Geochemical and petrogenetic features of schistose rocks of the Okemesi fold belt, Southwestern Nigeria

Geokemične in petrogenetske značilnosti skrilavih kamnin v sistemu gub Okemesi, jugozahodna Nigerija

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Abstract: Schist belts form a dominant component of the Precambrian basement complex of Nigeria. This study of schistose rocks around the Okemesi fold belt, Ife-Ilesha schist belt therefore, is with a view to evaluate their compositional features and petrogenetic affinities and to contribute further to the understanding of the geodynamic evolution of Nigeria's Schist belts.

Three lithologic varieties, namely quartzite, quartz schist and biotite muscovite schist are revealed from systematic mapping and petrographic examinations. Whole rock analytical results of major, trace and rare earth elements of fifteen samples using ICP mass spectrometer method show that the rock units are comparable to those of post Archean pelitic-supracrustal rocks. Variation plots involving Na_2O_3, Al_2O_3, and K_2O on one hand and TiO_2 and SiO_2 on the other hand reveal arkosic sedimentary progenitors for the rocks. In addition, La/Th and Th/U ratio suggest that the rocks especially biotite schist is associated with post Archean recycled Upper Crustal sources while Chondrite normalized rare earth signatures of samples further indicate low grade post Archean terrigenous sedimentation of rocks derived from possible mixture of granite- tonalities. Relatively intense weathering and maturity of source rocks is revealed from calculated values of Index of alteration (CIA) and Index of Compositional Variability (ICV). The study further elucidates the possibility of the rocks evolving in a rifted environment of rapid subsidence, followed by closure which led to contemporaneous deformation of the sediments

Original scientific paper

Izvleček: Metamorfni skrilavci so prevladujoča kamnina v predkambrijskem metamorfnem masivu Nigerije. Namen raziskave je določiti sestavo ter nastanek skrilavih kamnin Okemesi pasu, in sicer Ife-Ilesha pasu metamorfnih skrilavcev. Rezultati bodo prispevali k razumevanju geodinamičnega razvoja nigerijskih metamorfnih skrilavcev.

S sistematičnim geološkim kartiranjem in petrografskimi raziskavami smo ugotovili tri litiološke različke – kvarcit, kremenovi skrilavci in biotitno muskovitni blestniki. Z metodo ICP masno spektroskopijo smo določili vsebnost glavnih in slednih prvin ter prvin redkih zemelj v petnajstih vzorcih. Analize so pokazale, da so raziskovani tipi kamnin primerljivi s po-arhajskimi pelitskimi kamninami zgornje skorje. Tako variacijski diagrami Na_2O_3, Al_2O_3, in K_2O kot tudi TiO2 in SiO2 potrjujejo, da je bila izvirna kamnina sedimentna – arkoza.

Razmerji La/Th in Th/U nakazujeta, da so kamnine, zlasti biotitni blestnik, nastale iz po-arhajske reciklirane zgornje skorje. Iz vzorcev hondritsko normaliziranih REE sklepamo, da je bila prvotna kamnina nizko metamorfoziranih arhajskih terigenih sedimentnih kamnin mešanica granitov in tonalitov. Izračunane vrednosti indeksa preperevanja (CIA) in indeksa spremenljivosti sestave (ICV) kažejo na relativno močno preperevanje ter zrelost izvirnih kamnin. V študiji podajamo možnost nastanka kamnin v okolju hitrega pogrezanja razpornega bazena, ki mu je sledilo zapiranje; to je povzročilo sočasno deformacijo sedimentov.

Key words: schist, archean, sedimentary, rifted, compositional
Ključne besede: metamorfni skrilavci, kvarcit, arhaik, sedimentne kamnine, zgornja skorja

Introduction

Schistose rocks which occur in defined belts are known to be a dominant feature and constitute a distinct component of the western half of the Precambrian Basement Complex of Nigeria. This basement complex itself, apart from the schist belt, is made of the Gneiss- migmatite complex and the Pan African Older Granite rocks. The schist belts are made up of mainly low-medium grade metasediments which are usually associated with minor assemblages of mafic-ultramafic rocks, iron deposits and carbonates (Muotoh et al., 1988; Okunlola, 2001).

