвига, простирающейся а северо-восточном направлении.

Тектоника покрова, залегающие складки, анатаксис и синтектонические гранитоиды возраста примерно в 650 миллионов лет характеризуют раннюю стадию пан-африканского орогенеза в районе Hoggar и могут рассматриваться, как результат утолщения и расплавления коры в следствие столкновения глыб. Поздняя пан-африканская тектоника характеризуется сужением всей цепи гор Hoggar, простирающихся в восточно-западном направлении, в результате чего появились складки, направленные на северо-юг, находящиеся

в геометрической связи с гигантской системой зоны сдвига и разломов. При этом древние массивы в блоках, вытянутые и ориентированные на северо-юг, распались и дали боковое смещение до нескольких сот километров. Такая картина распределения структур является следствием чрезвычайно мощной, направленной с востока на запад коллизии двух застывших глыб подвижной зоны: кратона западной Африки и восточной части Сахары, которые при этом совершали поворот влево. Во время этой фазы — 550 до 600 миллионов лет — имело место, ещё количественно не оцененное, укорочение горной цепи в восточно-западном простирании, которая, возможно, оказалась абсорбированной боковыми смещениями вдоль сопряженной зоны сдвига с господствующей левой компонентой. Возраст минералов и время процессов диагенеза отложений пан-африкансуих моляссов разрешает отнести последнее после-орогенное поднятие гор Hoggar к после кембрийскому периоду.

1. Introduction

The central saharian Hoggar shield situated immediately to the E of the West African craton stable since about 1800 m. y. is composed essentially of crystalline Precambrian rocks affected by the Pan-African orogeny (c. a. 600 m. y.) (Picciotto, 1965; Black, 1966, 1967; Caby, 1970). The shield covers an area of about 500 000 square kilometres, is beautifully exposed, and is a key area for studying multiple aspect of the Pan-African. In the last fifteen years many detailed investigations have been carried out (Bertrand *et al.*, 1966; Arène, 1968; Gravelle, 1969; Caby, 1970; Vitel, 1971; Latouche, 1972; Boissonnas, 1973; Bertrand, 1974; etc.) following the pioneering work of Kilian (1932), Monod & Bourcart (1932), Lelubre (1952) and Blaise (1957, 1961). A reconnaissance survey by geologists of the B.R.M.A led to the publication of the geological map on the scale of 1 : 500 000 compiled by Reboul *et al.* (1962). The first general synthesis presented by Lelubre (1952) is a fundamental work on the general geology of the Hoggar. With the advent of geochronology and recent detailed structural studies, the time is now ripe to attempt an outline of the geodynamic evolution of this segment of the Pan-African orogenic belt.

a) Geochronological data: main orogenic cycles and lithostratigraphic sequences

The compilation of mineral ages given by Bertrand & Lasserre (1976) shows that, except for the older In Ouzzal block, all the figures fall in the range 600—500 m. y. with some younger ages indicating that the Hoggar belongs to the Pan-African mobile belt. However recent dating by Rb/Sr whole rock and U/Pb on zircons allow us to define a sequence of orogenic events which can be indirectly used to date lithological units ranging from the Archean (> 2700 m. y.) to the late Proterozoic. Archean ages are reported from the In Ouzzal block (Ferrara *et al.*, 1966; Allègre & Caby, 1972) and from the Oumelalen area in northeastern Hoggar (Latouche & Vidal, 1974).

Three main orogenic cycles have been distinguished:

— The Eburnean (2000 ± 100 m. y.) is well dated in several places (Tassendjanet, In Ouzzal, Aleksod, Oumelalen) (Allègre & Caby, 1972; Bertrand & Lasserre, 1976; Latouche & Vidal, 1974);

— The "Kibaran event" (1000 ± 100 m. y.) was reported from the central Hoggar (Bertrand, 1974; Bertrand & Lasserre, 1976). It is not so well

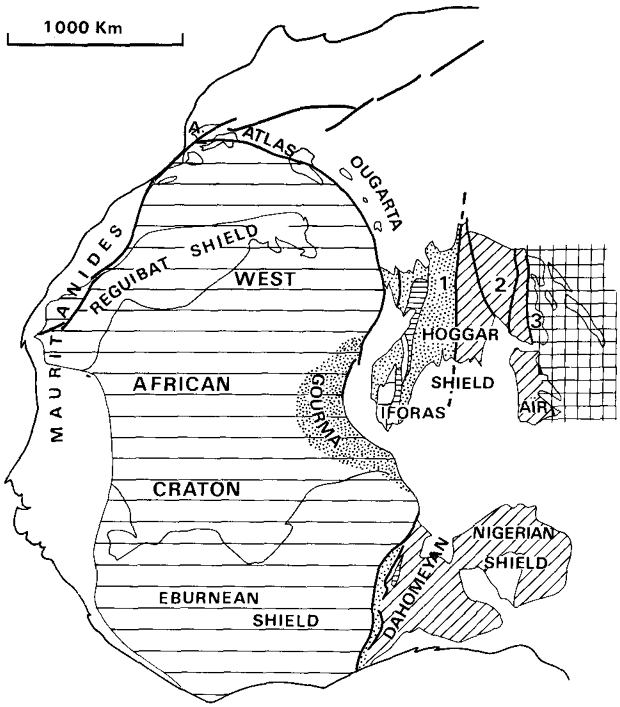

Fig. 1. Map of West Africa showing the location of the Hoggar shield. 1. Pharusian belt. 2. Polycyclic province of central Hoggar. 3. Eastern Hoggar including the margin of the East Saharian craton.

documented as the previous one and requires checking by the U/Pb method on zircon;

— The Pan-African *s. l.* (800—550 m. y.) which may be subdivided into:

1. Pre-tectonic magmatic events (800—650 m. y.);

2. The early Pan-African (c. a. 650 m. y.) which is well defined in the western part of Hoggar where it is mainly supported by the age of syn-tectonic granites (Picciotto *et al.*, 1965; Allègre & Caby, 1972, and unpublished results);

3. The late Pan-African (c. a. 600 m. y.) dated in Eastern Hoggar (Bertrand *et al.*, in press) and post-tectonic granites yielding even younger ages by Rb/Sr scattered across the whole shield (Boissonnas *et al.*, 1969; Boissonnas, 1973).

On the basis of geochronological and field evidence, the following lithostratigraphical units have been distinguished:

1. Units of Archean age (> 2700 m. y.): Ouzzalian (Lelubre, 1969; Allègre & Caby, 1972), oldest basement of the Oumelalen area (Latouche & Vidal, 1974), Arechchoum unit *pro parte* (Bertrand, 1974);

2. Units of lower Proterozoic age (2000 ⩽ 2700 m. y.): Tassendjanet Formation (Caby, 1970), Arechchoum Formation (Bertrand, 1974), Oumelalen Formation (Latouche, 1972);

3. Units of middle Proterozoic age (1000 ⩽ 2000 m. y.): Aleksod Formation (Bertrand, 1974), Ahnet Quartzite Formation (Caby, 1970), Toukmatine Formation (Latouche, 1972);
4. Units of Upper Proterozoic age (1000—800 m. y.): "Série à stromatolites" (Caby, 1970), "Pharusien I" (Bertrand *et al.*, 1966);
5. Units of late Proterozoic age (800—650 m. y.): "Série verte" of western Hoggar (Caby, 1970), "Pharusien II" (Bertrand *et al.*, 1966; Gravelle, 1969), Tiririne Formation (Bertrand *et al.*, in press);
6. Units of Eocambrian to Cambrian age: "Série pourprée" (Caby & Moussu, 1967) and "Séries intermédiaires" (Gravelle, 1969).

b) Definition of structural provinces

Detailed structural studies carried out since 1965 have shown a complex story of sedimentation, volcanism, folding, metamorphism, often initiated in the Archean area. It is possible to distinguish irrespective of the metamorphic grade, areas where the structural history is: monocyclic and due only to the Pan-African orogeny, polycyclic with a Pan-African imprint on older structures, and zones devoid or weakly affected by the Pan-African (Fig. 5). In this paper three provinces have been distinguished on the basis of the following criteria:
— the proportion and lithology of the upper Proterozoic,
— the type and grade of Pan-African folding and metamorphism,
— the presence or absence of an assumed Kibaran event,
— the age of syn-kinematic granites,
— the presence or absence of molassic deposits.
The three provinces from W to E are as follows (Fig. 1):
— The Pharusian belt that is mainly constituted by upper Proterozoic sediments and volcanics, divided in two branches by the In Ouzzal granulite block;
— The polycyclic central Hoggar which on the contrary consists of pre-Pan-African basement rocks folded and metamorphosed during the Kibaran and Eburnean events and reactivated to varying degrees during the Pan-African orogeny:
— The eastern Hoggar which is characterized by two different basement blocks of pre-Pan-African age, separated by a narrow linear belt (the Tiririne belt) folded and metamorphosed during the late Pan-African.

2. The Pharusian belt of central western Hoggar

The Pharusian belt lies between the edge of the West African craton and the polycyclic central Hoggar (Fig. 2). This belt comprises mostly rock units formed between c. a. 1750 m. y. and 600 m. y. which outcrop in two branches which show an almost similar evolution, separated by an older longitudinal block of granulite facies rocks, the "In Ouzzal block". Within these two branches, only a few basement remnants of 2000 m. y. age are exposed. Five main lithostratigraphic units can be defined in central western Hoggar: basement units, middle Proterozoic, upper Proterozoic, late upper Proterozoic, and molassic deposits (Fig. 2).

