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GEOTHERMOMETRIC AND GEOBAROMETRIC SIGNATURES OF METAMORPHISM IN THE PRECAMBRIAN BASEMENT COMPLEX ROCKS AROUND KEFFI, NORTH-CENTRAL NIGERIA

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Abstract

Field and petrographic studies on the Precambrian basement complex rocks around Keffi, North-central Nigeria reveal that they consist of porphyroblastic gneiss, migmatitic banded gneiss, garnet-mica-schist, staurolite-mica-schist, kyanite schist and the garnetiferous granite. The migmatitic banded gneiss differs from the porphyroblastic gneiss in its possession of a pronounced gneissose foliation (banded structure), cross-cutting quartzo-feldspathic veins, ptygmatic folds, boudinages of paleosomes and lack of porphyroblastic fabric. The grade of metamorphism of the two gneisses is constrained to be middle to upper amphibolite facies, with assemblages of garnet, biotite, cordierite, plagioclase and K-feldspar. The following reaction could have occurred:

Muscovite + Biotite + Quartz =
$6[KAl_2(AlSiO_3O_{10})(OH_2)]$ $2[K(MgFe)_3(AlSi_3O_{10})(OH)_2]$ $15SiO_2$

K-feldspar + Cordierite + water (T~700 °C and P~ 6.5 Kb). (1)
$8(KAlSi_3O_8)$ $3[(MgFe)_2Al_3(AlSi_5)O_{18}]$ $8H_2O$

On the other hand, the schists, characterised by the assemblages of biotite, muscovite, garnet (almandine) and staurolite. are constrained to have been formed mainly in the Greenschist, up to the middle amphibolite facies through the reactions:

Phengite + Chlorite = Biotite +
$4K(Mg, Fe)(AlSi_4O_{10})(OH)_2$ $(Mg, Fe)_5Al(AlSi_3O_{10})(OH)_8$ $3K(Mg, Fe)_3(AlSi_3O_{10})(OH)_2$

Muscovite + Quartz + Water (T|~ 500-600 °C and P~ 3-6.5 Kb) (2)
$KAl_2(AlSi_3O_{10})(OH)_2$ $7SiO_2$ $4H_2O$

Chlorite + Muscovite + Almandine =
$2(Mg,Fe)_4Al_4Si_2O_{10}(OH)_8$ $5KAl_2(AlSi_3O_{10})(OH)_2$ $Fe_3Al_2Si_3O_{12}$

Staurolite + Biotite + Quartz + Water (3)
$2Fe_2Al_9O_6(SiO_4)_4(O,OH)_2$ $K_5Mg_4Fe_3Al(SiO_{10}Al_6O_{40})(OH)_8$ $4SiO_2$ $7H_2O$

(T~600 – 670 °C and P~3- 4 Kb).

Retrograde conditions in the Precambrian basement complex rocks are suggested by the presence of myrmekitic intergrowths, sericitisation of plagioclase and the mantling of hornblende by epidote. The results of the study corroborate the multiple grades of metamorphism common in other parts of the Nigerian Precambrian basement complex.

Introduction

The Precambrian basement complex rocks in Nigeria consist of migmatites and migmatitic gneisses, which are the Basement *sensu stricto*. The complex, slightly migmatised to unmigmatised paraschists with interbeds of meta- and non-meta-igneous rocks are also referred to as the Younger metasediments or the Schist belts. The older granite suite consist mainly of different varieties of granitic rocks/granitoids, including charnockites (hypersthene granites), syenites, as well as minor gabbroic and dioritic rocks (Oyawoye, 1964; Rahaman, 1976; Ajibade, 1976; Ajibade, Woakes & Rahaman, 1987; Obiora, 2005). Unmetamorphosed dolerite and rhyolite porphyry dykes, pegmatite dykes and numerous veins of quartzo-feldspathic materials are intrusions commonly found in the basement complex (Obiora, 2005; Dada, 2006).

Radiometric ages indicate that the Nigerian basement complex is polycyclic and includes rocks of Liberian (2700±200Ma), Eburnean (2000±200Ma), Kibaran (1100±200Ma), and Pan-African (600±150Ma) (Black *et al.,* 1979; Caby, Bertrand & Black, 1981). In recent times, using the 2002 International Geological Time Scale in Faure and Mensing (2005), these ages can be referred to as, "Paleoarchean to Mesoproterozoic (3600 to 1600 Ma)" for Liberian and Eburnean, "Mesoproterozoic to Neoproterozoic (1600 to 1000 Ma)" for Kibaran and "Neoproterozoic to Early Paleozoic (1000 to 545 Ma)" for Pan-African. The metamorphic rocks in different parts of the Nigerian Precambrian basement complex represent different grades of metamorphism ranging from green-schist to upper amphibolite facies (McCurry, 1976; Rahaman, 1976; Onyeagocha, 1984; Dada, 2006).

In Keffi areas (Lat. 8° 30'- 9° 07'N and Long. 7° 37'- 8° 18') (Figs.1), there are not much records of detailed work carried out on the various units of the Precambrian Basement Complex. Most parts of the study area had been mapped as underlain by only the migmatites and migmatitic gneisses.

The occurrence of a schist belt was only shown in parts of the area in the geological map of Nigeria produced by the Geological Survey of Nigeria under Ojo (1994), as well as the most recent geological map of Nigeria (Malomo, 2004). Records of the temperature and pressure regimes of the paleo-metamorphism that produced the rocks in the area are also scarcely available.

