



Petrology and major element geochemistry of parts of Bansara and Mukuru basement complex of southeastern Nigeria

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Abstract

The source and geotectonic setting of structurally-controlled and spatially-related elliptical chains of Pan-African plutons were studied using field relationship and major element geochemistry. Mineral composition (garnet, kyanite, sillimanite and plagioclase), migmatization and complex deformation of the rocks indicate at least medium pressure-high temperature granulite facies of the Barrovian type. The enderbites are probably products of fractional crystallization of differentiating crustally contaminated mantle-derived magma. The greywacke-pelite sequence, the calc-alkaline nature of the enderbites, with high K_2O/Na_2O ratios and document peraluminous (S-type) nature, the Al_2O_3 contents ranging from 13.2% to 18.72%, suggest a possible granitic magmatism at an active continental margin of the Andean-type between the West African and Benin-Nigerian plates during the Pan-African orogeny.

Keywords: Petrology; Major Element; Geochemistry; Source; Geotectonic Setting; Bansara/Mukuru Area; SE Nigeria

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1. Introduction

Granulites are very important constituent of high grade metamorphic terrains and are therefore crucial in understanding the evolution of the lower crust, which forms under high Pressure-Temperature conditions. The study of the petrogenesis of charnockitic rocks such as enderbites from a terrain such as the western Bamenda Massif can help to reveal the processes of the formation of the granulites. For instance, Ferre and Caby (2006) reported that the crystallization of granulite facies of the Pan-African northern Nigeria was possible because of the heat supplied from the abundant anhydrous charnockites and monzodiorites in the area. Primitive mantle melts produced in the mantle wedge at subduction zones are mafic and must evolve to produce the more silicic magmas at arc volcanoes. The processes by which this evolution occurs likely take place within the crust and include: (1) crystallization of mafic melts in shallow crustal magma chambers [Sisson and Grove, 1993; Pichavant, 2002], (2) continuous evolution of the magma as it resides in and moves through multiple levels of magma reservoirs [e.g., Dufek and Bachmann, 2010], (3) differentiation that occurs almost entirely in the lower crust [e.g., Müntener et al., 2001; Annen and Sparks, 2002], (4) mixing with silicic melts of the surrounding country rock [e.g., Jackson et al., 2003; Tatsumi and Kogiso, 2003], and (5) mixing of melts formed by differentiation of mafic magma in the lower crust and by partial melting of crustal rocks [e.g., Hildreth and Moorbath, 2017; Annen et al., 2006]. In these models, formation of the required volumes of intermediate composition magma typically results in mafic cumulates that are far thicker than the observed mafic lower crust. These observations collaborates with some of our field evidence where massive quartz diorites and charnockites outcrop at the contact between Bansara Sheet 304 and Mukuru sheet 305 probably supplied the heat that led to formation of granulites facies in Mukuru area (Fig.1a and b). Such sources are common in collision zones where crustal thickening takes place. However, the petrogenesis of charnockitic rocks is fraught with debates, because they are believed to be either granitic rocks metamorphosed to the granulite facies (Newton et al. 1980) or igneous rocks whose pyroxene crystallized directly from magma (Wendlandt, 1981).

Elliptical chains of enderbites form a chain of extensive topographic highs and on plains and foot of hills and show no foliation in outcrops and phenocrysts are in random pattern in the area. Due to problems of rugged topography and poor accessibility of the area, the petrogenesis and tectonic setting of the enderbites have received little attention compared to the abundant information on the other basement terrains of Nigeria (McCurry and Wright, 1977; Rahaman, 1976; Ajibade and Fitches, 1988; Oluyide, 1988; Ekwueme, 1990a, 1998). There are no previous works in the area, except regional aeromagnetic studies of Precambrian Oban massif and Obudu Plateau, Iliya and Bassey, (1993). The age of the rocks are yet to be determined. This research is, therefore, an attempt to use petrology and the major element geochemistry of the rocks to determine the source and geotectonic setting of the migmatitic gneisses, granulites and enderbites from Bansara and Mukuru area.