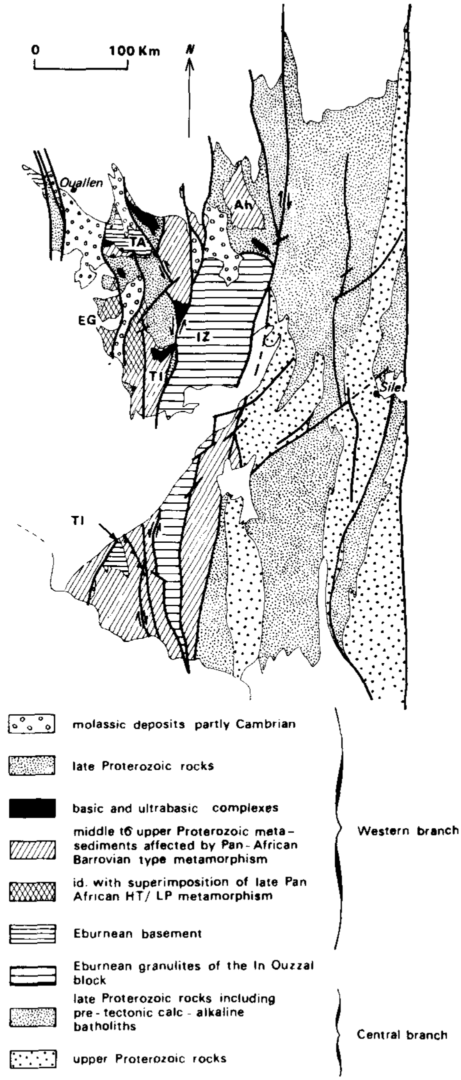

Fig. 2. Pharusian belt. Syntectonic and post-tectonic granites are not represented.

a) The border of the West-African craton: a possible paleo-rift system

Granites and gneisses refoliated during Pan-African greenschist facies metamorphism outcrop in the extreme West. They are considered to be of Eburnean age and are intruded by various dykes and plutons. North-South trending dyke swarms also characterize this zone. The earlier dykes are diabases and porphyritic andesites and are cut by a later generation mainly composed of alkaline to peralkaline rhyolites and various types of syenites including nepheline syenites and pegmatites. Subsequently folded and mylonitised under lower greenschist facies, these dykes have built linear zones sometimes entirely composed of dyke material. Gravimetric highs associated with some dyke swarms may imply a connection with more mafic rocks at depth (RECHENMANN, 1973).

All these pre-metamorphic dykes suggest a palaeo-rift system along the margin of the West African craton.

b) Pre-Pan-African basement units

I. The In Ouzzal block: case of a cold and unreactivated granulitic crust.

The In Ouzzal block elongated North-South comprises mainly granulite facies rocks (GIRAUD, 1961), the zircon U/Pb ages of which indicate a 2100 m. y. granulite facies metamorphic event (LANCELOT *et al*, 1973; LANCELOT, 1975). Various Pan-African *s. l.* dykes and granites cut the granulites. Both longitudinal margins are vertical mylonite zones, and the granulites are in tectonic contact with all metamorphic and tectonic levels of the Pharusian belt, from upper greenschist to lower amphibolite facies. Their trend is sharply cut by the mylonite and they are only affected by a partial greenschist facies retrogressive metamorphism and cataclasis in a zone from a few metres up to one hundred metres wide. The weak Pan-African imprint in the northern part of the block is shown by undeformed andesite and basalt flows and their feeder dykes of upper to late Proterozoic age, which are preserved in a faulted graben near the Akofou hill and have only been affected by zeolite facies metamorphism prior to the late Pan-African intrusive granites (CABY, 1970). Towards the South, the intensity of Pan-African retrogressive greenschist facies metamorphism progressively increases as the width of the block decreases, and at the southern extremity near the Malian border the In Ouzzal rocks are entirely composed of vertical refoliated granulites and mylonites showing a strong regular horizontal stretching lineation.

II. The Tassendjanet Pan-African nappe

This nappe structure was proven by detailed mapping (CABY, 1970, fig. 3). This structural unit is mainly composed of granites of Eburnean age (ALLÈGRE & CABY, 1972; LANCELOT, 1975) intruded in the Tassendjanet Formation, which comprises a meta-sedimentary sequence of meta-quartzites, alumina-schists, marbles, a gneissic formation of acidic volcano-detrital origin and amphibolite sills. The "Série à stromatolites" was deposited upon this basement, and has been thrusted with it.

c) Lithostratigraphic units of the Pharusian belt

These lithostratigraphic units are defined in the western branch, but they also constitute the rocks of the central branch, as reconnaissance work has shown (GRAVELLE, 1969; BERTRAND *et al.*, 1966; CABY, unpublished results).

I. Units of middle (?) Proterozoic age

These units have been previously described in north-western Hoggar as possible lateral equivalents to the "Série à stromatolites" (CABY, 1970), but

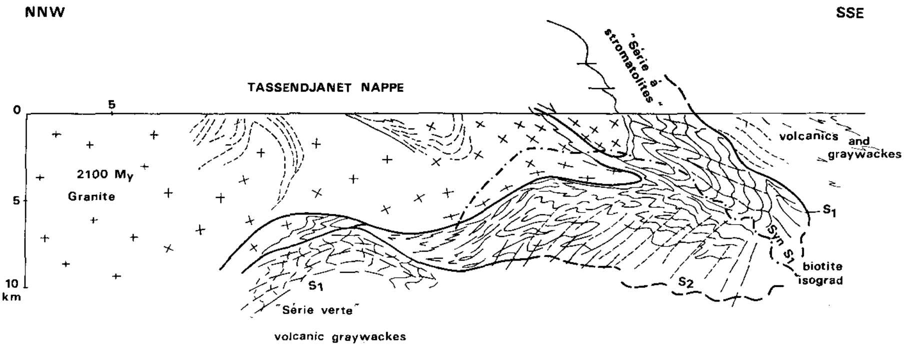

Fig. 3. The Tassendjanet Nappe in northwestern Hoggar.

recent geochronological work in progress suggests that they are much older. These units mostly build up the deepest tectonic level of the Pharusian belt, and except in the Ahnet region, they were affected by polyphase deformation during metamorphism of upper to lower amphibolite facies grade. It is suggested that they represent a thick accumulation of terrigeneous material over a wide subsiding ensialic area.

The Ahnet Formation (ARÈNE, 1968) constitutes a thick accumulation (> 3000 m) of typically fine-grained orthoquartzites with rare pelitic intercalations. The well preserved sedimentary features may reflect a fluviatile or deltaic environment. Marine quartzites with pelitic schists and stromatolite-bearing dolomites occur on the top of the succession.

The meta-quartzite units are thought to be the equivalent of the Ahnet Formation. They are well exposed in the western branch where they form the main reliefs (Taoudrart, Tideridjaouine) and are mainly composed of kyanite or sillimanite white meta-quartzites with pelitic schists, some marbles bands, and amphibolitised basic sills.

Pre-tectonic alkaline to peralkaline layered intrusions.

Widespread igneous activity occurred after the deposition of the quartzites. These magmatic rocks have been converted everywhere into gneisses and have been studied in some detail in two areas:

1. The Tideridjaouine complex offers the best preserved plutonic-volcanic suite only partly recrystallized in the chloritoid-kyanite zone (CABY, 1970). Felsitic alkaline meta-rhyolites with phenocrysts of blue quartz and perthite may represent either flows or thinly banded sills. They are intruded by sills of banded K_2O rich (5—8%) microgranite showing granophyric structure, which typically contains iron-rich dark green biotite and/or ferro-hastingsite, fluorite, and frequently sphene, allanite, zircon and other rare-earth minerals. Albitic leucocratic granites have also intruded these layered rocks. A Rb/Sr whole rock isochron on meta-rhyolites and associated microgranites has given an age of c.a. 1350 m. y. (ALLÈGRE, pers. communication, 1974) whereas zircons from the microgranites have given U/Pb ages in the range of 1750 m. y. (LANCELOT, pers. communication, 1974, work in progress). Plutonic rocks of an adjacent area

associated with these rocks are porphyritic gneissose granites containing ferro-hastingsite, and some alkaline pegmatoids.

2. Close to a North-South vertical mylonite zone, another complex is gradually affected northwards by lower amphibolite to L. P. granulite facies metamorphism. It is entirely composed of layered to banded gneisses of alkaline to peralkaline composition with some syenite gneisses. The intrusive character of these rocks is shown by their sharp, and often oblique contacts with meta-sedimentary rocks (impure quartzites and calc-silicate rocks) interlayered with the complex. The original magmatic layering, defined by compositional variations, and especially well developed in the fine-grained strongly alkaline rocks, is often preserved despite the strong metamorphic recrystallization and the discrete mobilisation. The ferro-magnesian minerals observed are: ferro-augite, ferro-hastingsite, iron-rich biotites, aegyrine-augite and oxydes. Aegyrine and amphiboles of the riebeckite-arfvedsonite series are frequently found in bands a few centimetres thick.

II. The upper Proterozoic shelf deposits

In the Pharusian belt, typical shelf deposits showing various degrees of metamorphism are found. The similarity of facies and the stromatolite associations strongly support the existence of a single stratigraphic unit in this area, which can now be correlated with the Atar Group of the West African craton (Bertrand-Sarfati, 1969; Caby, 1970), deposited between 1000 and 800 m. y. (Clauer, 1973).

The "Série à stromatolites" was defined in western Hoggar (Caby, 1970) where it overlies the Tassendjanet basement, or rests concordantly upon the Ahnet quartzites. In the Tassendjanet area, the series is 4000 m thick. Typical fluviatile quartzites (50—500 m) with intraformationnal conglomerates are found at the base. To the North-East, the basal conglomerate contains quartzite boulders showing typical polished striated faces of glacial origin. This quartzite unit rests unconformably upon alkaline rhyolites of Adrar Ougda which gave a whole-rock Rb/Sr isochron of 1100 m. y. (Allègre & Caby, 1972). The overlying limestones and dolomites contain many stromatolite biostromes, the most characteristic of which is a *Conophyton* marble layer which can be traced over more than 50 km without significant lateral change, some other stromatolite beds are characterized by Tungussides (Bertrand-Sarfati, 1969). The rest of the series comprises alternating limestones, dolomites, siltstones and quartzites, which become more abundant on the top. The upper beds are brecciated and silicified dolomites with jaspers probably deposited at the onset of basic magmatic activity. This series is correlated with the Tin Aberda series, also resting upon an old granitic basement NW of the Iforas (Caby, 1970) and in the eastern branch, the marbles of the Timesselarsine Series (Gravelle, 1969) and the *Conophyton* marbles of Timgaouine (Gravelle & Lelubre, 1957) also overlying basement gneisses and granites, may represent the same beds. Thus, these shelf deposits of cratonic type may have been deposited over large areas both on the West African craton and within some areas incorporated in the Pharusian belt.

