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# Outline of the Pan-African Geology of Adrar des Iforas (Republic of Mali)

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With 5 figures

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With 5 figures

## Zusammenfassung

Das Iforas-Gebiet (60 000 km$^2$) gehört zur pan-afrikanischen Bewegungszone, die in Mali an das westafrikanische Kraton grenzt. Diese Zone wird von N-S Scherbewegungen parallel zum Kraton durchzogen, wobei größere horizontale Versetzungsbeträge langgestreckte Blöcke herausgetrennt haben. Der zentrale Teil von Iforas besteht im wesentlichen aus reaktiviertem prae-panafrikanischem Basement, das in pan-afrikanischer Zeit von syn- und posttektonischen, intermediären und sauren Plutoniten intrudiert wurde. Dieses Gebiet wirkt als relativ starrer Block, der während der pan-afrikanischen Orogenese den Orogengürtel in einen westlichen und einen östlichen Ast teilt. Das westliche Iforas-Gebiet zeigt eine E-W Zonierung: eine Ophiolith-Sutur, einen vulkano-sedimentären Gürtel und einen Rand-Batholithen.

Zentral-Iforas wird aus zwei Einheiten aufgebaut: ein mehrfach metamorphisiertes Basement und einen Granitblock.

In den überregionalen Scherzonen lassen sich drei Stress-Felder erkennen: eine ältere 20° streichende sinistrale Scherzone, eine N-S dextrale Scherzone und jüngere NNW und dextrale ENE Bruchzonen.

Spät-pan-afrikanische Ereignisse sind durch Heraushebung und Abtrag, Granitintrusionen und wechselnden Dehnungs- und Kompressionsbewegungen gekennzeichnet.

## Abstract

The Iforas (60 000 km$^2$) falls within the Pan-African mobile belt bordering the West-African craton in north-eastern Mali Republic. It is characterized by major N-S shear belts parallel to the edge of the craton which delimit longitudinal blocks some of which have undergone considerable horizontal displacements. The central core of the Iforas which consists largely of reactivated pre-Pan-African basement injected by Pan-African syn- and post-tectonic intermediate and acid plutonic rocks, has behaved as a relatively rigid blocks during the Pan-African dividing the orogenic belt into a western Iforas and an eastern Iforas.

Western Iforas displays W to E zonation: an ophiolitic suture (Timetrine); trench volcano-sedimentary deposits cut by gabbros diorites and acid granitoids (Tilemsi); and a late orogenic composite "coastal range" batholith intruding the pre-Pan-African basement of Central Iforas and its overlying volcano-sedimentary deposits which here display a littoral facies and a tillite.

Central Iforas consists of two major units: a polycyclic pre-Pan-African base-

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ment metamorphosed under high amphibolite facies conditions of presumed Eburnean age and the Iforas granulite block bound to the W, N and E by shear zones.

Eastern Iforas was totally separated during metamorphism and deformation from the Iforas granulite block. From West to East, three lithological assemblages have been recognised separed by shear belts: a Quartzite Group, a Gneissic Group and a Pelitic Group the latter representing the southern prolongation of the central Hoggar Pharusian province.

Shear zones are an essential feature of Pan-African tectonism East of the West-African craton. The superimposed stress fields have been recognised producing: early N20° trending sinistral shear zones, a north-south dextral shear zone (Andjour-Tamaradant shear zone) and late conjugating sinistral NNW and dextral ENE wrench faults.

Late Pan-African events reflect the uplift and unroofing of the Pan-African composite batholith, the intrusion of circular granite plutons often located close to shear zones and alternating episodes of distension and compression.

Lastly the simple model proposed for the closing stages of the Pan-African in the Iforas is that of an active continental plate margin separated from the West African craton by an oceanic domain. Subsequent continental collision to the South with a promotory of the West African craton led to the formation of the Dahomeyan thrust front and modified the stress field. Closure of the oceanic domain of western Iforas is thought to have taken place by continued eastward subduction of the oceanic plate and sinistral movement along an inferred north westerly trending transform fault coinciding with the future Cretaceous Gao trough and an alignement of strong positive gravity anomalies. It was accompanied by the northerly migration of central and western Iforas along the conjugating dextral N-S Andjour-Tamaradant shear zone. Further shortening led to folding of the arcuate Timetrine-Ydouban-Gourma fold belt overlying the deformed margin of the West African craton.

**Résumé**


L'Adrar des Iforas (60 000 km²) fait partie de la zone mobile pan-africaine en marge du craton ouest-africain au Nord-Est de la République du Mali. La région est caractérisée par d'importants accidents mylonitiques parallèles à la bordure du craton qui délimitent des compartiments longitudinaux dont certains ont subi des déplacements horizontaux considérables. La zone dorsale des Iforas qui consiste essentiellement en un socle pré-pan-africain réactivé et injecté au Pan-Africain par des roches plutoniques intermédiaires et acides, syn- et post-tectoniques, s'est comportée en compartiments relativement rigides au cours du Pan-Africain, divisant la chaîne en un rameau occidental et un rameau oriental.

Le rameau occidental présente une zonation d'Ouest en Est: une suture ophiolitique (Timetrine); des dépôts volcano-sédimentaires de fosse recoupés par des gabbros et des diorites; et un vaste batholite composite tardi-orogénique qui recoupe le socle pré-pan-africain de la zone dorsale des Iforas et sa couverture de dépôts volcano-sédimentaires ici à faciès littoral.

La zone dorsale des Iforas comprend deux unités majeures: un socle pré-pan-africain polycyclique métamorphisé dans le faciès amphibolite, d'âge éburnéen présumé et le môle granulitique des Iforas, délimité à l'W, au N et à l'E par des accidents mylonitiques.

Le rameau oriental était séparé du môle granulitique des Iforas lors du métamorphisme et de la déformation. D'W en E, on trouve trois unités séparées par des zones mylonitiques: un Groupe de Quartzites, un Groupe de Gneiss et un Groupe de Pélites. Ce dernier représente le prolongement vers le Sud de la province pharusienne du centre Hoggar.