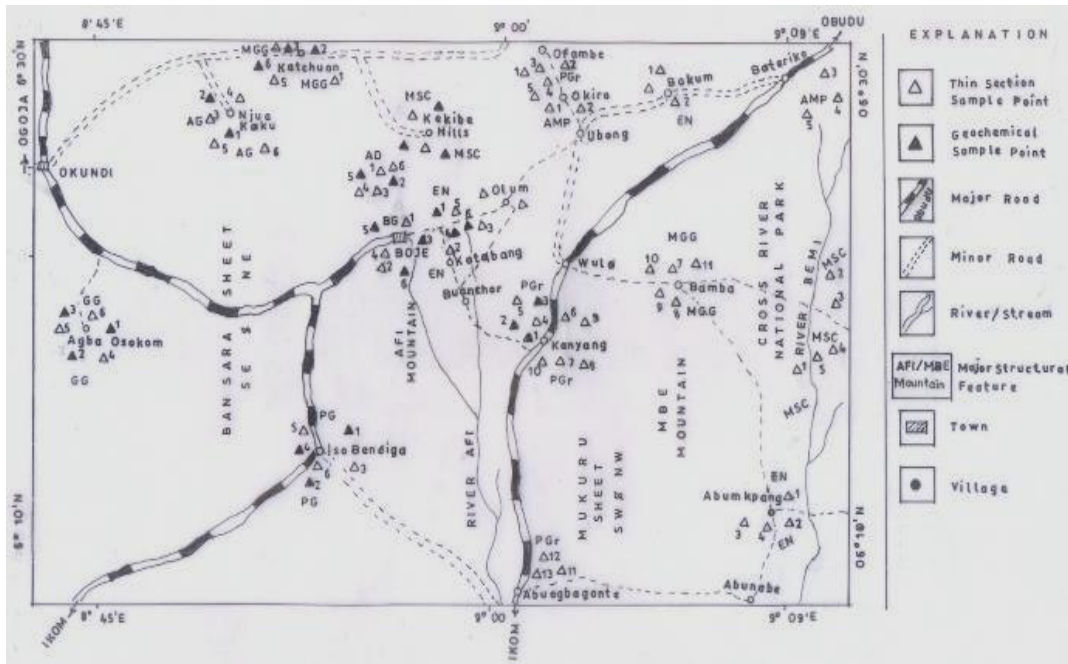


Figure 1a. Sample location map showing Bansara and Mukuru area (Egesi, 2015)

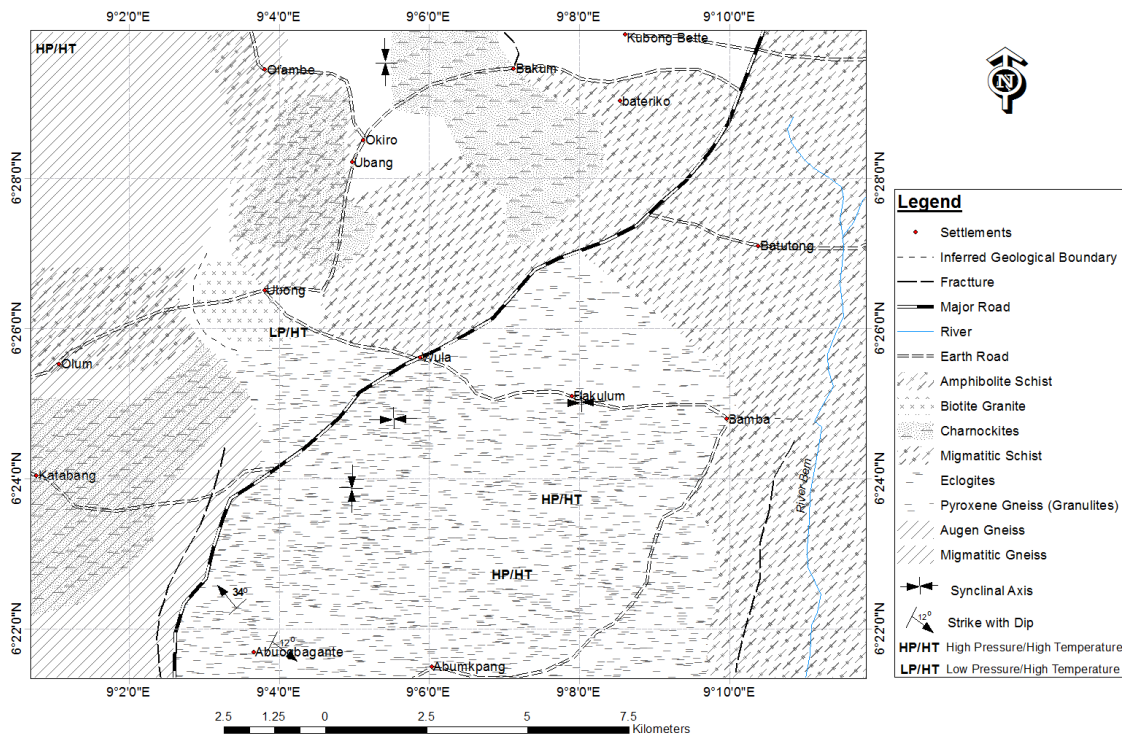


Figure 1b. Geological map showing parts of Bansara and Mukuru area (Egesi, 2015)