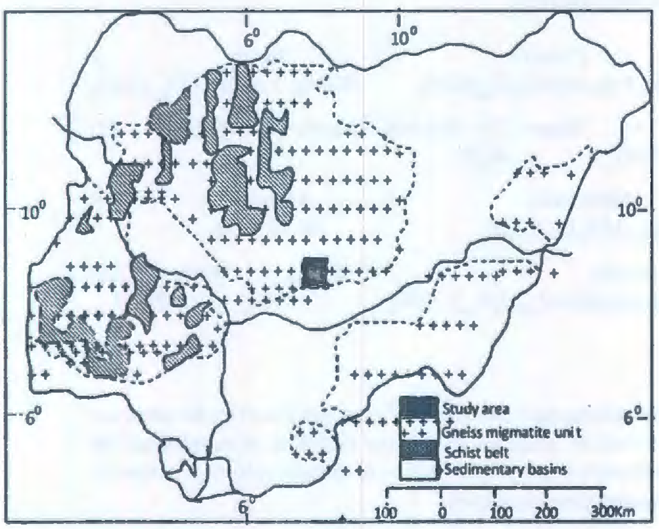


Fig. 1. Map of Nigeria showing the Precambrian Basement Complex

The purpose of this work, therefore, is to delineate the different rocks that constitute the various units of the Nigerian Precambrian basement complex in the study area and to examine the nature of the metamorphism and the geothermometric and geobarometric signatures preserved in the rocks.

Experimental

Description of field occurrences and petrography

The study area is underlain by porphyroblastic/augen gneiss, migmatitic banded gneiss, garnet-mica-schist, staurolite-mica-schist, kyanite-bearing schist, garnetiferous granite and complex pegmatites (Fig. 2). The gneisses constitute the Basement *sensu stricto*, and are either overlain or intruded by the other units. They generally have NNE-SSW trending gneissose foliations with few ENE-WSW and NNW-SSE trends and dip values which vary from as low as 15° to as high as 75°, in both ESE and WNW directions. Gradational and sharp contacts exist between gneisses and schists as observed at Locations E21 and E12, respectively, (Fig. 2).

the gneisses, which have been subdivided into Porphyroblastic /Augen gneiss unit and the migmatitic Banded Gneiss unit. The schists occupy the central parts of the study area and are second most dominant rocks in the area. They are notably found within the low-lying regions and valleys, especially along the river valleys.

Results

The Porphyroblastic/Augen gneiss (PAG)

This was studied at locations E16, E17, E18, E19, E20, E21, E23 and E24 (Fig. 2). It is characterised

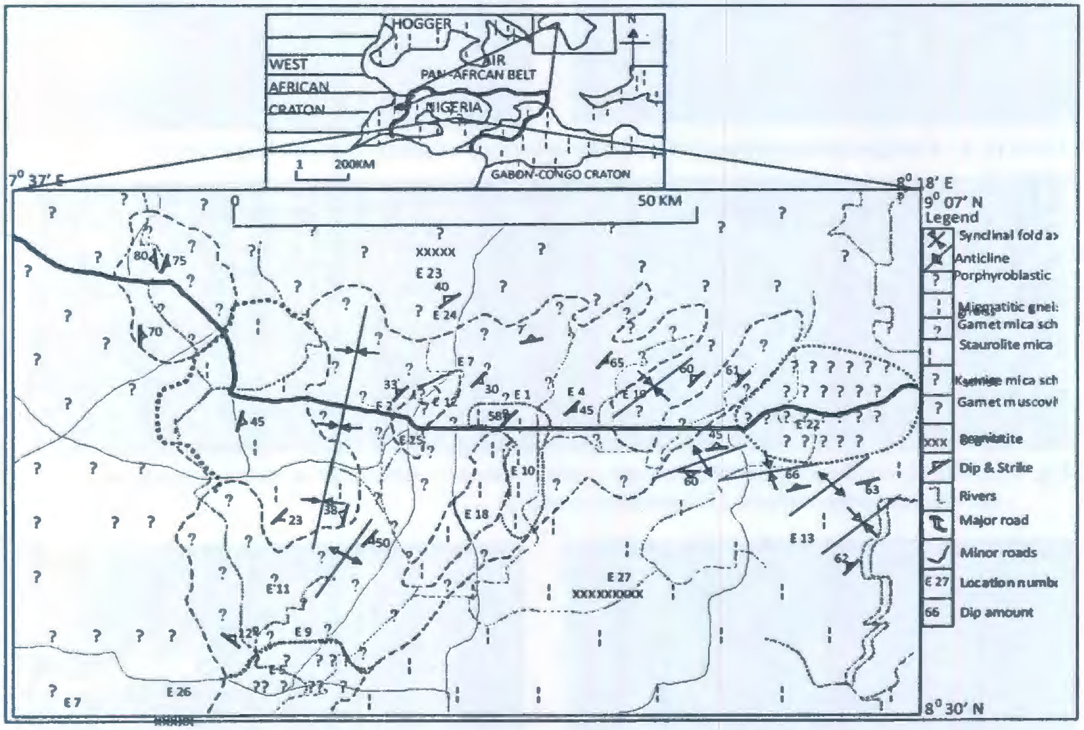


Fig. 2. Geological map of Keffi and its environs, North-central Nigeria. (The inset is a map of the Pan-African belt of West Africa, located between the West African and Gabon-Congo cratons).