These northerly trending schist belts occur prominently west of 8^0 Meridian (Oyawoye 1964, 1972; Mccurry, 1976). However, it is now known that some extend eastwards of this meridian (Ajibade, 1976; Emeronye, 1988; Eneh et al., 1989; Ekwueme and Shing, 1987). They exhibit distinct petrological and structural features. The belts in the southwest include the Iseyin-Oyan, Igarra, Egbe-Isanlu and Ife-Ilesha schist belts (Rahaman, 1976; Odeyemi, 1977; Elueze, 1981; Annor et al., 1996). The Lokoja-Jakura, Toto-Gadabuike belts (Muotoh et al., 1988; Elueze, 1981; Okunlola, 2001) while the Obudu schist belt is the recently highlighted southeastern belt (Ekwueme & Shing, 1987). So far, there is no complete agreement on delineation, geological nomenclature and geodynamic setting of this major rock unit of the Nigerian Precambrian basement Complex. In this study attempts are made to elucidate the geochemical and petrogenetic features of the schistose rocks around the Okemesi fold belt area, which is a part of the Ife- Ilesha schist belt. The latter has one of the most complex lithological and structural frameworks amongst the Nigeria's metasedimentary belts (Olobaniyi, 2003). The present study, it is hoped will assist in understanding the evolution of this major rock unit of the Precambrian of Nigeria.

Materials and methods

The study involves systematic geological mapping on a scale of 1 : 50 000 collection and thin section study of 15 fresh representative samples of all the lithological units mapped. Four samples each were collected from the quartz schist and biotite muscovite schist and 7 from the quartzite. Variation in sample numbers is largely due to availability of fresh unweathered and uncontaminated samples. For geochemical investigations, collected samples were dried at 60 °C, crushed, pulverized and sieved to -80 mesh. A 0.2 g samples aliquot was weighed into a graphite crucible and mixed with 1.5 g of $LiBO_2/LiB_4O_7$ The sample charge was heated in a muffle furnace for 30 min at 980 °C. The cooled bead is dissolved in 100 mL of 5 % HNO_3 (ACS grade nitric acid in de-mineralized water). An aliquot of the solution was poured into a propylene test tube. Calibration standards and verification standards are included in the sample sequence. Sample solutions are aspirated into an ICP mass spectrometer (Perkin-Elmer Elan 9000) for the determination of major, minor and rare earth elements at the Acme Laboratories in Vancouver Canada. Quality control protocol incorporates a sample preparation blank (G1) as the first sample in the procedure which is carried through all stages of preparation to analysis. Also, the procedure incorporates a pulp duplicate to monitor analytical precision, a reagent blank to measure background and aliquots of in-house reference material STD SO-18.

RESULTS AND DISCUSSION

Lithological relationship and petrography

The Okemesi Fold Belt lies between Latitudes 7^0 45' and 7^0 52' and Longitudes 4^0 54' and 4^0 50' E and covers an area of 132.25 km^2. It has an antiformal structure comprising massive quartzite, quartz schist, and mica schist with subordinate gneisses and amphibolites (Figure 1). These metasedimentary assemblages has been hitherto referred to as the Effon psammite formation (DE SWARDT, 1953; HUBBARD, et al., 1975).

The quartzite samples are mostly whitish in color but some ferruginized varieties display reddish bands. They are medium to fine-grained, steeply dipping, with an average dip of 54^0 E. They consist mainly of quartz which occurs as irregular fine to medium grained crystals with interlocking grains of muscovite. In thin section, the quartz

