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Geology and Geotectonic Setting of the Basement Complex Rocks in South Western Nigeria: Implications on Provenance and Evolution

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1. Introduction

1.1 Regional geology of Nigeria

Nigeria lies approximately between latitudes 4^{o}N and 15^{o}N and Longitudes 3^{o}E and 14^{o}E, within the Pan African mobile belt in between the West African and Congo cratons. The Geology of Nigeria is dominated by crystalline and sedimentary rocks both occurring approximately in equal proportions (Woakes et al 1987). The crystalline rocks are made up of Precambrian basement complex and the Phanerozoic rocks which occur in the eastern region of the country and in the north central part of Nigeria. The Precambrian basement rocks in Nigeria consist of the migmatite gneissic –quartzite complex dated Archean to Early Proterozoic (2700-2000 Ma). Other units include the NE-SW trending schist belts mostly developed in the western half of the country and the granitoid plutons of the older granite suite dated Late Proterozoic to Early Phanerozoic (750-450Ma).

2. Geology of southwestern Nigeria basement complex

The area covered by the southwestern Nigeria basement complex lies between latitudes 7^{oN} and 10^{oN} and longtitudes 3^{oE} and 6^{oE} right in the equatorial rain forest region of Africa (Fig.1). The main lithologies include the amphibolites, migmatite gneisses, granites and pegmatites. Other important rock units are the schists, made up of biotite schist, quartzite schist talk-tremolite schist, and the muscovite schists. The crystalline rocks intruded into these schistose rocks. For the purpose of this chapter, discussion is limited to the crystalline basement rocks of southwestern Nigeria.

2.1 The Amphibolite and the hornblende gneiss

The amphibolite and the hornblende gneiss are the mafic and intermediate rocks in south western Nigeria. The amphibolites are made up of the massive melanocratic and foliated amphibolites. In Ilesha and Ife areas these amphibolites occur as low lying outcrops and most are seen in riverbeds. The massive melanocratic amphibolite is darkish green and fine grained. Commonly hornblende gneiss outcrops share common boundaries with the melanocratic amphibolite. This rock (hornblende gneiss) crops out at Igangan, Aiyetoro and Ifewara, along Ile-Ife road as low lying hills in southwestern Nigeria. The hornblende gneiss is highly foliated, folded and faulted in places.

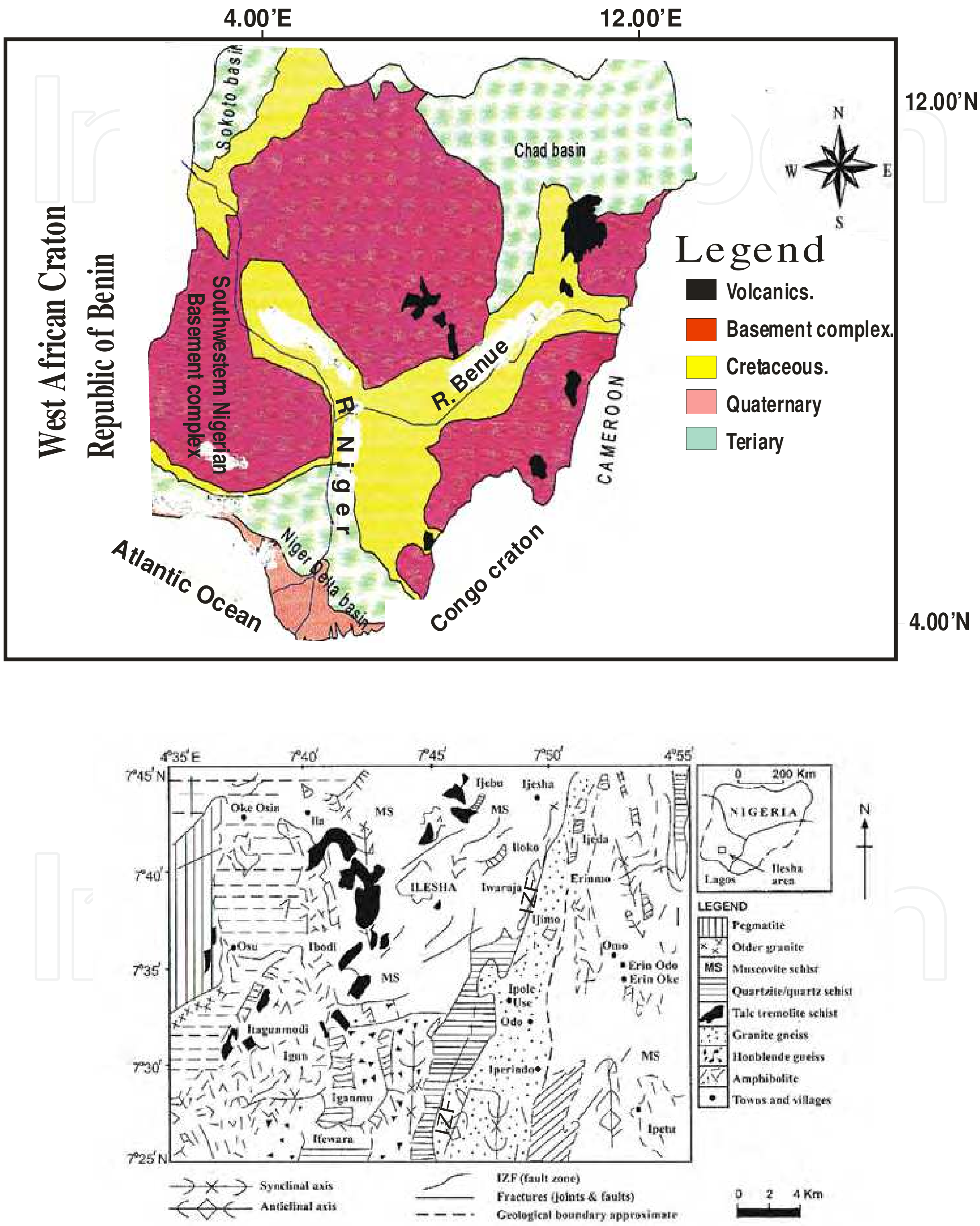

Fig. 1. a) Geological map of Nigeria; b) Geological map of Ilesha schist belt Southwestern Nigeria (modified from Elueze, 1982)

2.2 The Magmatite -gnessic complex

This geotectonic complex which constitutes over 75% of the surface area of the south-western Nigerian basement complex is said to have evolved through 3 major geotectonic events:

- Initiation of crust forming process during the Early Proterozoic (2000Ma) typified by the Ibadan (Southwestern Nigeria) grey gneisses considered by Woakes et al; (1987) as to have been derived directly from the mantle.
- Emplacement of granites in Early Proterozoic (2000Ma) and
- The Pan African events (450Ma-750Ma). Rahaman and Ocan (1978) on the basis of geological field mapping reported over ten evolutionary events within the basement complex with the emplacement of dolerite dykes as the youngest. On the basis of wide geochemical analyses and interpretation, geotectonic studies, field mapping and plumbotectonics, Oyinloye (1998 and 2011) had suggested a modified Burke et al; (1976) sequence of evolutionary events in the Southwestern Nigeria basement complex as detailed in Table1.

S/N	**Sequence of Evolutionary Events in the South Western Nigeria basement complex**
11	Shearing, Chloritic and Zeolite mineralization of uncertain age.
10	Emplacement of dolerite dykes and gold mineralization at about 550Ma **(Oyinloye, 2006b)**
9	Formation of unsheared pegmatite, unfolded granitic veins of mid-Pan African age.
8	Major remobilization and deformation in Early Pan-African
7	Minor metamorphic deformation in Kibaran
6	Emplacement of microdiorite
5	Emplacement of Ibadan-Ile-Ife-Ilesha Granite gneiss: F2 folding fabrics in Granite, Gneiss.
4	Emplacement of microdiorite dykes of uncertain age
3	Emplacement of semiconcordant aplite sheets in the banded gneiss, collision of plates subduction of ocean slab in to the mantle **(Oyinloye, 2002b)**
2	Deposition of ocean sediments covering the whole basement complex **(Oyinloye 2002a)**
1	Generation and differentiation of wet basaltic magma and formation of proto continent, **(Oyinloye, 2004a)**.