III. The upper Proterozoic magmatic cycle and the conversion at c. a. 800 m.y. of a sialic crust to a basic or intermediate crust

This major magmatic cycle is well defined in the Tassendjanet area of NW Hoggar. Basic to ultrabasic rocks were emplaced into the shelf deposits of the "Série à stromatolites". Gabbroic sills from a few metres up to 300 m thick, were intruded in the pelitic and siltstone horizons and now form about 40% in volume of the frontal part of the Tassendjanet Nappe. Hornfelses close to thick sills yield Rb/Sr whole rock ages of c. a. 800 m. y. (CLAUER, 1976), a figure which is interpreted as the age of intrusion. The Ougda layered lopolith (about 400 km^2) was also emplaced within the "Série à stromatolites" which now is only preserved as hectometric size pendants. Partly serpentinised harzburgites containing a few chromite veins, green spinel-amphibole rich rocks, pyroxenolites and amphibole gabbros, may constitute the root of this lopolith with frequent garnetiferous, often anorthositic inclusions, and are cut by more acidic aplites. Heterogeneous gabbroic rocks with an agmatitic texture, and quartz diorite sheets showing fluidal texture constitute most of the body with layered labradorites, trondjhemites, granodiorites and porphyritic granites representing the upper part.

Another smaller layered intrusion of the Tassendjanet area is formed by various banded gabbros with cumulates, whereas serpentinised ultrabasic rocks are found as intrusive sheets within the dolomites at the top of the series. Strongly serpentinised ultrabasic rocks, associated with often leucocratic amphibole bearing diabases also constitute a layered unit, 4000 metres thick, which is cut by a dyke complex of diabases.

In the central branch of the Pharusian belt, ultrabasic rocks are mostly serpentines and metagabbros. These are lenticular bodies and were tectonically emplaced along shear zones during the Pan-African orogeny. A few of these ultrabasic rocks are associated with marbles tentatively correlated with the "Série à stromatolites" and may also represent intrusive sheets subsequently deformed. Associated with these mafic intrusions are some diorites and large batholiths of intermediate composition, mainly quartz diorites, trondjhemites and calc-alkaline granites, which intrude volcanic rocks of the Timesselarsine Series, including basalts, andesites and intermediate to acidic rocks (GRAVELLE, 1969). Porphyritic calc-alkaline granites, and syenites were also emplaced in the central branch during the late stages of this magmatic period.

This upper Proterozoic magmatic activity seems to be present everywhere in the Pharusian belt. It is not linked to any regional deformation or metamorphism but the plutonic rocks emplaced form more than 70% of the upper Proterozoic crust upon which the late upper Proterozoic volcanoclastic deposits are deposited. Upwelling of mantle-derived rocks at c. a. 800 m. y. through shelf sediments deposited upon a sialic crust fits well with the concept of oceanisation developed by soviet geologists and others (see REZANOV & FAYTELSON, 1976), though at about the same period typical oceanic crust was formed now represented by the obducted ophiolites of South Morocco and northern Mali (LEBLANC, 1976).

In the central branch of the Pharusian belt, the preponderant role of calc-alkaline batholiths would suggest an Andean type development upon sialic crust during the same period, as suggested by the presence of granulite xenoliths from the Recent basaltic volcanoes (GIROD, pers. communication, 1976). Later on, this enormous volume of newly erupted material was submitted to deep erosion, probably during the onset of late Proterozoic calc-alkaline volcanism which seems to have affected the whole belt and the In Ouzzal block.

IV. The late upper Proterozoic volcano-clastic rocks, volcanic rocks and associated pre-tectonic intrusives: a possible island-arc type environment

The rocks of late upper Proterozoic age, mostly in the greenschist facies, are essentially composed of metavolcanics, volcano-clastic rocks and calc-alkaline intrusives. They correspond roughly to the "Pharusian" of LELUBRE (1952), and more precisely, to the "Upper Pharusian" of BERTRAND *et al.* (1966) defined in the central branch of the belt by a basal unconformity upon deeply weathered quartz-diorite batholiths, outlined by marble lenses and polygenic conglomerate with coarse boulders always of local origin (BERTRAND *et al.*, 1966; GRAVELLE, 1969).

In the western branch, the following suite has been defined (CABY, 1970):

1. Andesites from western Hoggar and adjacent areas. Andesite complexes are preserved at three localities: along the margin of the West African craton, in the Tassendjanet area resting upon gabbroic rocks, and on the In Ouzzal block. The Tassendjanet-Ougda andesites (6000 m thick) are the best preserved. Resting upon basic and ultrabasic rocks, they comprise very fresh andesite flows, tuffs and agglomerates, and rhyo-dacites at the top of the succession (CABY, 1970; CHIKHAOUI & DUPUY, 1977). A lateral change to volcanic conglomerates and green graywackes of the "Série verte" has been mapped (CABY, 1970).

2. Volcanic graywackes and associated plutonic-pebble conglomerates from western Hoggar. Named "Série verte" by CABY (1970), these rocks make up more than 80% of the formations of this age. Up to 6000 metres thick, the deposits exhibit flysch-type sedimentary features. The rocks are entirely made up of volcanic and plutonic detritus derived from penecontemporaneous calc-alkaline igneous complexes, andesite fragments being dominant (CABY *et al.*, 1977). The lack of typical sialic components in these deposits strongly suggest trough deposition close to an island-arc or a very active continental margin along which calc-alkaline volcanics of Andean type were exposed (CABY *et al.*, in press). In the central branch, very similar deposits laterally grade into a terrigeneous semi-pelitic unit which near the eastern margin is restricted to the base of the succession (GRAVELLE, 1969).

3. Acidic volcanic complexes. Acidic volcanics, predominantly dacites and rhyo-dacites, have been deposited upon the terrigeneous formation. Keratophyres in connection with polymetallic sulphide deposits have also been recorded. Many acidic plutons often rich in albite may represent magmatic chambers related to this episode.

4. Calc-alkaline batholiths. These pre-tectonic batholiths are mainly quartz-diorites to calc-alkaline granites, and are widespread in the northern part of the central branch, where they were subsequently sheared under greenschist

facies conditions. They often contain a great number of basic to semi-basic intraplutonic dykes.

5. Basic rocks. Basalts, diabases and quartz-diabases sills were emplaced in the graywacke or pelitic formations. They probably belong to several generations but seem to represent the latest intrusions in many areas.

V. The molassic deposits

The main molassic deposits up to 6000 m thick in the Ouallen area crop out in N—S trending graben and in residual basins from western Hoggar, where they were first described as "Série pourprée" de l'Ahnet (MONOD & BOURCART, 1932). This series has been later subdivided into several units (CABY & MOUSSU, 1967). Resting unconformably upon any structural and metamorphic level of the Pharusian belt, intruded by the 580 m. y. old post-tectonic granites, the basal group is often outlined by glacial deposits including: a typical moraine displaying sorted blocks of local origin, polygenic fluvioglacial conglomerates and in many areas a regular tillitic horizon mostly associated with carbonates containing either stromatolites (BERTRAND-SARFATI, 1968) or erratic blocks up to several cubic metres. The overlying jaspers and acidic volcanic ashes are thought to derive from the In Zize ignimbritic rhyolites, dated at 530 m. y. by Rb/Sr (ALLÈGRE & CABY, 1972). This association of tillite, carbonates and jaspers is tentatively correlated with the glacial deposits of the Bthaat Ergil Group resting upon the West African craton (TROMPETTE, 1973). Most of the overlying rocks which show very rapid lateral facies changes, are continental red arkosic sandstones and polygenic conglomerates with a few siltstone and clay horizons. The upper group of probable lacustrine or marine origin comprises West of Ouallen more than 1500 metres of varved clays overlain by a tillite, and North of the In Semmen graben a 2000 metres thick green flysch unit including volcanic graywackes containing basaltic detritus is cut by a syenite. A 470 ± 18 m. y. age, interpreted as the age of diagenesis, has been obtained on clays from an unfolded area, South-East of Ouallen (CLAUER, 1976) and this figure confirms the attribution to the Cambrian of this Series proposed by CABY (1967).

In the central branch, similar deposits crop out South-West of Silet (GRAVELLE & THEBAULT, 1965). Here the lower unit includes green beds similar in facies to the underlying metagraywackes and conglomerates of upper Proterozoic age. The upper unit is composed of red arkosic sandstones and polygenic conglomerates, which are intruded by rhyolitic sills.

d) Pan-African structures and metamorphism of the Pharusian belt

The deformation is best documented in the western branch. Three phases of folding have been described (CABY, 1970).

I. The earlier deformation (F 1) is displayed in the deepest structural level (Tideridjaouine area). Isoclinal folds developed during Barrovian type metamorphism in the quartzite formation. These folds are kilometric in size, and face NNW. The syn-kinematic isograds related to this major tectonic phase have been mapped in this region (CABY, 1970) and are characterized by a wide kyanite zone with a low temperature zone in which chloritoïd appears. Local occurrences of eclogitic rocks have been found in the kyanite and in the sillimanite zones: the transition between these two zones is very gradual, and there is a complete lack of migmatisation and associated syn-kinematic intrusions.