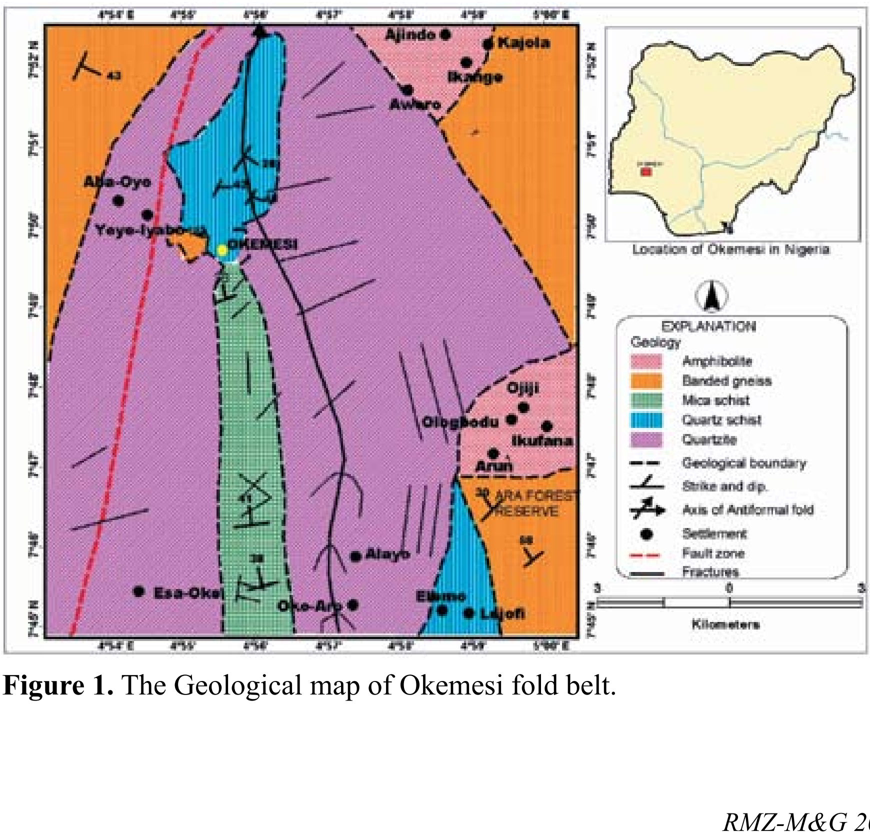

Figure 1. The Geological map of Okemesi fold belt.

grains are colorless to grey in transmitted light. The quartz schist which forms the innermost parts of the Okemesi anticline, occur as low-lying outcrops. They are fine to medium–grained, display incipient schistosity and contain quartz, microcline, muscovite with accessory hematite and zircon. Quartz occurs as randomly oriented crystals. Two generations are evident. The first one is coarser grained, usually anhedral and elongated parallel to the fabric. Some grains exhibit wavy extinction. The finer grained variety occurs as localized granoblastic aggregates and show uniform extinction. This variety may likely be of secondary origin. Microcline which is present in minor amounts as crosshatched twinned elongate fine blasts are located sometimes in intergranular spaces of the interlocking quartz blasts.

The biotite- muscovite schist also occurs in lowland areas between the quartzite ridges and trend generally in the NNE-SSW direction. The foliation on the outcrop is defined by mica streaks, particularly biotite. The schist is generally coarse-grained and contains mainly muscovite, biotite and minor quartz. In thin section, quartz occurs as coarse-grained, stretched, and white to greyish anhedral blasts. Biotite occurs as light brown leaflet sometimes slender and prismatic with occasional stumpy laths and is pleochroic from light brown to reddish brown. Muscovite is subhedral, showing alignment in the foliation plane (Figure 2). Plagioclase is of oligoclase-andesine composition, mostly colourless but in the absence of twinning it is often distinguished from quartz by the alteration to sausurite. Euhedral to subhedral garnet is predominantly almandine with minor amounts of spessartine and grossularite. They sometimes exhibit poikiloblastic texture and are characterized by inclusion of fine quartz and some mica. The schistose rocks occur in association with banded gneiss and amphibolites which occupy mainly the outer portions of the anticline and are more prominent in the eastern side.

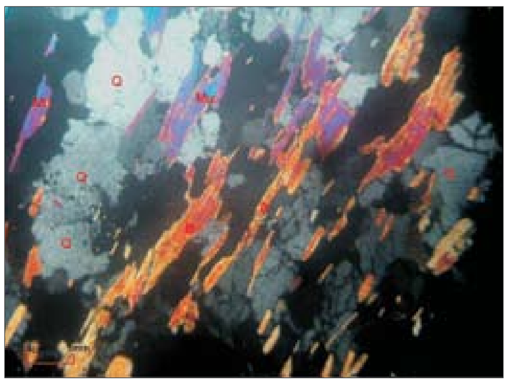

Figure 2. Photomicrograph of biotite-muscovite schist in transmitted light showing Quartz (Q), Biotite (B), and Muscovite (Mu)

The banded gneiss consists of alternating bands of felsic minerals notably plagioclase feldspars and quartz, and the dark bands consisting of biotite and hornblende. Quartz is present as coarse-grained randomly oriented crystals. The amphibolite which is mostly low lying is laminated in places with leucocratic bands of plagioclase and quartz. Hornblende is the main mineral with minor quartz and plagioclase. Quartz is heterogranoblastic, colourless in transmitted light and in some parts, fractured. The hornblende crystals are pleochroic from brown to light green.

