Chapter 16

PAN-AFRICAN OCEAN CLOSURE AND CONTINENTAL COLLISION IN THE HOGGAR—IFORAS SEGMENT, CENTRAL SAHARA

R. CABY, J. M. L. BERTRAND and R. BLACK

ABSTRACT

The late Precambrian to early Palaeozoic tectonic development of the Hoggar—Iforas region in the central Sahara is interpreted in terms of a complete Wilson cycle with ocean opening and closing between the West African craton and the Touareg shield.

Rifting along the eastern margin of the West African craton occurred around 800 Ma ago with a triple point in Mali, the Gourma being interpreted as an aulacogen. Continental fragmentation was accompanied by the injection, at the base of the crust and at high levels, of basic and ultrabasic magmas. The presence of basalts of possible oceanic origin, island arc and marginal trough volcano-clastic assemblages, widespread calc-alkaline plutonism, and paired metamorphic belts, including high-pressure eclogitic schists, strongly suggest that active subduction processes were at work. In the western part of the Touareg shield (Pharusian belt) widespread, prolonged continental Cordilleran conditions prevailed, the oldest being dated at 885 Ma. Three major tectonic events have been distinguished: (1) stabilization of the eastern Hoggar—Ténéré domain around 725 Ma ago; (2) N—S collision in the western Pharusian branch around 700 Ma ago and, finally, (3) oceanic closure around 600 Ma ago which led to the E—W collision between the passive continental margin of the West African craton and the active continental margin of the Touareg shield. The suture is marked by a string of positive gravity anomalies corresponding to the emplacement of ultrabasic and basic rocks. The 600 Ma collision was accompanied by the translation of foreland nappes onto the West African craton and affected the entire Touareg shield. The reactivation of older gneissic terrains in the central and eastern part of the shield is marked by greenschist metamorphic overprinting, intense intraplate deformation in N—S linear belts accompanied by crustal thickening, generation of granites and major lateral displacements along megashear zones. An analogy is drawn with Asia and the Himalaya fold belt.

The large amount of predominantly calc-alkaline rocks generated during the Pan-African s.l. (900—500 Ma) corresponds to a major period of crustal accretion which led to the cratonization of Africa.

INTRODUCTION

Ten years ago attention was drawn to the existence of Pan-African island arc and marginal trough volcano-detritic assemblages in the western Hoggar, associated with magmatism of oceanic affinities (Gravelle, 1969; Caby, 1970), and ophiolites were recognized at Bou Azzer (Morocco) along the northern edge of the West African craton (Leblanc, 1970). Burke and Dewey (1970) presented a plate-tectonic model for circum West African Pan-African belts, suggesting a Himalaya-type situation for most of the crust situated to the east of the West African craton. Bertrand and Caby (1978), in an attempt to synthesize the geology of the Hoggar, proposed a model involving subduction processes in the western Hoggar and showed the complexity and varying degree of Pan-African intracontinental deformation across the 800 Km wide shield. Recently, the preliminary results of a detailed geological and geophysical investigation of the critical Iforas—Gourma region in Mali, crossing the West African craton and the Pan-African belt to the east, showed convincing evidence of a Wilson cycle ending with collision between a passive continental margin in the west and an active continental margin in the east (Black et al., 1979b).

The major tectonic units in the region that we shall examine (Fig. 16-1) are, in the west, the West African craton stable since around 1700 Ma ago, and to the east, the Touareg shield (Hoggar, Iforas, Aïr) which belongs to the Pan-African mobile belt. Major N—S shear zones divide the Touareg shield from west to east into the following tectonic domains: (1) The Pharusian belt, comprising a western and an eastern branch, both characterized by the abundance of Upper Proterozoic volcano-detritic material; (2) the polycyclic central Hoggar—Aïr domain largely composed of ancient gneisses reactivated and injected by abundant granitoids during the Pan-African; (3) the eastern Hoggar—Ténéré domain which apparently was to a large extent stabilized at an early stage of the Pan-African episode around 725 Ma ago.

The aim of this chapter is to discuss the relationships between subduction—collision and ensialic processes within the Touareg shield, which underwent a multistage evolution during a period lasting several hundred million years. Whilst we feel that events marking the closing stages of the Pan-African episode related to collision with the West African craton are beginning to be well documented, our enquiry into the older events is much more speculative, but the tentative model presented is compatible with present-day plate-tectonic processes (Dewey, 1977).

For the geological background the reader may refer to regional syntheses by Bertrand and Lasserre (1976), Bertrand and Caby (1978), Bertrand et al. (1978), Black (1978), Black et al. (1979a), to detailed regional accounts by Gravelle (1969), Caby (1970), Bertrand (1974), Davison (1980), and early pioneering work of Lelubre (1952) and Karpoff (1960).

In this paper the term Pan-African covers the time period 900—550 Ma. All ages quoted are recalculated with the new decay constants recommended by Steiger and Jäger. Recent age determinations are given with 1 sigma error.

CONTRASTING PRE-PAN-AFRICAN HISTORY OF THE WEST AFRICAN CRATON AND THE TOUAREG SHIELD

When comparing the nature of the basement constituting the West African craton with that of the pre-Pan-African inliers occurring within the Touareg

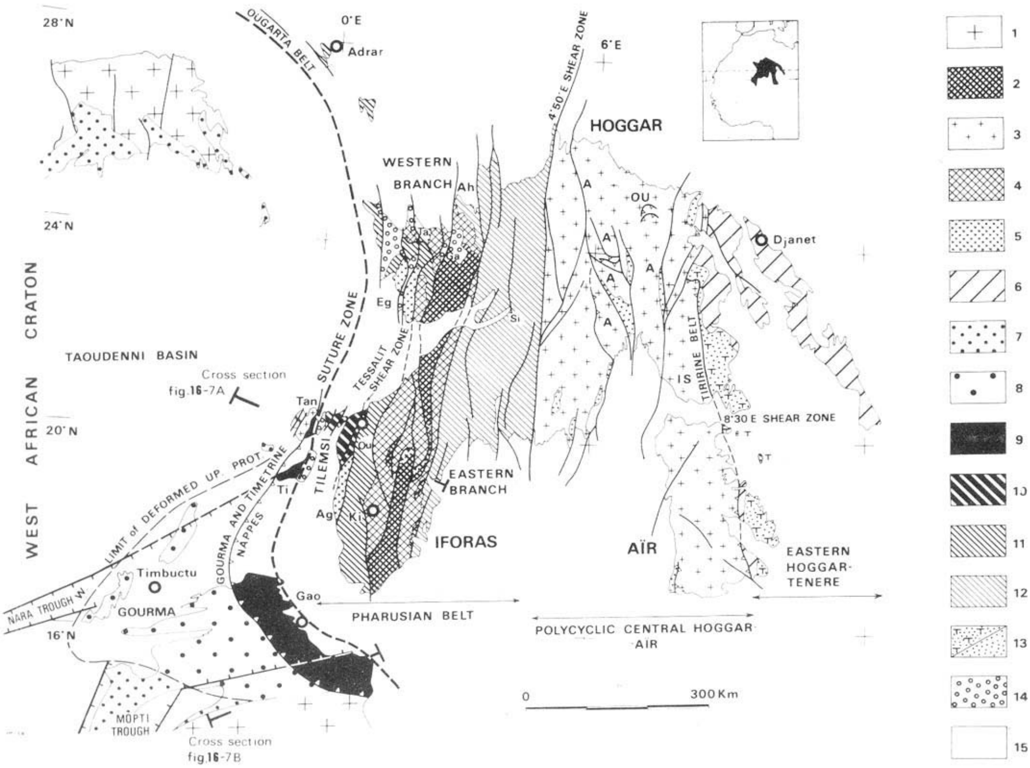


Fig. 16-1. Simplified geological map of the Touareg shield and adjacent areas. *1* = Reguibat and Leo Shields; *2* = slightly reactivated Eburnean granulites within the Pharusian belt; *3* = reactivated pre- Pan-African gneisses; *4* = undifferentiated gneisses highly reactivated during the Pan-African; *5* = *4*, affected by late high-temperature—low-pressure metamorphism; *6* = undifferentiated rocks of the eastern Hoggar (metamorphism at c. 725 Ma); *7* = Upper Proterozoic shelf sediments; *8* = slope-basin sediments of the Gourma aulacogen; *9* = Gourma and Timétrine nappes; *10*—*12* = late Upper Proterozoic greywackes and magmatic rocks of the Tilemsi accretion zone (*10*), of the western Pharusian belt (*11*), of the eastern Pharusian branch (*12*); *13* = late Upper Proterozoic volcano-detritic schist belts in the central and eastern Hoggar with *T* = Tiririne and Proche—Ténéré Groups; *14* = molassic "Série pourprée" (partly Cambrian); *15* = Palaeozoic and Mesozoic cover. *A* = Aleksod assemblage; *Ah* = Ahnet; *Ag* = Aguelhoc; *Eg* = Egatalis; *Tan* = Taounnant; *Ti* = Timétrine; *IS* = Issalane; *Ki* = Kidal; *OU* = Oumelalen; *Ta* = Taoudrart; *Ga* = Gara Akofou; *Ou* = Oumassène; *Si* = Silet.

shield, the most obvious feature is the widespread presence of high-grade rocks in the latter whereas the craton, at least its southeastern part, is composed of low-grade granite metavolcanic-greywacke assemblages reminiscent of Archaean greenstone belts.

Bessoles (1977) in his review of the West African craton underlined its division into: (1) a western domain of Liberian age ($\simeq$ 3000 Ma) almost unaffected by Eburnean reactivation ($\simeq$ 2000 Ma) and consisting essentially of granulites (western Mauritania, Sierra Leone, Liberia, western Ivory Coast), but including some Archaean low-grade greenstone belts (Sierra Leone); (2) the eastern domain is characterized by pre-Eburnean (2700 Ma) reactivated basement and NNE—SSW-trending Birrimian (Lower Proterozoic) belts of metavolcanic-sedimentary rocks, with widespread syntectonic and late tectonic granites emplaced in the time span 2000 ± 100 Ma. Except for some Eburnean molassic formations, late granites (1700—1600 Ma) and dolerites (1300 Ma), the Middle Proterozoic (c. 2000—1000 Ma) is generally absent in the West African craton, which has remained remarkably stable for the last 1700 Ma.

Pre-Pan-African basement remnants are known in most domains of the Touareg shield. All of these consist of high-grade rocks, often belonging to the granulite facies, metamorphosed during the Eburnean event (2150—2050 Ma). The largest inliers of Eburnean granulites (In Ouzzal—Iforas) display a dominant ENE—WSW structural trend. Their presence however is not due to Pan-African uplift as suggested by Shackleton (1976) as they are unconformably overlain by Middle and Upper Proterozoic formations. Some of the inliers are of Archaean age but the corresponding structure and metamorphism are largely unknown (Ferrara and Gravelle, 1966; Latouche and Vidal, 1974). Unlike on the craton, the Middle Proterozoic is well developed in the Pharusian belt where it is represented by alumina-rich quartzites and associated pelitic schists. They often contain intercalated sills and sheets of alkaline-peralkaline meta-igneous rocks which have yielded zircon Concordia dates of 1742 ± 12 Ma and 1843 ± 3 Ma (U. Andreopoulos-Renaud, unpubl. data). In the central Hoggar several sequences of supracrustal rocks have also been attributed to the Middle Proterozoic (Bertrand, 1974; Latouche, 1978).