In the North, the very high level Tassendjanet Nappe composed of Eburnean rocks and its cover of the "Série à stromatolites" moved southwards. The lower part of the nappe gradually exposed towards the West is in the biotite-staurolite zone of medium pressure type. Upper Proterozoic meta-graywackes affected by recumbent folds represent the autochtonous terranes beneath and in front of the Nappe. High-level klippen of the "Série à stromatolites" are also preserved.

II. The F2 phase has build N—S trending recumbent folds facing West, which define anticlinoria and a major synclinorium of late Proterozoic graywackes. These structures are associated with an increase of temperature shown by pseudomorphs of andalusite after kyanite in the lower units. Parautochtonous diapiric plutons of granite *s. l.* dated at 640 m. y. (ALLÈGRE & CABY, 1972) were intruded in the core of isoclinal folds facing West.

III. The F3 phase has affected the whole area. It produced folds with vertical axial planes, the direction of which is mostly oblique to the shear zones with a main NNW trend. Open folds associated with low-grade greenschist facies conditions in the core of the metagraywacke synclinorium where they apppear to be the only phase of deformation, tighten towards the West, while the metamorphic grade increases. The westernmost area of Egatalis is affected by late to post-kinematic HT/LP metamorphism with local occurrences of granulite facies rocks related to a late high thermal gradient produced by syn-metamorphic noritic intrusions.

The later deformations which postdate the post-kinematic granites and partly the molassic formations of Cambrian age are related to horizontal and vertical movements along strike slip faults, and strong differential uplift of blocks related to graben tectonics.

In many areas of the central branch, N—S trending folds seem to be the only Pan-African deformation in greenschist facies metamorphism (GRAVELLE, 1969). Polyphase deformation however is general in deeper structural metamorphic levels and steeply plunging folds are also very frequent in the western part of this zone. Moreover, local post-molassic thrusting has been observed (R. CABY, unpublished results) indicating the high mobility of this zone, cut by the Taourirt granites at 560—540 m. y. (BOISSONNAS *et al.*, 1969) which forms a characteristic province in this branch.

3. The polycyclic central Hoggar province

The lithology, metamorphic history and structural evolution of the central Hoggar, differ completely from the Pharusian belt. The main characteristic is the considerably smaller areal extent of low grade upper Proterozoic units, less than 10% of the whole area. Pan-African granites however are abundant particularly in the West. Older Archean and Eburnean rock units are gneisses and high grade schists whereas granulite facies rocks are found in some places but have been involved in a polymetamorphic and polytectonic evolution during the "Kibaran" orogeny according to BERTRAND (1974), and in superimposed Pan-African deformation of variable intensity.

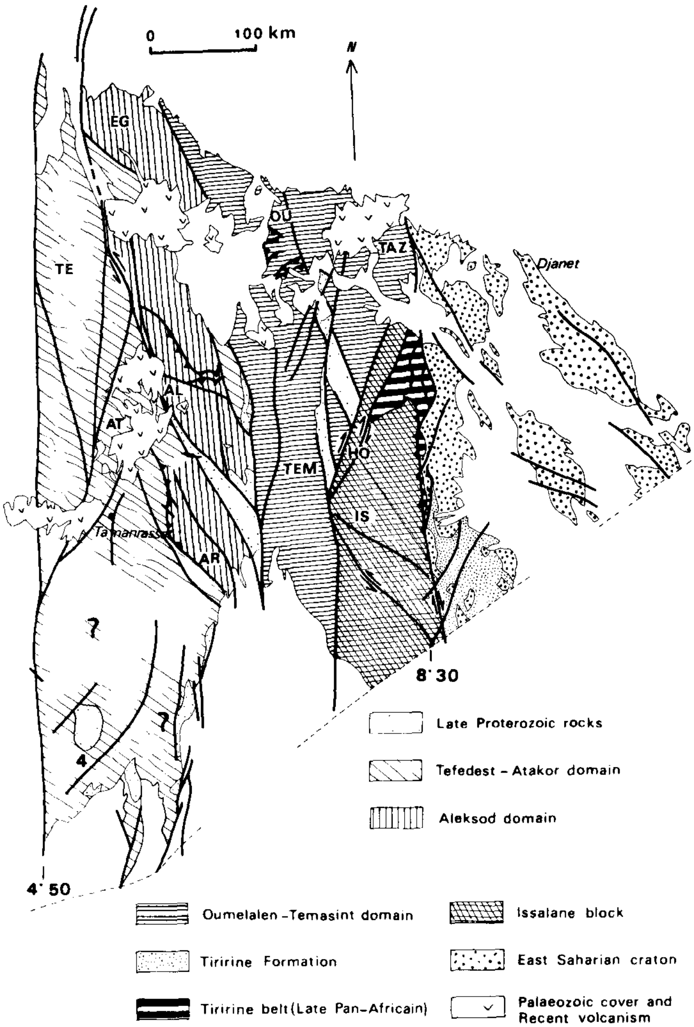

Fig 4. Central Hoggar and eastern Hoggar. Syn-orogenic and post-orogenic granites are not represented.

a) Polycyclic rock units

On the basis of structural and metamorphic criteria, three main polycyclic domains have been distinguished:

I. The Aleksod domain

The Aleksod area has been described by BERTRAND (1974). Similar Pan-African basement areas are found in the Egere, Tourha and Arefsa regions although they have not been studied in detail.

The domain is characterized by:

1. an Eburnean basement composed of banded grey granodioritic gneisses, augen gneisses and some meta-sediments which are cut by amphibolitised dykes. The augen gneisses have been dated at 1940 m. y. (BERTRAND, 1974) and this age is in good agreement with the Eburnean age of granite emplacement defined elsewhere in Africa (BONHOMME, 1962). The age of the banded gneisses is not so well established: a Rb/Sr reference isochron (BERTRAND & LASSERRE, 1973) indicates an age of 2200 m. y., but isolated whole rock model ages suggest an older age (~ 2500 m. y.). Thus there is some evidence of a pre-Eburnean history for this gneiss complex.

2. the Aleksod unit, a high grade complex of amphibolites and meta-sediments resting with a structural disconformity upon the Eburnean basement, which from base to top consists to: massive amphibolites with chemical composition close to continental tholeiites and similar in composition to the basic dykes cutting Eburnean basement, plagioclase bearing gneisses, associated with kyanite garnet schists and calc-silicate layers, calc-silicate rocks associated with garnet amphibolites, pyroxene amphibolites, marbles and thin layers of kyanite-garnet schists and locally lenses of banded ironstone, veined muscovite bearing gneisses, meta-sedimentary rocks mainly alumina-rich kyanite bearing schists, associated with marbles, quartzites and some amphibolites, and veined biotite hornblende gneisses.

Apparently the whole sequence does not exceed 1500 metres.

The earliest deformation observed in the Aleksod unit also folds the cross-cutting amphibolitised dykes in the Eburnean basement and proves the existence of a major break between both units. This F 1 phase of folding in the Aleksod unit produced large scale recumbent folds during high-grade often migmatitic barrovian type metamorphism. The F 2 folds are also recumbent but smaller in size with associated metamorphism of lower grade. Both phases have been attributed to the "Kibaran" orogenic cycle in the light of geochronological data (BERTRAND, 1974; BERTRAND & LASSERRE, 1976). Rb/Sr whole rock isochrons have yielded an age of 1040 m. y. on migmatised pelitic gneisses of the Aleksod unit and respectively 910 and 930 m. y. on blastomylonites formed during F 1 deformation and on schists in the Eburnean basement.

The type and intensity of the Pan-African deformation varies from place to place: tight upright F 3 folds associated with retrograde metamorphism are found near N—S trending shear zones and are in continuity with similar structures found in monocyclic schist belts of assumed upper Proterozoic age. The wave-length of the F 3 folds decreases away from the shear zones. Rare granodiorites and granites cross-cut all previous structures. Fresh cordierite and sillimanite occur in alumina-rich gneisses within the aureoles. Late post-metamorphic thrusting has been described from the Ouadenki area (BERTRAND, 1974) and is probably related to late movements along shear zones.

II. The Oumelalen-Temasint domain

The tectonic and depositional history of this area characterizes most of the eastern part of central Hoggar. The following units have been distinguished:

1. Pre-Eburnean rocks ("Série rouge des Oumelalen") have been

reported on the basis of structural and geochronological data (LATOUCHE, 1972; LATOUCHE & VIDAL, 1974).

2. Eburnean basement constituted mostly of meta-sediments metamorphozed in the granulite facies (Oumelalen Formation) at c. a. 2000 m. y. (LATOUCHE & VIDAL, 1974) associated with isoclinal folding.

3. The Toukmatine Formation (LATOUCHE, 1972) and the Tit n'Afara Unit (GUÉRANGÉ, 1966) are probably equivalent in age to the Aleksod Unit. They consist of a monotonous sequence of alumina-rich schists with some quartzites, amphibolites, marbles and calc-silicate rocks, serpentinites and locally layered alkaline orthogneisses. In contrast to the Aleksod area, the metamorphism of barrovian type amphibolite facies is devoid of migmatisation and possibly decreases eastward to the greenschist facies. The main phase of deformation which produced the foliation and isoclinal folding and later thrusting in the Toukmatine area can be considered by comparison with the Aleksod area as "Kibaran". Such an interpretation would be in agreement with the 750 m. y. data obtained on the granodiorite emplaced after this main deformation (LATOUCHE & VIDAL, 1974). In the Toukmatine area a late phase of upright tight folds is thought only to be related to the Pan-African (LATOUCHE, 1972). In the Temasint area the present authors (unpublished results) have observed two phases of deformation believed to be Pan-African: (1) recumbent folding facing W under greenschist facies conditions producing intense retrograde metamorphism; (2) later tight upright folds. North-East of this domain, the Tazat Unit (BLAISE, 1967) comprises a thick fluviatile quartzite formation deposited upon a granitic basement (BERTRAND *et al.*, 1968) which is tentatively correlated with the Ahnet Formation of western Hoggar, involved in polyphase deformation during one single orogenic cycle (Pan-African?).