Les grands accidents de cisaillement sont un fait marquant du tectonisme pan-africain à l'Est du craton ouest-africain. Trois champs de contraintes superposées ont produit des accidents précoces sénestres de direction N20, un accident N-S dextre (Andjour-Tamaradant), et des failles cisaillantes tardives conjuguées d'orientation NNW sénestres et ENE dextres.

Les événements pan-africains tardifs sont marqués par la surrection et l'érosion des batholites pan-africains, la mise en place de plutons granitiques souvent à proximité des grands accidents et par des alternances de distensions et de compressions.

Enfin un modèle simple est proposé pour les stades ultimes du Pan-Africain dans l'Adrar des Iforas: une marge continentale active séparée du craton ouest-africain par un domaine océanique; suite à une collision au Sud avec un promontoire du craton ouest-africain qui aurait produit le front de chevauchement dahomeyen et modifié le champ de contraintes, la fermeture du domaine océanique de l'Ouest Iforas se serait produite par subduction à l'E de la plaque océanique et une translation sénestre le long d'une faille transformante orientée NW et coincidant avec le fossé crétacé de Gao et un alignement d'anomalies gravimétriques positives. Elle aurait été accompagnée par le déplacement vers le N de l'Iforas occidental et central le long de l'accident cisaillant dextre d'Andjour-Tamaradant. Cette fermeture aurait provoqué les plissements de la chaîne du Timetrine-Ydouban-Gourma qui repose sur la bordure déformée du craton ouest-africain.

**Краткое содержание**

Район Ифорас (60 000 км$^2$) принадлежит пан-африканской подвижной зоне, граничащей в Мали с западноафриканским кратоном. Через этот район проходит в североюжном направлении сдвиг, простирающийся параллельно к кратону, причем отмечают большие горизонтальные смещения вытянутых в длину глыб. Центральная часть Ифораза состоит, в основном, из реактивированного до-пан-африканского фундамента, в который во время пан-африканского орогена одновременно с тектоническими процессами и сразу после них оказались интрудированы средние и кислые плутониты. Весь этот район напоминает сравнительно застывший блок, который во время пан-африканского горообразовательного процесса разделил пояс орогена на западную и восточную ветви. Западная часть Ифораза проявляет зональность в восточно-западном направлении: офиолитовый шов, вулканов-осадочный пояс и краевые батолиты.

Центральная часть Ифораза состоит из двух единиц: многократно метаморфизированного фундамента и гранитного блока.

В зоне надвига можно наблюдать три зоны: более древнюю зону сдвига, простирающуюся 20° влево; правую зону сдвига, простирающуюся на севереюг и позднюю, простирающуюся на северо-северо-запад зону сдвига и правую востоко-северо-восточную зону разломов.

Позднейшие пан-африканские процессы характеризуются поднятием, сносом, гранитными интрузиями и попеременными поворотами и сдавлениями.

## I. Introduction

The Iforas forms the south-western promontory of the central saharan Hoggar shield where it covers an area of about 60 000 square kilometres in the Republic of Mali (Fig. 1). The southern prolongation of the Pharusian of north-western Hoggar (Caby, 1970; Bertrand & Caby, 1977), it falls within the Pan-African mobile belt bordering the West African craton, itself stable since c. a. 1750 m. y. and covered by flat-lying Upper Proterozoic sediments in the Taoudenni and Voltaic basins (Black, 1966, 1967). A cryptic suture underlined by an array of positive gravity anomalies (Crenn, 1957; Louis, 1970) is believed to run beneath the Mesozoic-Tertiary-Quaternary sediments of the Tilemsi valley and Gao trough. It welds the

Iforas, made up of metamorphosed Upper Proterozoic sediments and reworked older basement, sliced by spectacular N-S trending shear zones and injected by abundant Pan-African calc-alkaline volcanic and plutonic rocks, to the arcuate Timetrine-Ydouban-Gourma fold belt consisting of thick shelf deposits of assumed Upper Proterozoic age overlying the margin of the craton. This belt is locally affected by HP-LT metamorphism and plutonic activity is totally absent (REICHELT, 1972). The region is thought to be a key one for studying the internal deformation and movement pattern during the Pan-African as well as craton-mobile belt structural relationship and palaeogeography.

Previous work includes surveys undertaken in the forties and early fifties by LELUBRE (1952), H. RADIER (1957) and KARPOFF (1958) who produced an excellent reconnaissance geological map on the scale of 1:1 000 000 and some unpublished mineral reports in the late fifties by the Bureau Minier de la France d'Outre-Mer and the Service de Géologie et de Prospection Minière de l'A.O.F., but few detailed investigations have been carried out in the area. Our study is a southern

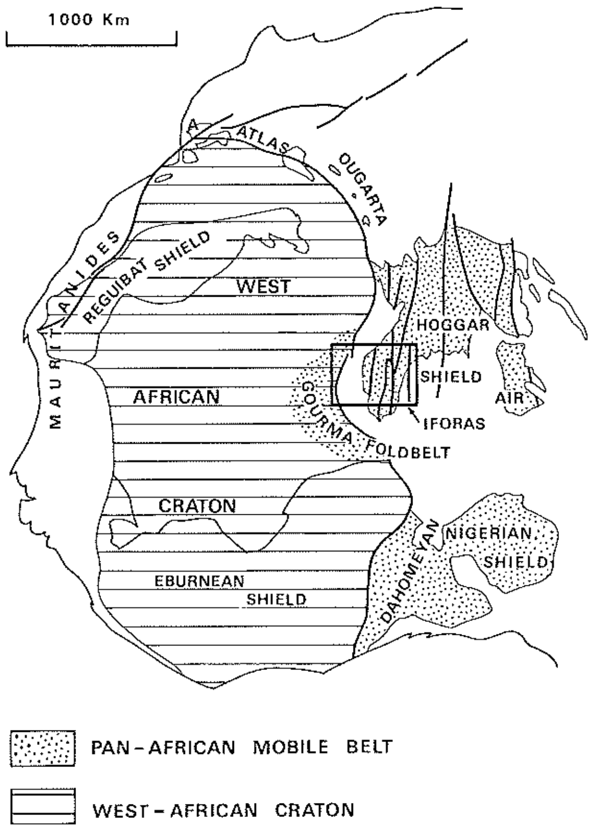


Figure 1. Location of the investigated area.

extension of work carried out in Hoggar and Aïr during the last fifteen years (CABY, 1970; BERTRAND, 1974, BLACK et al., 1967). Here we report preliminary results obtained during the last two winter field seasons 1975—1976, 1976—1977 in Mali.