Gneisses are the most dominant rocks in the study area. They crop out prominently within the schist-dominated areas, enclosing the schists. All elevated areas are conspicuously underlain by by porphyroblasts of feldspars occasionally exhibiting an eye-like (augen) and zoning structure. The rock is generally mesocratic to leucocratic. It essentially lacks banding, but closer

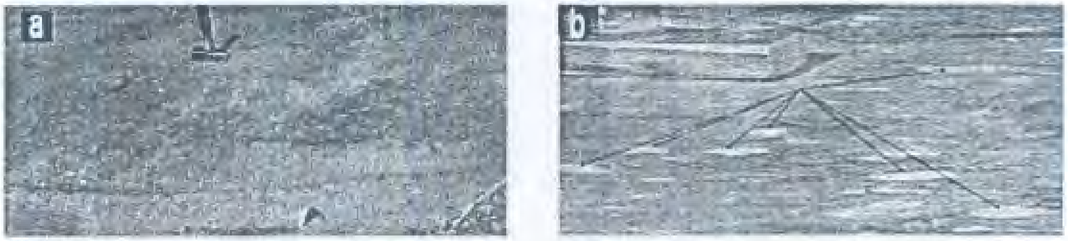
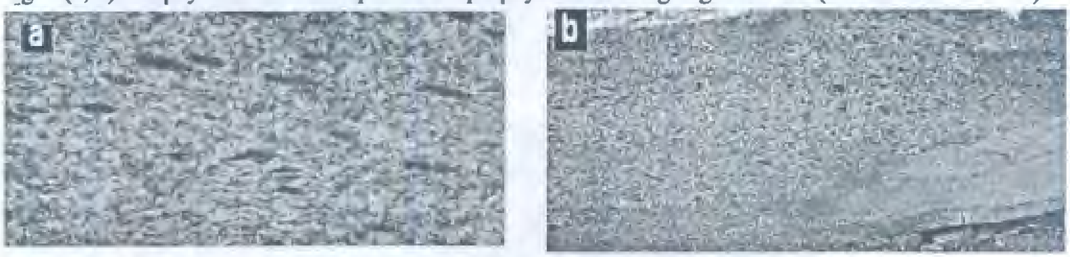


Fig. 3 (a, b). Porphyroblasts of feldspars in the porphyroblastic /augen gneiss unit. (The hammer as scale).



. Fig. 4 (a, b). Elongate porphyroblasts of biotite at an outcrop of porphyroblastic/augen gneiss.

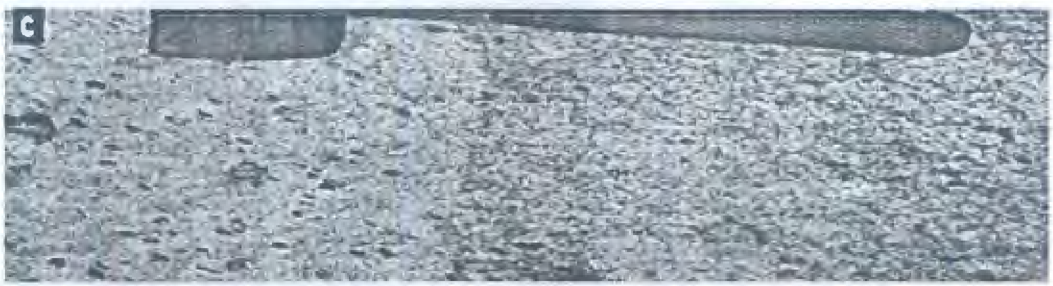


Fig. 4 (c). Cavities in the porphyroblastic/augen gneiss formed by differential weathering and erosion of the biotite porphyroblasts. (The hammer as scale).

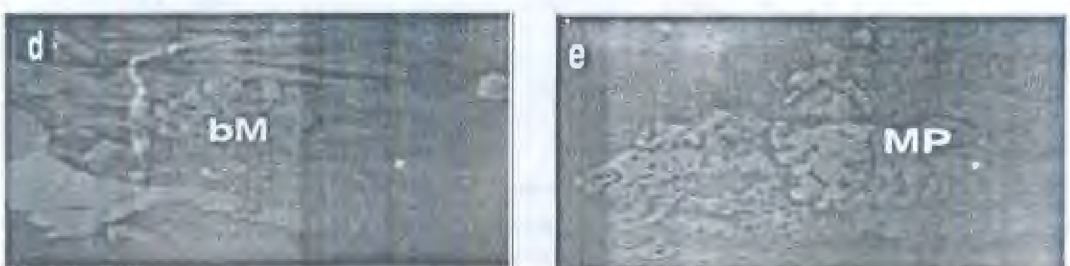


Fig. 4 (d,e). Bulbous myrmekite (BM) in the porphyroblastic/augen gneiss. Crossed polars (x 20).

observation reveals stretching of the constituent minerals occasionally creating augen structures. Some of the feldspar porphyroblasts measure over 5 cm in length and 1.5 cm across. A few are spherical with diameters measuring 1 - 2 mm, while others range between these two extremes (Figs. 3ab). The unit is alternated with layers of micaceous quartzite, which is a very fine grained, weakly foliated, micro-porphyroblastic and leucocratic rock, with average thickness of about 0.5 m and length of over 20 m. In some places, the porphyroblastic/augen gneiss is characterised by elongate porphyroblasts of biotite which measure 2 cm in length and 4 mm across and are mostly aligned in the NE-SW direction (Fig. 4ab). Cavities are formed in the rock by the differential weathering and erosion of the biotite porphyroblasts (Fig. 4c).

The modal compositions of the porphyroblastic/augen gneiss and the other rocks in the study are presented in Table 1. Biotite is the commonest dark-coloured mineral in the porphyroblastic/augen gneiss. It is black and flaky in hand specimen. In thin section, it has one directional perfect cleavage, exhibiting pleochroism from light brown to dark brown. The crystals show middle to upper second order interference colours with near parallel extinction. The colourless nature of muscovite crystals in plane polarized light distinguishes them from biotite crystals.