III. The Tefedest-Atakor domain

In contrast with the previous areas this domain is intruded by abundant Pan-African granites (PICCIOTTO *et al.*, 1965; MAISONNEUVE, 1970; VITEL & VIALETTE, in press). Almost all the gneisses surrounding the granites have been affected by an important phase of approximately N—S trending folding with vertical axial planes which decreases in intensity southward. This folding is accompanied by high grade, low pressure type metamorphism (cordierite, sillimanite and sometimes andalusite) and intense migmatisation grading into syn-kinematic granites. Relict high pressure mineral assemblages including kyanite-bearing rocks and granulite facies in the Tamanrasset area (GRAVELLE, 1969; DESCHAMPS, 1973) and the Tefedest (VITEL, 1971) are interpreted as pre-Pan-African. South of Tamanrasset as the domain widens flat-lying foliations prevail and may represent an unreactivated zone unconformably overlain by residual basins of upper Proterozoic rocks. It is noteworthy that the high level W-Sn bearing granites and greisens are concentrated in this zone (BOISSONNAS, 1973).

b) Monocyclic upper Proterozoic units

They form two types of structures: narrow linear belts of low grade schists and volcanics (Arefsa, Serkout, Temasint), and small basins (Laouni, In Ebeggui).

The state of knowledge of the structural evolution of these occurrences is poor.

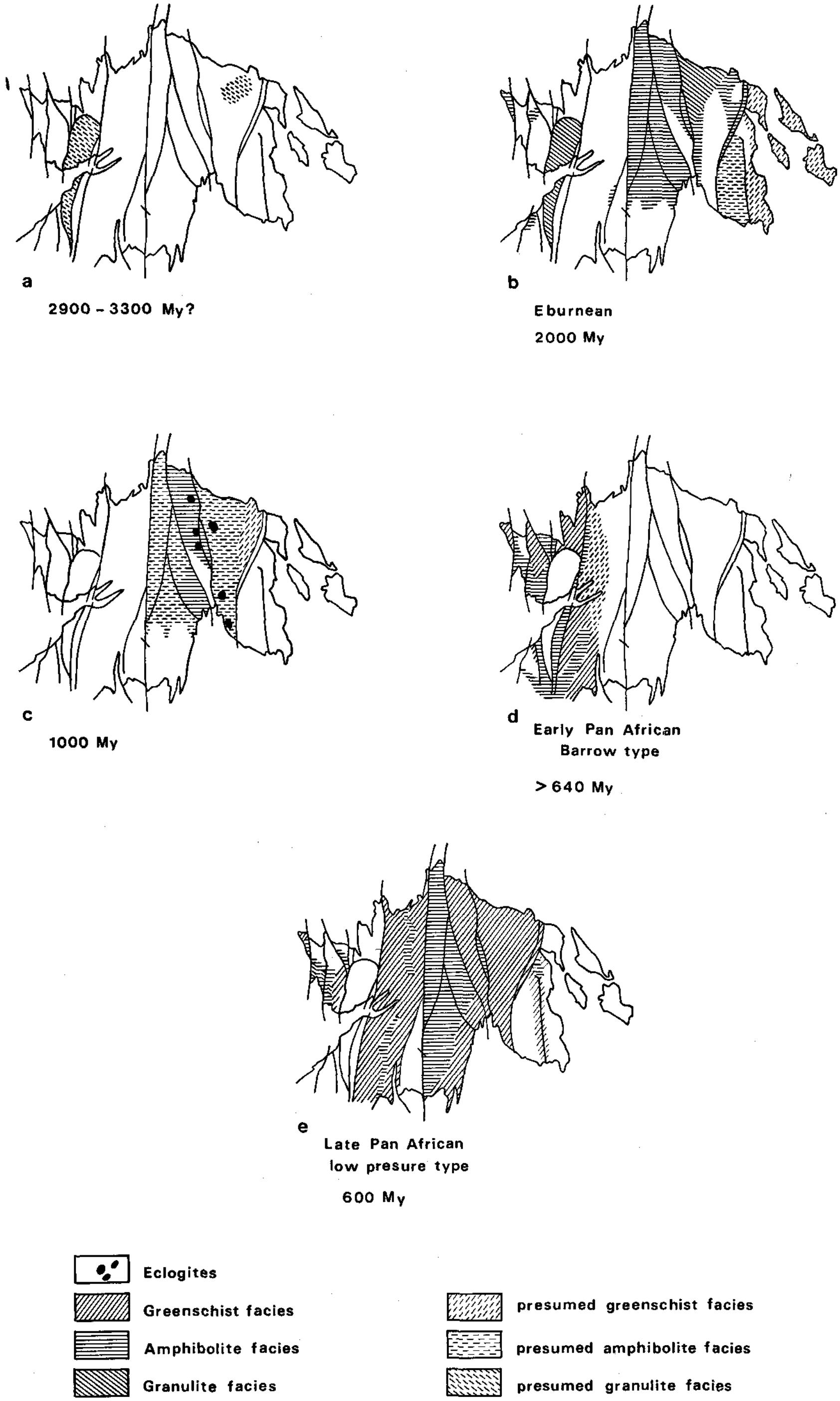

Fig. 5. Metamorphic provinces of the Hoggar shield.

Local unconformities have been described (KILIAN, 1932; LELUBRE, 1952) but their structural significance is uncertain. In most cases the belts are bounded by tectonic contacts or by late granitic intrusions. The most extensive is the Arefsa belt which follows the Amguid-Arefsa shear zone. Although polyphase deformation has been observed in schists, the prograde mineral assemblages of greenschist facies locally up to the staurolite-almandine zone in the northern part (BERTRAND, 1974) account for a monocyclic evolution of Pan-African age. Locally high-level granites developing contact metamorphism cross-cut the schists.

4. The eastern Hoggar

This domain has been subdivided into three structural domains. Two different pre-Pan-African basement units which are also very dissimilar to the basement units described in the Pharusian belt and in the central Hoggar, are separated by a narrow rectilinear belt of upper Proterozoic rocks, the Tiririne belt, folded and metamorphosed during the late Pan-African. Many granites are associated with this event, and the western boundary of the Issalane domain is cut by post-kinematic granites which form the elongated N—S Honag zone.

a) The Issalane pre-Pan-African domain

The lithology of this unit is very homogeneous. Some marker horizons may be followed more than one hundred kilometres. They comprise banded and veined granitic gneisses, meta-sedimentary unit composed of green Cr-bearing quartzites, marbles and calc-silicate rocks, and pelitic gneisses with associated coarse-grained migmatites. Very characteristic of this unit is the occurrence of thin but extensive layers of alkaline to peralkaline leucocratic gneisses which probably represent intrusive pre-tectonic sills.

The polyphase deformation and metamorphism predate deformation in the Tiririne belt which only affects the eastern margin of the Issalane basement. The coarse-grained migmatites are associated with E—W trending folds developed during high temperature low pressure metamorphism (sillimanite, cordierite, wollastonite in marbles). This event is superimposed upon large scale earlier isoclinal folds. Relict kyanite and rutile may be related to this earlier event.

The age of these rocks and of the metamorphism is unknown.

b) The Tafassasset-Djanet domain, part of the East Saharian craton

This domain is mainly composed of large batholiths of predominant calc-alkaline granites overlain by the flat-lying Tiririne Formation. It comprises also low grade flysch-type deposits, a marble calc-silicate sequence and various pre-tectonic volcanic and plutonic rocks including alkaline gneisses and granites and ultrabasic rocks. West of Djanet, semi-pelitic schists and graywackes cut by foliated granites built extremely deformed vertical N—S trending shear belts which also predate deposition of the Tiririne Formation.

The Tiririne Formation which has been described in the Niger as the Proche-Ténéré Formation (RAULAIS, 1959; BLACK *et al.*, 1967) comprises three groups of rock sequences composed of arkoses, graywackes, silts and conglomerates (BERTRAND *et al.*, in press). Lithologically strikingly similar to the "Série verte of western Hoggar", this formation is 1500 metres thick and slightly deformed in the South. A pre-tectonic sill of granodiorite has given a U/Pb zircon age of 660 m. y. a figure which gives an upper limit age for the deposition of the formation (BERTRAND *et al.*, in press). To the North this formation is more than 8000 metres thick, and is progressively affected by deformation and metamorphism in the Tiririne belt, entirely controlled by the 8° 30′ E shear zone.

c) The Tiririne belt

The structural setting of the belt is described elsewhere (BERTRAND *et al.*, in press). It may be summarized as follows:

In the southern part gentle open folds are only found close to the shear zone and flat-lying beds are however affected by an incipient vertical N—S trending slaty cleavage.

In the central part of the belt overthrusting to the East of the Issalane basement rocks upon Tiririne rocks took place along the 8° 30′ E shear zone which gradually decreases in dip. In the Tiririne rocks, recumbent folds facing East were formed under greenschist facies metamorphic conditions up to the biotite zone going North. The margin of the Issalane domain is affected by mylonitisation of upper greenschist facies grade over a zone 5 to 10 km wide.

In the northwestern part of the belt, preserved only as pendants within large syn to post-kinematic granites emplaced at c. a. 604—585 m. y. (BERTRAND *et al.*, in press), gneisses affected by polyphase deformation were recognised to represent high grade equivalents to the Tiririne rocks with relicts of some meta-conglomerates and some pecular horizons, despite a lower amphibolite HT/LP type metamorphism and partial migmatisation.

The tectonic development of this narrow ensialic belt is entirely controlled by the 8° 30′ E shear zone, which appears as a late tilted major thrust, and thus this belt only related to the late Pan-African, implies an E—W shortening of c. a. 30 km (BERTRAND *et al.*, in press).