These differences of the basement in the craton and in the Touareg shield are thought to be significant. They suggest that the position of the future Pan-African belt may have been predetermined by the presence of a high-grade Eburnean mobile belt so that oceanic opening eventually occurred along a line of weakness on the edge of the granulites.

On the craton the early Upper Proterozoic (c. 1000—800 Ma) is represented by flat-lying platform deposits, the best known and most representative being the Atar el Hank Group which consists of sandstones, overlain by stromatolite-bearing limestones (Bertrand-Sarfati, 1972; Trompette, 1972). Within the Pan-African belt a very similar sequence was first described in the northwestern Hoggar under the name "Série à stromatolites" (Fabre and Freulon, 1962; Caby, 1970) and this group, with similar shelf-type facies and stromatolite associations (Bertrand-Sarfati, 1969), has now also been identified in several areas in the western part of the Touareg shield. The early Upper Proterozoic marks a period of very widespread cratonic sedimentation, and we believe that there may have been continuous continental crust from the West African craton to the Touareg shield.

EARLY PAN-AFRICAN RIFTING DURING THE UPPER PROTEROZOIC

Development of a passive continental margin

A major change in sedimentation occurred about 800 Ma ago with rifting along the eastern margin of the West African craton, leading to the development of a passive continental margin. In Mali, a triple point coincides with an embayment in the craton: the Gourma (Fig. 16-1) is thought to be a failed arm which evolved as an aulacogen, a comparable situation with that of the Benue trough with respect to the Gulf of Guinea in the Cretaceous (Grant, 1971). The Gourma basin is characterized by deep subsidence with an accumulation of over 8000 m of sediments (Reichelt, 1972). The observed sedimentary sequences comprise an early terrigenous clastic phase at the base, followed by differentiated carbonate sediments indicating lateral passage platform—slope—trough, and end with prograde continental clastic deposits. These sediments thicken eastwards and are typical of deposits formed along the passive continental margin adjoining a mature wide ocean (Moussine-Pouchkine and Bertrand-Sarfati, 1978). The shape of the basin, as defined by the distribution of slope sedimentary facies and the gravity pattern, is that of a trough oriented WSW—ENE and representing a gulf within the West African craton. The aulacogen is marked by positive gravity anomalies which can be traced westwards across the craton where they split, defining the axes of the Nara and Mopti troughs. The Gourma formations have been affected by open folding parallel to the trend of the aulacogen, prior to late Pan-African regional folding which outlines the concave virgation of the Gourma.

To the south, in Togo-Benin, recent studies of the Upper Proterozoic (Simpara, 1978; Trompette, 1980) also indicate a passage from thin platform deposits to thick marine continental margin deposits as one goes eastwards towards the edge of the craton.

Magmatism associated with continental fragmentation

The first stage of rifting is preserved in the northwestern Hoggar where deformed pre-metamorphic dyke swarms of alkaline and peralkaline metarhyolites, undersaturated soda-trachytes and phonolites with associated

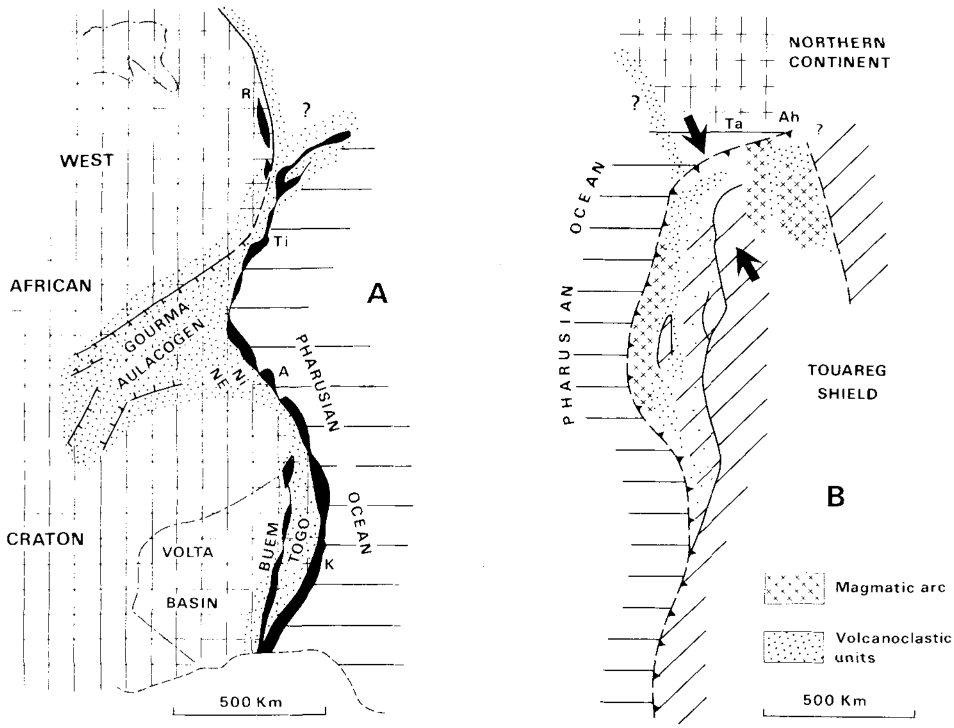


Fig. 16-2. Tentative palaeogeographical reconstructions.
A. Passive margin of the West African craton after ocean opening at c. 800 Ma. Dots represent the strongly subsiding areas; zone of basic and ultrabasic intrusions in the collapsed margin are shown in black; *Ti* = Timétrine; *A* = Amalaoulaou; *K* = Kandé; *R* = palaeorift. *Ni* and *NE* = inferred areas of sedimentation of internal (*Ni*) and external nappes (*NE*) compared to Togo-Atacorian and Buem, respectively.
B. Active margin of the eastern continent (Touareg shield) with its western accretion domain dying out southwards and its northern magmatic arc. Arrows outline the early NNW—SSE collision with a northern continent at c. 700 Ma. *Ta* = Tassendjanet nappe; *Ah* = Ahnet deltaic quartzites.

plutonic rocks are superimposed on earlier basic dyke swarms (Fig. 16-2A). On field, petrological and geochemical grounds, this complex is interpreted as representing the roots of a palaeorift (Dostal et al., 1979).

The intrusion of voluminous basic and ultrabasic rocks in the form of sills, laccoliths and stocks has occurred over wide areas of both continental margins. These complexes show some petrological and geochemical affinities with ophiolites but field observations (Caby, 1970, 1978) have shown these mantle-derived complexes to have been intruded into sediments prior to regional low-grade metamorphism. They belong to a large-scale magmatic event occurring around 800 Ma ago (Clauer, 1976; De la Boisse, 1979) and are thought to be related to the process of continental fragmentation (Fig. 16-2A). Three examples are given below:

(1) The Ougda—Tassendjanet complex ($\simeq 900\,km^2$), outcrops along one side of a major fault which may have controlled its emplacement into quartzites and limestones of the "Série à stromatolites". Garnetiferous metagabbros grading into garnet amphiclasites and pyriclasites may represent early stages of cooling of a gabbroic magma deep in the crust in granulite-grade conditions. Amphibole gabbros, fine-grained carbonate-rich serpentinites and foliated quartz diorites cut through stromatolite-bearing marbles and dolomites, producing high-grade contact metamorphism. Heterogeneous quartz-gabbros, tonalites and trondhjemites constitute the bulk of the complex, with lesser amounts of granodiorites. Many amphibolitized dykes of andesitic composition are also associated with the gabbros and may represent late sub-volcanic conditions. A recent geochemical study (C. Dupuy, pers. commun., 1979) concluded that the gabbroic rocks are LREE-depleted and display patterns typical of oceanic tholeiites and that younger rocks show progressive calc-alkaline affinities.

(2) The Amalaoulaou meta-igneous complex (Fig. 16-7B) coincides with a positive gravity anomaly marking the suture with the West African craton. It comprises layered amphibole-garnet pyriclasites, two pyroxene pyriclasites and serpentinites. According to De la Boisse (1979) metagabbros have primarily crystallized in granulite facies conditions at the base of the crust from a magma of tholeiitic affinity and have subsequently been tectonically emplaced along the suture. U-Pb dating on zircon (De la Boisse, 1979) has given an age of 810 ± 50 Ma, considered as that of magmatic crystallization. Undeformed quartz gabbros were intruded at 730 ± 40 Ma ago before the development of greenschist facies metamorphism with local blue amphibole.

(3) The Timétrine ultrabasic rocks occur as four elongated boudinaged massifs, interpreted as being incorporated in a nappe west of the suture (Fig. 16-3). They are composed of highly serpentinized rocks and represent metadunites and some metawherlites, lherzolites and harzburgites, displaying a foliation and strong chromite lineation. Lenses of metagabbro and diabase are found within the serpentinites. The presence of blue amphibole and aegyrine in the surrounding country rocks is restricted to some tens of metres close to the ultrabasic bodies (Karpoff, 1960). Overlying the chlorite-albite schists and the sericite quartzites which surround the serpentine massifs are found pillow basalts and their feeder dykes. Leblanc (1976) suggested that these rocks represent a dismembered ophiolite sequence obducted into a thick epicontinental sedimentary formation. On the other hand, Caby (1978) indicated that the contacts between fine-grained carbonated serpentinites and compact chlorite schists may be regarded as magmatic and that the ultrabasic rocks were intruded as sills and dykes into the schists.