2. Materials and methods

Field observations of migmatitic gneisses, granulites, schists, amphibolites and enderbites were made, thirteen fresh and representative samples across the study area for geochemical determination of the major element compositions. Random sampling of only accessible exposures was employed during field exercises due to the rugged topography and uneven exposure of fresh enderbites, but the samples were representative of good exposures. Samples collected represent all the varieties of the rock suites that were considered important in achieving the objectives of this study. Field photograph and photomicrograph of migmatitic gneisses are shown in Fig. 2a and b. Analytical technique involved the use of fusion dissolution methods of Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the Activation Laboratories, Ontario, Canada. The advantage of this technique over Atomic Absorption Spectrometer (AAS) is the ability to determine 20-60 elements simultaneously in a circle time of 2-3 minutes. The linear dynamic range of 3-5 order of magnitude means both major and trace elements could be determined in the same solution i.e. no dilutions. Details of fusion dissolution methods are in Thompson and Walsh (1983).



Figure 2a. Field Photograph showing reverse fault (minor) in mafic xenoblast of amphibolite in granite gneiss and exfoliation joints at Agba Osokom.



Figure 2b. Photomicrograph showing that feldspars are the dominant minerals in granite gneiss with prismatic orthoclase and cross-hatching microcline twinning (XPL 40)

3. Major element geochemistry

The major geochemistry was analyzed using Criss, Iddings, Pirsson and Washington, CIPW and Niggli normative minerals (wt%) of the samples, they are grouped according to their increasing SiO_2 values to illustrate their sialic trend as presented in Table 1. The metamorphic rocks have SiO_2 contents ranging approximately from 47% to 73%, comprising migmatitic gneisses (66-73% SiO_2) and granulites (58-66% SiO_2), schist (52-58% SiO_2), amphibolites 47%, whereas the charnockitic rocks have SiO_2 contents ranging approximately from (54 - 71%). The Al_2O_3 contents range from 12.86% to 18.72%. The major element compositions, CIPW and Niggli normative minerals of the analyzed rock samples, are presented in Table 1. Charnockite = 1 and 2, Granulite = 3 and 6, Amphibolite = 5, Schist = 4 and 8, Migmatite Gneiss = 7, 9 and 11 and Granite Gneiss = 10, 12 and 13.

On the $(\text{Fe}_2\text{O}_3 + \text{MgO}) - \text{Na}_2\text{O} + \text{K}_2\text{O}$ ternary and $\text{K}_2\text{O} + \text{Na}_2\text{O} - \text{SiO}_2$ binary diagrams (Figs.3 and 4) respectively, some of the gneisses are similar to greywackes and lithic arenites in composition. Plotting mostly in the calc alkaline and sub-alkaline environment, a few with high content of ferromagnesian minerals plotted in the tholeiitic field.

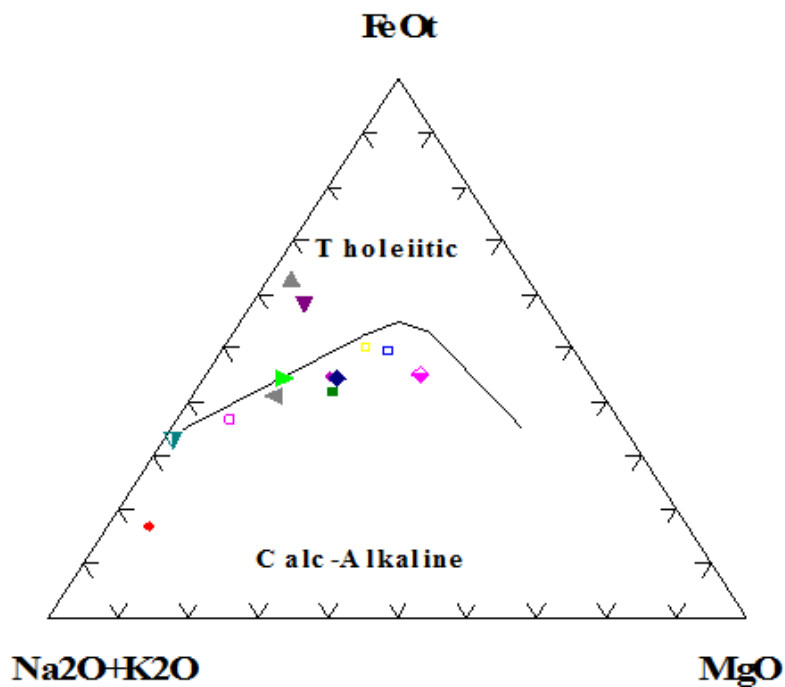


Figure 3. AKF ternary diagram (Winkler, 1979) showing mostly Calc- alkaline metamorphic character