Table 1. A modified sequence of events in the basement rocks in Ibadan-Ile-Ife-Ilesha area (modified from Burk et al; 1976)

2.3 Metamorphism in the southwestern Nigeria basement rocks

On the basis of petrology a medium pressure Barrovian and Low-medium pressure types of metamorphism had been suggested for the Precambrian basement rocks in south western Nigeria (Rahaman 1988). These metamorphic types are based on the occurrence of index minerals like chlorite, biotite and sillimenite in the basement rocks of southwestern Nigeria. Rahaman (1988) therefore concluded that metamorphism in all Nigerian Precambrian complex rocks especially that of Ife-Ilesha (Southwestern Nigeria) ranges from green schist to lower amphibolite metamorphic facies. However, Oyinloye (1992) on the basis of petrology, field mapping and structural analyses reported that the prominent gneissic foliations observed on some of the gneisses suggest that metamorphism actually reached an upper amphibolite facies in the rocks of the basement complex in Southwestern Nigeria. Egbuniwe (1982) suggested 3 phases of metamorphism (M_1, M_2 and M_3) associated with 3 phases of deformation (D1, D2, D3) within the crystalline rocks of the basement complex in northern Nigeria. According to this author M1 represents a period of progressive metamorphism to lower amphibolite facies. M2 is described as retrogressive and reached only green schist grade as did M3. In the southwest Boesse and Ocan (1988) recognized 3 phases of metamorphism but only 2 phases of deformation. M1 is considered to be a syntectonic progressive phase of metamorphism to amphibolite facies with isoclinal folding, mineralogical banding and development of staurolite, sillimanite and garnet. M2 is described as syntectonic and associated with shear deformation and M3 being static retrogressing the earlier formed garnet and biotite to chlorite. Oyinloye (1992) however suggested that M1 is syntectonic and perhaps synchronous with the formation of the large scale major fault zone indicated by formation of mylonite outcrops at Iwaraja, Southwestern Nigeria. M2 is also syntectonic and contemporaneous with D2 as indicated by the development of micro faulting folding (Plate 1), fracturing, shearing, formation of phyllonite and mylonite with distorted garnet crystals surrounded by syllimanite crystals and mylonitised granite gneisses.

3. Geochronology of the basement rocks of southwestern Nigeria

It has been established that the Precambrian basement complex of Nigeria including Southwestern Nigeria is polycyclic in nature, (Ajibade and Fitches 1988). The southwestern Nigeria basement complex had undergone 4 major orogenesis in:-

i. Liberian (Archaean) 2500Ma-2750± 25Ma
ii. The Eburnean orogeny (Early Proterozoic), 2000Ma-2500Ma
iii. The Kibaran orogeny (Mid Proterozoic), 1100Ma - 2000Ma
iv. The Pan African Orogeny, 450Ma-750Ma.

Of all the above, the Eburnean and the Pan-African are major events which modified the Precambrian Geology of Nigeria including the Southwestern Nigerian basement complex. The Eburnean event is marked by the emplacement of the Ibadan granite gneiss in Southwestern Nigeria which has been dated 2500±200Ma (Rahaman 1988) and a pink granite gneiss at Ile-Ife Southwestern Nigeria dated 1875Ma using U-Pb on Zircon. Thus Archaean to Pan African ages had been suggested for the basement rocks of the Southwestern Nigeria.

Oyinloye (2006b), based on Pb-Pb model dating suggested 2750±25Ma (Archaean age) for the gneisses in Ilesha area Southwestern Nigeria. Few studies have been carried out on the basement complex due to its assumed monotonous petrology and mineralogy and the erroneous belief that it contains no mineralization. This current chapter will therefore contribute immensely to the debate on geology of the basement complex of Southwestern Nigeria.

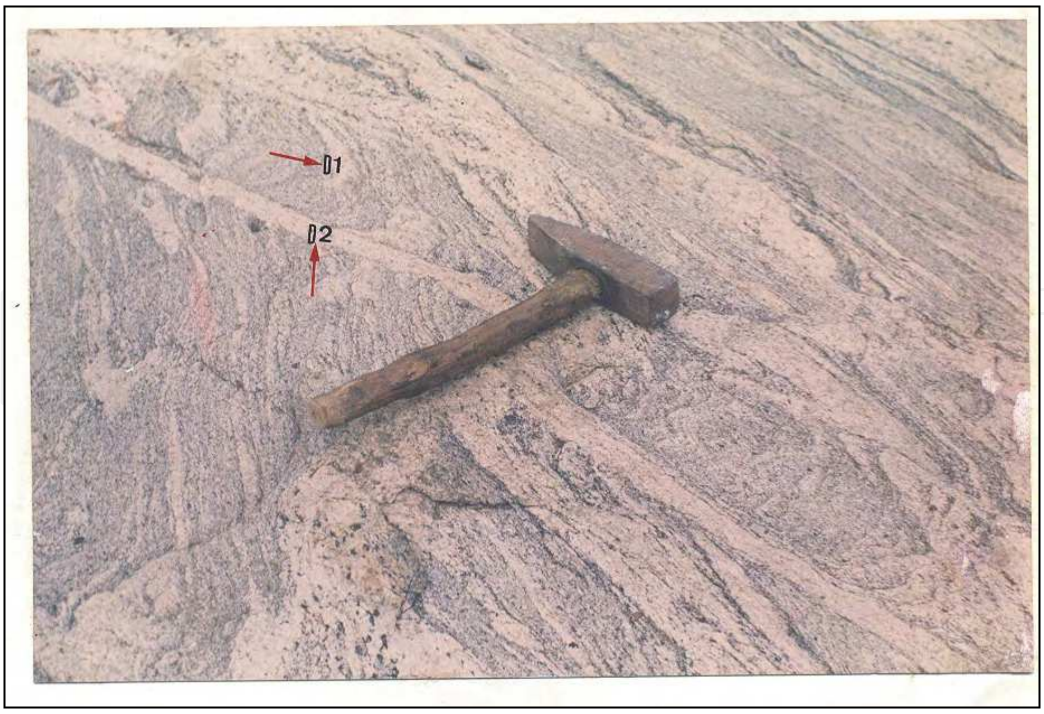

Plate 1. Deformation structures in the blotite granite gneiss, Iperindo area, Ilesha schist belt southwestern Nigeria, D2 (qtz vein) cuts across foliation planes (D1), The Hammer (2cm wide) marks a minor fault displacement

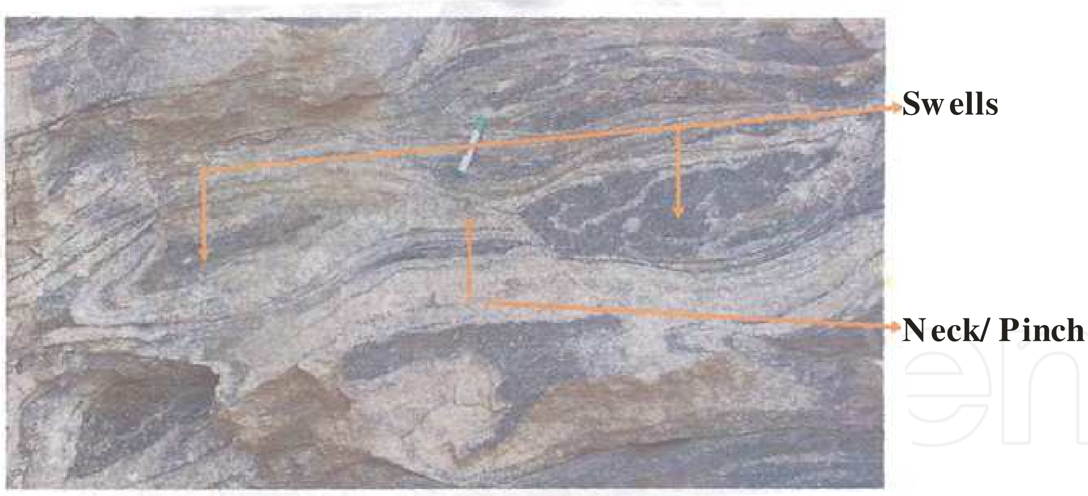

Plate 2. Showing Pinch and Swell Stuctures

4. Geological setting of southwestern Nigeria basement complex

The basement rocks which occur in southwestern Nigeria are all duplicated in the Ilesha area of southwestern Nigeria and samples of rocks here were analyzed and used as a case study of the basement rocks in Southwestern Nigeria to avoid repetition. These rocks are amphibolite, the hornblende gneiss and the granite gneisses. These rocks are described in that order.

4.1 The massive melanocratic amphibolite

Amphibolite occurs widely in southwestern Nigeria in Ile-Ife area, Ibodi, Itagunmodi in Ilesha area. Most outcrops of the massive melanocratic amphibolites are exposed in streams and river channels in these areas. The overburden soil here is strikingly red due to the presence of hematite and magmatite liberated during the weathering of the amphibolites to form the overburden soil. Two major textural varieties of amphibolites occur in this region. These are the leucocratic amphibolites and (not discussed in this study) the massive melanocractic amphibolites. The massive melanocratic amphibolite is darkish green and fine grained without any obvious folds or foliations. In places thin colourless quartz veins occur on the outcrops. This amphibolite variety is composed of hornblende, actinolite and tremolite. In thin section the mineral composition includes (apart from the above) magnetite, sphene calcite and minor monazite and zircon. The skeletal olivine contains small, opaque inclusions which are probably magnetite.