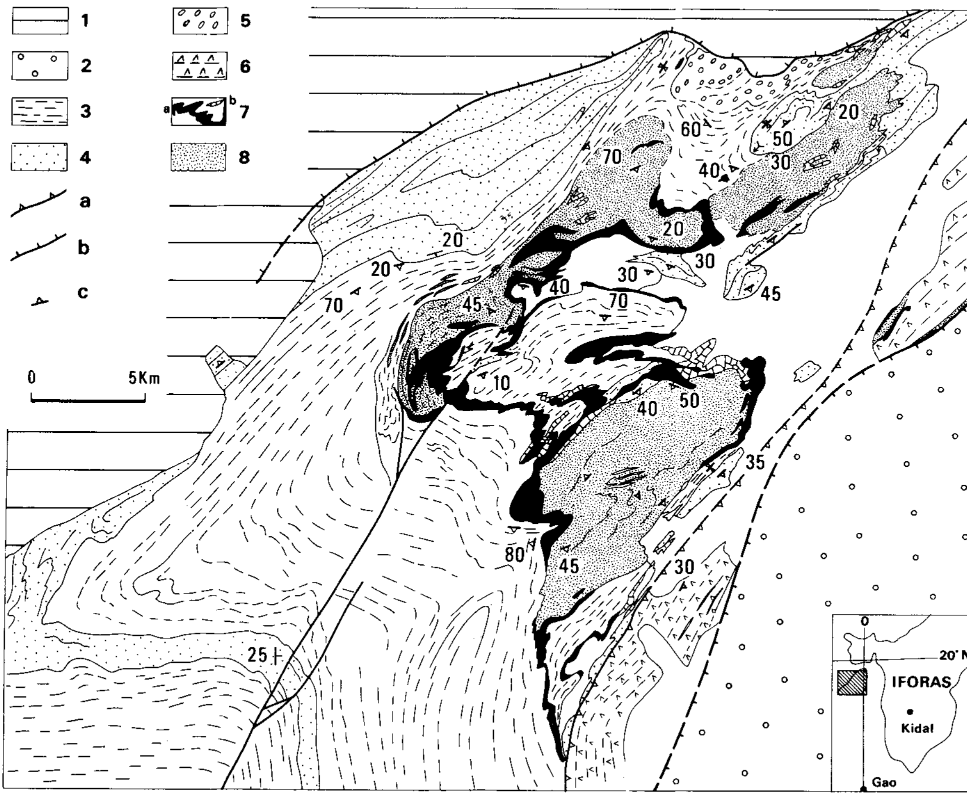


Fig. 16-3. Simplified geological map of the Timétrine area (presumably allochthonous). *1* = Cretaceous cover; *2* = molassic deposits (Nigritian), partly of Cambrian age; *3* = sericite-chlorite schists; *4* = sericite quartzites; *5* = pillowed metabasalt and related diabase, apparently conformable on *3; 6* = diabase and metabasalt (blue amphibole bearing); *7a* = red hematite jaspers; *7b* = Ca-Fe-Mg carbonates; *8* = ultrabasic rocks; *a* = thrust; *b* = fault; *c* = cleavage.

INITIATION OF OCEAN CLOSURE AND SUBDUCTION: CORDILLERAN-TYPE EVOLUTION IN THE PHARUSIAN BELT

In the western part of the Pan-African Touareg shield, the late Upper Proterozoic deposits of the Pharusian belt are totally different from those of the West African craton. They have many characteristics comparable with island arc and modern active continental margins suggesting the existence of an open ocean separating two continents. The deposits reflect a very complex palaeogeography of basins, troughs and volcanic chains and were accompanied by widespread calc-alkaline volcanism and plutonism. Deposition was not everywhere synchronous and several cycles have been distinguished.

The oldest known rocks occur in the central part of the eastern Pharusian branch around Silet (Fig. 16-1). Two important lithological units separated by an unconformity (Bertrand et al., 1966) have been recognized by Gravelle (1969):

(a) A *lower unit* consisting of a volcano-detritic sequence with flows and sills of intermediate to acid composition, pillow basalts, sills and dykes of dolerite. It overlies marble and quartzites injected by basic and ultrabasic rocks. This assemblage is cut by a large composite batholith of quartz diorite, granodiorite, trondhjemite and adamellite which has yielded a U-Pb Concordia date on zircons of 887 ± 1 Ma (U. Andreopoulos-Renaud, unpubl. data). Early regional folding and greenschist facies metamorphism seem to be related to this major cycle.

(b) An *upper unit* comprising a volcano-sedimentary sequence including pelites and greywackes with a basal conglomerate and a volcanic sequence almost exclusively composed of andesites, dacites, pyroclastics, cut by dykes of andesitic composition.

During this magmatic cycle quartz diorites and adamellites dated at 831 ± 5 Ma (U-Pb on zircons, U. Andreopoulos-Renaud, unpubl. data) were emplaced in the form of elongate N—S-trending batholiths, up to 80 km long and 10—35 km wide, with numerous intraplutonic sub-volcanic rocks suggesting a high-level of emplacement, the country rocks being converted to hornfels. In the northwestern part of the eastern Pharusian branch thick accumulations of slightly deformed lavas of andesitic to rhyolitic composition are cut by calc-alkaline batholith and crop out over wide areas which are little known. Their relationships with adjacent poly-deformed metagreywackes and lavas and with the units distinguished by Gravelle (1969) have not yet been established. The vast amount of predominantly calc-alkaline volcanic and plutonic rocks emplaced during a period exceeding 200 Ma suggests a long Cordilleran-type evolution in the eastern Pharusian branch (Fabriès and Gravelle, 1977). Detailed geochemical studies of the volcanics from the Silet region show that the majority of samples display calc-alkaline trends with moderate LREE enrichment and La/Yb ratios between 5 and 8, typical of modern island-arc calc-alkaline rocks. They also resemble andesites and high-Al basalts from central-south Chile which are related to a relatively flat-lying Benioff zone (Chikhaoui et al., 1980). The old continental crust underlying Cordilleran-type assemblages is known from some high-grade slices along major faults and has been sampled as sialic granulite xenoliths in recent volcanoes (M. Girod, pers. commun., 1979).

In the western Pharusian branch (Fig. 16-1) one can distinguish late Upper Proterozoic volcano-detritic sequences which have been affected by two major phases of Pan-African deformation (e.g. the "Série verte"), and others which have only been subjected to late Pan-African tectonism (e.g. Taoudrart, Gara Akofou and Oumassène). The earlier (pre-700 Ma) "Série verte" occurs in synclinoria superimposed on subsiding basins already initiated during the Middle Proterozoic. It consists of a 6000 m thick sequence of flysch, volcanic greywackes and pebble conglomerates with intercalated andesites, dacites and dacitic breccias which may be derived from volcanic islands. Basic and calc-alkaline plutonic rocks (diabase, quartz diorite and granodiorite) have invaded the greywackes in the form of sills and stocks, but similar rocks are also found in the conglomerates suggesting an auto-cannibalistic evolution. The chemical composition of the greywackes is similar to modern examples and points to a lack of terrigenous and clay components even in fine-grained rocks (Caby et al., 1977). In contrast, the later *Taoudrart volcanics* (5000 m thick) are composed of andesite flows and intercalated pyroclastics with dacites and continental polygenic conglomerates on top, laterally interfingering with agglomerates, tuffs and greywackes. The *Gara Akofou volcanics* consist of a 2000 m thick sequence of basic and intermediate lava flows with intercalated pyroclastics, preserved in a fault-bounded monocline within the granulitic In Ouzzal unit. It probably represents the relics of an extensive volcanic cover. The *Oumassène volcanics* (2000 m) in the Iforas are composed mainly of andesite flows with intercalated pyroclastics. Trace element data for the volcanics from these three occurrences (Taoudrart, Gara Akofou and Oumassène) are consistent with derivation by partial melting from an upper-mantle source enriched in LILE (Chikhaoui et al., 1978). The rock suites display typical calc-alkaline patterns with pronounced LREE enrichment and La/Yb ratios between 12—14, typical of modern continental margin andesites associated with steeply dipping Benioff zones. Such similarities can be extended to other trace elements such as Zr, Nb, Hf and P (Chikhaoui et al., 1980).

The Tilemsi strip (Fig. 16-1) close to the West African craton is believed to represent a zone of accretion largely devoid of ancient basement. It is composed of greywackes with turbidites and associated conglomerates as well as occasional Al-rich pelitic layers, which may represent deep-sea clays overlying dacitic breccias and a lower metabasalt unit. These rocks are injected by a large volume of pretectonic plutonic rocks in the form of sills, dykes and massifs, a pretectonic adamellite having yielded a U-Pb Concordia age on zircon of 633 ± 3 Ma (U. Andreopoulos-Renaud, unpubl. data). These plutonic rocks exhibit a marked E—W polarity: whilst quartz gabbros abound close to the suture, eastwards the terrain is invaded by large massifs of quartz diorite. As one approaches the margin of the Iforas, granodiorites and adamellites predominate. A polarity is also displayed by the nature of the sediments, the amount of clay and terrigenous material increasing eastwards. In contrast to the deep trough environment in the west, syn- and late-tectonic flysch-molasse deposits and associated andesites occur along the eastern margin of the Tilemsi. Farther east, in the western Pharusian branch underlain by ancient basement, we have already pointed out the presence of thick andesite sequences displaying typical geochemical characteristics of continental margin, Cordilleran-type volcanics which we relate to an easterly dipping subduction zone.

We are not yet in a position to formulate a clear plate-tectonic reconstruction of the Tilemsi accretion zone. However, pending detailed mapping and geochemical studies, our field observations suggest a transition between an island arc in the west and a Cordilleran-type continental margin to the east, although a back-arc suture has not yet been discovered. The permanent contribution of mantle-derived rocks to this zone is exemplified by some syn- and late-tectonic high-level gabbro-peridotite bodies.

To conclude, the sharply contrasting sedimentological environments which developed in the late Upper Proterozoic, correspond to the formation of a passive continental margin on the edge of the West African craton and an active continental margin along the western margin of the Touareg shield. This has led us to question the hypothesis of a fixed Gondwanaland throughout the Proterozoic (Piper et al., 1973), which has strongly influenced geological thinking in Africa (Shackleton, 1976). The geological evidence from West Africa shows that continental fragmentation occurred around 800 Ma ago as was the case around the North American continent (Stewart, 1976). Critical reappraisal of the palaeomagnetic evidence supports the idea that important horizontal displacements occurred in the late Upper Proterozoic (Burke et al., 1976; Briden, 1977; Morel-à-l'Huissier and Irving, 1978; Black, 1978). There are very few palaeomagnetic data from West Africa and new measurements are urgently required in order to estimate the possible width of a Pharusian ocean situated to the east of the West African craton.

MULTISTAGE STRUCTURAL EVOLUTION OF THE PAN-AFRICAN TOUAREG SHIELD

Structural domains in the Touareg shield

In contrast to the West African craton, which has been stable throughout the Middle and Upper Proterozoic, parts of the Pan-African Touareg shield have had a complex history of deformation prior to collision with the West African craton around 600 Ma ago. A striking feature of the shield is the spectacular development of N—S shear zones which delimit the following structural domains (Fig. 16-1) from west to east:

The Pharusian belt

The Pharusian belt, as we have seen, is characterized by thick accumulations of late Upper Proterozoic volcano-detritic assemblages and associated calc-alkaline plutonism. We distinguish:

(a) The *Tilemsi strip*, lying immediately to the west of the Iforas which is believed to represent an accretion zone apparently largely devoid of ancient sialic basement. It has been affected by pronounced E—W shortening.

(b) The *western Pharusian branch*, floored by Eburnean granulites with a cover of Middle and Upper Proterozoic strata and their products of reworking during the Pan-African event. It has been affected by two major phases of Pan-African deformation, producing early WSW—ENE-trending structures and late N—S-trending folds.