5. The shear zones, a mega strike-slip fault sytem

N—S trending, often sinuous and branched major vertical shear-zones and faults are a striking feature beautifully displayed on ERTS photographs of the whole Hoggar shield. These structures have been interpreted as a mega strike-slip fault system of continental scale (CABY, 1968). The permanence of this N—S trending shear system within the shield is indicated by the distribution of some alkaline intrusive complexes of middle Proterozoic age in the western branch and the pre-Pan-African age of the N—S shear belts of the Tafassasset-Djanet domain. Nevertheless, the major movements along the shear zones of western central Hoggar are of Pan-African age and their genetic relation with the late phase of N—S trending upright folds has been proven in many areas (CABY, 1970; LATOUCHE, 1972; BERTRAND, 1974; VITEL, 1975; BERTRAND *et al.*, in press). Moreover the permanent mobility of main shear zones is shown by shearing of late to post-kinematic Pan-African granites themselves cutting mylonites, and post-Palaeozoic and *pro parte* post-Cretaceous reactivation is also shown by the structures of the cover North of the shield (LELUBRE, 1952; BLACK & GIROD, 1970).

Although only preliminary results on strain analysis and petrofabrics of the mylonites are available (Boullier, work in progress), they are generally in the greenschist facies and the overall horizontal stretching lineations imply mostly pure horizontal movements. In many cases the drag of foliation trends adjacent to the mylonites together with the help of geological markers allows the tentative determination of the sense of movement. On these grounds, a 350 km sinistral displacement of the In Ouzzal block with respect to the Iforas granulite block has been advanced (Caby, 1968) and such a proposal best explains the juxtaposition of unreactivated granulites with different structural and metamorphic levels of the western Pharusian branch. A left lateral displacement of 45 km has also been recognized along another strike-slip fault along the eastern margin of the Tassendjanet Nappe (Caby, 1970). The Amguid-Arefsa shear zone which coincides with the monocyclic meta-sediments of the Arefsa to the South, would be a left lateral wrench fault of possibly more than 400 km displacement. On the other hand, opposed lateral movements along sinuous N—S trending, faults would imply pure lateral-slip related to E—W flattening of an arcuate fault bounded block. The major 4° 50′ E shear zone which delimits Pharusian belt and central Hoggar, outlined by a mylonite zone many kilometres wide with a horizontal stretching lineation is probably also one of the major wrench faults of the shield of unknown lateral displacement. The 8° 30′ E shear zone shows that it has been active throughout the tectonic history of the Tiririne belt, and represents the late evolution of a major thrust.

A second order conjugated system of NW—SE and NE—SW strike-slip faults with minor displacements related to the same E—W shortening is superimposed upon the shear zones, and extends beyond the Hoggar shield (Ball, 1977).

Though the system of shear zones considerably obscures the exact geometric relationships of different domains and provinces which have been defined, they constitute a key for understanding the global tectonics of the Hoggar shield. The overall picture of the shear pattern formed during the late Pan-African is one of pronounced E—W tightening with an important sinistral component.

6. Discussion

An attempt to correlate the major rock units and the major igneous and orogenic events in the Hoggar shield is given in Fig. 6.

a) The structural assymetry of the shield

Despite of the picture of N—S trending longitudinal block and shear zones due to the late stages of the Pan-African orogeny which affects the shield over a width of 800 km, in fact, the Hoggar exhibits a strong assymetry in lithology, metamorphic grade and age, and Pan-African structures.

To the West, the Pharusian belt, divided into two branches by the In Ouzzal block which can be regarded as a micro-continent, corresponds to newly formed crust of upper Precambrian age (Fig. 7 A, B).

East of the 4° 50′ E shear zone, the central Hoggar is part of an old cratonic area of Eburnean or older age covered by younger supracrustal rocks, which was partly affected by thermotectonic events of assumed "Kibaran" age, and later by the Pan-African orogeny.

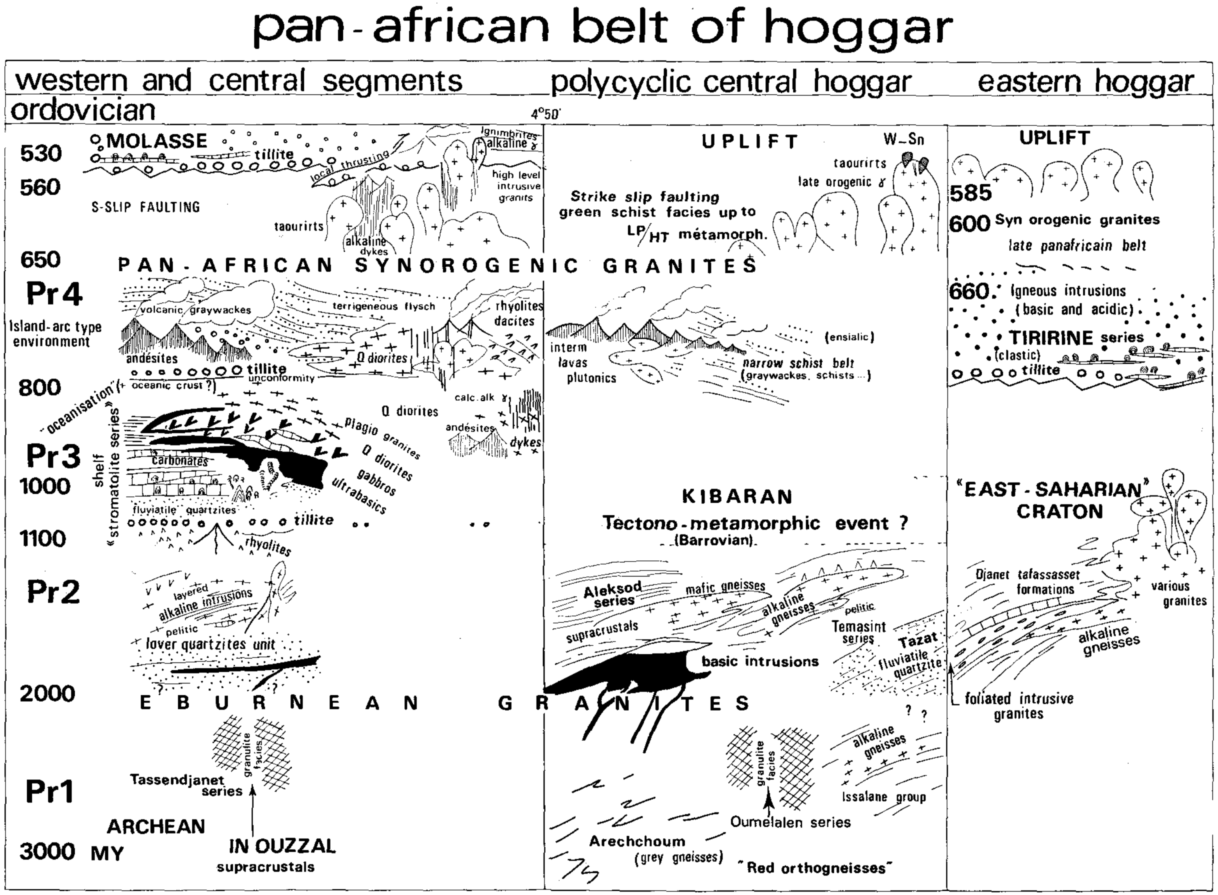

Fig. 6. Synoptic table of the main geologic events in the Hoggar shield.

The thermo-tectonic events related to the "Kibaran" orogeny may have affected the central part of central Hoggar only, but it must be pointed out that syn- or post-orogenic granites which could be related to that cycle are very scarce. U/Pb ages on zircons are required to precise the timing of this post-Eburnean event.

b) The main stages of palaeotectonic development of the Pharusian belt

Three main stages of palaeotectonic development outlined by three major magmatic cycles can be defined:

I. Middle Proterozoic subsiding areas and cratonic magmatism.

At a rather imprecise period (1800—1750, or 1350 m. y. ?) terrigeneous sediments were deposited in subsiding ensialic basins. A subsequent magmatic cycle of alkaline to peralkaline type was responsible for layered intrusions of hypovolcanic rocks and granites. It is likely that intrusions of this age identified in western Hoggar belong to a greater province, as it is frequently the case for such a cratonic magmatism. The localisation of alkaline intrusions along some N—S trending shear zones may indicate the very early creation of deep lithospheric tensional faults subsequently reactivated during the Pan-African.

II. Cratonic shelf type upper Proterozoic sedimentation and the basic-ultrabasic magmatic cycle at c.a. 800 m. y.

Stable conditions characterize the period between c.a. 1100—800 m. y. during which shelf-type very uniform sediments with the preponderance of carbonates were directly deposited over a sialic basement which was possibly part of a greater palaeo-West-African craton, and also concordantly upon the basins of middle Proterozoic age. It was followed by a continental scale tension regime which was initiated at c. a. 800 m. y. In the western branch, widespread basic and ultrabasic intrusions represent the basification of the older sialic crust and its cover, and they announce the forthcoming arc-type development with calc-alkaline magmatism (Fig. 7 A).

In the central branch, ultrabasic intrusions are less abundant than quartz-diorites and granodiorites which also cross-cut shelf-type sediments and various volcanics suggesting crustal consumption in this zone. Subsequent strong positive vertical movements led to the erosion of these eruptive rocks and to the formation of an ephemeral palaeo-topographic surface.

N—S trending metamorphic dyke swarms of predominantly hypovolcanic and volcanic rocks of basaltic, syenitic and peralkaline composition may represent the remnants of a rifting stage. This longitudinal zone coincides with the actual border fault which delimits the margin of the West African craton. Thus,, this fault may be regarded as a cryptic suture zone, since typical ophiolites are preserved along it both to the North in southern Morocco (LEBLANC, 1976) and to the South in Mali (LEBLANC, pers. communication, 1976), but no convincing evidence of upper Proterozoic oceanic crust has yet been found anywhere in Hoggar.