The platy minerals (biotite and muscovite) define the weak foliation, being aligned in a parallel to sub-parallel manner. The light coloured minerals are quartz, feldspar and occasionally muscovite. In hand specimen, the quartz grains are transparent to smoky and anhedral, with conchoidal fractures. In thin section, they are colourless with first order grayish white to dark-grey interference colours and show undulose extinction. The feldspars in thin section are also colourless, showing first order grey to white interference colours and albite twinning (for plagioclase) and crosshatched twinning (for microcline). The porphyroblasts in the rocks are commonly euhedral to subhedral crystals of feldspars and sometimes quartz in a medium to coarse-grained groundmass of mainly quartz, feldspars and biotite. Various forms of myrmekitic intergrowths are commonly associated with the porphyroblasts of feldspars in this rock (Figs. 4de).

Migmatitic Banded Gneiss (MBG)

The (MBG) unit as sampled at locations E14 and E15 possesses qualities of migmatites such as the occurrence of mixtures of different rock types, microfolding of gneissose foliation, ptygmatic folds and cross-cutting veins of quartzo-feldspathic materials (Fig. 5ab). This medium- to coarse-grained, mesocratic to leucocratic rock unit is characterised by alternating layers of dark- and light-coloured minerals, otherwise described as banded structure. The dark-coloured layers consist mainly of biotite and occasional hornblende which are arranged in a parallel to sub-parallel manner. Hornblende is dark, elongate/slender and prismatic in hand specimen. In thin section, it is distinguished from biotite by its oblique extinction habit in longitudinal sections with maximum extinction angle of 20°. The basal sections show two directional cleavages intersecting at 124° and 56°. The light-coloured layers, on the other hand contain feldspars and quartz, with tiny specks of biotite. This rock unit is occasionally associated with banded hornblende gneiss, which occurs as a melanosome.

This melanosome is a fine to very fine-grained, melanocratic rock, containing large amount of prismatic mafic minerals, namely; hornblende, epidote, biotite, together with plagioclase (andesine, An_{35}). Epidote is colourless and occurs in a granular to columnar aggregates with characteristic fractures, which make it to stand out in relief. The crystals show middle first-order to second-order colours with anomalous blue colours in the middle first-order. Elongate sections exhibit parallel extinction. Some occur as mantles around hornblende.

Fig. 5 (a). Mixtures of paleosome (p), mesosome(m) and neosome(n) at an outcrop of the Migmatitic banded gneiss. (The pen as scale)..

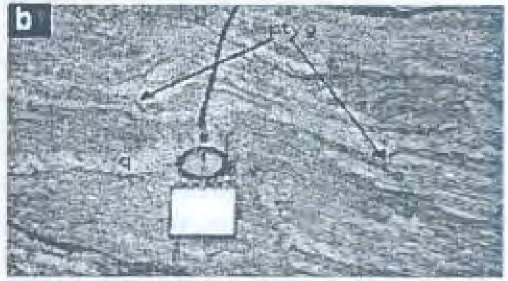


Fig. 5 (b). Quarzofeldspathic injections(q) and ptygmatic folds(ptyg) in migmatitic banded gneiss.(The compass as scale).

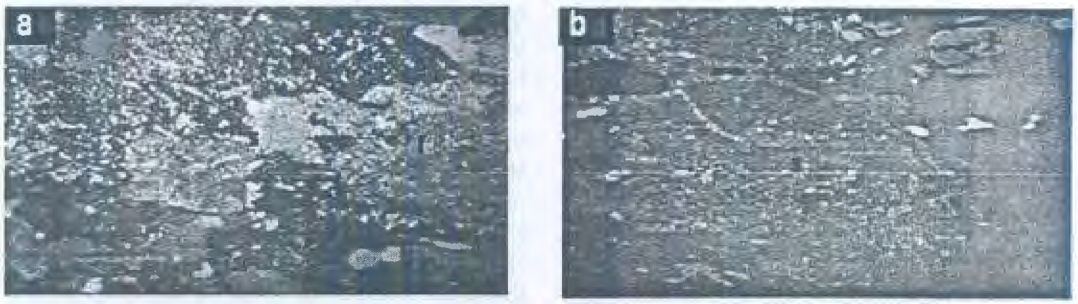


Fig. 6 (a, b). Alteration of feldspars(f) into sericitic minerals(s) in Garnet-mica-schist. Crossed polars (× 12).

Fig. 6 (c). Pennine (chlorite) in garnet-mica-schist from location E1. Plane polarized light (x 24).

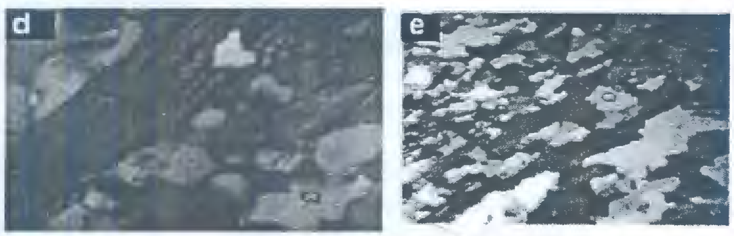


Fig. 6 (d, e). Berlin-blue interference colour of pennine (chlorite) (Pn) in garnet-mica-schist from location E1. Crossed polars (x 24)