4.2 The hornblende gneiss

The hornblende gneiss shares a common boundary with the massive melanocratic amphibolite in Ilesha area, southwestern Nigeria. This rock crops out as low lying hills in Ife-Ilesha area Southwestern Nigeria. It is composed predominantly of porphy- roblastic plagioclase and hornblende phenocrysts almost in equal proportion. This rock is highly foliated folded and faulted in places and varies from medium to coarse in texture. These outcrops trend in a NE-SW direction and dip to the east at an average angle of between 50-70°. The apparent character varies from intermediate to acid. Microbands of foliation rich in plagioclase and some K-feldspars alternate with bands rich in amphiboles. In thin section this foliated hornblende gneiss consists largely of hornblende and plagioclase porphyroblats in a ground mass of ilmenite fine grained recrystallized quartz and pyroxene fragments. Brown coloured epidote (with dark cracks) apartite, sphene, zircon and monazite constitute major accessory minerals in this rock. Foliations defined by parallel arrangement of feldspars alternating with amphiboles are conspicuous in thin sections. Fine grained quartz and orthoclase feldspars are observed in the felsic microband, garnet, monazite, calcite and microcline containing well formed zircon crystals (as inclusions) occur in this rock as observed in thin sections.

4.3 The biotite granite gneiss complex

This rock group occurs widely in every part of the southwestern Nigerian basement complex. Again description is restricted to Ilesha area to avoid repetition.

Biotite granite gneiss complex occurs in the southern part of Ilesha schist belt. Outcrops of this rock group consist of high and low lying hills with myriads of flat boulders on top in places and roundish boulders on tops of hills elsewhere. This rock complex is foliated and folded with prominent synclinal and anticlinal axes. In places microfolds and microfaulting are observed (Plate1). Wide and narrow quartz veins are commonly seen on the rock and some of these are deformed to form folds and micro faults as described above. Foliations are defined by mafic (biotite rich) and felsic (quartz and feldspars) mineral bands. Drilled core samples from the biotite granite gneiss revealed that microfolds,pinkish garnet rich mylonite, greenish friable schistose phyllonite,occur in this rock.

In thin section the mylonite contains fine grains of biotite and sillimanite surrounding large crystals of garnet which show some evidence of distortion. The mylonite contains little quartz and the biotite flakes form thin foliation bands which are closely packed around garnet crystals. In some of the cores examined recovery failures are recorded indicating fracturing as described above. This biotite granite gneiss contains deformation fabrics which may be regarded as D2 and probably contemporaneous with the M2 phase of metamorphism following D1 and M1 (Plate 1). These later events may be due to movements along the major Ifewara-Zungeru fault system. The biotite granite gneiss are surrounded by muscovite-quartzite schists and in places the later are in-foled into the gneisses where they occur as reminants. At outcrop scale, the biotie granite gneiss is composed of biotite, K-feldsper, quartz and garnet. In thin section the biotite flakes are pencil-like as a result of metamorphic deformation and are aligned in parallel to sub parallel manner. The K-feldspar is mostly microcline and is porphyroblastic in texture. Well formed zircon crystals occur in association with some of the microcline grains. Apartite, monazite, magnetite, ilmenite and sphene are other accessory minerals.

In places distorted and fractured garnet grains due to metamorphic deformation are observed. Continuous well defined foliation bands of micas and felsic minerals are also common features of this gneiss. These gneissic fabrics probably indicate that metamorphism here was perhaps higher than the green schist-lower amphibolite facie regarded as the meramorphic grade for rocks in the basement complex in southwestern Nigeria. The presence of mylonite, mylonitised granite and gneissic banding are probable indications of a localized dynamic metamorphism possibly reaching an upper amphibolite facie.

4.4 The pink granite gneisses

This variety of gneiss occurs widely in the southwestern Nigeria basement complex at Ile-Ife, Ibadan, Iseyin, Eruwa and Iwaraja and in Ilesha area. The granite gneiss is pinkish with large pherocrysts of K-feldspar and porphyroblasts of hornblende. The texture of the pink granite gneiss varies from medium grained to very coarse almost becoming pegmatitic in places. Augen structures are commonly observed on the pink granite gneiss. This pink granite gneiss is fractured in places and elsewhere folded. Augen structures with clear elongate lozenges (boudins) and neck or pinch structures (pinch and swell) as a result of stressing are commonly seen on the pink granite gneiss in this region (Plate 2).

In thin section, foliation is defined by elongate hornblende and drawn out K-feldspar porphyries. Other minerals include quartz, plagioclase, some biotite flakes, garnet, apartite and zircon. Monazite forms an important accessory mineral in this rock. Commonly, phenocrysts of orthoclase occur within a matrix of recrystallised quartz and microcline. At Iwaraja, a major fault marked by a mylonite outcrop is observed within the pink granite gneiss terrain. This mylonite marks the southern extension of the Ifewara – Iwaraja-Zungeru major fault which runs in a NE-SW direction across the country. Deformation fabrics in the southwestern Nigeria basement complex are commonly aligned parallel to the direction of the Ifewara-Zungeru fault zone implying that this fault has a profound and wide influence on fabric and metamorphism in this region. According to Boesse and Ocan (1988) this major fault (marked by the mylonite outcrops) marks a break between the granite gneissic complex and the metasediments in this region.

4.5 The grey granite gneiss

The grey granite gneiss occurs prominently at Ibadan, Oyan, and in Ilesha areas of southwestern Nigeria basement complex. Usually outcrops consist of high and low hills and at Erinmo in Ilesha area occur very close to the pink granite gneiss and only separated by a narrow strip of muscovite quartzite schist. The overall colour is greyish. The texture of this variety of gneiss is fine to medium grained with well developed foliation defined by preferred orientation of biotite. This rock is mostly composed of quartz, biotite, plagioclase, K-feldspar and hornblende. In thin section recrystallised fine grained quartz covers the surface of microcline phenocrysts as overgrowths. This is a common phenomenon in all the granite gneisses investigated in this study. Mosaic textures formed by fragments of plagioclase, biotite and recrystallised quartz are also observed. Intergrowths of orthoclase and microcline forming a perthitic texture occur in places. Quartz crystals consist of fractured and recrystallised fine varieties. Well formed rod-like and fragmented zircon crystals, apatite, monazite plus minor garnet form important accessory minerals.

5. Geochemistry

The geochemical data described in this chapter are presented in the following order.

1. Massive Melanocratic Amphibolite
2. The Hornblende Gneiss
3. The Biotite Gneiss
4. The Pink Granite Gneiss

Note:- The average geochemical data discussed here are not included in this write up because of space. These are available from the author on request.

5.1 The massive melanocratic amphibolite: Major elements

In this study it is observed that element concentrations in the massive melanocratic amphibolite vary little even between samples collected from outcrops almost 1km apart. The mean SiO_2 concentration in this rock is 49% (17samples) alumina 15%, total iron 11%, MgO 10% and CaO 12%. The high iron concentration in the melanocratic amphibolite reflects the abundance of titanomagnetite and the high CaO content is an indication of the preponderance of Ca-rich pyroxene. T_iO_2 content (average 1%) reflects some sphene in addition to titanogmagnetite . The total alkaline concentration is very low reflecting the sub-alkaline nature of this rock. Na_2O is consistently higher than K_2O in this rock perhaps reflecting the dominance of albite in the massive melanocratic amphibolite.

MgO/ Fe_2O_3+MgO ratios vary between 0.45 to 0.48 with a mean of 0.46. This is considerably lower than that of a pure primitive upper mantle which has a range of 0.68-0.75 and a mean of 0.70 (Wilson, 1991).

5.2 Trace elements

In the massive melanocratic amphibolite Rb is characteristically low, 11ppm on average indicating low K-feldspar concentration as observed in the thin section studies. Sr with an average of 169ppm is relatively high in the massive melanocratic amphibolite due to substitution of Sr for Ca in the pyroxene and amphiboles as is Zr (58ppm) due to minor zircon. Zr can also substitute for Ti in accessory phase in sphene and rutile. Y concentrations are appreciable (mean 19ppm) since this element is readily accommodated in amphiboles which are the dominant minerals of the amphibolite. The low Th in this rock reflects fractionation into more felsic magmatic franctions. The average concentrations of compatible elements (Ni, Cr, and Co) in the massive melanocratic amphibolite are 102ppm, 81ppm and 54pm respectively. These values are too low for an amphibolite originating from a pure primitive upper mantle. The low concentrations of compatible elements suggest that the precursor rock of the amphibolite is from a depleted or metasomatised mantle and this has a significant implication on provenance and geotectonic setting in which the rock was formed.

5.3 Rare earth elements

Rare earth elements are significantly recorded in the massive melanocratic amphibolite. The average total REE in the massive melanocratic amphibolite is 71ppm. The dominance of light rare earth elements (59ppm) over the heavy ones average 12ppm reflects the relative abundance of monazite in the amphibotite and further suggests that this mafic rock is not from a pure primitive mantle.