(c) The *eastern Pharusian branch*, which is also floored by an ancient substratum. Lithological and metamorphic gradients are N—S and there is evidence for a pre-885 Ma tectonic event; the main orogenic imprint produced intense folding with a N—S trend.

The polycyclic central Hoggar—Aïr domain

The polycyclic central Hoggar—Aïr domain consists mainly of pre-Pan-African basement rocks (Archaean and Lower Proterozoic), injected by abundant Pan-African granitoids. The existence of a presumed "Kibaran" event (Bertrand, 1974; Latouche, 1978) and of narrow volcano-sedimentary belts of presumed Upper Proterozoic age is reminiscent of the pattern described in south- and northwestern Nigeria (Grant, 1978; Holt et al., 1978; Hubbard, 1978).

The eastern Hoggar—Ténéré domain

The eastern Hoggar—Ténéré domain, apparently stabilized around 725 Ma ago, includes along its western margin a late Pan-African ensialic linear belt developed along a shear zone (Tiririne belt, Bertrand et al., 1978). The eastern edge of the polycyclic central Hoggar—Aïr domain is affected by this late Pan-African event.

The "Kibaran" event (1200—900 Ma ago)

This event, recorded in Nigeria (Grant, 1972; Ogezi, 1977), is thought to have affected the Aleksod (Bertrand, 1974) and Gour Oumelalen (Latouche, 1978) regions of the Hoggar and may have had a wider extension in the central Hoggar—Aïr polycyclic domain (Fig. 16-1). Structural relationships with the early event in the eastern Pharusian branch are still unknown. In both the Aleksod and Gour Oumelalen areas a supracrustal sequence, forming large scale recumbent folds of Pennine-type overturned to the NW, has undergone Barrovian metamorphism in high-grade amphibolite facies with widespread migmatization. The supracrustal sequence is structurally unconformable on basement of Eburnean or Archaean age. The "Kibaran" ages, however, should be accepted with caution as both in Nigeria and in the Hoggar they have been obtained using Rb-Sr whole-rock and K-Ar methods (Picciotto et al., 1965; Grant, 1972; Bertrand and Lasserre, 1976) on metamorphic rocks only.

The event around 725 Ma ago

Poorly known tectonic events of this age are developed in the eastern Hoggar—Ténéré domain (Fig. 16-1). This region was metamorphosed under low greenschist to upper amphibolite facies conditions and has suffered strong E—W shortening, responsible for tight upright folds with N—S to NNW—SSE trend and associated b-lineations. Synkinematic sub-alkaline granitoids and a late granodiorite batholith have yielded a U-Pb Concordia age on zircon of 726 ± 22 Ma (U. Andreopoulos-Renaud, unpubl. data). A similar age was obtained on some granites west of the 8°30′E shear zone (Latouche and Vidal, 1974) but their extent and significance is still unknown. Note that the lithologies, metamorphism and structures differ completely on either side of the 8°30′E shear zone, indicating that this lineament may be the locus of a cryptic suture hidden to the north beneath the late Upper Proterozoic Tiririne Group. Thus, the eastern Hoggar—Ténéré domain which, in the absence of geochronological data, had previously been called the eastern craton (Bertrand et al., 1978), now appears to represent an early Pan-African mobile belt stabilized around 725 Ma ago. The Tiririne Group (or Proche—Ténéré Group in Niger) is the molasse related to this early Pan-African orogenic belt.

The event around 700—680 Ma ago

A major orogenic event, affecting both the early Upper Proterozoic "Série à stromatolites" and the volcano-clastic "Série verte", occurred in the western Pharusian branch. It is marked by NNW—SSE movements causing overthrusting of older crust and important crustal thickening.

In the northwestern Hoggar very high structural levels are exposed in the Tassendjanet nappe (Caby, 1970) (Figs. 16-2B and 16-4). This nappe of

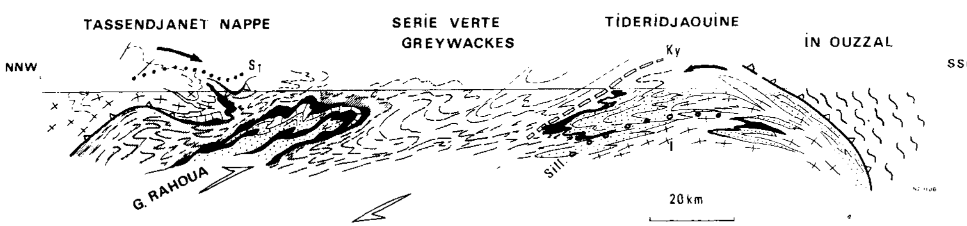


Fig. 16-4. The early Pan-African collision in the western Hoggar at c. 700 Ma. The Tassendjanet nappe is considered as part of a northern continent. S_1 is the upper limit of slaty cleavage. Ultrabasic rocks (in black) associated with quartzites may represent a lower thrust unit (Gour Rahoua). The Tideridjaouine quartzites (dotted) and gneisses (crosses) belong to a deeper structural level of isoclinal folds facing north. Both units moved synchronously and are interpreted as related to the closure of a sub-oceanic domain with a basified crust covered by many thousand metres of greywacke of the "Série verte".

Eburnean granites, with its overlying cover of the "Série à stromatolites" tectonically accumulated at its front, moved south-eastwards over more than 40 km as demonstrated by the presence of a tectonic window and frontal klippen. The underlying para-autochthone is composed of greywackes and plutonic rocks of the "Série verte". Deeper structural levels are gradually exposed to the south below the "Série verte" in the underlying Middle Proterozoic quartzites which are isoclinally folded in amphibolite facies conditions of Barrovian type. These folds, generated at depth, face northwards in contrast to the southward directed movement of the Tassendjanet nappe.

Contemporaneously, an elongated N—S unit of Eburnean granulites was thrust to the north-northwest farther south in the Iforas (Boullier et al., 1978; Boullier, 1979; Wright, in press). The unit has been later affected by lateral mylonite zones which sharply cut Eburnean and early Pan-African structures. The lithologically similar but little deformed In Ouzzal granulite unit of the northwestern Hoggar is also laterally cut by important vertical faults and contrasts tectonically with all levels of the adjacent, highly deformed Pan-African edifice. To the south, the In Ouzzal unit is progressively incorporated in the tangential structures of the Iforas granulite nappe.

Following Boullier et al. (1978), the Iforas granulite unit is underlain by a complex gneissic unit of high-grade amphibolite facies of Barrovian type with widespread migmatites underlying the granulite nappe in the Iforas. Its main structural characteristics are a well-defined flat-lying foliation or banding, often refolded, and a ubiquitous NNW—SSE-trending lineation parallel to the motion direction of the nappe (Boullier, 1979). All the contacts between the heterogeneous components of the assemblage are either tectonic or intrusive, but lateral transition to a less-deformed assemblage shows that it consists essentially of retrogressed Eburnean granulites, a cover of Upper Proterozoic age and pre-tectonic magmatic rocks.

As we have seen this major event involving refolding of huge crystalline nappes during high-grade, Barrovian metamorphic conditions exhibits opposite transport directions in the northwestern Hoggar and in the Iforas. We tentatively link this crustal shortening event to plate motion along NNW—SSE direction and to the closure of an E—W-tending sub-oceanic domain along the northern edge of the In Ouzzal granulite block and possible non-identified oceanic crust hidden beneath greywacke and trough deposits (Fig. 16-2B).

The precise dating of this early Pan-African collision around 700—680 Ma has still to be confirmed as it is based on only two results: a U-Pb determination on zircon from a syntectonic granite in the Iforas which gave a Concordia age of 693 ± 1 Ma (Ducrot et al., 1979) and a Rb-Sr date of 685 ± 15 Ma (Clauer, 1976) obtained on clay minerals from the "Série à stromatolites", incorporated in the Tassendjanet nappe.

The fact that the events around 1200—900 Ma, 725 Ma and 700—680 Ma are each confined to a particular structural domain implies that important lateral displacements occurred along the major shear zones delimiting the domains and suggests that the Touareg shield consists of an amalgam of microplates (Black, 1978).

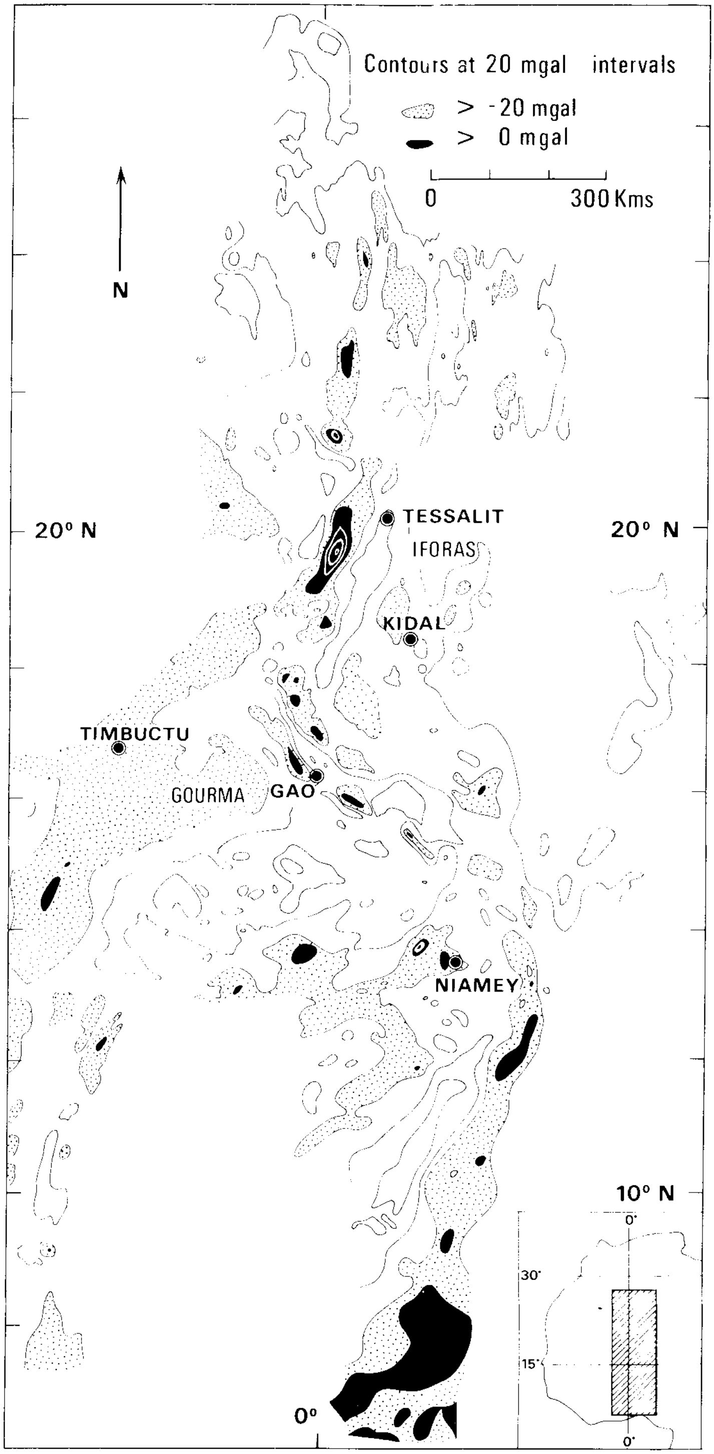
PAN-AFRICAN COLLISION OF THE WEST AFRICAN CRATON WITH THE TOUAREG SHIELD AROUND 600 Ma AGO

This major event affects the entire Touareg shield and overprints the earlier tectonic patterns. East—west shortening varies in intensity and is probably diachronous across and along the Pharusian belt.