TABLE 1
Model composition of rocks in Keffi area

Minerals / Sample No.s	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*
Quartz	30	50	35	55	35	45	30	40	40	25	45	10	15	35	30	35	25	10	30	30	35	15	30	40	60	20
Plagioclase			15			40	15		5			5	10	35	20	15	25	10	30	35	40	25	30	10	10	40
K-feldspar/Microcline												5			15	20	30		10	10		25	30	20	15	35
Biotite	15	25	20	30			38	30	35	10	40	40		15	10	10	10	30	20	10	15	5	5	15	15	
muscovite	30	20	10		20	15	5	25	5	15		10					5			10		10	3	5		
Cordierite										15					10			30				10		10		
Staurolite			10		30					20												8				
Sphene																			3							
Garnet	5	3	5	13	5		10	3	2	10	10	5		10		5	3			2	5	5				5
Chlorite	10									5			5		10			15								
Sericite	10						2				5								3							
Hornblende													60			15			5							
Epidote								2					10													
Zircon															5			5								
Kyanite					10				10			25														
Opaques		2	5	1					1					5							5	2				

Explanation:
Sample nos. 1, 2, 4, 6, 7, 8 and 11, represent the Garnet Mica Schists. Nos. 3 and 10 represent the Staurolite Mica Schists. Nos. 5, 9 and 12, represent the Kyanite schists. No. 13 is the Banded Hornblend Gneiss. Nos. 14 and 15 represent the Migmatitic Banded Gneiss. Nos. 16, 17, 18, 19, 20, 21, 23 and 24 represent the Porphyroblastic/Augen gneisss. No.22 is Garnetiferous Granite. No. 25 is Micaceous Quartzite. Nos. 26 and 27 are Pegmatites.

TABLE 2
Summary of the different rock

Rock types	*Minerals index*	*Temperature ranges*	*Pressure ranges*	*Metamorphic facies*
Porphyroblastic/augen gneiss	garnet (almandine) + biotite + cordierite + K-Feldspar	600-700 °C	3-6 Kb	Middle to Upper Amphibolite
Migmatitic gneiss	garnet + biotite + plagioclase (An_{35})	670-700 °C	~6 Kb	Upper Amphibolite
Garnet-mica-schist	garnet + biotite	500-600 °C	4 -6.5 Kb	Upper Greenschist to Epidote Amphibolite
Staurolite–mica -schist	staurolite + biotite + cordierite	600-670 °C	3-4 Kb	Middle-Amphibolite
Kyanite schist	biotite + garnet + kyanite	670-700 °C	4 -7 Kb	Upper Amphibolite

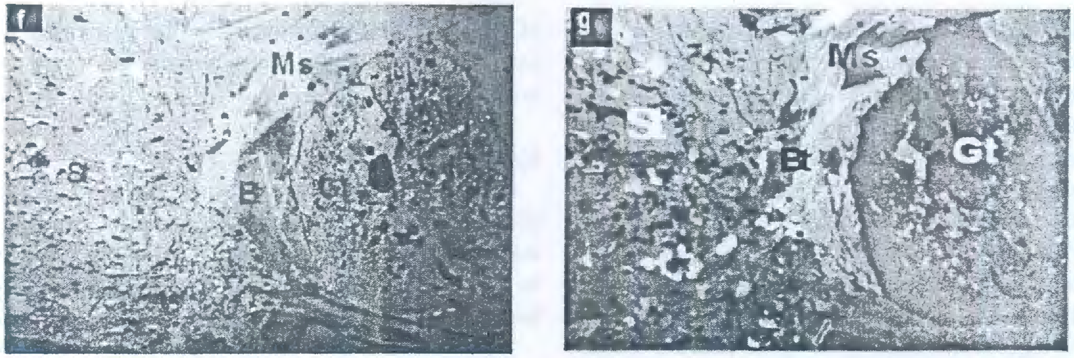


Fig. 6 (f). Poikiloblastic porphyroblasts of Staurolite (S) and garnet (Gt) in Garnet-mica-schist (Location E6) enclosed by the maze of muscovite (Ms) and biotite (Bt) crystals. Plane polarized light (x 60). (g) Same view. Crossed nicols (× 60).

Garnet-mica-schist (GMS)

The GMS unit is exposed at locations E1, E2, E4, E7, E8, E11 and E18b (Fig. 2). The rock unit is the most dominant type of the schistose rocks in the study area. It is generally dark brown and indurated, alternating irregularly with bands of leucocratic quartzo-feldspathic materials. A white coloured variety of the unit occurs at the boundary between the dark-brown variety and the staurolite-bearing schist (Location E6). Some varieties consist of muscovite and large crystals of feldspars which are deeply sericitized (Fig. 6ab). The GMS is dominantly melanocratic, medium to coarse-grained and possesses well-developed schistose foliation, which is defined by platy minerals, namely; chlorite and micas (biotite and muscovite). Other constituent minerals include quartz and garnet (almandine), which occurs as porphyroblasts.

Chlorite occurs mostly as elongate thin scaly aggregates with few sections which are tabular and almost six-sided. The elongate sections have fairly high relief with perfect one directional cleavage traces and are pleochroic from light to dark greenish brown (Fig. 6c). The chlorite has a characteristic Berlin-blue anomalous interference colour (Fig. 6de) which is common in a variety known as penninite. The extinction is parallel to the cleavage traces. Garnet in thin section is neutral, in colour, high relief and occurs in subhedral to euhedral crystals, which are essentially six-sided (Fig. 6f). Some crystals are variously fractured and riddled with inclusions of light and dark-coloured minerals. It is isotropic (Fig. 6g).

Sericite is a silky-tread-like mineral which is colourless with low relief. It has moderate to high birefringence and interference colours of the middle to upper second order. It commonly occurs in irregular matted, felt-like shreds within and or in place of large feldspar crystals. Within these matted, felt-like shreds occur very tiny crystals showing maximum second order interference colours, much like tiny muscovite. The recognition of relicts of partially altered feldspar and muscovite crystals closely associated with sericite is clear evidence that it is an alteration (replacement) product from these minerals.

Staurolite-mica Schist (SMC) unit.