5.4 The horblende gniess

Field and petrological studies revealed that this rock consists of intermediate to acid varieties. The average SiO_2 (63%) in the hornblende gneiss is much higher than that of the massive melanocratic amphibolite. TiO_2 and Fe_2O_3 averages are lower than that of the amphibolite reflecting the less mafic character of the hornblende gneiss. The relatively higher total alkalis (mean 7%) and K_2O/Na_2O ratios (0.8) are indicative of more abundant feldspars in the hornblende gneiss than the amphibolite which is consistent with field and thin section observations. The MgO/Fe_2O_3+MgO mean ratio is 0.32 and this is lower than in the amphibolite and thus further from pure upper mantle value. In this rock the average concentration of Rb (68ppm) is more than 6 times its concentration in the amphibolite paralleling the increase K-feldpar content. Sr and Ba are also strongly enriched (1266ppm and 1493ppm respectively). This is perhaps due to substitution of Ba for K in the K-feldspar and Sr for Ca in plagioclase. The higher Y (mean 37ppm) concentration in the hornblende gneiss compared with the amphibolite may be due to the presence of more hornblende (dominant mineral in the hornblende gneiss) which often concentrates this element. Low Th concent of the hornblende gneiss average (6ppm) might be due to minimal crustal contribution. In the hornblende gneiss, the mean concentraction of Ni, Cr, are less still (26ppm and 39ppm respectively) reflecting the less mafic character of this rock.

5.5 Rare earth elements (REE)

In the hornblende gneiss, there is a high concentration of REE most especially the light ones. The average total REE in the hornblende gneiss is 3232ppm. The light REE in this rock has a mean of 2174ppm. The mean concentration of the heavy REE in the hornblende gneiss (58ppm) is relatively higher than in the amphibolite reflecting more abundant REE concentrating minerals e.g. sphene and monazite.

6. The biotite granite gneiss

6.1 Major elements

The biotite granite gneiss is one of the series of granitic rocks with SiO_2 higher than 70% in southwestern Nigeria basement complex. TiO_2 average concentration in this rock (0.42%) is slightly higher than in the hornblende gneiss. Al_2O_3 mean (15%) is slightly higher in this rock than in the hornblende gneiss. Unlike the amphibolite and the hornblende gneiss, the Na_2O concentration is consistently less than K_2O in the biotite granite gneiss. K_2O/Na_2O ratios are consistently higher than 1 (one) in the biotite granite gneiss although the average total Na_2O and K_2O (8%) in the biotite gneiss is only 1% higher than that of the hornblende gneiss. The concentration of SiO_2, Al_2O_3, Na_2O and K_2O in the biotite granite gneiss indicates an abundance of felsic silicates e.g. feldspars and quartz. The consistently higher concentration of K_2O than Na_2O (thus K_2O/Na_2O ratios greater than 1) in the biotite granite gneiss reflects the abundance of K bearing rock forming silicates (i.e microcline and biotite). This trend is also characteristic of Archaean granitic rocks (Martin (1986). In the biotite granite gneiss, the concentrations of Fe_2O_3, MnO, MgO, CaO and P_2O_5 are much less than the average values in the amphibolite and hornblende gneiss. This reflects its less mafic character.

Although major elements of gneisses are sensitive to metamorphic alteration, AFM diagrams can be used to study the enrichment of these rocks in alkalis and Fe in a general way. When the AFM diagram is plotted for the hornblende gneiss and the biotite granite gneiss, both rocks plot in the calc alkali fractionation trend (Fig.2) reflecting enrichment in Al_2O_3, Na_2O and K_2O due to development of biotite and K-feldspars in the biotite granite gneiss and plagioclase in the hornblende gneiss as observed in the petrological studies.

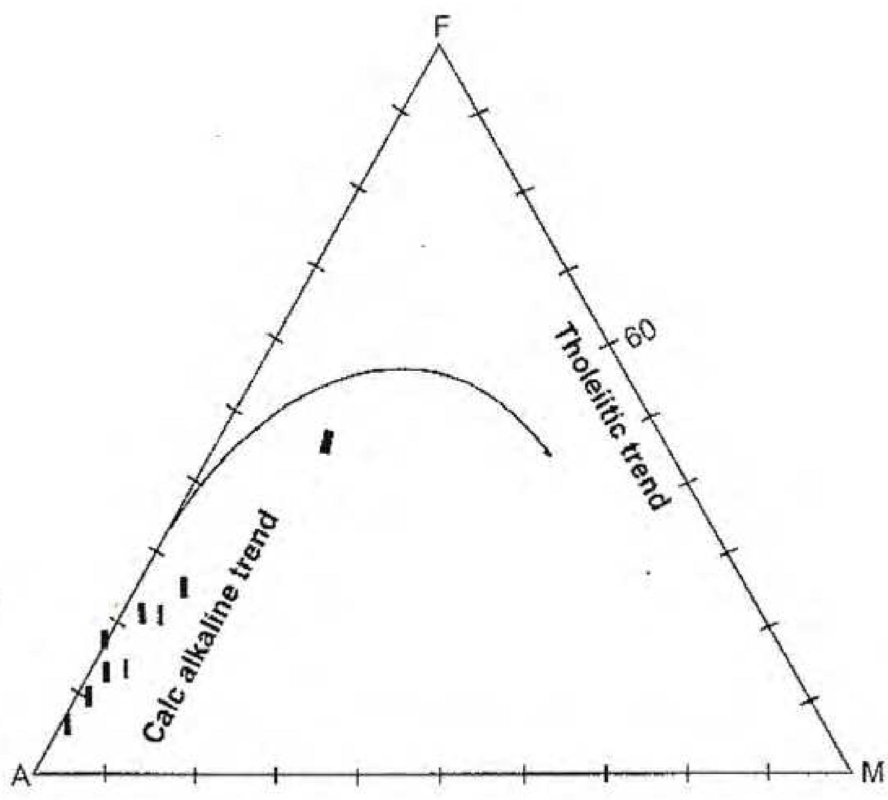

Fig. 2. A=Al_2O_3; F=FeO (total iron); M=MgO (AFM) diagram for the biotite granite gneiss, from Ilesha area

6.2 Trace elements

The average concentration of Rb in the biotite granite gneiss (182ppm) is more than double its average concentration in the hornblende gneiss. The high concentration of Rb in the biotite granite gneiss is due to substitution of Rb for K in the microcline and biotite which are abundant in this rock. The average concentration of Sr (299ppm) is less than 25% of its concentration in the hornblende gneiss. This reflects the low concentration of plagioclase, hornblende and pyroxene in which Sr can substitute for Ca in the biotite gneiss. Zr is more concentrated in the biotite gneiss than in the hornblende gneiss. Th whose average concentration is 2ppm in the amphibiolite and 6ppm in the hornblende gneiss is relatively highly concentrated in the biotite gneiss (average 33ppm) in the biotite granite gneiss due to increased K-feldspar content which concentrates this element. The average concentration of Y (32ppm) is lower than its concentration in the hornblende gneiss reflecting less hornblende in the biotite gneiss.

The concentration of compatible heavy elements (Cr, Ni and Co) are relatively minor in the biotite gneiss reflecting its acid nature.

7. Rare earth elements (REE)

The average total REE in the biotite granite gneiss is 328ppm of which the light ones account for 320ppm, and heavy rare earth elements only 18ppm. As in the amphibolite and hornblende gneiss, higher amount of light rare earth elements are concentrated in the biotite granite gneiss than the heavy rare earth elements. However, the total REE in the biotite granite gneiss is lower than that of the hornblende gneiss due to lower abundance of sphene, plagioclase and hornblende in the biotite granite gneiss than in the hornblende gneiss.

7.1 The pink granite gneiss

The average concentrations of SiO_2 (76%) and Na_2O (2.40%) recorded in the pink granite gneiss in this region reflect higher concentration of K-feldspar in the pink granite gneiss than in the biotite granite gneiss. Al_2O_3, K_2O, CaO, P_2O_5 average concentrations in this rock are lower than in the biotite granite gneiss. The averages of K_2O/Na_2O ratios which are greater than 1 and the total K_2O+Na_2O (7%) on the average in the pink granite gneiss show the same trends as in the biotite granite gneiss. AFM plot for this rock also show a calc-alkali franctionation trend.

7.1.1 Trace elements

Ba and Sr concentrations in the pink granite gneiss are lower than in the biotite granite gneiss indicating lower plagioclase in the former than in the later. Higher concentration of Rb in the pink granite gneiss than in the biotite granite gneiss reflects more abundant K-feldspar in the pink granite gneiss. Zr has lower average in the pink granite gneiss than in the biotite granite gneiss which corresponds to lower zircon occurrence in the pink granite gneiss. Th mean concentration in the pink granite gneiss is higher than in the biotite granite gneiss which may be due to higher sedimentary contribution to the precursor of this rock. In the pink granite gneiss an increase of Y concentration is recorded compared with its average concentration in the biotite granite gneiss. This may be due to higher hornblende component of the pink granite gneiss than in the biotite granite gneiss.