The suture

The presence of a suture zone was first suggested in southern Morocco by Leblanc (1970), who interpreted the Bou Azzer basic and ultrabasic complex as obducted Upper Proterozoic ophiolites, now squeezed in a major vertical lineament (*see also Leblanc, this volume, Chapter 17, ed.*). The lineament was considered to extend, without interruption, from Morocco to the western Hoggar and to represent the eastern limit of the West African craton (Caby, 1970) where it is outlined by elongated positive gravity anomalies (Crenn, 1957; Louis, 1970). In Mali these anomalies have been shown to correspond to basic and ultrabasic rocks, but overthrust sheets were also emplaced west of the lineament upon the edge of the West African craton (Caby, 1978, 1979; Wright, in press). The most striking feature, however, is the abrupt juxtaposition, along the lineament, of terrigenous sediments deposited on a passive continental margin to the west, with volcano-clastic plutonic assemblages formed by accretion processes in a typical active continental margin to the east. This led us to consider the lineament as a suture zone (Black et al., 1979a, b). Reactivation of this lineament occurred during the Hercynian event (Ougarta belt) and during the Mesozoic—Tertiary (Gao trough).

Detailed gravimetric surveys (Fig. 16-5) have shown the existence of a string of positive gravity anomalies with amplitudes of over 30 mgal, locally reaching 80 mgal, which may be followed over a distance of 2000 km. The anomalies are of two types: (a) in Togo-Benin positive and negative anomalies of long wave-length which, taking into account the lighter sediments of the passive continental margin (Buem—Atakorian), can be interpreted in terms of thickening of the West African craton towards the suture and a steep contact with an even thicker, dense Pan-African block (Louis, 1978); (b) positive anomalies of shorter wave-length correspond to more superficial structures which display subvertical to easterly dipping geometries in accord with the general vergence and thrusting motion towards the craton.


Contours at 20 mgal intervals
> -20 mgal
> 0 mgal
0
300 Kms
N
20° N
20° N
TESSALIT
IFORAS
KIDAL
TIMBUCTU
GOURMA
GAO
NIAMEY
10° N
0°
0°
30°
15°
0°

These correspond to the position of basic and ultrabasic complexes, and the interpretation of gravity profiles shows these bodies to be rootless and to continue to depths of 6 to 20 km (Bayer and Lesquer, 1978; Ly, 1979).

The location of the two types of anomalies seems to be related to the geometry of the craton which we believe reflects the original shape of the continent before collision. The first type of paired gravity anomalies in Togo-Benin occurs where the craton forms a promontory. This situation led to the complete disappearance, by subduction, of the oceanic floor, thus locally bringing into direct contact by flat underthrusting the low-grade metasediments along the passive continental margin of the craton and the high-grade gneisses of the eastern continent. In contrast, the second type of anomalies is located in an embayment where island-arc and Cordilleran volcano-clastic assemblages of the active margin of the eastern continent have been preserved (Black et al., 1980).

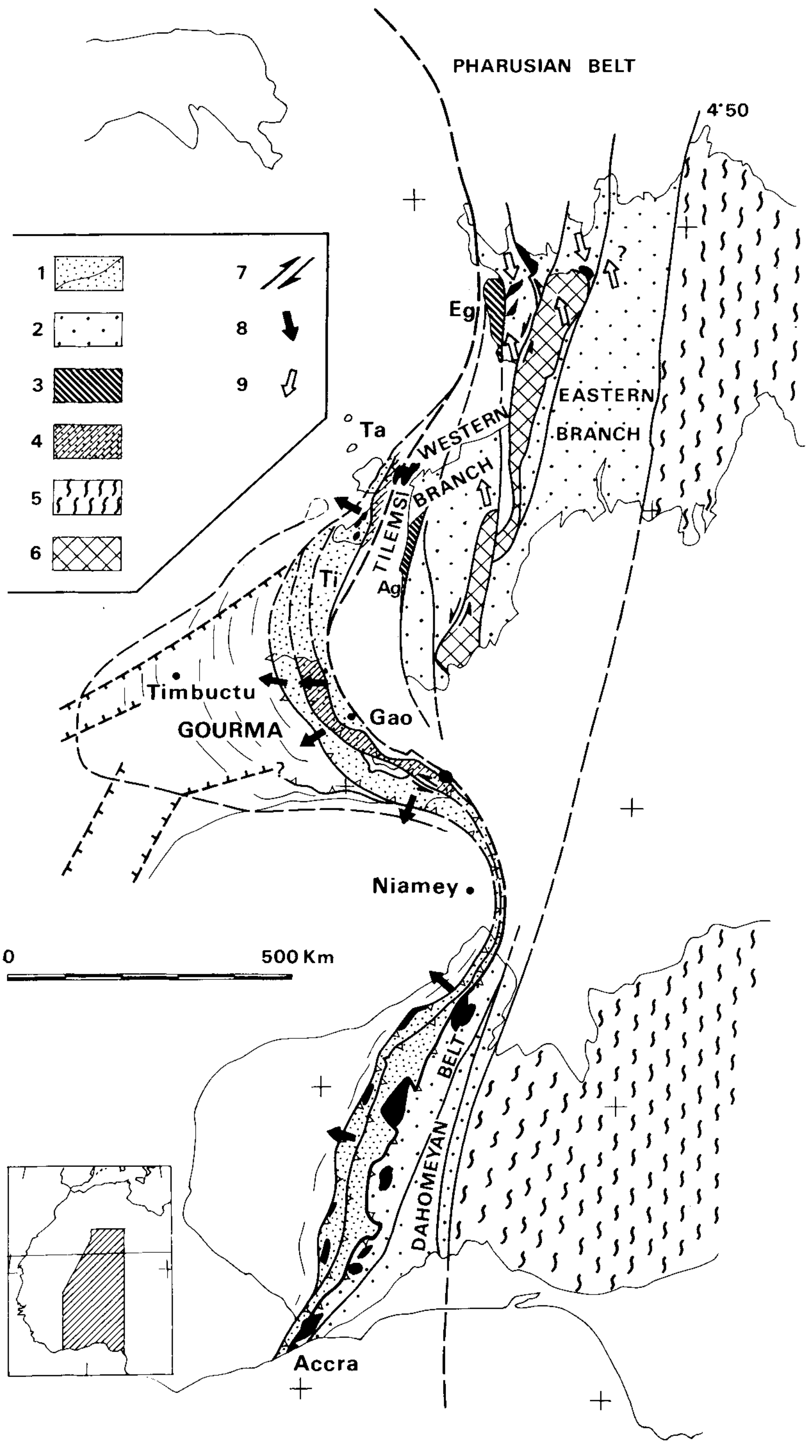
Foreland nappes west of the suture

Nappes have been translated westwards onto the West African craton. In the Taounnant region (Figs. 16-1, 6 and 7A) mylonitized quartzites belonging to the passive margin are overlain by a nappe of blue amphibole-bearing metabasalts, associated with lenses of serpentine which may represent oceanic material. These rocks rest directly upon Eburnean rocks of the craton. Farther south in Timétrine the quartzites, phyllites, serpentines and metabasalts are also probably allochthonous.

In the Gourma aulacogen the sediments have been strongly deformed, implying shortening of several tens of kilometres (Fig. 16-7B). In the east, towards the mouth of the aulacogen, one observes a pile of pellicular nappes which have been transported westwards and south-westwards over about 80 km (Caby, 1978, 1979). The schists forming the external nappes belong to the passive margin and have been metamorphosed in the greenschist facies. In contrast, the quartzites and schists of the internal nappes have undergone high-pressure metamorphism with development of eclogitic mineral assemblages. Farther south the front of the Dahomeyan belt also shows a succession of units thrust westwards which have been described by African (1975), Simpara (1978) and Trompette (1980).

The striking feature of this external zone of the Pan-African belt west of the suture and on the passive margin of the West African craton is the complete absence of autochthonous Pan-African magmatism.

Fig. 16-5. Simplified Bouguer anomaly map of the eastern margin of the West African craton.


PHARUSIAN BELT
4°50
1
2
3
4
5
6
7
8
9
Eg
Ta
WESTERN
BRANCH
TILEMSI
EASTERN
BRANCH
Ti
Ag
Timbuctu
GOURMA
Gao
Niamey
0
500 Km
DAHOMEYAN
BELT
Accra

Paired metamorphic belts

The Tilemsi zone of accretion immediately east of the suture has been interpreted as representing the relic of an island arc and a marginal cordillera. It is flanked by zones of contrasting metamorphic type (Fig. 16-6). To the west allochthonous rock units resting on the West African craton close to the suture display high-pressure—low-temperature metamorphism, whereas to the east, along the border of the western Pharusian branch, zones of low-pressure—high-temperature metamorphism are developed. The former are characterized in the northeastern Gourma by eclogitic micaschists which contain jadeitic pyroxene. Probe-data indicate formation under pressure of the order of 15 kb and a temperature of about 650° C (Reichelt, 1972; De la Boisse, 1979). The blue amphibole-bearing metabasalts of Timétrine and Taounnant may also belong to this metamorphic unit. The latter zone of low-pressure—high-temperature metamorphism, represented by the Aguelhok gneisses (Iforas) and the Egatalis gneisses (northwestern Hoggar), displays fresh mineral assemblages of cordierite-garnet-sillimanite-spinel, and these gneisses are sometimes associated with hypersthene-bearing rocks. They represent zones situated along the western edge of the Touareg shield which were subjected to a high-thermal regime and to strong uplift following collision, as confirmed by young biotite cooling ages.

Deformation in the Pharusian belt east of the suture

In the Tilemsi accretion zone polyphase deformation in amphibolite facies grade close to the suture passes eastwards into N—S trending open to tight folds of high structural level.