Geochemical features

From the results of the major oxide data (*w*/%), trace and rare earth element (μg/g) composition presented in Tables 1 and 2, the Okemesi metasedimentary rocks are generally siliceous, ($w(SiO_2) > 65$ %) with quartzite being chemically similar to quart-sandstones (BLATT, et. al., 1972). These values are also similar to those for the Jebba quartzite and micaceous quartzite, central Nigeria (OKONKWO, 2006).

Table 1. Major Element Oxides (*w*/%) results of schistose rocks from Okemesi

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	88.91	81.11	83.32	84.17	65.31	65.42	65.38	96.97	96.64	94.18	94.10	94.21	96.61	94.21	94.67
Al_2O3	6.52	9.37	8.51	8.21	13.55	13.81	13.82	0.79	1.17	4.11	2.34	1.98	2.31	2.62	2.11
Fe_20_3	0.68	1.29	1.21	1.63	6.30	6.41	6.42	1.22	0.74	0.38	2.1	2.45	0.52	2.41	1.56
MnO	0.0 11	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	<0.01
MgO	0.08	0.75	0.71	0.80	2.97	2.64	2.61	0.07	0.12	0.09	0.09	0.06	0.11	0.12	0.11
CaO	0.11	0.410	0.12	0.11	0.11	0.12	0.13	0.12	0.14	0.10	0.09	0.12	0.10	0.11	0.13
Na_2O	0.14	0.68	0.61	0.58	0.14	0.13	0.14	0.01	0.02	0.01	0.04	0.03	0.02	0.02	0.03
K_2O	1.76	3.89	3.11	2.64	1.76	2.1	2.5	0.04	0.21	0.07	0.08	0.06	0.05	0.04	0.07
P_2O_5	0.10	0.22	0.17	0.11	0.10	0.20	0.21	0.03	0.03	0.02	0.03	0.02	0.01	0.01	0.03
$Ti0_2$	0.24	0.23	0.23	0.22	0.24	0.31	0.32	0.05	0.07	0.20	0.16	0.07	0.08	0.07	0.08
Cr_2O_3	0.011	0.012	0.012	0.013	0.011	0.021	0.019	0.046	0.048	0.017	0.020	0.043	0.021	0.042	0.045
LOI	1.2	1.8	1.2	1.3	1.2	1.3	1.3	0.7	0.8	0.8	1.0	1.0	1.0	0.9	1.0
Total	99.75	99.79	99.22	99.99	99.75	99.86	99.81	100.05	99.99	99.98	99.97	99.95	100.83	100.6	99.83

1, 2, 3 and 4 = Quartz Schist
5, 6 and 7 = Biotite-muscovite Schist
8–15 = Quartzite

Table 2. Showing Trace Elements (μg/g) analytical results of rocks from Okemesi

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sc	13	4	7	6	2	6	4	ND	1	1	1	1	1	ND	1
Be	2	1	2	2	3	2	3	ND	4	2	1	4	2	1	2
V	63	ND	61	61	21	45	40	ND	ND	ND	8	ND	ND	8	8
Ba	93	911	902	880	968	942	902	85	15	60	42	65	62	59	71
Sr	325	201	202	362	64	58	60	12	27	46	32	40	55	31	28
Y	44	47	45	42	33	36	38	32	16	32	22	18	5	10	21
Zr	630	133	589	579	733	829	812	211	318	93	242	200	195	181	262
Co	11	ND	10	10	3	4	4	1	1	1	1	1	1	1	1
Ni	25	20	24	20	20	21	22	20	20	3	4	3	3	3	3
Cu	29	4	4	28	2	3	3.8	6	3	3	4	4	5	4	3
Zn	88	2	81	71	14	30	28	5	5	4	4	5	4	4	3
Ga	20	7	11	10	7	11	10	1	4	4	3	5	5	5	4
As	ND	ND	ND	ND	ND	ND	ND	5	5	ND	ND	3	ND	ND	ND
Rb	127	76	108	109	118	120	119	31	26	35	25	14	31	21	21
Nb	21	11	20	20	6	6.5	6	5	4	5	5	2	3	4	5
Sn	8	11	7	8	2	4	4	1	1	1	1	1	1	1	2
Cs	2	2	2	2	4.5	2	2	ND	2	3	5	6	6	5	4.
Au	ND	ND	ND	ND	1	1	1	ND	ND	ND	ND	ND	ND	ND	ND
Rb/Sr	0.39	0.38	0.54	0.30	1.84	1.98	1.98	2.55	0.96	0.75	0.78	0.34	0.57	0.67	0.76
Sr/Ba	0.35	0.22	0.22	0.41	0.07	0.07	0.07	0.15	1.85	0.78	0.75	0.63	0.89	0.52	0.39