## II. Main structural units

Like the entire Hoggar shield, the Iforas is characterized by major vertical north-south trending shear belts parallel to the edge of the craton which delimit longitudinal blocks some of which have undergone considerable horizontal displacements. From West to East as one moves from the craton into the mobile belt the following units can be distinguished (Fig. 2):

1. The Timetrine inlier situated on the margin of the West African craton is composed of assumed Upper Proterozoic shelf sediments metamorphosed in low greenschist facies and a probably obducted ophiolitic assemblage. Granites are completely absent.

2. The western Iforas block bounded to the East by the Tessalit-Aguelhok-Anefis shear belt is separated from the Tilemsi inlier by Cretaceous-Tertiary-Quaternary sediments filling the Tilemsi Valley. This unit is dominantly a Volcano-Sedimentary Group comparable to the "Série Verte" of NW Hoggar of Late Proterozoic age (CABY, 1970). It is cut by abundant gabbros, diorites and adamellites and metamorphosed in greenschist facies locally attaining amphibolite grade. The Aguelhok horst is composed of high grade gneisses and migmatites and is possibly an older basement as originally suggested by KARPOFF (1958); it displays however LP/HT mineral assemblages unaffected by retrograde metamorphism and may represent a rapidly surrected LP catazone to the Pan-African belt.

3. The Kidal block situated between the Tessalit-Aguelhok-Anefis shear belt to the West and the Iforas granulite block to the East. It is characterized by the presence of pre- Pan-African basement unconformably overlain by the Volcano-Sedimentary Group and cut by a large composite Pan-African batholith. The pre-Pan-African basement is polycyclic and by analogy with NW Hoggar could be of Eburnean age. It is composed of leucocratic gneisses and migmatites with subordinate quartzites, marbles, amphibolites and metadiorites with basic and ultrabasic rocks being particularly abundant North-West of the Iforas granulite block. They display dome basin type interference fold pattern complicated by N-S shears and Pan-African deformation and have suffered an epizonal retrograde metamorphism. In the northern part of the block there are some cores of retrograde granulite facies rocks in the pre-Pan-African basement but their mutual relationships have not been elucidated. Also occurring in this region are meta-quartzites and marbles similar to the Upper Proterozoic "Série à stromatolites" of Tin Aberda (CABY, 1970) which unconformably overly the pre-Pan-African basement. In contrast, SW of Kidal, the basement is unconformably overlain by the Volcano-Sedimentary Group containing a marine tillite and metamorphosed in low greenschist facies. North-East of Tirharhar a thick sequence of meta-andesites, meta-basalts and agglomerates is thought also to belong to this group. The late-and post-orogenic stage of the Pan-African is marked by the intrusion of circular plutons of adamellite close to major

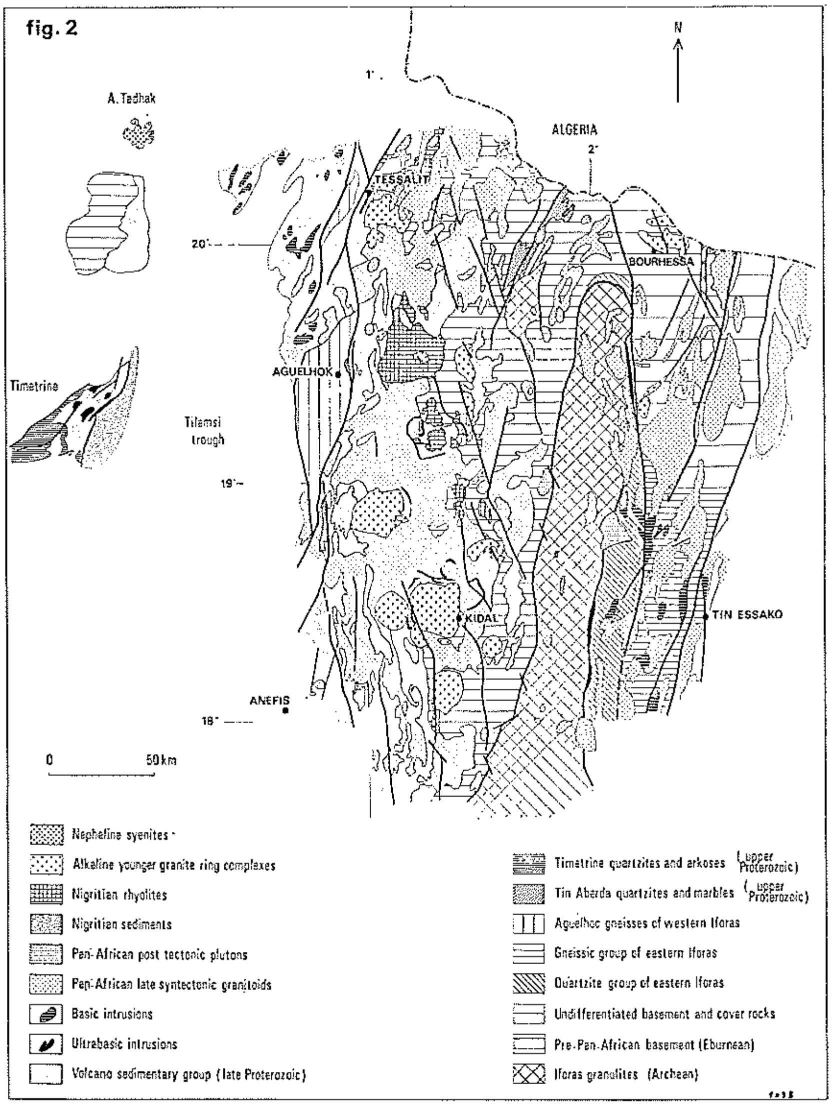


Figure 2. Schematic map of the Iforas.

shear belts and by uplift and erosion of the Pan-African batholith. It is followed by the injection of spectacular dyke swarms, the extrusion of flat-lying Nigritian rhyolites and the emplacement of a series of alkaline Younger Granite ring complexes. Small grabens of post-orogenic nigritian sediments comparable to the "Série Pourprée" of NW Hoggar (CABY & MOUSSU, 1967) occur especially along the margin of the block.