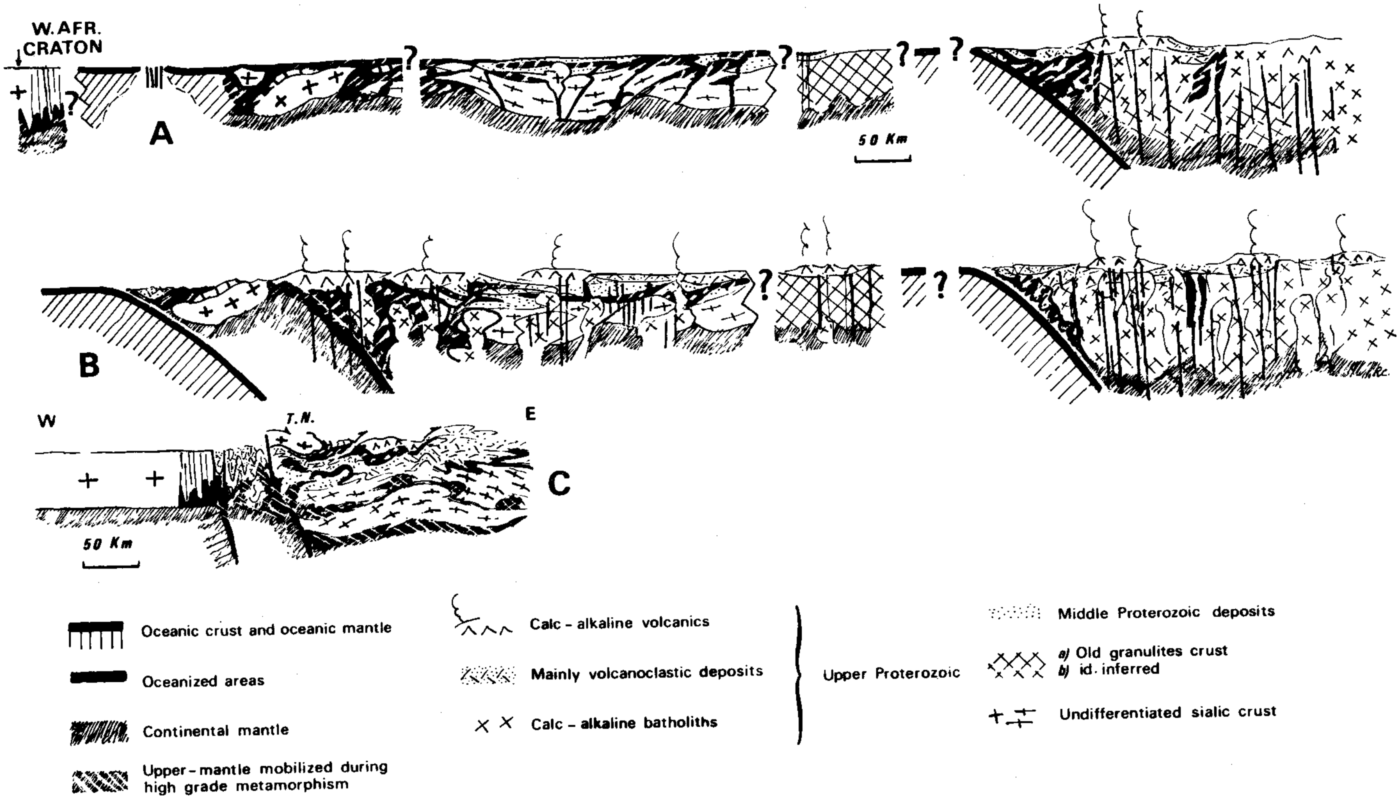
W. AFR.
CRATON
A
50 Km
B
W
T.N.
E
C
50 Km
Oceanic crust and oceanic mantle
Oceanized areas
Continental mantle
Upper-mantle mobilized during high grade metamorphism
Calc-alkaline volcanics
Mainly volcanoclastic deposits
Calc-alkaline batholiths
Upper Proterozoic
Middle Proterozoic deposits
a) Old granulites crust
b) id. inferred
Undifferentiated sialic crust

Fig. 7. A schematic reconstruction of the western part of the Pan-African mobile belt in terms of present views on global tectonics appplied to the upper Proterozoic. (A) is the opening stage (c. a. 800 m. y.) during which crustal thinning, basification process, together with the formation of oceanic crust took place. Calc-alkaline batholiths of the eastern part suggest early subduction zones dipping East (B) represents the posible site during which the main calc-alkaline volcanics and plutonics were emplaced (c. a. 750—650 m. y.?) in relation to East dipping subduction zones. In these two palinspatic sections, the question marks outline the gaps of unknown width due to lateral displacements along the shear zones. The location of oceanic crust is only inferred from the widespread calc-alkaline rocks which may derive from partial melting of descending oceanic lithosphere, and also from the existence of ophiolites in South Morocco and northern Mali. (C) gives a possible section of the western Pharusian branch just after the complete oceanic closure and after the initial major phase of Pan-African deformation (c. a. 650 m. y.) which produced nappes, recumbent folding and a global crustal thickening (T. N.: Tassendjanet Nappe). The lower part of this section is highly speculative.

III. The late Proterozoic calc-alkaline cycle suggesting a possible island-arc type environment (c. a. 800—650 m. y.) (Fig. 7 B).

This third magmatic cycle represents the main rock forming process, and by the volume of rocks generated this period may correspond to crustal accretion process. Indeed, calc-alkaline volcanics (andesites, dacites, rhyodacites) and immature volcanoclastic deposits mainly volcanic graywackes are predominant (CABY *et al.*, 1977) together with pre-tectonic batholiths ranging from diorites to calc-alkaline granites which in the central branch crop out over as much as 50000 km^2. It is likely that such a widespread calc-alkaline magmatism may have been linked with subduction zones. The western branch andesites which overlie basic and ultrabasic rocks may correspond to an island-arc adjacent to volcanic graywackes trough deposits, whereas the calc-alkaline batholiths and associated rhyo-dacites of the central branch may represent an Andean-type assemblage, possibly initiated earlier East of the In Ouzzal block, which was buried beneath andesite and basalts.

The Pan-African orogeny *s. s.* was initiated after the third magmatic cycle was completed. Very unequal uplift of the belt in connection with the development of the strike-slip fault system and the later horst graben tectonics are responsible for a rather complex metamorphic and structural pattern. Moreover, the degree of metamorphism and deformation depends also on the nature of the crust. It is remarkable, indeed, that a very weak deformation under upper greenschist facies conditions occurs as a rule in the areas of pre-tectonic volcanics and magmatism of the central branch which may represent an Andean-type assemblage lying upon a possible granulitic crust, while middle to lower amphibolite conditions accompanied by anatexis and syn-kinematic granites are localised in zones of predominant meta-sediments of middle Proterozoic or late Proterozoic age. The absence of Pan-African metamorphic tectonic events is also striking in the In Ouzzal block, as shown by the horizontal attitude of the pre-Pan-African peneplain outlined by the late Proterozoic andesites.

Pan-African polyphase deformation and recumbent folding seem to be restricted to the deepest structural level of the two branches of the Pharusian belt, whereas N—S trending folds with mainly vertical axial planes are the only structures recorded both in the low-grade synforms of late Proterozoic rocks, close to the eastern margin of the central branch, and in the polycyclic units of central Hoggar.

The 650 m.y. zircon ages on syn-kinematic granites both in the Pharusian belt and in central Hoggar (PICCIOTTO *et al.*, 1965; ALLÈGRE & CABY, 1972) may indicate large scale crustal melting processes during the peak of the "early phase" of the Pan-African orogeny, but in the western branch, the peak of Barrovian type metamorphism predates these granites (CABY, 1970). Assymetry is also displayed by the preponderance of basic and intermediate syn-orogenic plutonism (gabbros, diorites) indicating a large contribution from the mantle in the Pharusian belt compared to the prevalence of more K-rich adamellites and granites in central Hoggar suggesting an origin involving partial melting of a thickened sialic crust.

Heterochronism of the deformation between western central Hoggar and the eastern Hoggar is suggested by geochronological data which indicate tension and pre-tectonic magmatic activity in the site of the ensialic Tiririne belt at 660 ± 5 m.y. (BERTRAND *et al.*, in press) roughly contemporaneous with syn-kinematic granite emplacement in the Pharusian belt. Geochronological data also show that polyphase deformation within the Tiririne belt is younger than in the rest of the shield and occurred slightly before the syn-kinematic granites dated at 604 ± 13 m.y. (BERTRAND *et al.*, in press).

c) Geodynamic model for the Pan-African belt of Hoggar

The shear belt and strike-slip fault system of the shield can be compared in scale and geometry, to that of the northern Himalayas which is clearly related to different stages of the collision between India and Asia (MOLNAR & TAPONNIER, 1975). The shear belts and strike-slip faults of Hoggar are the result of the collision between two plates: the West African craton, rigid since some 2000 to 1800 m.y. to the West, and the East Saharian craton, which was also rigid before 660 m.y.

The early stage of the collision (c.a. 650 m.y.) (Fig. 7 C) may have produced crustal thickening by recumbent folding at depth and thrusting. These early structures mostly tightened and refolded may have had a geometry induced by that of the inferred east dipping subduction zones. At a later stage the same tectonic event was culminating with a compression which produced N—S trending folds with vertical axial planes, the thrusts evolving into more or less vertical strike-slip faults outlined by mylonites of always greenschist facies grade. We suggest that though unquantified a rather important shortening may have been absorbed by lateral movements along conjugate shear zones. The localisation of 100% dyke complexes, both gabbroic and strongly acidic alkaline, emplaced after F 1 in tension zones within some major strike slip faults, such as the western fault of the In Ouzzal block for which a sinistral displacement of 350 km has been postulated, accounts for the importance of such faults which may affect the whole lithosphere (Fig. 8).