In the western Pharusian branch E—W shortening is negligible in the Tassendjanet nappe but gradually increases southwards (Caby, 1970). N—S-trending structures with recumbent to isoclinal folds and later open folds with similar trend represent the main structures, both in the "Série verte" and the high-grade rocks of Egatalis. The structural evolution of the northwestern Hoggar is bracketed within the time range 625—570 Ma (Allègre and Caby, 1972); the first figure corresponds to syn-kinematic granite emplacement and the second figure to late granitoids, believed to be roughly synchronous with the peak of metamorphism at Egatalis. Late stages

Fig. 16-6. Simplified sketch-map of the Pharusian—Dahomeyan belt after collision between the West African craton and the Touareg shield. *1* = Gourma and Buem—Atacora nappes; *2* = undifferentiated rocks mainly of Pan-African metamorphism (*Eg* = Egatalis and *Ag* = Aguelhoc); *4* = high-pressure—low-temperature metamorphism of the Gourma nappes; *5* = undifferentiated reactivated pre-Pan-African rocks in the central Hoggar and Nigeria; *6* = Eburnean granulites; in black: metabasic to ultrabasic rocks; *7* = strike-slip fault; *8* = late movements related to the collision with the West African craton; *9* = early collision in the Northern Iforas and western Hoggar; *Ta* = Taounnant; *Ti* = Timétrine.

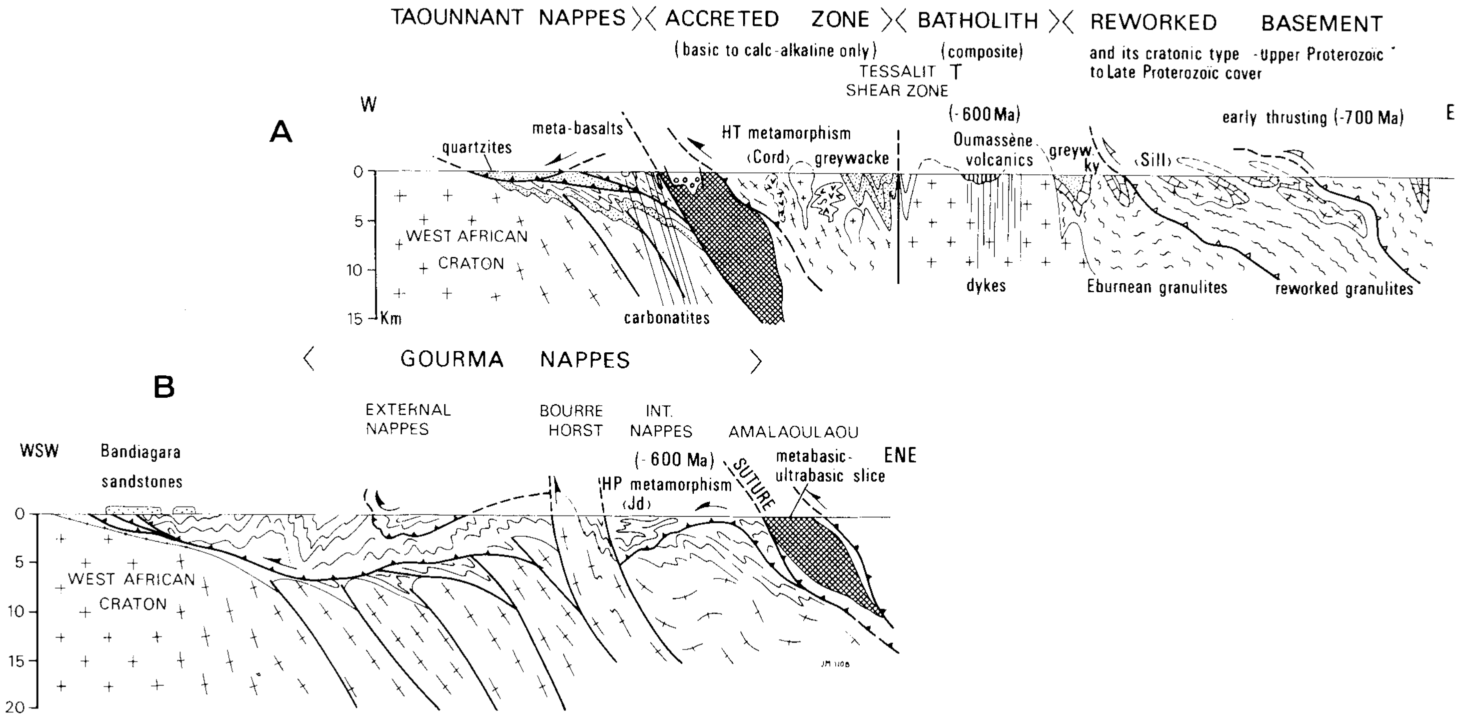


Fig. 16-7. Schematic geological cross-sections A. northern Adrar des Iforas; B. the Gourma nappes. The location of the sections is indicated in Fig. 16-1.

of this deformation are related to the main N—S-trending sinistral shear zones and branching strike-slip faults (Caby, 1970), some of which are outlined by ultrabasic to basic and peralkaline rocks. Farther south, in the central Iforas, E—W shortening is less pronounced but important shearing took place at that time. N—S-trending sinistral movement along shear zones and gneissic doming are followed by the emplacement of a composite late- to post-tectonic calc-alkaline batholith with spectacular intrabatholitic dyke swarms between 615 and 590 Ma ago (Ducrot et al., 1979). The zone was subjected to continuous uplift, leading to unroofing and outpouring of flat-lying Nigritian rhyolites, followed by the intrusion of alkaline ring-complexes. ^{39}Ar-^{40}Ar whole-rock and U-Pb Concordia data on a sheared granite yielded 560 and 540 Ma, respectively, and suggest late movement along the edge of the granulite nappe (Lancelot et al., in press).

In the eastern Pharusian branch N—S-trending open folds of very high structural level in the north gradually pass southwards into tight folds with associated greenschist facies metamorphism, grading to amphibolite facies and migmatization around synkinematic granites (Lelubre, 1952; Gravelle, 1969). U-Pb zircon dating of such granites (Picciotto et al., 1965) has given recalculated ages between 647—620 Ma. Later folds and thrusting locally occurred after the deposition of molasse-type sediments. Late- to post-tectonic granites yield ages in the range 600—550 Ma (Boissonnas, 1973).

The molasse of the Pharusian belt is represented by the "Série pourprée" which partly has a Lower Cambrian age (Caby, 1970; Clauer, 1976).

Reactivation of the polycyclic central Hoggar—Aïr domain and the Tiririne linear intracontinental belt

The 4°50′E shear zone, which is a transcontinental lineament that can be traced to Benin, marks the eastern limit of the Pharusian belt. The amount of lateral movement along this major strike slip fault is unknown. Neither lithological nor structural correlations between the Pharusian belt and the adjoining central polycyclic Hoggar—Aïr domain are possible, except for the latest events related to collision with the West African craton. The Pan-African in this domain is characterized by a greenschist metamorphic overprint, intense deformation localized along N—S schist belts, large-scale granite emplacement and lateral movement along shear zones.

The linear Tiririne intracontinental belt (Bertrand et al., 1978) is situated along the eastern margin of the polycyclic Hoggar—Aïr domain and provides a model for the reactivation process (Fig. 16-1). Here two different basement units (polycyclic central Hoggar—Aïr and eastern Hoggar—Ténéré domain) face each other along the 8°30′E shear zone which corresponds to a dextral transcurrent fault. The orogenic event at 725 Ma, which affected the eastern Hoggar—Ténéré domain (see page 419), was followed by deposition of the flat-lying molasse-type Tiririne Group, containing sills of diorite, diabase and gabbro intruded around 660 Ma ago. A trough filled by more than 8000 m of sediments developed in proximity to the shear zone and subsequently evolved into a linear fold belt with greenschist metamorphism locally reaching amphibolite facies grade with anatexis. A late-tectonic granite yielded a U-Pb Concordia age on zircon of 604 ± 13 Ma and dates this event (Bertrand et al., 1978). Reactivation of the polycyclic central Hoggar—Aïr basement to the west (Issalane) is indicated by: (1) a westerly dipping cataclastic to mylonitic new foliation in an area up to 10 km wide, displaying a strong stretching lineation at high angle to the 8°30′E shear zone; (2) a zone of recumbent folds, and (3) emplacement of a 585 ± 14 Ma old high-level batholith (Bertrand et al., 1978). The model proposed for this ensialic linear belt involves westward underthrusting of the eastern Hoggar—Ténéré domain with its overlying Tiririne formation, producing local crustal thickening, anatexis and generation of granites at depth and subsequent strike-slip movement along the shear zone.

The narrow N—S-trending belts of low-grade metasediments of assumed Upper Proterozoic age associated with predominantly acid volcanics and occurring within the central Hoggar—Aïr domain (Fig. 16-1) could represent diachronous equivalents of the Tiririne belt and, by analogy, they may also be associated with early underthrusting, causing crustal thickening as well as lateral shear. In this connection re-examination of some of the major, now vertical, shear zones indicates that they have had a complex history and bear the imprint of an early deformation when they behaved as thrusts (A.M. Boullier, pers. commun., 1979). McCurry and Wright (1977) regard such belts of transcurrent faulting in Nigeria as part of a fossil collision zone between two continental blocks. Abundant Pan-African granitoids about 650—600 Ma have invaded large areas of the central polycyclic Hoggar—Aïr domain and have played an important role in reactivation, locally producing low-pressure—high-temperature metamorphism superimposed on earlier mineral assemblages (Bertrand, 1974; Vitel, 1979). Although it is difficult to relate these granitoids to subduction processes there is an overall zonality in the Touareg shield: diorites and granodiorites which may be related to a subduction zone predominate in the Pharusian belt, whereas adamellite and K-rich varieties abound in the polycyclic central Hoggar—Aïr domain. Although isotopic studies are still in their infancy, preliminary results indicate low initial Sr ratios for diorites in the Pharusian domain (Davison, 1980), whereas values ranging between 0.707 and 0.72 have been obtained in the central polycyclic domain (Bertrand, 1974; Vialette and Vitel, 1979) and in Nigeria (Van Breemen et al., 1977), suggesting that crustal fusion related to crustal thickening may have played an important role.