Exposures of SMC unit are most prominent at locations E3 and E10. The unit is exposed over a distance of 1km in a river valley. The surface of the outcrop is dotted with long and slender, euhedral, staurolite crystals. Other mineral constituents of the rock include biotite, muscovite, quartz, kyanite, garnet and cordierite. Averagely, the staurolite crystals are 2.5 cm long and 0.3 cm wide. In thin section, staurolite crystals are like biotite, but lack one directional cleavage. They are mostly poikiloblastic, with inclusions of mainly quartz (Fig.6fg). The basal sections are mostly isotropic although some show low interference colors.

Kyanite is light brownish to pale blue and weakly pleochroic. It occurs in elongate plates that are tabular (Fig. 7ab). The sections have high relief and show perfect to imperfect one directional cleavage. It has first order interference colours, which range up to a maximum of red. Most of the sections show maximum extinction angle of 30°. Cordierite occurs in large rounded hexagonal crystals which are colourless, lacking visible cleavage traces with numerous inclusions. Some of the inclusions are surrounded by pleochroic haloes. It has maximum interference colour of first order grey (Figs. 7cd).

Kyanite Schist (KS)

KS unit was sampled at locations E5, E9 & E12 (Fig. 2). The unit is grayish black and more indurated than most of the other schistose rocks in the study area. It consists of kyanite, quartz, biotite and muscovite.

Garnetiferous Granite (GG)

GG is a leucocratic, coarse-grained rock which lacks preferred orientation of minerals. It was studied at location E22. The constituent minerals are garnet, cordierite and muscovite, in addition

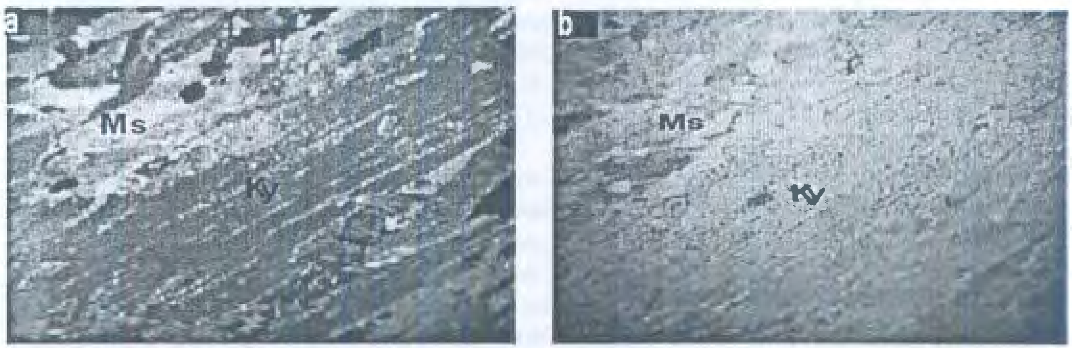


Fig. 7 (a). Broad, columnar crystals of kyanite (Ky) and muscovite (Ms) in Kyanite schist. Crossed polars (x 20). (b) Same view. Plane polars (x 20).

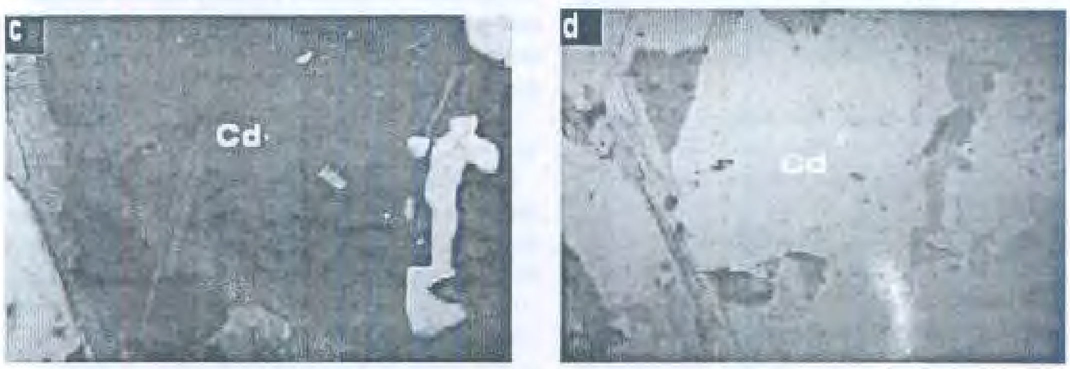


Fig. 7 (c). Somewhat rounded hexagonal crystals of Cordierite (Cd) in garnetiferous granite. Crossed polars (x 16). (d) Same view. Plane polarized light (x 16).

to the common granitic minerals, namely, quartz, plagioclase, microcline and biotite. Plagioclase occurs in colourless and cloudy, subhedral rectangular crystals. The crystals are twinned according to the albite law and have low birefringence with first order grey interference colour. The maximum extinction angle of the crystals is 5° corresponding to oligoclase (An_{17}). The plagioclase is partly sericitized.

Complex pegmatites (CPs)

CPs are exposed at locations E26 and E27. They occur mainly as dykes emplaced within the migmatitic banded gneiss. They are coarse-grained and leucocratic and constituted by quartz, feldspars, mica books, hornblende, aquamarine and tantalite. The pegmatites are varied in their orientations, sizes and rare metal constituents. For instance, cassiterite (tin ore) and topaz are mined in large quantities from location E27 only.