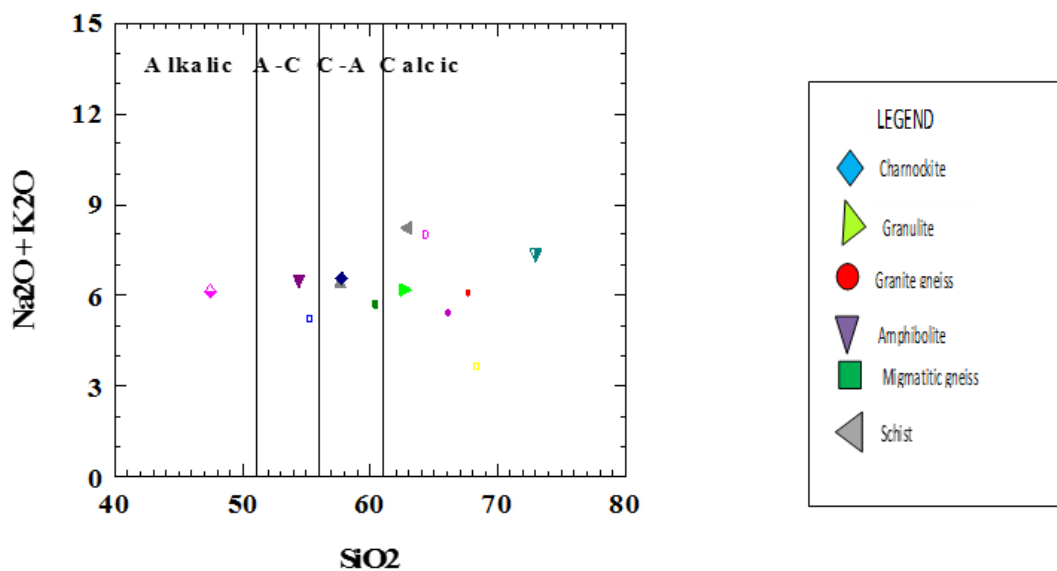


Figure 4. SiO₂ vs Na₂ + K₂O binary diagram showing sub-alkaline nature of the metamorphic rocks after Peacock, 1931

Table 1. Major element Geochemistry of ocks in Bansara and Mukuru (Egesi 2015)

	MAJOR ELEMENTS GEOCHEMICAL ANALYSIS												13
	1	2	3	4	5	6	7	8	9	10	11	12	
SiO ₂	54.38	57.62	64.56	55.48	47.48	62.74	68.56	57.76	72.95	62.81	66.33	67.85	60.65
TiO ₂	2.04	1.41	1.28	1.59	2.12	1.13	0.70	1.19	0.32	1.09	1.09	0.12	0.50
Al ₂ O ₃	14.30	13.56	14.52	17.03	13.81	15.43	13.2	17.43	12.86	16.88	14.33	18.72	16.58
Fe ₂ O ₃	1.21	1.33	0.58	1.05	1.27	0.79	0.67	1.08	0.41	0.69	0.71	0.14	0.67
FeO	10.91	11.99	5.18	9.40	11.38	7.14	6.02	7.92	3.68	6.20	6.37	1.27	6.07
MnO	0.18	0.21	0.69	0.20	0.16	0.10	0.13	0.11	0.05	0.10	0.12	0.02	0.12
MgO	1.41	0.63	1.25	4.84	7.75	2.06	2.59	3.42	0.17	1.63	2.78	0.54	3.08
CaO	5.40	4.60	2.43	2.76	6.79	1.31	1.11	2.26	1.38	2.89	1.89	5.02	6.01
Na ₂ O	2.28	2.13	2.55	2.52	2.04	2.23	1.49	3.15	1.83	3.82	2.71	5.14	3.82
K ₂ O	4.17	4.31	5.37	2.57	4.12	6.00	2.05	3.41	5.51	2.37	2.62	0.82	1.75
P ₂ O ₅	1.45	0.77	0.69	0.15	0.47	0.04	0.08	0.23	0.08	0.09	0.12	0.03	0.28
LOI	0.38	0.51	0.43	0.62	0.95	0.27	1.90	1.31	0.30	0.22	0.42	0.22	0.53
Total	98.09	99.06	98.91	98.21	98.34	99.23	98.49	99.08	99.52	98.77	99.48	99.99	100.10
ACNK	1.21	1.23	1.40	2.17	1.07	1.62	2.82	1.98	1.48	1.82	1.99	1.71	1.43
			CIPW NORM										
Q(s)	8.50	12.24	20.32	12.09	0.00	16.26	43.11	11.87	35.77	19.24	28.58	22.59	11.64
Or	25.24	25.87	32.05	15.58	25.02	35.85	12.55	20.59	32.84	14.22	15.64	4.86	10.40
ab	19.72	18.27	21.75	21.82	14.32	19.04	13.04	27.18	15.58	32.75	23.12	43.54	32.44
an	16.8	14.88	8.08	13.14	16.74	6.33	5.22	10.07	6.43	14.02	8.76	24.8	22.99
lc	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ne	0.00	0.00	0.00	0.00	1.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