1, 2, 3 and 4 = Quartz Schist
5, 6 and 7 = Biotite-muscovite Schist
8–15 = Quartzite

Average Al_2O_3 content is lowest in the quartzites (1.93 %). The biotite muscovite schist has a much higher average value of Al_2O_3 (13.92 %) than the quartz schist (8.15 %). The same trend is also noticeable in the mean Fe_2O_3 content of the metasediments where the values are less than 7 %. Mean MnO content is generally low (< 0.15 %) in the entire samples. These trends probably denote an increase in chemically unstable grains (lithic components) with decrease in quartz content. The values are however within the range for metasediments (Weaver, 1989). Average MgO, CaO, and Na_2O values are generally less than 0.60 % except for the mica schists that have a mean MgO value of 2.74 %. Mean K_2O content is highest in the quartz schist with the quartzites having the lowest value of 0.57 %. The depleted MnO, Na_2O may suggest paucity of movement of metamorphic remobilized fluids during the Pan African or earlier events. Some of Nigeria's schist belt especially the shear zones host auriferous quartz that are presumed to be formed by metamorphic dewatering of the country rocks during the Pan African tectonic phase. (Olobaniyi, 2003) This result therefore, explains the paucity of auriferous veins as noted in an earlier study around this sector of the Ife-Ilesha Schist belt compared to the more mineralized eastern parts about 80 km from this study area (Elueze, 1992) . The values are still within those for metasedimentary rocks (Brown et al., 1979) and comparable to that of Scottish metapelites (Okonkwo, 1992), Igarra quartz mica schist (Okeke & Meju, 1985) and Burum Marble (Okunlola, 2001). Average TiO_2 is highest in the biotite muscovite schist, 0.21 % for the quartz schist and 0.29 % for the mica schist, whereas the quartzite has a mean TiO_2 value 0.10 %. Mean Cr_2O_3 content is generally low in all the samples of both the schists (0.012–0.017 %) and the quartzite (0.035 %). Compared with the post Archean metasediments, the Okemesi rocks are depleted in CaO and Al_2O_3, while they are richer in K_2O when compared with the Archean mudstone (Taylor & Mclennan, 1985). Also a seemingly positive trend is noticed between the Al_2O_3 and TiO_2 values in the biotite muscovite schist, suggesting that TiO_2 may have been held in the clay mineral lattices. (Figures 3 and 4).This is, unlike the indiscernible or scattered trend in the quartzite and the quartz schist, suggesting that both oxides are contained in the heavy mineral phases. Conversely Zr and Nb in the quartz schist shows a positive trend and this suggest their containment in the heavy mineral phases (Figure 5).