Discussion

Geothermometry and Geobarometry

Porphyroblastic/augen gneiss: The assemblage in porphyroblastic/augen gneiss represents middle to upper amphibolite facies conditions of metamorphism with temperatures of 600-700 °C and pressures of 3-6 Kb based on the stability of the index minerals, namely; garnet (almandine), biotite and cordierite, from the reactions:

$$6[KAl_2(AlSiO_3O_{10})(OH_2)] \quad 2[K(MgFe)_3(AlSi_3O_{10})(OH)_2] \quad 15(SiO_2) = 8(KAlSi_3O_8)$$

Cordierite + water

$$3[(MgFe)_2Al_3(AlSi_5)O_{18}] \quad 8(H_2O) \qquad (4)$$

Muscovite + Biotite + Quartz = K-feldspar +

$$2[KAl_2(AlSiO_3O_{10})(OH_2)] \quad 2[K(MgFe)_3(AlSi_3O_{10})(OH)_2] \quad (SiO_2) = 4(KAlSi_3O_8)$$

Almandine + Al_2SiO_5 + water

$$Fe_3Al_2Si_3O_{12} \quad 4(Al_2SiO_5) \quad 4(H_2O) \qquad (5)$$

However, the presence of K-feldspar and plagioclase might be that the conditions reached the upper amphibolite facies metamorphism (670-700 °C) (Massone & Schreyer, 1987).

Migmatitic banded gneiss

The mineral assemblage of quartz + biotite + garnet (almandine) + plagioclase (An_{25}) + hornblende zircon + opaque in this rock represents high-grade (upper amphibolite facies) condition because of the index minerals: garnet + biotite + plagioclase (An_{25}) with stability ranges of 670-700 °C and pressures of ~6 Kb (Massone & Schreyer, 1987). These index minerals could be formed from the following reactions:

Chlorite + Muscovite + Quartz = Almandine +

$$3(Mg, Fe)_4Al_4Si_2O_{10}(OH)_8 \quad KAl_2(AlSi_3O_{10})(OH)_2 \quad 10SiO_2 = 3(Fe, Mg)_3Al_2Si_3O_{12}$$

Biotite + Water

$$K(Mg, Fe)_3Al_3(Si_{10}Al_6O_{36})(OH)_2 \quad 12H_2O \qquad (6)$$

The presence of K-feldspar in the absence of muscovite should be expected at temperatures of e" 750 °C if Al_2SiO_5 (Kyanite/Sillimanite) was present through the following reactions:

Muscovite	+	Quartz	=	K feldspar	+	Kyanite/Sillimanite	+	Water	
$KAl_2(AlSiO_3O_{10})(OH)_2$		SiO_2	=	$KAlSiO_3O_8$		Al_2SiO_5		H_2O	(7)

Otherwise, K-feldspar could be suspected to be detrital.

Garnet-mica-schist.

The assemblages of chlorite + biotite + garnet (almandine) + quartz + muscovite in the garnet-mica-schists represent upper greenschist to epidote amphibolite facies conditions based on the index minerals garnet + biotite, which are stable around temperatures of 500-600 °C and pressures of 4–6.5 Kb. The index minerals could be formed from the reaction:

Phengite + Chlorite = Biotite +

$4K(Mg, Fe)(AlSi_4O_{10})(OH)_2$ $(Mg, Fe)_5Al(AlSi_3O_{10})(OH)_8$ $3K(Mg, Fe)_3(AlSi_3O_{10})(OH)_2$

Muscovite + Quartz + Water

$KAl_2(AlSi_3O_{10})(OH)_2$ $7SiO_2$ $4H_2O$ (8)

Muscovite + Chlorite = Biotite +

$3KAl_2(AlSi_3O_{10})(OH)_2$ $5(Mg, Fe)_5Al(AlSi_3O_{10})(OH)_8$ $3K(Mg, Fe)_3(AlSi_3O_{10}(OH)_2$

Al-rich Chlorite + Quartz + Water

$4(Mg, Fe)_4Al_4Si_2O_{10}(OH)_8$ $7SiO_2$ $4H_2O$ (9)

Al-rich Chlorite + Muscovite + Quartz = Almandine +

$3(Mg, Fe)_4Al_4Si_2O_{10}(OH)_8$ $KAl_2(AlSi_3O_{10})(OH)_2$ $10SiO_2$ $3(Fe, Mg)_3Al_2Si_3O_{12}$

Biotite + Water

$K(Mg, Fe)_3Al_3(Si_{10}Al_6O_{36})(OH)_2$ $12H_2O$ (10)

Staurolite-mica-schist.

The assemblage of staurolite + quartz + muscovite + cordierite + biotite and chlorite in the staurolite-mica-schist could also be formed at temperatures of about 600-670 °C and pressures of 3-4 Kb (Hyndman, 1972) in the mid-amphibolite facies of metamorphism based on the presence of the index minerals; staurolite + biotite + cordierite according to the following reactions:

(1) Al-rich Chlorite + Muscovite + Almandine = Staurolite +

$2(Mg, Fe)_4Al_4Si_2O_{10}(OH)_8$ $5KAl_2(AlSi_3O_{10})(OH)_2$ $Fe_3Al_2Si_3O_{12}$ = $2Fe_2Al_9O_6(SiO_4)_4(O,OH)_2$

Biotite + Quartz + Water

$K_5Mg_4Fe_3Al(SiO_{10}Al_6O_{40})$ $4SiO_2$ $12H_2O$ (11)

(2) Al-rich Chlorite + Muscovite = Staurolite +

$3(Mg, Fe)_4Al_4Si_2O_{10}(OH)_8$ $5KAl_2(AlSi_3O_{10})(OH)_2$ $= 2Fe_2Al_9O_6(SiO_4)_4(O,OH)_2$

Biotite + Quartz + Water

$K_5Mg_5Fe_3Al_3(Al_6Si_{10}O_{40})(OH)_8$ $3SiO_2$ $11H_2O$ (12)

(3) Chlorite + Muscovite + Quartz = Cordierite +

$(Mg, Fe)_5Al(AlSi_3O_{10})(OH)_8$ $KAl_2(AlSi_3O_{10})(OH)_2$ $2SiO_2$ $(Mg, Fe)_2Al_3(AlSi_5)O_{18}$

Biotite + Water.