4. The Iforas granulite block is bound to the W, N and E by mylonite zones. This block may be correlated with the Archaean In Ouzzal block of western Hoggar where the granulite facies metamorphism has been shown to be Eburnean (Lancelot et al., 1973). It is composed of lenses and horizons of granulitic meta-sediments (quartzites, khondalites, kinzigites, marbles) ultrabasic intrusions displaying high pressure granulite facies mineral associations. They are intimately associated with a huge volume of amphibole bearing alkaline orthogneisses and cut by weakly foliated charnockites and norites. In contrast to the undisturbed in Ouzzal granulites of NW Hoggar, the Iforas granulite block has been strongly affected by the Pan-African s. l. This event is indicated by the injection of several generations of basic, dioritic and dacitic dykes in mesozonal and epizonal conditions in relation to movements along the major mylonite zones, by retrograde metamorphism of variable intensity and by the emplacement of masses of gabbro, diorite and adamellite. A narrow faulted syncline of quartzite attributed to the Upper Proterozoic and a small trough of Nigritian sediments unconformably overly the granulites.

5. The eastern Iforas block falls in an entirely different domain. Three lithological assemblages have been recognized separated by N-S shear belts: a Quartzite Group, a Gneissic Group and a Pelitic Group the latter being widespread East of the Adrar Fault where it represents the southern prolongation of the central Hoggar Late Proterozoic Pharusian province. These rocks have been affected by at least two major phases of deformation and by metamorphism varying from low greenschist to high amphibolite facies. Whereas meta-gabbros and alkaline gneisses intercalated in the Quartzite Group are pre-tectonic, massifs of gabbro, diorite and adamellite have been emplaced between the two major phases of deformation and are cut by small post-tectonic massifs of gabbro, anorthosite and granite.

In conclusion, the eastern Kidal and Iforas granulite blocks which consist largely of reactived pre-Pan-African basement injected by syn- and post-tectonic intermediate and acid plutonic rocks have behaved as relatively rigid blocks during the Pan-African s. s. dividing the orogenic belt into a western Iforas and an eastern Iforas which display pronounced lithological and structural differences.

## III. Western Iforas

Western Iforas essentially records the history of the closing stages of the Pan-African orogeny represented by the deposition of the Volcano-Sedimentary Group and the intrusion of the composite Pan-African batholith in the Kidal block. There is a clear W-E zonation between the West African craton and the central core of the Iforas.

On the craton to the West the Timetrine Upper Proterozoic shelf sediments consist of finely banded sericite-quartzites, impure quartzites, white feldspathic quartzites, arkoses and arkosic grits with intercalated conglomeratic beds and sericite phyllites and rare horizons of pink marble. These sediments appear to overlie geometrically chlorite phyllites and prasinites with thin horizons of tourmaline bearing jaspers, and an ophiolitic assemblage. This assemblage is represented by ultrabasic massifs now serpentinised, including dunites, harzburgites, wherlites some exhibiting tectonite structures, slightly deformed ultrabasic and basic cumulates (wherlite, troctolitic gabbro, olivine anorthosite), associated with banded gabbros, diabases, basic lavas, tuffs, keratophyres and banded jaspillites. All these rocks have been affected by greenschist metamorphism and by two major phases of deformation: the first produced large scale recumbent folds overturned towards the north, the second isoclinal folds overturned towards the north-west; a third phase of north-easterly trending chevron folds also overturned towards the north-west is sometimes found. Probe analysis shows that the glaucophane described by KARPOFF (1958) in phyllites and carbonates close to the serpentine bodies is a variety of crossite. Field observations suggest that the ophiolitic assemblage was obducted at an early stage and may have undergone meteoric alteration producing a siliceous cap (birbirite) on altered serpentines prior to the deformation.

The Volcano-Sedimentary Group in the Upper Tilemsi valley and along the western margin of the Iforas is composed of greywackes, conglomerates, andesites, basalts, tuffs and abundant acid volcanics and may represent trench deposits as have been described further north in the "Série Verte" (CABY, 1970; CABY et al., 1977). The Group has been subjected to at least two phases of deformation, the first produced isoclinal folding with the development of biotite defining the axial plane schistosity, the second more open folds with subvertical NNE-SSW trending axial planes often accompanied by weak schistosity. The grade of metamorphism is mostly greenschist facies but attains amphibolite facies in the Anefis region. Abundant gabbros and diorites with subordinate adamellites, both pre- and late-tectonic cut the formation often forming elongated bodies parallel to the dominant NNE-SSW trend.

Further East on the Kidal block the Volcano-Sedimentary Group has been studied in some detail South-West of Kidal (Tafeliant region). Here it lies unconformably on the pre-Pan-African basement and displays a littoral facies. General metamorphism is of low greenschist facies but increases to amphibolite grade in the contact aureoles of diorites belonging to the Pan-African batholith. A single phase of isoclinal folding produced a subvertical N-S trending axial plane cleavage but little penetrative deformation, sedimentary features being perfectly preserved. From base to top the succession is as follows: a basal breccia consisting of locally derived pre-Pan-African basement boulders overlain by arkoses and conglomerates indicative of a fluviatile or littoral facies; 500—1000 metres of pelites, silts, arkoses and greywackes probably deposited in a high energy intertidal or subtidal environment with the first appearrance of magmatic activity represented by sills and andesites flows; 500—1000 metres of silts, pelites, fine-grained greywackes with abundant intercalated meta-basalts, meta-andesites and diabases; a transgressive conglomeratic formation at least 500 metres thick displaying all the characteristics of a marine tillite (abundant matrix, absence of sorting, presence of varves, etc), overlain by some tens of metres of fluvioglacial arkoses, sandstones and graywackes; 500 metres of acid leucocratic volcanics and tuffs. The presence of the marine tillite which is also well exposed 200 km further north in the Tessalit region (KARPOFF, 1958) supports a glacial origin for the "tilloids" described by CABY (1970) in the "Série Verte" of NW Hoggar.