The average Ni in the pink granite gneiss has diminished compared with the hornblende gneiss and biotite granite gneisses and Cr concentration in the pink granite gneiss is below the detection limit (3ppm) of the XRF used for these analyses due to implied less concentration of mafic minerals in this rock.

7.2 Rare earth elements (REE)

The total absolute REE on the average is 235ppm out of which light Rare Earth Elements account for 215 ppm and heavy rare earth elements 20ppm. The average ratio of

LREE/HREE: 11, recorded in the pink granite gneiss is lower than those of the biotite granite gneiss. However, the average HREE in the pink granite gneiss is higher than in the biotite granite gneiss. The lower concentration of REE in the pink granite gneiss than in the biotite granite gneiss reflects the less abundant REE concentrating minerals in the pink granite gneiss.

8. Geochronology

There had been some reported determination of the age of the basement complex rocks generally in Nigeria including the southwestern Nigeria basement rocks. On the basis of isotopic studies, Archaean and Proterozoic ages had been suggested as the ages of emplacement of the basement rocks in Nigeria by Dada et al; (1998) and Annor (1995). According to Ajibade et al, (1987) the southwestern Nigeria basement complex are of two age generations, one represented by migmatite gneiss complex probably of Archaean to Early Proterozoic age while the other is believed to be of Late Proterozoic age. Age determination of the southwestern Nigeria basement complex rocks has not been completed as much work needs to be done to actually date these rocks satisfactory. However Oyinloye (2006b, this author) carried out a Pb-Pb, 2-stage model age based on Stacey and Kramers (1975) on the granite gneisses in Ilesha area of southwestern Nigeria and part of the result is reproduced here.

8.1 Lead (Pb-Pb) model dates

The whole rock and feldspar samples analysed for lead isotopes in this study were from the biotite granie gneiss in Ilesha area of southwestern Nigeria. On plotting, these samples revealed limited scatter points on the Pb-Pb isochron (Fig.3) but with a well defined trend. Pb-Pb data for the six K-feldspar seperates (plotted in addition) are from the same biotite granite gneiss and are comparable to the equivalent whole rock. These results fit well to the indicated best fit line which corresponded to a two-stage isochron 2750±25Ma with an initial ratio of 12.809 and MSWD of 16 (Fig.3). On the Stacey and Kramers (1975) growth curve, the biotite granite gneiss whole rock and feldspar Pb experimental points plotted to the left of the geochron Q-P (Fig.5) crossing the growth curve at point N giving an initial ratio of 12.809 which was due to geochemical differentiation. The experimental Pb-Pb isochron yields a model age of 2750±25Ma (Fig.3). This implies that Pb was withdrawn from the unradiogenic reservoir and incorporated into the feldspars and the protolith of the biotite granite gneiss at about 2750±25Ma . This Pb-Pb age which is Archaean is therefore the age of emplacement of the precursor rock which gave rise to the biotite granite gneiss in Ilesha area of southwestern Nigeria.

On ploting the Pb-Pb data on Zartman and Doe (1981) evolutionary curve, (Fig.4) five out of the six whole rock samples and five out of the feldspar samples plot between the two curves OR and UP, (Fig.4). While only one sample of each (feldspar and whole rock) of the feldspar and whole rock samples plot outside the curves. Samples which plot within the two curves UP and OR (Orogen) in Figure 4 indicate that their precursor rocks were derived from a tectonic environment where crustal/sedimentary and mantle materials were partially metted to generate the initial magma from which the protolith of this biotite granite gneiss was formed, (Cf. Zartman and Doe 1981). Furthermore, Pb-Pb isotope data show that the whole rock samples from the biotite granite gneiss are extremely homogenerous with only very slight deviations from the mean values. The feldspar separates show more isotopic homogeneity.(Oyinloye 2006b). This type of extreme isotopic homogeneity in rocks and feldspars is characeteristic of rocks derived from a subduction related environment like a back arc or an island arc, where mantle and upper crustal materials are thoroughly mixed to generate a magma (Billstrom 1990). Burke and Dewey (1972) had earlier described the Ilesha area in southwestern Nigeria as one that evolved in an island arc marginal basin but Oyinloye (2006b) showed that it evolved in a back arc tectonic setting.

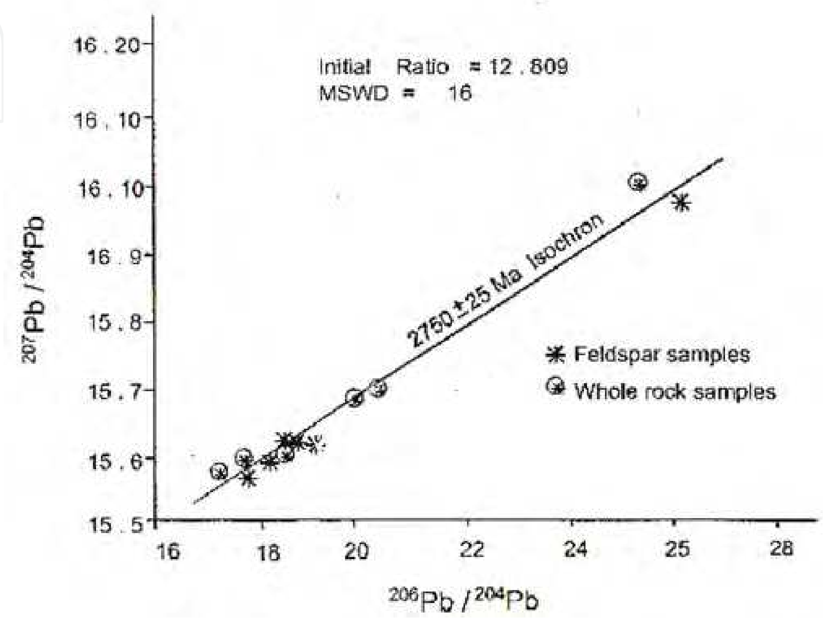

Fig. 3. Lead (Pb-Pb) whole rock and K-feldspar isochron diagram for biotite granite gneiss and K-feldspar from Ilesha schist belt , southwestern Nigeria

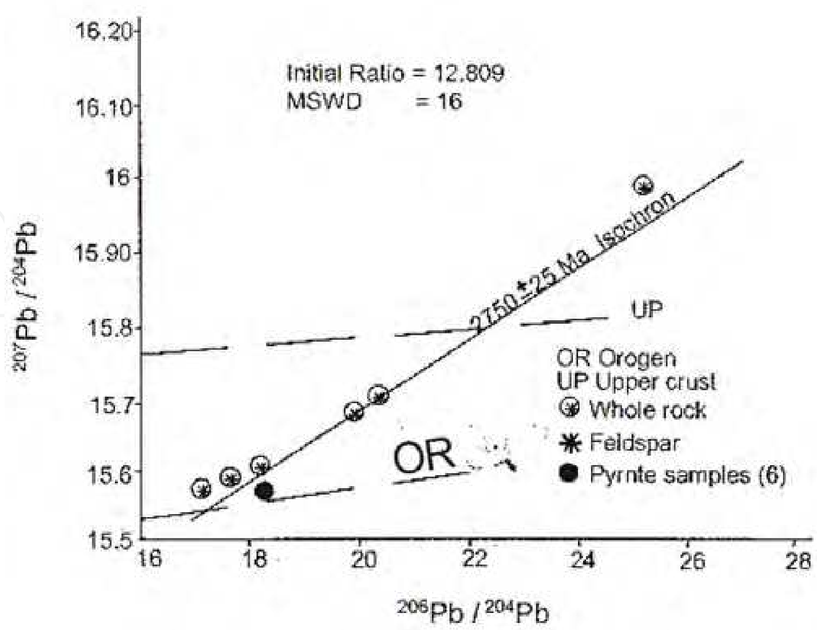

Fig. 4. Plumbotectonic plots using Pb-Pb from K-feldspar whole rock and pyrite samples (based on Zartman and Doe, 1981)

8.2 Mineralisation in Southwestern Nigeria basement complex

The crystalline rocks of the basement complex intruded the schists in the schist belts in southwestern Nigeria. The schist belts are critical to the understanding of the geology of the basement complex in Nigeria. Infact the schist belts are integral part of the southwestern Nigerian basement complex. Minerals are localized in rocks within the schist belts in southwestern Nigeria. Some of the minerals found within the southwestern Nigeria basement complex include, gold in Oyan and Ilesha schist belts, in Okolom and Gurungaji in Egbe schist belt southwestern Nigeria. Gold is the major metal found in the southwestern Nigeria basement rocks. However unproven reserves of cassiterite, columbite and tantalite are found in Ijero-Ekiti area of southwestern Nigeria. Others include gem stones – amythyst, tourmaline and quartz. Gold is the only metallic mineral of substance that has been studied in this area especially by this author. A summary of the geology and geochemistry of the gold deposit at Ilesha in southwestern Nigeria is reported here.