$K(Mg, Fe)_3(AlSi_3O_{10})(OH)_2$ $4H_2O$ (13)

(4) Al-rich Chlorite + Muscovite + Quartz = Cordierite +

$3(Mg, Fe)_4Al_4Si_2O_{10}(OH)_8$ $2KAl_2(AlSi_3O_{10})(OH_2)$ $11SiO_2$ $= 3(Mg, Fe)_2Al_3(AlSi_5)O_{18}$

Biotite + $Al_2SiO\text{-}_5$ + Water.

$2K(Mg, Fe)_3(AlSi_3O_{10})(OH)_2$ $2Al_2SiO_5$- $12H_2O$ (14)

The kyanite schists.

The assemblage of biotite + kyanite + muscovite + quartz + garnet (almandine) + K-feldspar + plagioclase in the kyanite schist represents upper amphibolite facies metamorphism, which could occur at temperatures of 670-700 °C and pressures of 4 -7 Kb. This is based on the presence of the index minerals; biotite, garnet and kyanite (Massone & Schreyer, 1987; Barker, 1998). The following reactions could have occurred:

(1) Al-rich Chlorite + Muscovite + Quartz = Almandine +

$3(Mg, Fe)_4Al_4Si_2O_{10}(OH)_8$ $KAl_2(AlSi_3O_{10})(OH)_2$ $10SiO_2$ $= 3(Fe, Mg)_3Al_2Si_3O_{12}$

Biotite + Water

$K(Mg,Fe)_3Al_3(Si_{10}Al_6O_{36})(OH)_2$ $12H_2O$ (15)

(2) Chlorite + Muscovite + Quartz = Kyanite +

$3(Mg, Fe)_4Al_4Si_2O_{10}(OH)_8$ $4KAl_2(AlSi_3O_{10})(OH)_2$ $4SiO_2$ $10Al\text{-}_2SiO_5$

Biotite + Water

$4K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$ $12H\text{-}_2O$ (16)

The presence of the large quantity of kyanite suggests higher pressure condition than in the rest of the assemblages. A summary of the different rock units in the study, their constituent index minerals and their possible temperature and pressure conditions of formation and corresponding metamorphic facies is shown in Table 2.

The metamorphic conditions attained by the rocks in the study were similar to those in rocks in other parts of the Nigerian basement complex. Most of the assemblages recorded in the migmatite-gneiss complex reflected the staurolite-almandine sub-facies of the amphibolite facies (Rahaman, 1976; Ekwueme & Ekwere, 1989; Ejimofor, Umeji & Turaki, 1996; Obiora, 2006). However, higher metamorphic grades containing sillimanite and sometimes, kyanite, which represent the highest grade of the Barrovian type of metamorphism, have also been obtained (McCurry, 1976; Onyeagocha, 1984). Conditions in the range of Upper Amphibolite to Granulite facies have also been recorded in the gneisses (Onyeagocha & Ekwueme, 1990; Dada, 2006). Elueze (1981) recorded assemblages of quartz + muscovite + chlorite + biotite, which are indicative of the upper Greenschist facies and biotite + garnet + staurolite, indicative of middle amphibolite facies in the rocks of the Ilesha Schist belt.

The occurrence of augen structures, paleosomes, and abundant quartzo-feldspathic veins and dykes suggests that the gneisses in the study could have been affected by partial melting (anatexis), which commonly occurs at extreme high-grade of metamorphism. The growth of garnet, with inclusions of muscovite, and staurolite, with inclusions of quartz is some of the microstructures, indicating prograde metamorphism. The presence of myrmekitic intergrowths, which are commonly associated with the breakdown of feldspars in the gneisses (Barker, 1998), is also evidence that the rocks attained the amphibolite facies grade of metamorphism, but were later affected by a retrograde metamorphism. Although there are records of retrograde metamorphism in the Schist belts (Annor, 1995, 1998), there seems to be agreement among researchers in the progressive nature of the metamorphism in the Precambrian basement complex of Nigeria (McCurry ,1976; Rahaman, 1976; Dada, 2006).

Conclusion

An assessment of the temperature and pressure conditions of metamorphism in the study area, using the stability ranges of index minerals contained in the metamorphic rocks revealed that the rocks were formed under conditions ranging from upper Greenschist to upper amphibolite facies. The porphyroblastic/augen gneiss and migmatitic banded gneiss were formed under conditions in the range of middle to upper amphibolite, representing temperatures in the range of 600–700 °C and pressures of 3–6 Kb. The garnet-mica schist and staurolite-mica schist were formed in the range of upper Greenschist to middle amphibolite, which represent temperatures in the range of 500 - 670 °C and pressures of 3–6.5 Kb whereas the kyanite schist was formed in the upper amphibolite facies, representing temperatures in the range of 600–700 °C and pressures of 4–7 Kb.

The stage of anatexis might have been reached during the metamorphism as suggested by the occurrence of augen structures, paleosomes, and abundant quartzo-feldspathic veins and pegmatite dykes. Although the metamorphism is essentially progressive, retrograde conditions had occurred as shown by the presence of myrmekitic intergrowths, sericitisation of plagioclase and the mantling of hornblende by epidote. The metamorphic conditions attained by the rocks in the study were similar to those in rocks in other parts of the Nigerian basement complex.

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