To the North-East of Tirharhar in the Oumassene region there is a Volcanic

Group at least 2000 metres thick composed of flows and sills of banded fine-grained meta-andesites and meta-basalts frequently displaying porphyritic textures and volcanic breccias and agglomerates intercalated with some acid flows. Although the basal contact was not observed they apparently overly a pre-Pan-African basement consisting of meta-basites, amphibolites and garnet bearing marbles metamorphosed in the amphibolite facies and are overlain in unconformity by the flat lying Nigritian rhyolites. The Volcanic Group is affected by thermal metamorphism and by folding of kilometric amplitude along a N-S axis and is cut successively by various intrusives belonging to the Pan-african batholith. The Volcanic Group is therefore considered to be roughly contemporaneous with the Volcano-Sedimentary Group but is thought to have been layed down in a continental environment.

The Pan-African batholith is a complex body, partly unroofed, which occupies about 40 % of the surface of the Kidal block. It is composed of a sequence of calc-alkaline intrusions, the general order of intrusion being diorite, tonalite, porphyritic granite and a variety of leucocratic adamellites. Following uplift and erosion it is the locus for the intrusion of post-tectonic dyke swarms, the emission of Nigritian rhyolites and the emplacement of alkaline Younger Granite ring complexes.

Thus the general picture of the western Iforas during the Pan-African can be summarised in terms of a suture on the margin of the craton, indicated by the presence of an ophiolitic assemblage in the Timetrine, trench volcano-sedimentary deposits cut by pre-tectonic gabbros and intermediate and acid granitoids in the Tilemsi and western margin of the Iforas, and a late to post orogenic batholith intruding in the Kidal block and its overlying volcano-sedimentary deposits displaying littoral and perhaps continental facies. Studies of strain and mineral associations indicate a gradient of deformation and metamorphism which increased westwards towards the Tilemsi valley. This general disposition strongly evokes an oceanic closure with an easterly dipping palaeo-Benioff plane.

## IV. Eastern Iforas

The geology of eastern Iforas is more complex and our observations which are limited at present to a zone delimited by latitudes 18° N and 19° N between the Iforas granulite block and the Ordovician cover East of Tin Essako, do not extend northwards and East of the Adrar fault where one falls into the southern prolongation of the Central Hoggar Late Proterozoic Pharusian province consisting essentially of conglomerates, pelites and semi-pelites and volcano-sedimentary rocks injected by basic and ultrabasic bodies with abundant diorites and granodiorites (Lelubre, 1952; Karpoff, 1958).

In the region studied three lithological units have been distinguished separated by N.S. trending shear zones: along the eastern margin of the Iforas granulite block a Quartzite Group at least 5000 metres thick composed largely of quartzites with pelitic horizons and abundant basic sills towards the base; also found higher up in the succession are fine-grained banded alkaline orthogneisses intercalated in pure quartzites and locally overlain in apparent conformity by pelitic schists and polygenic conglomerates with a graywacke matrix which are reminiscent of conglomerates in the central Hoggar Pharusian province (KARPOFF, 1958); to the East a 15 kilometres wide band consisting of a Gneissic Group composed of pink migmatitic alkaline gneisses associated with grey calco-magnesian gneisses, green quartzites with microconglomeratic horizons and intrusive acid orthogneisses which cut the paragneisses and quartzites; a Pelitic Group consisting of 2000 metres of chlorite phyllites and slates, probably equivalent of the pelites of the central Hoggar Pharusian province is found East of the Adrar fault and forms a narrow strip bound by N-S faults North of Tin Essako; this unit disappears towards the south where it is replaced by a band of augen orthogneiss. Most of the region is affected by at least two major phases of deformation and a third phase has been observed in the Pelite Group. The first phase affects early banding ($S_0$) and forms a $L_1S_1$ fabric. To the South of the Kidal-Tin Essako road the axes of the folds dip steeply to the South whereas to the North the folds turn plunge gently to the NE. Everywhere one observes the second phase $P_2$ N-S trend with vertical N-S trending axial planes and the local development of an axial plane schistosity $S_2$. In the Gneissic Group two phases of migmatisation the first syn-$P_1$, the second post-$P_1$ pre-$P_2$ have been recognized. The meta-gabbro sills and alkaline gneisses intercalated in the Quartzite Group are pre-$P_1$. Massifs of gabbro, diorite, tonalite and adamellite considered to be of Pan-African age often display a N-S foliation and have been emplaced between the two major phases of deformation; they are cut by small post-tectonic massifs of gabbros, anorthosite and granite which are not abundant in this sector. Prograde regional metamorphism varies longitudinaly from low greenschist to high amphibolite facies with or without accompanying migmatisation and was followed by the intrusion of syn-tectonic granites producing contact metamorphism with andalusite. Late retrograde metamorphism is seen in the syn-tectonic granitoids and in the aureoles by the transformation of andalusite into chlorite and white mica.

The segment of the eastern Iforas which we have examined can be regarded as representing a deeper structural level of the Pan-African whose complex structural and magmatic history recording pre- and early-Pan-African events will only be deciphered by detailed geochronological investigations. The Quartzite Group has considerable extension and can be traced 500 kilometres to the North where it is represented by the Meta-Quartzite Formation and the Ahnet Quartzite Formation described by CABY (1970) and ARÈNE (1968). Preliminary results yielding a Rb/Sr isochron age of 1350 m. y. on the intercalated meta-rhyolites and a U/Pb age of 1750 m. y. on zircon from associated microgranites quoted by BERTRAND & CABY (in press) suggest deposition of these shelf deposits and extensive alkaline magmatism on the present site of the Pan-African to be of Middle Proterozoic age. The abundant basic sills and intrusions found towards the base of the Quartzite Group raises the problem of basification of a sialic crust which in NW Hoggar has been dated at 800 m. y. (CLAUER, 1977; CABY, 1970).

In contrast with the western Iforas which shows clear evidence of an oceanic influence, eastern Iforas may well have had an ensialic evolution during the Pan-African orogeny.