There are two (2) types of gold mineralization in Ilesha area. The first type is an alluvial form which occurs within the amphibolite terrain in Ilesha area southwestern Nigeria. This has not been well studied. The second one is a primary gold deposit found as auriferous quartz veins localized in a shear zone about 4km from the major Ifewara-Zungeru fault zone described within the pink grnite gneiss in this study. The biotite granite gneiss described in this report is the host rock of the Ilesha primary gold deposit, known as the Iperindo primary gold deposit. This gold deposit occurs as a system of auriferous quartz veins infillings, structurally localized at a folded boundary between biotite granite gneiss host rock and the adjacent metasedimentary complex. The granite gneiss host rock was altered by an invading hydrothermal fluid. The alteration selvages which form the hanging and footwall rocks are dominantly phyllic in nature with a minor chlorite overprinting in the foot wall rocks. These alteration selvages are relatively narrow but prominent and intensive around all the mineralized quartz veins at Iperindo. Geochemical analyses of the country and selvage rocks of this lode gold deposit show that the altered rocks are enriched in Cu, Zn, Pb and rare earth elements generally and heavy rare earth elements in particular relative to the country wall rocks reflecting presence of chalcopyrite, sphalerite, galena, and rare earth elements concentrating minerals and development of secondary alteration products such as sericite in the alteration selvages. General studies carried out using, stable carbon 13, oxygen 18 isotopes and plumbotectonics show that mineralization of gold at Iperindo near Ilesha was meteoric in origin. Ore fluid inclusion studies of selected samples from the auriferous quartz veins from Iperindo gold deposit indicate that the ore fluid was rich in carbondioxide. Microthermometric measurements show that there are two types of fluid inclusions in this gold deposit and these two homogenized at high temperatures but underwent phase separation at low temperatures. These two fluids are: 2-phases carbondioxide, (gas and liquid) and 3-phases, carbondioxide gas, carbondioxide liquid and water. Fluid inclusion studies also show that mineralization of gold took place at a temperature in excess of 286^{o}C.

The data obtained from Pb isotope studies from pyrite which is found in Iperindo gold deposit show an extreme homogenous relationship. On Zartman and Doe (1981) evolutionary plot all the pyrite Pb plot within the two curves just like the whole rock and feldspar separates (Fig.4) indicating genetic relationship (note: only one of the pyrite Pb samples appears in Figure 4 because they all clustered at a point). The model ages calculated for each pyrite sample varies from 559Ma-573Ma with a mean of 550Ma (Oyinloye 2006b).

Also, the pyrite lead data showed that Pb isotopes in pyrites from the Iperindo lode gold are extremely homogeneous and very similar in value to those obtained from the whole rock and feldspar separates. Therefore going by the earlier interpretation of Pb homogeneity in feldspar, and hole rocks samples the Pb homogeneity observed in pyrite samples from this gold deposit might indicate derivation from a mixed crustal and mantle sources (Volcano-proto-continent precursor rocks of amphibolites and amphibolite schists) for the Pb in pyrite which forms a prominent gangue in Iperindo gold deposit.
The component of the ordinary Pb was probably withdrawn from its reservoir before 2750±25Ma as a result of magma generation and protocontinent rock formation. There was an hydrothermal invation of the volcanics leading to leaching of Au from these rocks, removal of Pb from the reservoir and incorporation into pyrite at about 550Ma, the age of gold mineralization in Ilesha area of southwestern Nigeria.

9. Provenance and evolution of the Southwestern Nigeria basement rocks

A controversial aspect of the geology of the Nigeria basement complex is its geotectonic origin. Only very few workers had applied geotectonics to interprete the origin of the basement rocks in southwestern Nigeria. In my research studies, I was able to use sophisticated equipment like scanning electron microscope Cambridge 250model in the United Kingdom to determine the spot chemical composition and empirical formulae of nearly all rock forming minerals in the rocks of the basement complex of southwestern Nigeria as represented by the amphibolite and granite gneisses in Ilesha area. A mineral known as monazite was discovered in this process. This mineral is present as a notable accessory mineral in all the crystalline rocks of the basement complex here in Ilesha area even in the amphibolite which is supposed to be purely igneous. Hither to except in the Younger Granites in the north central Nigeria and in sedimentary rocks in Lokoja and Auchi areas, monazite has not been described by any worker in the rocks of the basement rock of southwestern Nigeria in general and in Ilesha area in particular. It is in my research that monazite is being described for the first time in the rocks of the southwestern Nigeria and in Ilesha area in particular.
Monazite is a phosphate of the rare earth elements, especially the light ones e.g. (La, Ce, Nd) PO_4. Monazite is known to be a crustal or sedimentary mineral. Its presence in a supposedly igneous rocks of mantle origin therefore raises a petrogenetic question. The petrogenetic implication of the presence of monazite in the crystalline rocks of the southwestern Nigeria is that the initial magma from which the precursor rocks were formed contain some input from a crustal or sedimentary source. As described in this text. The $MgO/(Fe_2O_3+MgO)$ ratios recorded for the amphibolite are lower than that of the basalts derived from a pure primitive mantle and this ratio decays further from the hornblende gneiss to the granite gneisses.
In order to further unravel the provenance of these rocks in southwestern Nigeria, normative corundum of the hornblende gneiss and the granite gneisses were plotted against the Mol.%$Al_2O_3/(Na_2O+K_2O+CaO)$. Also, the histogram of the Mol.%$Al_2O_3/(Na_2O+K_2O+CaO)$ distribution for the gneisses were plotted (Figs.6 A and B). Most of the gneisses samples plot in S-type field while few samples plot in the I-type field (Fig. 6A). In Figure 6B, the gneisses sample show a bimodal histogram with a mode at I-type field and another at the S-Type field. Also the hornblende gneiss samples occur in both I-Type and S-Type fields. These plots imply

that the magma which gave rise to the precursor rocks of these gneisses originated from a mixed source, containing igneous and sedimentary materials. Generally, all the plots show that the granitoids are very homogenous, related petrogenetically and are derived from a mixed source. The index trace elements were used to plot many discriminating diagrams (only one is shown here because of space). On plotting Ti versus Zr (Fig.8 based on Pearce et al; 1984) the massive melanocratic amphibolites data plot in the arc lavas field indicating a volcanic arc (similar to a back arc tectonic setting). Further more, it is observed that the average concentration of the compatible elements, (Ni, Cr, Co) in these rocks are extremely lower than that of the normal rocks derived from a primitive upper mantle source implying that the magmatic source had been metasomatised.

Chondrite normalized REE were plotted for all the crystalline rocks described in this study including the massive melanocratic amphibolite. The massive melanocratic amphibolite shows a slight negative Eu/Eu* anomaly and high La_N/Yb_N ratios. The gneisses show similar REE patterns and a higher negative Eu/Eu* anomally. These trends show a progressive differentiation from the basalts to the gneisses (Fig.7). The implication of these is that the precursor of these rocks originated from a basalt that differentiated progressively to the granite precursor rocks of the gneisses as shown in Figure 7.

The extreme Pb isotopic homogeneity as observed in the biotite granite gneiss samples and its feldspar separates indicates derivation from a subduction related environment like a back arc or an island arc where mantle and upper crust materials are thoroughly mixed to generate a magma (Billstron 1990). The southwestern Nigeria basement complex as typified by the Ilesha schist belt had earlier been described as one that evolved in a subduction related environment of island arc and marginal basin, Burke and Dewey (1972). But Oyinloye (2002a), Oyinloye and Steed (1996), and Oyinloye and Odeyemi (2001) on the bases of petrological, geochemical, plumbotectonics and structural analyses showed that the environment of the emplacement of the protocontinent which were the precursors of the rocks of the southwestern Nigeria basement rocks was a back arc basin. The linear trends displayed by the whole rock Pb data on the growth curve (Fig.5) reflects a mixing process between varying amounts of upper crust and mantle materials as in an island arc or a back arc environment, Billstrom (1989). The various discrimination diagrams based on the trace elements considered immobile during metamorphic alteration show that the rocks of the basement complex of southwestern Nigeria may possibly be derived from a low-K-Tholeritic magma, (Oyinloye and Odeyemi 2001). These plots also indicate a possible volcanic arc for these rocks. (Fig.8) both back arc and island arc are grouped in volcanic arch in Fig.8. A volcanic arc characteristic of the massive melanocratic amphibolite suggests that subduction tectonics was important in the formation of its parent magma. The flat shape of the REE curve (Fig.7A) with slight Eu anomaly is typical of a back arc basic rock (Wilson, 1989). Also the spider diagrams for the massive-melanocratic amphibolites (not shown) are similar to those of a spreading tectonic settings (e.g. Mid Ocean Redge basalt, or a back arc setting). But none of the samples in the discriminating diagrams plotted in the Mid Ocean Ridge Besalts Field (Fig.8). Furthermore the development of a negative Eu anomaly shown by these rocks especially the massive melanocratic amphibolite (Fig.7A) is alien to a mid-ocean ridge basalt or an island arc. A back arc tectonic setting will adequately account for the characteristics displayed by these rocks in the discrimination and REE fractionation trends as described above.