Attention has already been drawn to the striking similarities between the shear pattern of the Touareg shield, characterized by branching and sub-parallel shear zones (Bertrand and Caby, 1978; Ball, 1980), and the Cenozoic fault pattern of northeastern Asia, produced by the collision of

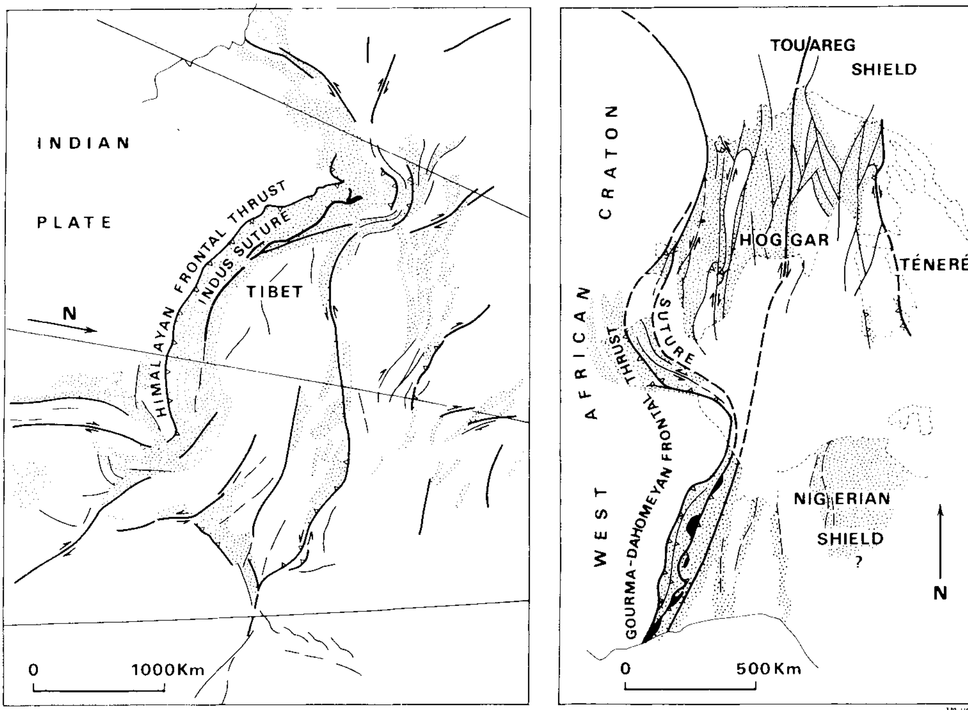


Fig. 16-8. Comparison between Cenozoic to Recent fault-thrust pattern of NE Asia (after Molnar and Tapponnier, 1975) and Pan-African tectonics in northwestern Africa. Dotted areas represent Tertiary and late Pan-African deformation, respectively.

India with Asia (Molnar and Tapponnier, 1975; Fig. 16-8). We suggest that the Pan-African reactivation of the central polycyclic Hoggar is related to collision with the West African craton, and the present surface may represent the deep structural level of the same processes which are now at work in northeast Asia.

CONCLUSION

Evidence from many earth science disciplines suggests the existence of a Wilson cycle ending around 600 Ma ago with collision and suturing between the passive continental margin of the West African craton and the active margin of the Touareg shield to the east.

The geochronological data, although still fragmentary, show the time range (900—550 Ma) for Pan-African events in the central Sahara to be comparable to that of the Arabian—Nubian Shield (Greenwood et al., 1976; Kröner, 1979). However, one must distinguish tectonically quiet periods of island-arc and Cordilleran development and periods of intense deformation related to continental collision within the above time range. The large amount of predominantly calc-alkaline magmatic rocks generated in this time interval corresponds to a major period of crustal accretion which led to the cratonization of Africa.

The long pre-collisional Cordilleran-type evolution in the western part of the shield and the multistage collisional history, involving stabilization of the eastern Hoggar-Ténéré domain at around 725 Ma, N—S collision in the western Pharusian branch at around 700 Ma ago and, finally, E—W collision against the West African craton at around 600 Ma, suggest that the Touareg shield is composed of an amalgam of plates. Thus the collision of a cold rigid craton in the west against an amalgam of relatively hot and more ductile micro-plates in the east produced extensive reactivation over a width of several thousand kilometres in northeastern Africa.

The most pertinent argument in favour of Pan-African active subduction processes operating in this part of Africa, besides the presence of rock assemblages characteristic of island-arc and continental Cordilleran environments and the results of geochemical investigations on associated andesites, is the existence of distinctly paired metamorphic belts. The high-pressure—low-temperature eclogitic rocks thrust onto the passive continental margin display mineral assemblages which strongly indicate that they have formed in a subduction zone and were subsequently thrusted.

It has been pointed out that the reactivation of the entire Touareg shield as a consequence of collision with the West African craton is marked by greenschist metamorphic overprinting of older gneissic terrains, intraplate deformation in linear belts with pronounced E—W shortening accompanied by crustal thickening, and generation of granite. If the analogy which we draw with the tectonic model proposed for the Himalayan—Tibetan region (Molnar and Tapponnier, 1975) is correct, the amount of lateral displacement along shear zones in the central Touareg shield may well exceed the dimensions of the shield.

The basification process through intrusion of ultrabasic and basic bodies of tholeiitic affinities, followed by calc-alkaline magmatism, is thought to have played an important role in the history of the central Sahara.

Our conviction is that detailed studies of the Pan-African edifice, beautifully exposed at a deep structural level in the Sahara region, will throw new light on the processes that were at work in ancient active continental margins, on the nature and degree of intracontinental deformation and, more generally, on the geochemical evolution of the crust in late Precambrian times.

ACKNOWLEDGEMENTS

We are much indebted to all members of the Centre Géologique et Géophysique as well as colleagues from Leeds University, the Direction de la Géologie et des Mines of Mali, Algiers University, SONAREM and SONATRACH. We benefited from financial support of the Centre National de la Recherche Scientifique, Bureau de Recherches Géologiques et Minières, Institut National d'Astronomie et de Géophysique and Office de la Recherche Scientifique et Technique Outre-Mer, and the aid of the authorities of Algeria and Mali who provided many facilities. The constructive criticisms of A. Kröner, I. G. Gass, H. Martin and J. Fabre are gratefully acknowledged. We thank Mme Arléry for typing the manuscript and Mmes Jonquet and Montesinos for drawing the figures. The paper is a contribution to IGGP Project No. 164.

REFERENCES

Affaton, P., 1975. Etude géologique et structurale du Nord-Ouest Dahomey, du Nord' Togo et Sud-Est de la Haute-Volta. Trav. Lab. Sci. Terre, St. Jérôme, Marseille, B,10, 201 pp.

Allègre, C. J. and Caby, R., 1972. Chronologie absolue du Précambrien de l'Ahaggar occidental. C.R.Acad. Sci. Sér. D, 275: 2095—2098.

Ball, E., 1980. An example of very consistent brittle deformation over a wide intracontinental area: the late Pan-African fracture system of the Touareg and Nigerian shield. Tectonophysics, 61: 363—379.

Bayer, R. and Lesquer, A., 1978. Les anomalies gravimétriques de la bordure orientale du craton ouest-africain: géométrie d'une suture pan-africaine. Bull. Soc. Géol. Fr., XX: 863—876.

Bertrand, J. M. L., 1974. Evolution polycyclique des gneiss précambriens de l'Aleksod (Hoggar central, Sahara algérien). Aspects structuraux, pétrologiques, géochimiques et géochronologiques. Thèse d'Etat, Univ. Montpellier. Ed. CNRS (CRZA), Sér. Géol., 19, 350 pp.

Bertrand, J. M. L. and Caby, R., 1978. Geodynamic evolution of the Pan-African orogenic belt: a new interpretation of the Hoggar shield (Algerian Sahara). Geol. Rundsch., 67 (2): 357—388.

Bertrand. J. M. L. and Lasserre, M., 1976. Pan-African and pre-Pan-African history of the Hoggar (Algerian Sahara) in the light of new geochronological data from the Aleksod area. Precambrian Res., 3: 343—362.

Bertrand, J. M. L., Boissonnas, J., Caby, R., Gravelle, M. and Lelubre, M., 1966. Existence d'une discordance dans l'Antécambrien du "Fossé pharusien" de l'Ahaggar occidental (Sahara central). C.R.Acad. Sci. Sér. D, 262: 2197—2200.

Bertrand, J. M. L., Caby, R., Lancelot, J. R., Moussine-Pouchkine, A. and Saadallah, A., 1978. The late Pan-African intracontinental linear fold belt of the eastern Hoggar (central Sahara, Algeria): geology, structural development, U-Pb geochronology, tectonic implications for the Hoggar shield. Precambrian Res., 7: 349—376.

Bertrand-Sarfati, J., 1969. Etude comparative des édifices stromatolitiques de plusieurs horizones calcaires du Précambrien supérieur de l'Ahaggar occidental (Tanezrouft et Ahnet). Bull. Soc. Hist. Nat. Afr. Nord, 60: 21—37.

Bertrand-Sarfati, J., 1972. Stromatolites columnaires du Précambrien supérieur, Sahara nord-occidental. Ed. CNRS (CRZA), Sér. Géol. 14, 242 pp.

Bessoles, B., 1977. Géologie de l'Afrique. Le craton ouest-africain. Mém. Bur. Rech. Géol. Min. Fr., 88, 402 pp.

Black, R., 1978. Propos sur le Pan-Africain. Bull. Soc. Géol. Fr., XX: 843—850.

Black, R., Ba, H., Ball, E., Bertrand, J. M. L., Boullier, A. M., Caby, R., Davison, I., Fabre, J., Leblanc, M. and Wright, L. I., 1979a. Outline of the Pan-African geology of Adrar des Iforas (Republic of Mali). Geol. Rundsch., 68 (2): 543—564.

Black, R., Caby, R., Moussine-Pouchkine, A., Bayer, R., Bertrand, J. M. L., Boullier, A. M., Fabre, J. and Lesquer, A., 1979b. Evidence for late Precambrian plate tectonics in West Africa. Nature, 278: 223—227.

Black, R., Bayer, R. and Lesquer, A., 1980. Reply to comment by Thomas et al. Evidence for late Precambrian plate tectonics in West Africa. Nature, 284: 192.

Boissonnas, J., 1973. Les granites à structures concentriques et quelques autres granites tardifs de la chaîne pan-africaine en Ahaggar (Sahara central, Algérie). B.R.G.M. and Mém. C.N.R.S. (CRZA) Sér. Géol., 16: 662 pp.

Boullier, A. M., 1979. Charriages et deformations de l'unité granulitique des Iforas au cours de l'orogenèse pan-africaine. Rev. Géogr. Phys. Géol. Dyn., 21: 377—382.

Boullier, A. M., Davison, I., Bertrand, J. M. L. and Coward, M., 1978. L'unité granulitique des Iforas: une nappe de socle d'âge pan-africain précoce. Bull. Soc. Géol. Fr., XX: 877—882.

Briden, J. C., 1977. Palaeomagmatism and Proterozoic tectonics. Tectonophysics, 38: 167—168.

Burke, K. and Dewey, J. F., 1970. Orogeny in Africa. In: T. F. J. Dessauvagie and A. J. Whiteman (Editors), African Geology. Ibadan Univ. Press, Ibadan, pp. 583—608, 1972.

Burke, K., Dewey, J. F. and Kidd, W. S. F., 1976. Precambrian palaeomagnetic results compatible with contemporary operations of the Wilson cycle. Tectonophysics, 33: 287—299.

Caby, R., 1970. La Chaîne pharusienne dans le Nord-Ouest de l'Ahaggar (Sahara central, Algérie); sa place dans l'orogenèse du Précambrian supérieur en Afrique. Thèse d'Etat, Univ. Montpellier, 335 pp.