## V. The Iforas granulite block: Pan-African reactivation of an Archean block

### 1. The granulite series

By far the predominant rock type of the Iforas granulite block is a banded alkaline orthogneiss containing Fe-rich amphiboles and clinopyroxenes (ferro-hastingsite, hedenbergite), sometimes green biotite and iron oxides (ilmenite, magnetite); the K-feldspar is a mesoperthite and is accompanied by subordinate acid plagioclase; accessory minerals are abundant and include sphene, apatite, allanite and zircon. As HP granulite facies minerals and coronitic structures are absent the gneisses are thought to be syn-metamorphic intrusions post-dating the HP granulite conditions registered in the interfoliated granulitic meta-sediments. They have undergone intense deformation and processes or differentiation and proto-anatexis as shown by the presence of mobilisates. The granulitic meta-sediments represent only a small proportion of the block and consist of meta-quartzites with blue quartz, some marbles and a characteristic kinzigite-khondalite association with associated layers and lenses of norite. In the kinzigites coronitic structures are present and consist of HP relicts of kyanite, garnet, rutile and hypersthene enveloped by a later mineral association of cordierite, spinel, biotite, hypersthene II ± sillimanite ± K-feldspar ± plagioclase. Ultrabasic rocks show strong retrograde metamorphism to serpentine chlorite, tremolite etc . . . Bands and veins of metagabbro are readily distinguished from the homogeneous norites and should also be interpreted as late syn-metamorphic intrusives which have not been affected by HP granulite conditions. The banding in the granulite series is frequently folded into large recumbent isoclinal structures which have been refolded to produce tight vertical folds striking ENE and accompanied by the development of a new axial plane foliation. These structures are cut by charnockites, dioritic charnockites and alkaline rocks with syenitic varieties similar in composition to the alkaline orthogneisses.

### 2. Pan-African events

The Iforas granulite block has been affected by important magmatic and metamorphic events related to the Pan-African s. l.

Early N-S trending dyke swarms have been studied particularly in the north-western part of the Iforas granulite block. They form very dense swarms with individual dykes generally several tens of centimetres to a few metres thick. They consist of dolerites, basalts and rare acid porphyries which are often sheared and have been subjected to greenschist facies metamorphism, the basic members being transformed in varying degrees to amphibolite schists with blue-green amphibole, albite and quartz ± chlorite ± epidote ± biotite ± calcite while the magmatic olivine-clinopyroxene associations are only preserved in the core of thicker dykes. As sills of similar composition have been found intruding the quartzites considered of Upper Proterozoic age which unconformably overlie the Iforas granulite block the age of this magmatism by analogy with NW Hoggar is thought to be c. a. 780 m. y. (Clauer, 1977). A case of degranulitisation related to the emplacement of such a dyke complex was examined in some detail close to the northern tip of the Iforas granulite block. Here the country rock has been vertically sheared under mesozonal conditions with the crystallisation of porphyroblastic

6. Late sinistral NNW trending wrench faults are seen in the Kidal block and cut the Younger Granite ring-complexes with lateral displacements of several kilometres. Conjugate dextral ENE-trending wrench faults have been observed in the Tessalit region and offset the N-S Tessalit-Aguelhok-Anefis shear belt.

The shear pattern of the Iforas is complex and has developed over a period of time. Major transcurrent movements along shear belts operated in a greenschist facies environment and are generally related to the late Pan-African N-S upright folding. The constancy of horizontal stretching lineation and vertical mylonite foliation clearly indicates important transcurrent movements and a sinistral displacement of 350 km has been postulated between the Iforas granulite block and the In Ouzzal granulite block of NW Hoggar (Caby, 1968). This sinistral sense of movement is characteristic of the major N 20° trending shear zones. A change in the stress field then produced dextral movement along the N-S shear zone, and western and central Iforas moved northwards wtih respect to eastern Iforas. The late conjugate system of NNW sinistral and ENE dextral strike slip faults with minor displacements which is superimposed on the shear zones is related to late E-W shortening and extends over the entire Hoggar shield (Black & Girod, 1970; Ball, 1977).

## VII. Late Pan-African events

Late Pan-African events affect particularly the western Iforas (Fig. 3). They reflect uplift and unroofing of the Pan-African batholith and alternating episodes of distension and compression. The former is indicated by injection of dyke swarms, formation of grabens filled by Nigritian sediments, fissural emission of Nigritian rhyolites and emplacement of alkaline ring-complexes, the latter by deformation in the Nigritian and sinistral movement along NNW wrench faults.

1. Dyke swarms are a spectacular feature of the Iforas and are mainly restricted to the Kidal block and the area around Bourhesa West of the Adrar fault. Early swarms generally trend E-W, the most important being situated around Telabit and to the West of Timedjelalene. These swarms precede high level post-tectonic adamellites and are cut by N-S dyke swarms. Dominantly acid and calc-alkaline in chemistry they include dolerites, quartz microdiorites, micromonzonites, micro-adamellites and are abundant acid felsitic rocks. Composite dykes are frequent. Individual dykes vary in thickness from 10 cm—30 metres, the average being 5—10 metres. In the case of the 10 kilometres wide Telabit swarm where the density of dykes is extremely high, the integrated distension must amount to several kilometres and is seen to have been partly accomodated by transform faults perpendicular to the trend of the swarm. A case was observed where such a fault produced a syn-magmatic breccia in one dyke and cold transcurrent shear in the adjacent dyke. Further North between Tessalit and Tirharhar an early E-W swarm of lamprophyres (spessartite) is cut by dykes of microgabbro trending 50° E which in turn are crossed by of quartz microsyenites dykes orientated 20° E and by N-S trending dyke swarm of dominantly rhyolitic composition. These late N-S dyke swarms can be followed a distance of over 250 kilometres in the axis of the Pan-African batholith and coincide with the main outcrops of Nigritian rhyolites. They consist of subordinate early basic