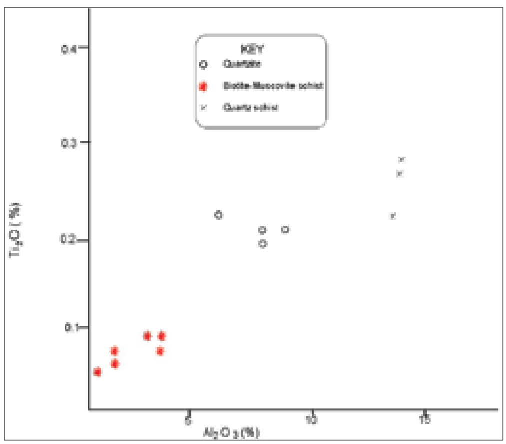

Figure 3. TiO_2 versus Al_2O_3 plot of rocks from Okemesi

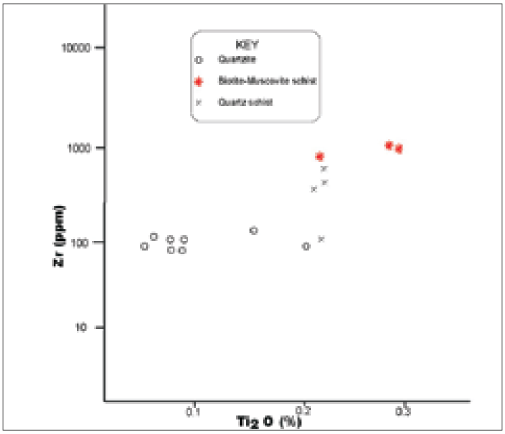

Figure 4. Zr versus TiO_2 plot of rocks from Okemesi

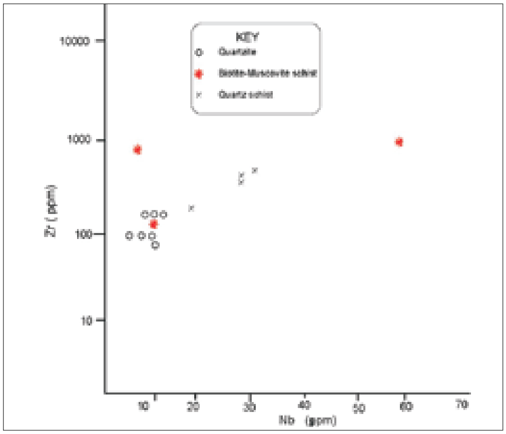

Figure 5. Zr versus Nb plot of rocks from Okemesi

Ba, Sr, Rb and Zr concentrations are more enhanced in the quartz schist than in the quartzite (Table 2) but are well within the range for supracrustal rocks (Brown et al., 1979; Babcock et al, 1979). In particular, the high Zr content may reflect the presence of detrital zircon in the rocks (Elueze, 1981). Zn, Cu and Co content (μg/g) is generally low. The schistose rocks are generally low in Sr/Ba ratios (< 0.4 %). However, Rb/Sr ratio (> 0.4 %) is typical for pelitic metasediments (Van De Kamp, 1968).

The petrogenetic character of the rocks as established on the Na_2O/Al_2O_3 versus K_2O/Al_2O_2 diagram (Garrels & Mackenzie, 1971) (Figure 6) shows that the rocks are largely of sedimentary origin. In the MgO-CaO-Al_2O_3 diagram (Figure 10) (Leyleroup, et al., 1977) the samples plot outside the magmatic field which also supports the sedimentary antecedent of the rocks. These features are similar to those for Ilesha metasediments (Elueze, 1981), Birnin Gwari schist (Ajibade, 1980) and Jebba schists (Okonkwo & Winchester, 1996; Okonkwo, 2006). However, the Na_2O versus K_2O plot (Pettijohn, 1975) (Figure 7) shows possible arkosic affinity of the metasediments, but the discrimination function diagram (Roser & Korsch,1988) (Figure 8) shows that the samples are generally of quartzose sedimentary provenance with the samples plotting deep into the quartzose sedimentary field. The TiO_2-K_2O-P_2O_5 plot (Pearce et al., 1975) (Figure 9) confirms the continental nature of the sediments. On the Al_2O_3–CN−K_2O plot, (Figure 10) the biotite schists and the quartzite plot close to the illite and kaolinite fields while the quartz schist plot close to the average shale. The relatively high content of Ba in contrast to Rb indicates the contribution of felsic components since Ba indicates K-feldspar-rich source rocks. (OKONKWO, 1992; OKONKWO & WINCHESTER, 1998) In addition, TAYLOR & MCLENNAN, (1985) have indicated the importance of such immobile trace elements as Th and La in provenance determinations of pelitic metasediments because they often reflect those of source rocks. The Th content of Okemesi metasediments (1.4–43.3 μg/g) is comparable to those derived from granitic composition. Also most of the samples analysed have low La/Th and Th/U especially those for the biotite

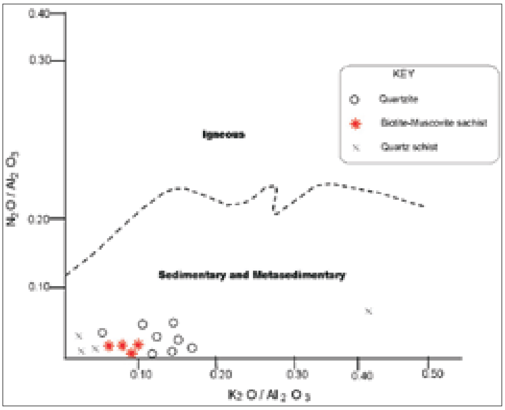

Figure 6. Na_2O/Al_2O_3 against K_2O/Al_2O_3 plot for the Okemesi metasediments (GARRELLS & MACKENZIE, 1971)