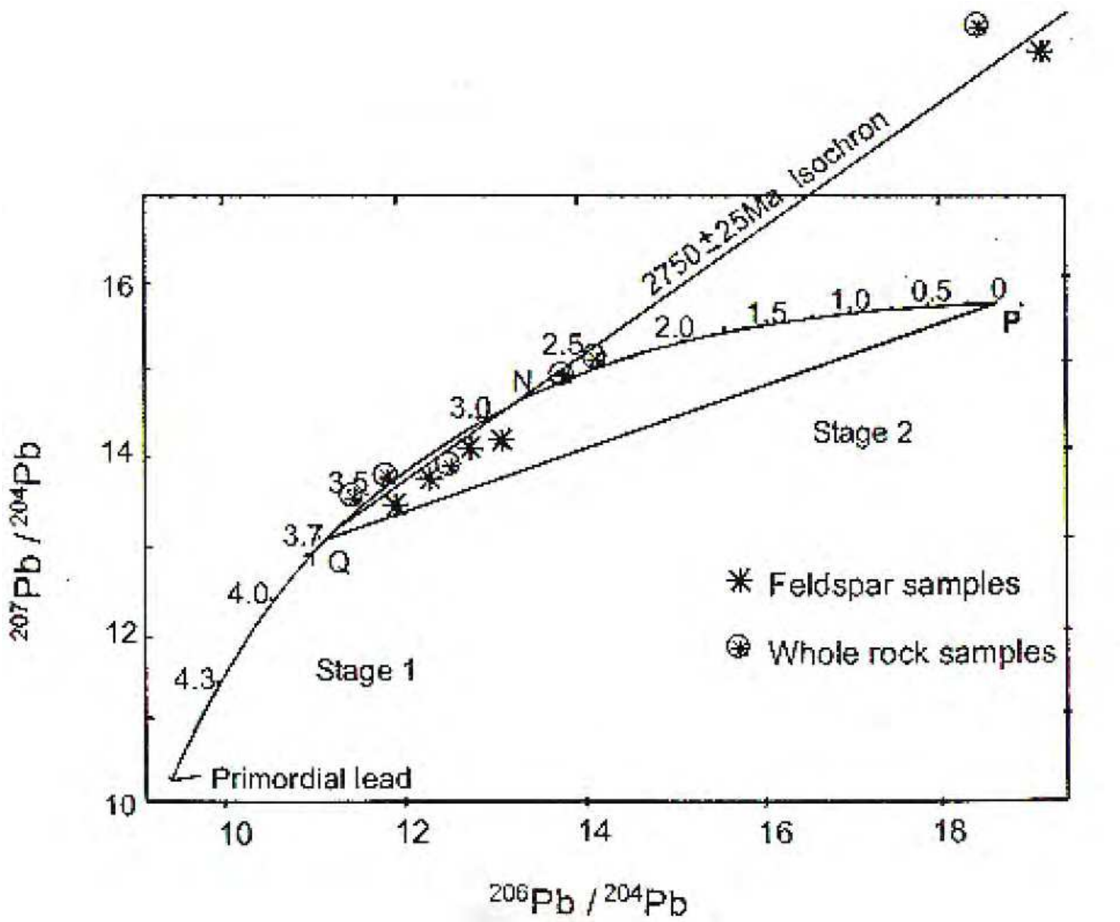

Fig. 5. Whole rock and K-feldspar Pb experimental data points on the two stage growth curve of Stacey and Kramer (1975)

The basement complex rocks of the southwestern Nigeria are believed to have developed in a back arc basin (Oyinloye and Odeyemi 2001). Rahaman et al; (1988), had suggested that an ocean was closing and opening at the West African margin. Holt et al (1978) based on geotectonic studies explained that the southwestern Nigeria basement complex resulted from the opening and closing of an ensialic basin with consequent extensive subduction during the Pan African events. Burke and Dewey (1972) from structural point of view believed that components of the schist belts containing the crystalline complex rocks in southwestern Nigeria had been formed in a back arc basin caused by the collision between the continental margin of the Tuareg shield (Hoggar belt in northwest Africa). But in this study and in the previous ones the petrological, geochemical and plumbotectonic studies revealed that these rocks originated from a mixed magma containing both mantle and sedimentary materials. Reviewing all the known tectonic environments especially island arcs and back arcs (which had been suggested as the geotectonic setting in which the rocks of the southerwestern Nigeria basement complex originated), the petrology, geochemistry and plumbotectonic studies of the rocks understudy implicate a back arc tectonic setting in which an ocean slab was subducted into the mantle. This subduction was due to a collision between an ocean slab and a continental shelf. In such an environment, the ocean slab would be subducted into the mantle with sedimentary materials and water which makes a wet mixed magma formation possible.

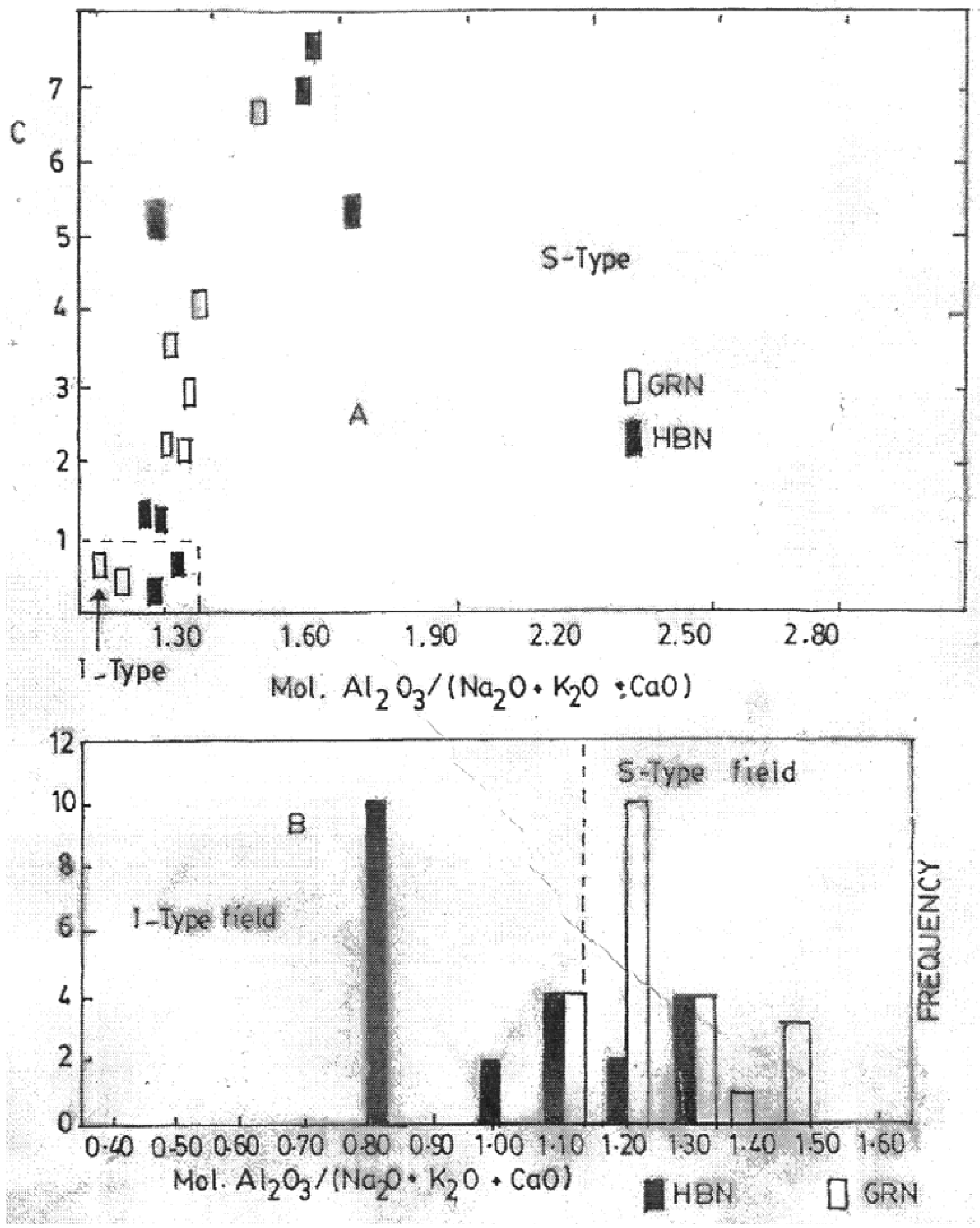

Fig. 6. a) Normative Corundum versus mol. Al_2O_3/(Na_2O+K^2O+CaO) for classification of I-Type and S-type igneous rocks, b) Histogram of mol. Al_2O_3/(Na_2O+K^2O+CaO) distribution for the Hornblende gneiss (HBN) and Granite gneiss (GRN). (Method based ov Vivaldo Waldo and David Rickard (1990)).