The presence of many granitic intrusions, subsequently sheared along some major faults may indicate alternating periods of tension and compression which can be correlated with sinuous paths of contiguous crustal blocks of different

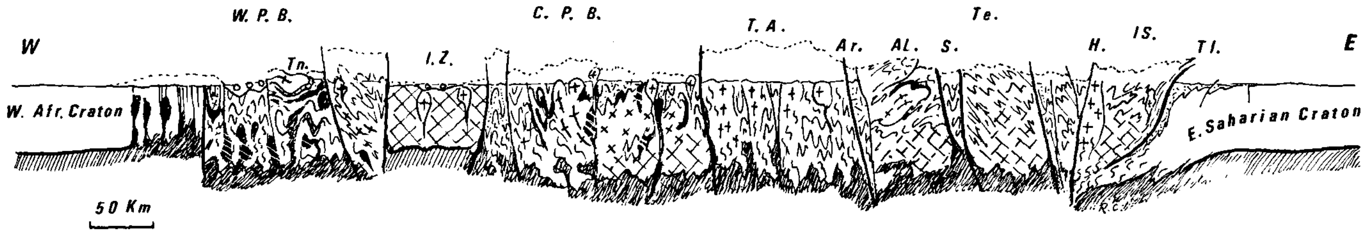

Fig. 8. Gross cross-section of the Pan-African belt of the Hoggar. Perpendicular to the shear zones and strike-slip faults, such a section is without great significance but gives a good illustration of the major role of the late phase of E—W thightening of the belt, which is responsible for the overall vertical attitude of rock-units, foliations and tectonic contacts. The major shear zones are thought to have affected the entire lithosphere. An attempt is made to distinguish unreactivated upper-mantle — lower crust and anatectic lower crust — mobile upper-mantle. Cross hatching: old granulite crust, and interrupted cross hatching: inferred granulite crust. The dotted line above the profile is an attempt to quantify the amount of uplift of the different structural domains. W. P. B.: West Pharusian branch. C. P. B.: Central Pharusian branch. T. N.: Tassendjanet Nappe. I. Z.: In Ouzzal block. T. A.: Tefedest-Atakor. Al.: Aleksod. Ar.: Arefsa upper Proterozoic schist belt. S.: Serkout. Te.: Temasint. Is.: Issalane. H.: Honag. Ti.: Tiririne belt.

rheologies. This fact is also frequently demonstrated by the sigmoid attitude of the main cleavage planes (and eventually their late folding with steep axes) along some faults. Most of the intrusive granites, especially the Taourirts (BOISSONNAS, 1973) were emplaced during this stage. On the other hand, the LP/HT metamorphic conditions which have locally generated fresh granulite facies rocks are only found to the West of the belt, in the Egatalis area.

The Tiririne belt localised on the edge of the East Saharian craton only formed after most of the collision was completed at 600—580 m. y. (BERTRAND *et al.*, in press) and the higher group of sediments of the Tiririne Formation is already a molasse. The late stages of collision are responsible for second order conjugated sets of strike-slip faults which are so characteristic of the Hoggar shield and Aïr mountains. Deposition of the molassic "Série pourprée" of western Hoggar was partly controlled by these second order strike-slip faults. Preserved in graben and in unfolded residual basins, for example North of the In Ouzzal block, these red deposits were subjected to diagenesis at c. a. 470 ± 18 m. y. (CLAUER, 1976) but other similar deposits South-West of Silet which are affected by thrusting account for the late mobility of the central branch of the belt. In the central Hoggar, it is also noteworthy that the young mineral ages in the range of 550—470 m. y. are explained by very late uplift just before deposition of the Ordovician sandstones of the Tassili.

7. Conclusions

The Pan-African belt of Hoggar, 800 km wide, is strongly assymetric. As old as middle Proterozoic, relative mobility of the originally ensialic zone located East of the West African craton is indicated by wide subsiding areas and by a first magmatic cycle (1750 or 1350 m. y. ?) of typical cratonic and anorogenic type. The c. a. 800 m. y. old magmatic event is related to a continental scale tensional regime and represents a large mantle contribution in the form of basification of some crustal blocks and their shelf type cover, and this event may be correlated with upper Proterozoic ophiolites of adjacent areas. A third major magmatic cycle of calc-alkaline volcanics and plutonics took place in the period 800—650 m. y., suggesting both island-arc type and Andean type assemblages and this major pre-tectonic event may have been linked to East dipping subduction zones and to the closure of an ocean as proposed by CABY (1970). Geochronological data suggest that the central Hoggar formed of sialic units of Eburnean and older ages and younger supracrustal rocks, had already been involved in a tectono-metamorphic event of assumed "Kibaran" age, before its reactivation during the Pan-African orogeny marked by N—S trending folds, metamorphism, and syn-orogenic Pan-African granites.

Recumbent folding at depth and thrusting account for the unquantified shortening realised by crustal thickening within the belt in the "old" stage of the Pan-African orogeny dated at c. a. 650 m. y. by synorogenic granites (PICCIOTTO *et al.*, 1965; ALLÈGRE & CABY, 1972). The conspicuous system of N—S trending vertical shear zones and strike-slip faults, to which the late N—S trending folds are geometrically linked also produced a very important E—W shortening realised by lateral movements along conjugate shear belts with a main sinistral component during the "late" stage of the Pan-African orogeny in the period

≅ 600—550 m. y., but geochronological data point out to some eastwards younging of the main Pan-African deformation. The younger mineral ages (550 to 470 m. y.) indicating late vertical uplift of central Hoggar is contemporaneous with molassic deposits preserved mainly in the western part of the belt.

The Pan-African orogeny in Hoggar is essentially due to the squeezing of the "mobile zone" between two colliding rigid plates: the West African craton and the East Saharian craton. Whilst an oceanic opening and closure may be inferred along the western branch of the Pharusian belt, the orogenic evolution of central and eastern Hoggar is believed to be ensialic.

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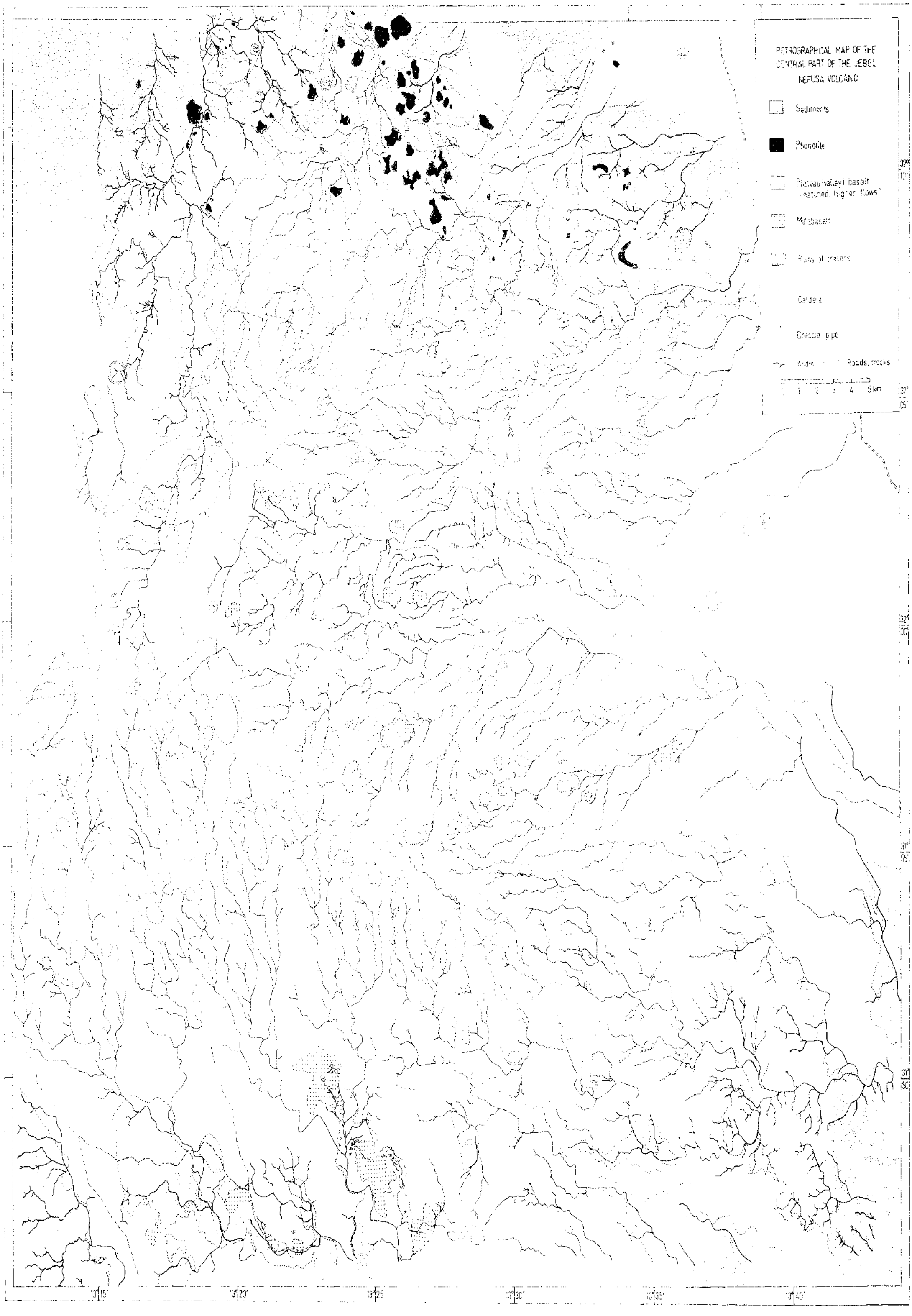

Plate 1: Petrographical map of the central part of the Jebel Nefusa Volcano.