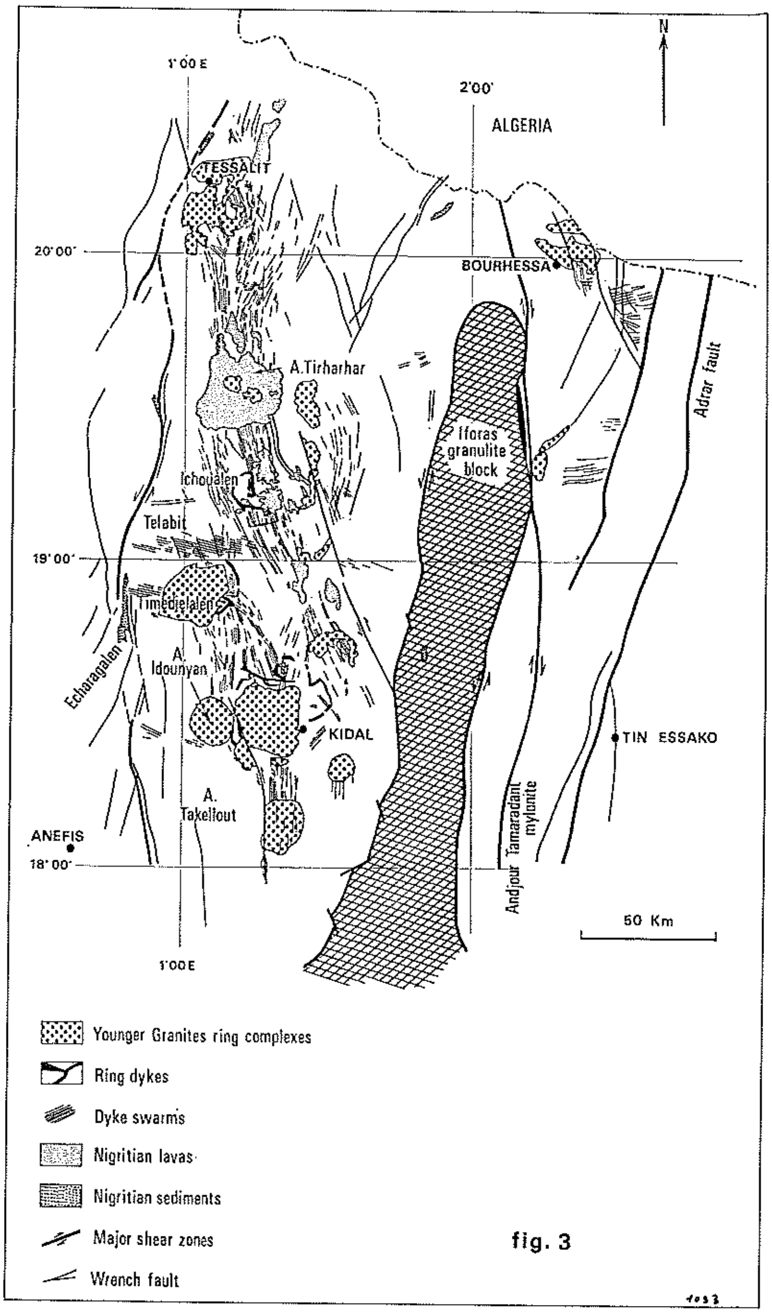


Figure 3. Post-orogenic alkaline complexes and dyke swarms.

grained arfvedsonite-biotite granite and granite porphyries West of Kidal the main in the northern part of the complex and along an E-W band in the southern half of the massif. Then a medium-grained arfvedsonite-biotite granite was intruded beneath the fine-grained biotite granite and the coarse-grained arfvedsonite-biotite granite in the centre of the massif opening out eastward in the form of a horse shoe. An associated fayalite-hedenbergite-hastingsite granite occurs at the northern tip of the horse shoe. Subsidence of a block to the SW of Kidal allowed the injection of a heterogranular hastingsite-biotite granite as a discontinous ring-dyke along the contact between the early 2-feldspar-biotite granite and the coarse-grained arfvedsonite-biotite granite and as a flat-lying sheet capping the 2-feldspar-biotite granite. A medium-grained hastingsite-biotite granite then intruded the medium-grained arfvedsonite-biotite granite and granite porpyries West of Kidal the main contact dipping gently (20°) to the North-West; it also outcrops to the South-West cutting the coarse-grained arfvedsonite-aegyrine granite and fine-grained biotite granites. The last major phase is a fine-grained albite-riebeckite granite to the North of Kidal occurring as a sheet dipping gently to the west beneath the medium-grained hastingsite-biotite granite. It is interesting to note that whilst early phases are cut by some N-S acid dykes, these are truncated by later phases. U/Pb dating of zircons from the hedenbergite granite has yielded an age of 586 ± 13 m.y. (Lancelot *et al.*, 1977).

I d o u n y a n (16 km in diameter) is a circular massif composed of an outer ring of coarse arfvedsonite-aegyrine granite, intruded by a heterogranular hastingsite-biotite granite and a central core of fine-grained biotite granite.

T i m e d j e l a l e n (32 × 22 km) is a typical ring complex (Fig. 5) with a ring-dyke of quartz-syenite porphyry and a panidiomorphic hedenbergite-hastingsite granite rich in sphene within which were successively intruded a coarse-grained arfvedsonite-aegyrine granite, a heterogranular hastingsite biotite granite, a 2-feldspar biotite granite and at the centre a riebeckite-aegyrine granite. Shallow outward dipping contacts are often observed, the later underlying phase displaying a marginal miarolitic facies. The complex truncates both E-W and N-S dyke swarms.

I c h o u a r e n forms a network of polygonal quartz-syenite porphyry ring-dykes which cut the horizontal Nigritian rhyolites.

Unsaturated complexes (A. Tadhak) of unknown age overlain in unconformity by the Cretaceous occur to the West on the margin of the craton but are probably totally unrelated to the Iforas Younger Granites.

The Iforas Younger Granites ring-complexes are good examples of alkaline and peralkaline granites intruded at high level by a process of major stoping where flat-lying roof structures are often well preserved. They are essentially plutonic structures and do not seem to have played the role of central volcanoes, the Nigritian rhyolites having been fed by dyke swarms. In the contrast to the much younger similar Younger Granites of Nigeria and Niger which are strictly anorogenic, the intrusion of the Iforas complexes follows closely in time the Pan-African orogeny and its associated calc-alkaline granitoids. The change in regime to tensional conditions is reflected in the chemistry of the magmatism which is predominantly calc-alkaline in the early E-W dyke swarms, alkaline in the N-S dyke swarms and peralkaline in the ring-complexes.