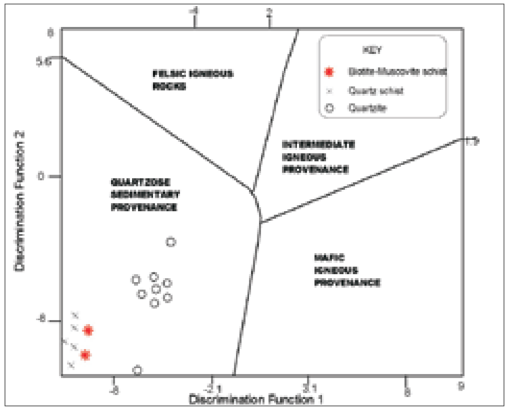

Figure 8. Discrimination Function Diagram of rocks from Okemesi (ROSER & KORSCH, 1988)

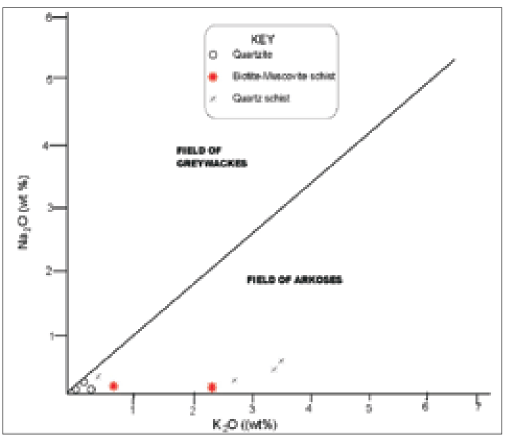

Figure 7. Na_2O versus K_2O plot of rocks from Okemesi (PETTIJOHN, 1975)

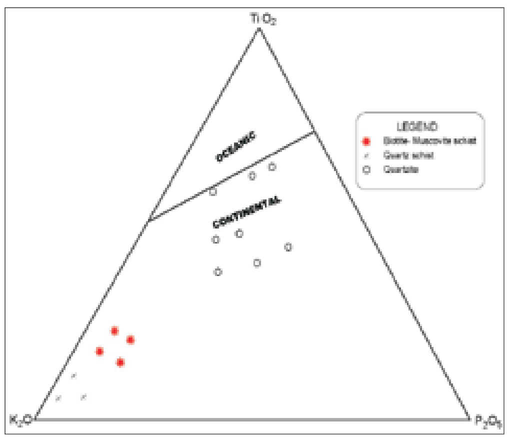

Figure 9. TiO_2-K_2O-P_2O_5 plot of rocks from Okemesi (PEARCE et al., 1975)

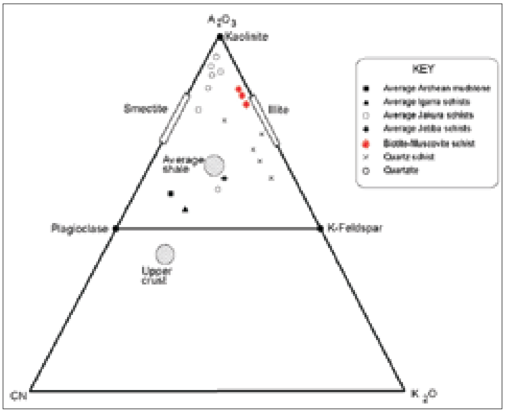

Figure 10. Al_2O_3-CN-K_2O plot for the Okemesi rocks

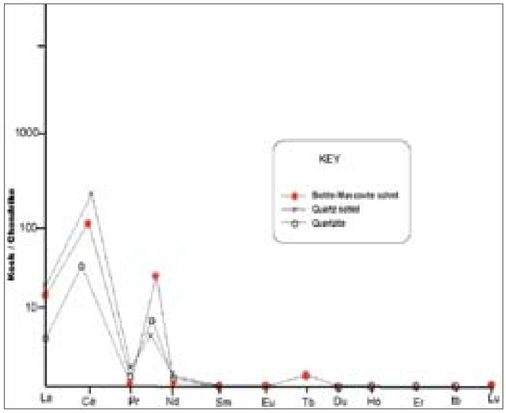

Figure 11. Chondrite normalised REE plot of the Okemesi rocks

muscovite schists. This feature is normally associated with post Archean recycled upper crust sources (Leyleroup et. al., 1977; Taylor et. al., 1986).