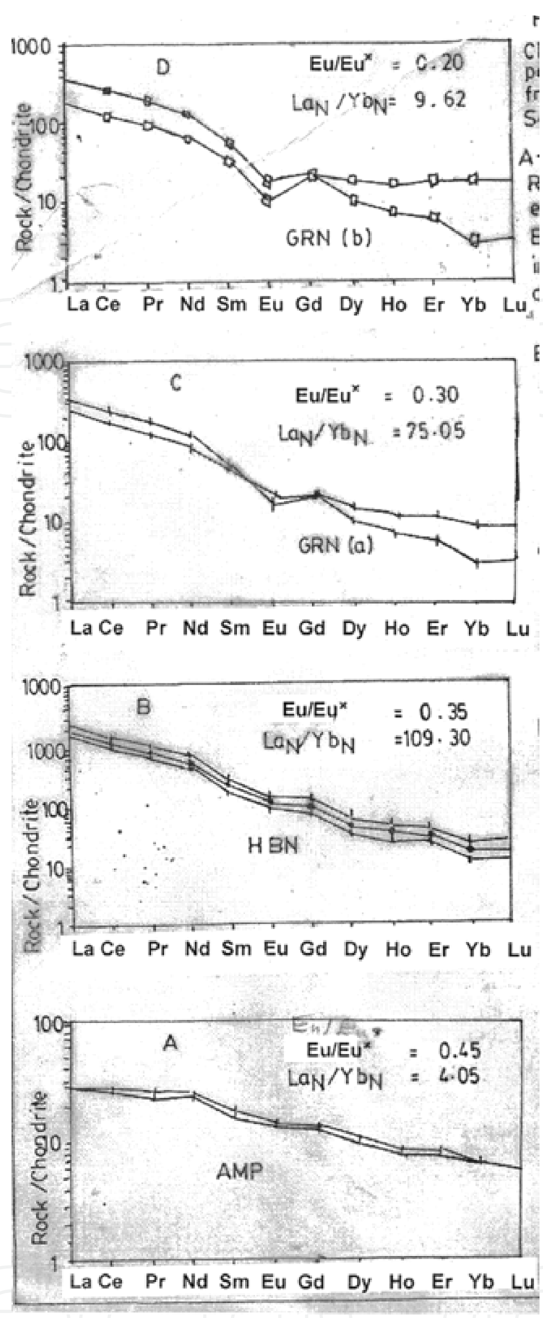

Fig. 7. Chondrite normalized REE patterns for AMP, HBN, GRN from the Ilesha schist belt Southwestern Nigeria, a) AMP chondrite normalized REE patterns showing essentially flat patterns, slight EU depletion and low La_N/Lb_N implying little or no differntation, b) HBN chondrite normalized REE patterns showing high LREE, low HREE, stepped patterns and moderate Eu depletion and very high La_N/Lb_N implying little or no differentation, c) GRN (a) chondrite normalized REE patterns showing high LREE, low HREE, pronaunced Eu depletion and high La_N/Lb_N showing very high differentiation of the source, d) GRN (b) GRN (a) chondrite normalized REE patterns showing high LREE, low HREE, high Eu depletion and moderate La_N/Lb_N showing little differentiation (last magmatic phase) These rocks shows an increase from AMP to HBN and decrease from HBN to GRN. These trends probably suggest a possible differentiation trends implicating differentiation of a basalitic magma.

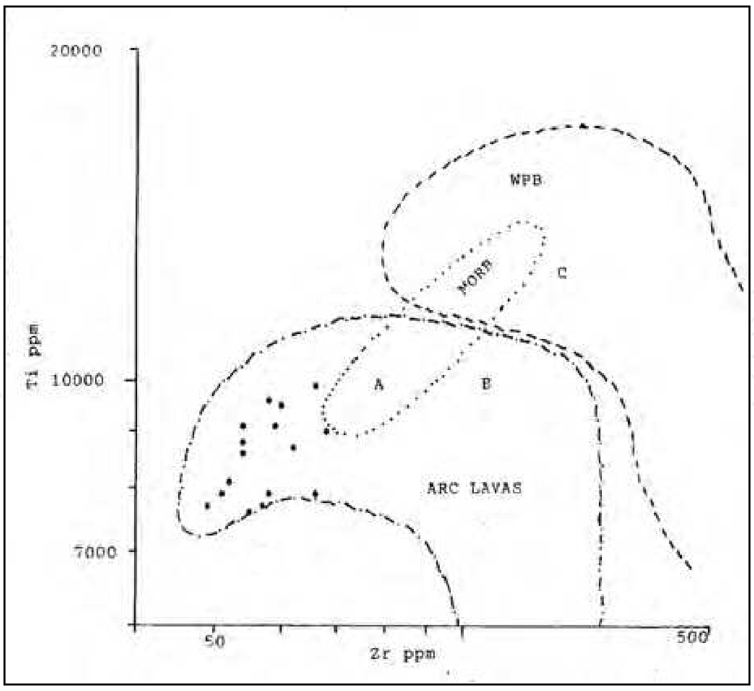

Fig. 8. Plot of Ti against Zr for the massive ampibolites in Ilesha schist belt Southwestern Nigeria. A) Mid-Ocean Ridge Basalt (MORB) field, B) Arc Lava field, C) Within Plate Basalt (WPB), (after Pearce et al. (1984)).

During collision between the continental shelf and the ocean plate, materials are scraped from the descending ocean slab and spread all over the area in southwestern Nigeria. Meanwhile, the descending ocean slab would carry sedimentary materials including water into the mantle. This is responsible for metasomatism of the mantle materials. There would be an exchange of materials in which the mantle portion of the wet magma formed would be enriched in sedimentary materials e.g. monazite and inproveriched in compatible elements e.g. Ni, Cr, Co. The basaltic wet magma thus formed intruded into the earlier laid down sedimentary cover. The magma differentiated to give rise to the amphibole rich rocks and granites which are protoliths of the later formed metamorphic rocks. After the arc magmatism, transpsressive forces operating in the magmatic chamber travelled along the magmatic channel, heat up the earlier laid down rocks and turned them into metamorphic rocks which are described in this chapter. The earlier laid down sediments were metamorphosed to give rise to the schists and metasediments found within the basement complex of southwestern Nigeria.

10. Summary and conclusions

Amphibolites, hornblende gneiss and granite gneisses are the main crystalline rocks in the basement complex of southwestern Nigeria. These rocks had undergone a polycyclic metamorphism which is mostly pervasive in Eburnean and Pan-African tectonothermal events. As a result of these, a series of deformation fabrics and evolutionary episodes had been recorded in these rocks. However, M_1 and M_2 phase of metamorphic deformation corresponding to two D_1 and D_2 phases of deformation are mostly discernible as recorded on these crystalline rocks. A two stage lead model age determination for the gneisses revealed that the protoliths of the basement rocks in southwestern Nigeria were emplaced in the Archaean (2750 ±25Ma). In this region gold mineralization was effected by the invation of a meteoric ore fluid at a temperature above 286^{o}C. Au (gold) was probably leached from the metavolcanics in the belt and deposited as a system of auriferous quartz veins in a shear zone at about 550Ma in this region.

Geochemical (major, trace elements and REE), geological and petrological studies revealed that all these crystalline rocks are genetically related (comagmatic) and had evolved by progressive differentiation of a parent basaltic magma to give rise to the protoliths of the amphibolites probably represent the parent basaltic magma. Chemical studies also revealed that the magma of the protoliths of these rocks were from a metasomatised mantle.

Plumbotectonics, petrological, geological and geochemical analyses and interpretations carried out in this study implicate a back arc tectonic setting as the environment of emplacement of these rocks. In this type of tectonic setting an ocean slab was subducted into the mantle after colliding with a continental shelf. The subduction of an ocean slab into the mantle would enhance the formation of a mixed wet basaltic magma, consisting of both mantle and ocean sediments thoroughly mixed to form a basaltic magma. This magma extruded and intruded the earlier laid down sediments in the region, differentiated and gave rise to the protoliths of these crystalline rocks in southwestern Nigeria.

Post-magmatic transpressive forces operating in this region were responsible for the metamorphism of the protoliths of the amphibolites, hornblende gneiss and the granite gneiss (Oyinloye 2007) . Further deformation of these rocks led to faulting, fracturing, shearing, folding gneissic banding and foliation fabrics observed on some of the rocks especially, the leucocratic amphibolites, hornblende gneiss and granite gneisses in the basement complex of southwestern Nigeria.

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