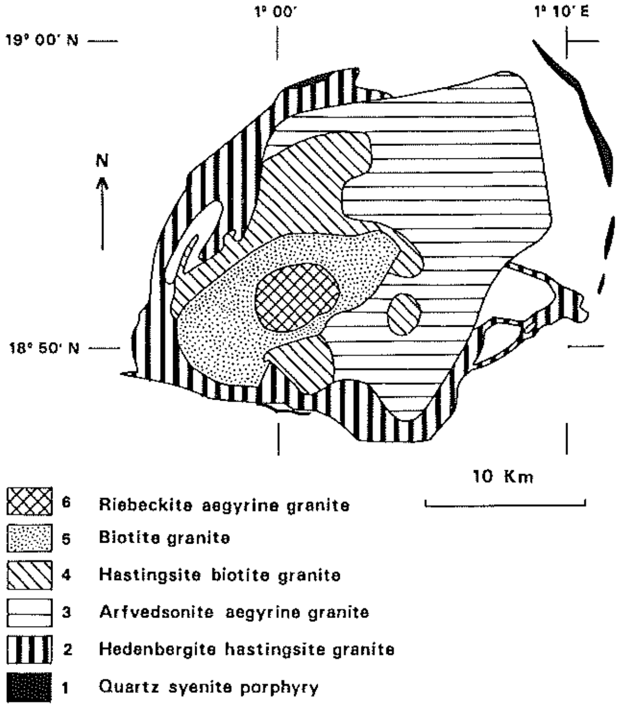


Figure 5. The Timedjelalen alkaline ring complex.

## VIII — Conclusions

Ideas on the Pan-African have evolved considerably since its definition by W. Q. KENNEDY (1964) as a major thermo-tectonic event in Africa. Since then it has been shown that one is dealing with a major orogenic belt with world wide ramifications marking the limit between the Precambrian and the Phanerozoic. Whilst evidence for an ensialic evolution was being gathered by workers in southern Africa (MARTIN & PORADA, 1977) where palaeomagnetic results suggest little movement between adjacent cratons (BRIDEN, 1973; PIPER *et al.*, 1973), a mobilistic conception appeared in Northern Africa (CABY, 1970) and in Saoudi Arabia (GREENWOOD *et al.*, 1976; BAKOR *et al.*, 1976) following the discovery of volcano-sedimentary sequences suggesting island arc and marginal trench environments and of ophiolites (LEBLANC, 1976; SHACKLETON, 1976). Important also has been the appreciation of the role played by transcurrent shear belts in the Pan-African.

The recognition of the Timetrine ophiolites, trench type volcano-sedimentary deposition and a "coastal range" batholith in the western Iforas points strongly to the existence of a cryptic suture along the eastern margin of the West African craton as proposed by CABY (1970), LEBLANC (1973) and BURKE & DEWEY (1973).

The presence of a string of positive gravity anomalies underlining the suture (CRENN, 1967; LOUIS, 1970) has been substantiated by more detailed gravity surveys (RECHENMANN, 1973, BOURMATTE, 1976).

However, the amount of opening and closure is unknown and only the palaeomagnetic approach can possibly provide an answer. A recent study (MOREL & IRVING, in press) using palaeomagnetic data on well dated rocks from Canada and South Africa gives reconstructions for 800 m.y. and 675 m.y. showing an open situation between North America and Gondwanaland and closure at 550 m.y. As there are no reliable Upper Proterozoic data from the West African craton, these results are also compatible with a line of split for the formation of a pre-Pan-African Atlantic along the eastern margin of the West African craton.

In contrast to western Iforas which shows clear evidence of an oceanic influence, the complex magmatic structural and metamorphic history of the eastern Iforas may well be ensialic and related to the intraplate shearing which affects the entire Hoggar shield.

This spectacular shear pattern although observed at a deeper erosional level is comparable to that displayed by Asia as a result of India-Eurasia collision where considerable shortening has been achieved by lateral expulsion of blocks bounded by conjugate strike-slip faults (MOLNAR & TAPPONNIER, 1975). In the light of existing data, the model which we propose for the Iforas is that of shearing with sinistral displacements along N 20° striking mylonite zones behind an active continental plate margin, separated from the West African craton to the West by an oceanic domain. Subsequent continental collision to the South with a promontory of the West African craton led to the formation of the Dahomeyan thrust front and modified the stress field. Closure of the oceanic domain of western Iforas is thought to have taken place by continued eastward subduction of the oceanic plate and sinistral movement along an inferred north-westerly trending transform fault coinciding with the future Cretaceous Gao trough and an alignement of strong positive gravity anomalies. It was accompanied by the northerly migration of central and western Iforas along the conjugating dextral N-S Andjour-Tamaradant shear belt. Final closure led to folding of the arcuate Timetrine-Ydouban-Gourma fold belt.

Compared to NW Hoggar, the Iforas consists of a more important volume of reactivated pre-Pan-African basement rocks. The Iforas granulite blocks has been affected by Pan-African igneous and metamorphic events whereas its counterpart to the North the In Ouzzal block remained cold except at its southern tip (CABY, 1970).

The tensional structures related to the late orogenic stage represented by extensive dyke swarms, the emission of Nigritian rhyolites and the emplacement of alkaline Younger Granite ring complexes closely followed in time Pan-African deformation and intrusion of calc-alkaline granitoids. The rapid switch to a tensional regime accompanied by alkaline magmatism recalls the situation in Corsica where similar alkaline Younger Granite complexes of probable Lower Permian age (LANCELOT *et al.*, 1977) cut Hercynian calc-alkaline granitoids and volcanic rocks (VELLUTINI, 1977). Lastly the 586 ± 13 m.y. age (LANCELOT *et al.*, 1976) obtained for the Kidal ring-complex indicates that the Pan-African orogeny ceased in the Iforas in Precambrian times. Comparison with ages obtained elsewhere in the Pan-African, for example, in the Damaran belt (HAWKESWORTH *et al.*, 1977) shows that diachronism exists between different segments of the chain.

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