The rock samples generally exhibit REE values and patterns typical of low grade Post Archean terrigenous sediments with variable enriched steep LREE and almost flat HREE with no discernible Eu anomaly. (Table 3, Figure 11). La/Yb ratio is also high, resembling the Yellowknife and Pilbara metasediments (Mclennan et al., 1983). These features suggest sediment derivation from a source dominated by felsic igneous rocks (Mclennan & Taylor, 1984). Taylor and co workers, (1986) have also suggested that sediments with steep LREE enrichments and low $Al2_2O_3/Na_2O$ ratio point to derivation from a possible mixture of granite–tonalite rocks to produce the sedimentary protolith.

The results of the Chemical Index of Alteration (CIA) (Nesbitt & Young 1982; Okunlola, 2003) reveal average values of 69.7 %, 85.9 % and 91.2 % for the quartz schist, mica schist and quartzite (Table 4). These values point to relatively intense chemical weathering of the source rocks. The Index of Compositional Variability (ICV) (Cox & Lowe, 1995) which measures the abundance of alumina relative to other constituents of the rock, except SiO_2, show that the quartz schist, biotite-mucovite schist and the quartzite have an average ICV values of 0.68, 0.85 and 0.83 respectively (Table 4). Compositionally immature pelitic rocks have high ICV, whereas mature pelititc rocks with very little non silicates or those rich in kaolinite group clay minerals possess low values (< 0.6) (Elueze & Okunlola, 2003). The calculated ICV value for the quartz schist (0.68) shows the matured nature of the sedimentary protolith prior to metamorphism. Mature to moderately mature pelitic metasediments are characteristic of relatively stable cratonic environments (WEAVER, 1989). This may be marked by sediment recycling or moderate to very intense chemical weathering of first cycle material (BERSHAD, 1966).

In terms of the geodynamic evolution of the rocks in the study area, The Ife-Ilesha schist belt has been thought by earlier workers to be an ensialic basin in an environment of thin and attenuated Crust (AJIBADE, 1976; ELUEZE, 1992; ANNOR, et.al., 1996). Therefore, the occurrence of sub greywacke rocks in the study area as evidenced, suggests a rapidly subsiding depocenter basin, or that there existed much difference in topographic elevation between the sediment source and depocenter. However, since typical deep water sediments and proximal distal-facies variations are absent, there is the possibility that only a moderate depth and width was attained in the basin in the absence of the development of a fully mature ocean. The rapid subsidence of the basin was accompanied contemporaneously with tectonic instability resulting in antiformal deformation and multidirectional fracturing. This may have aided the rapid removal of the sediments before deep weathering and mineralogical maturity was attained. This activity probably accounts for the shallowness of the depth of the basin. Similar characteristics have been noted for the Isanlu schist belt, central Nigeria (OLOBANIYI, 2003). The Nigeria's schist belt is believed to have evolved as a result of an initial continental extensional stage culminating in rift openings and sedimentation with contemporaneous magmatism in the formed basins. These processes were followed by basin closure which led to the deformation of sediments. (AJIBADE, et.al., 1987; ELUEZE, 1992). As seen in this study from petrographic and chemical signature, the Okemesi schistose rocks, which outcrops in the eastern part of the Ife- llesha schist belt,have most probably evolved in a rifted environment of rapid subsidence.

CONCLUSIONS

Systematic geological mapping, petrographic and geochemical evaluation of schistose rocks around the Okemesi fold belt show that the metasedimentary assemblages which form the inner portion of the Okemesi anticline are continental post Archean supracrustals. The sedimentary protolith prior to metamorphism and tectonism have had arkosic affinity and may have also been derived from original source rocks rich in felsic components. However, the discriminant plot of ROSER & KORSCH (1988), suggests contribution from a quartzose sedimentary provenance. Calculations of the Chemical Index of

Alteration (CIA) and Index of Compositional Variability (ICV) show that the schistose rocks are metamorphosed from intensely weathered and mature sediments. Furthermore, the REE signatures confirm the possible contribution of material to the sedimentary protolith from a mixture of granite and tonalite rocks. The rocks are believed to have evolved in a rifted environment accompanied by rapid subsidence.

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