Caby, R., 1978. Paléogéodynamique d'une marge passive et d'une marge active au Précambrien supérieur: leur collision dans la chaîne pan-africaine du Mali. Bull. Soc. Géol. Fr., XX: 857—861.

Caby, R., 1979. Les nappes précambriennes du Gourma dans la chaîne pan-africaine du Mali: comparison avec les Alpes occidentales. Rev. Géogr. Phys. Géol. Dyn., 21: 365—376.

Caby, R., Dostal, J. and Dupuy, C., 1977. Upper Proterozoic volcanic greywackes from western Hoggar (Algeria). Geology and geochemistry. Precambrian Res., 5: 283—297.

Chikhaoui, M., Dupuy, C. and Dostal, J., 1978. Geochemistry of late Proterozoic volcanic rocks from Tassendjanet area (NW Hoggar, Algeria). Contrib. Mineral. Petrol., 66: 157—164.

Chikhaoui, M., Dupuy, C. and Dostal, J., 1980. Geochemistry and petrogenesis of late Proterozoic volcanic rocks from northwestern Africa. Contrib. Mineral. Petrol., 73: 375—388.

Clauer, N., 1976. Géochimie isotopique du strontium des milieux sédimentaires. Application à la géochronologie de la couverture du craton ouest-africain. Sci. Géol., Univ. Strasbourg, 45, 256 pp.

Crenn, Y., 1957. Mesures gravimétriques et magnétiques en African, occidentale. ORSTOM, Paris, 39 pp.

Davison, I., 1980. Structural geology and Rb/Sr geochronology of Precambrian rocks from Eastern Iforas (Mali). Ph.D. Thesis, Univ. Leeds (unpubl.).

De La Boisse, H., 1979. Pétrologie et géochronologie de roches cristallophyliennes du Bassin du Gorma. Thèse 3e cycle, Univ. Montpellier, 54 pp. (unpubl.).

Dewey, J. F., 1977. Suture zone complexities: a review. In: M. W. McElhinny (Editor), The Past Distribution of Continents. Tectonophysics, 40: 53—67.

Dostal, J., Caby, R. and Dupuy, C., 1979. Alkaline gneisses from western Hoggar (Algeria). Geology and Geochemistry. Precambrian Res., 10: 1—20.

Ducrot, J., De la Boisse, H., Renaud-Andreopoulos, U. and Lancelot, J. R., 1979. Synthèse géochronologique sur la succession des événements magmatiques pan-africains au Maroc, dans l'Adrar des Iforas et dans l'Est Hoggar. 10th Coll. Afr. Geol. Abstr.: 40—41.
Fabre, J. and Freulon, J. M., 1962. Le Pharusien à stromatolites du Nord-Ouest de l'Ahaggar. C.R.Acad. Sci. Ser. D, 254: 4487—4490.
Fabriès, J. and Gravelle, M., 1977. Modalités du magmatisme au Protérozoïque supérieur dans la région de Silet (Hoggar central, Algérie). Bull. Soc. Géol. Fr., XIX: 995—1004.
Ferrara, G. and Gravelle, M., 1966. Radiometric ages from Western Ahaggar (Sahara) suggesting an eastern limit for the West-African craton. Earth Planet. Sci. Lett., 1: 319—324.
Grant, N. K., 1971. South Atlantic, Benue trough and Gulf of Guinea triple junction. Geol. Soc. Am. Bull., 82: 2295—2298.
Grant. N. K., 1972. Kibaran Metamorphic belt in Pan-African domain of West Africa. Nature Phys. Sci., 238: 90—91.
Grant, N. K., 1978. Structural distinction between a metasedimentary cover and an underlying basement in the 600 m.y. old Pan-African domain of northwestern Nigeria, West Africa. Geol. Soc. Am. Bull., 89: 50—58.
Gravelle, M., 1969. Recherches sur la géologie du socle précambrien de l'Ahaggar centro-occidental dans la région de Silet-Tibehaouine. Thèse d'Etat, Univ. Paris, 781 pp.
Greenwood, W. R., Hadley, D. G., Anderson, R. E., Fleck, R. J. and Schmidt, D. L., 1976. Late Proterozoic cratonisation in south-western Saudi Arabia. Philos. Trans. R.Soc. London, Ser. A, 280: 517—527.
Holt, R., Egbuniwe, I. G., Fitches, W. R. and Wright, J. D., 1978. The relationships between low grade metasedimentary belts, calc-alkaline volcanism and the Pan-African orogeny in NW Nigeria. Geol. Rundsch., 67: 631—646.
Hubbard, F. A., 1978. Precambrian crustal development in western Nigeria: indications from Iwo region. Geol. Soc. Am. Bull., 86: 548—554.
Karpoff, R., 1960. La géologie de l'Adrar des Iforas. Thèse, Paris, 1958. Publ. Bur. Rech. Géol. Min., Dakar, 30, 273 pp.
Kröner, A., 1979. Pan-African plate tectonics and its repercussions on the crust of north-east Africa. Geol. Rundsch., 68: 565—583.
Lancelot, J. R., Vitrac, A. and Allègre, C. J., 1973. Datation U.Th.Pb des zircons, grain par grain, par dilution isotopique. Conséquences géologiques. C.R.Acad. Sci. Ser. D, 277: 2117—2120.
Lancelot, J. R., Boullier, A. M., Maluski, H. and Ducrot, J., in press. Deformation and related radiochronology in the late Pan-African mylonite bearing shear zone, Adrar des Iforas (Mali). Contrib. Mineral. Petrol.
Latouche, L., 1978. Le Précambrien de la région des Gour Oumelalen. Thèse Doct. Etat. Univ. Paris VII, 255 pp. (unpubl.).
Latouche, L. and Vidal, Ph., 1974. Géochronologie du Précambrien de la région des Gour Oumelalen (NE de l'Ahaggar, Algérie). Un exemple de mobilisation du strontium radiogénique. Bull. Soc. Géol. Fr., 14: 195—203.
Leblanc, M., 1970. Un complexe ophiolitique dans le Précambrien II de l'Anti-Atlas central (Maroc): description, interprétation et position stratigraphique. In: Coll. intern. sur les Corrélations du Précambrien (Anti-Atlas occidental et central). Notes Mém. Serv. Géol. Maroc, 236: 119—144.
Leblanc, M., 1976. Proterozoic oceanic crust at Bou Azzer. Nature, 261: 34—35.
Leblanc, M., 1981. The late Proterozoic ophiolites of Bou Azzer (Morocco): evidence for Pan-African plate tectonics. In: A. Kröner (Editor), *Precambrian Plate Tectonics*. Elsevier, Amsterdam, pp. 435—451 (this volume).

Lelubre, M., 1952. Recherches sur la géologie de l'haggar central et occidental (Sahara central). Bull. Surv. Carte Géol. Algérie, 2e sér., 22, Vol. 1: 343 pp., Vol. 2: 369 pp.

Louis, P., 1970. Contribution géophysique à la connaissance géologique du bassin du lac Tchad. Mém. ORSTOM, 42, 311 pp.

Louis, P., 1978. Gravimétrie et géologie en Afrique occidentale et centrale. Mém. Bur. Rech. Géol. Min. Fr., 91: 53—61.

Ly, S., 1979. Etude gravimétrique de l'Adrar des Iforas (Nord-Est Mali). Thèse 3e cycle, Univ. Montpellier, 107 pp. (unpubl.).

McCurry, P. and Wright, J. B., 1977. Geochemistry of calc-alkaline volcanics in northwestern Nigeria and a possible Pan-African suture zone. Earth Planet. Sci. Lett., 37: 90—96.

Molnar, P. and Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. Science, 189: 419—426.

Morel-à-l'Huissier, P. and Irving, E., 1978. Tentative paleocontinental maps for the early Phanerozoic and Proterozoic. J. Geol., 86: 535—561.

Moussine-Pouchkine, A. and Bertrand-Sarfati, J., 1978. Le Gourma: un aulacogène du Précambrien supérieur? Bull. Soc. Géol. Fr., 20: 851—857.

Ogezi, A. E. O., 1977. Geochemistry and geochronology of basement rocks from north western Nigeria. Ph.D. Thesis, Univ. Leeds (unpubl.).

Picciotto, E., Ledent, D. and Lay, C., 1965. Etude géochronologique de quelques roches du socle cristallophyllien du Hoggar. Actes du 15e Coll. intern. C.N.R.S., Géochronologie absolue, Nancy, pp. 277—289.

Piper, J. D. A., Briden, J. C. and Lomax, K., 1973. Precambrian Africa and South America as a single continent. Nature, 245: 244—248.

Reichelt, R., 1972. Géologie du Gourma (Afrique occidentale). Un "seuil" et un bassin du Précambrien supérieur. Stratigraphie, tectonique, métamorphisme. Mém. Bur. Rech. Géol. Min. Fr., 53: 213 pp.

Shackleton, R. M., 1976. Pan-African structures. Philos. Trans. R.Soc. London, Ser. A, 260: 491—497.

Simpara, N., 1978. Etude géologique et structurale des unités externes de la chaîne Pan-Africaine (600 Ma) des Dahomeyides dans la région de Bassar (Togo). Thése 3e cycle, Univ. Aix-Marseille III, 164 pp. (unpubl.).

Stewart, J. H., 1976. Late Precambrian evolution of North America: plate tectonic implications. Geology, 11—15.

Trompette, R., 1972. Le Précambrien supérieur et le Paléozoïque inférieur de l'Adrar de Mauritanie: un exemple de sédimentation de craton. Etude stratigraphique et sédimentologique. Trav. Lab. Sci. Terre St-Jérôme, Marseille, B7, 634 pp.

Trompette, R., 1980. La Chaîne pan-africaine des Dahomeyides et le bassin des Volta (Bordure SE du craton ouest-africaine). In: B. Bessoles and R. Trompette (Editors), Géologie de l'Afrique: la chaîne pan-africaine "zone mobile d'Afrique centrale (Partie sud) et zone mobile soudanaise". Mém. Bur. Rech. Géol. Min. Fr., 92: 11—61.

Van Breemen, O., Pidgeon, R. T. and Bowden, P., 1977. Age and isotopic studies of some Pan-African granites from north-central Nigeria. Precambrian Res., 4: 307—319.

Vialette, Y. and Vitel, G., 1979. Geochronological data on the Amsinassene — Tefedest block (central Hoggar, Algerian Sahara) and evidence for its polycyclic evolution. Precambrian Res., 9: 241—254.

Vitel, G., 1979. La région Téfedest-Atakor du Hoggar central (Sahara). Evolution d'un complexe granulitique précambrien. Thèse, Univ. Paris VII, 323 pp. (unpubl.).

Wright, L. I., in press. The pattern of deformation and movement during the Pan-African in the Adrar des Iforas of Mali. Bull. Soc. Géol. Fr.