C(A)	0.00	0.00	1.57	5.52	0.00	2.98	6.91	5.03	1.54	3.00	3.88	0.30	0.00
ac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ns	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Di	1.66	191	6.52	0.00	12.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.44
Hy	19.09	19.11	11.41	26.86	0.00	16.13	16.61	20.85	6.45	13.45	16.63	3.41	15.14
Ol	0.00	0.00	0.00	0.00	22.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
mt	1.80	1.96	0.85	1.56	1.89	1.16	1.01	1.60	0.60	1.02	1.04	0.20	0.98
he	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ilm	3.97	2.72	2.45	3.1	4.14	2.17	1.38	2.31	0.61	2.10	2.09	0.23	0.95
ap	3.24	1.71	1.52	0.34	1.05	0.09	0.18	0.51	0.18	0.20	0.26	0.07	0.61
	NIGLI NORM												
al	26	26	35	30	23	35	37	41	42	37	34	46	31
fm	39	40	29	48	62	37	44	28	24	31	40	8	33
c	18	16	10	9	2	5	6	10	8	12	8	23	20
alk	15	16	24	12	13	23	13	21	29	20	17	23	16
k	0.54	0.57	0.58	0.40	0.57	0.64	0.48	0.44	0.66	0.29	0.39	0.097	0.24
mg	0.113	0.049	0.24	0.039	0.55	0.38	0.41	0.83	0.07	0.31	0.43	0.42	0.47
Q	+104	+29	+73	+19	-19	+48	+169	+47	+212	+57	+97	+91	+29
Si	170	191	262	166	133	240	321	231	428	237	265	283	193

4. Results and discussion

The major element compositions show that the enderbites have intermediate to acidic properties. The enderbites are high in Al_2O_3 and Fe_2O_3 , normal in CaO , Na_2O and K_2O and low in MnO , TiO_2 , P_2O_5 and MgO compared to contents of elements in granites (Taylor, 1964). Furthermore, Fe_2O_3 , CaO , TiO_2 , P_2O_5 and MgO decrease and K_2O increases with increase in SiO_2 content, while Al_2O_3 and Na_2O remain constant. Considering the alumina saturation index, the enderbites have no corundum in their norms but are peraluminous. This is confirmed by the A/CNK vs A/NK plot 1.5/1.4. Thus, the A/CNK ratio is greater than unity in both rock types. The rocks are Q-normative and K-rich. The enderbites classify as quartz monzonites to granites on the CaO-

Na₂O-K₂O ternary diagram (Fig.5) and as granites on the QAP ternary diagram (Fig.6). Comparison with similar rock types in the Nigerian Basement Complex and other terrains indicates that the enderbites differ in major element geochemistry from the Obudu type enderbites, Nigeria (Orajaka, 1971), Kabbal and Yelachipalaiyarn charnockites, India (Janardhan *et al.* 1982) and charnockitic and granitic rocks of Akure and Ado-Ekiti, Nigeria (Olawajaju, 1988). However, the major element composition of enderbites from Mukuru area compare very well with the major element composition of Swarnavati charnockites of India (Janardhan *et al.* 1982). Of significance is the high total alkali, K₂O, K₂O/Na₂O and low Al₂O₃ and MgO contents of the enderbites of Mukuru area compared to values obtained elsewhere in the Basement Complex of Nigeria. Generally, the major element composition of the enderbites is similar to that of the intermediate charnockites (enderbites) of southern India (Rajesh and Santosh, 2004).

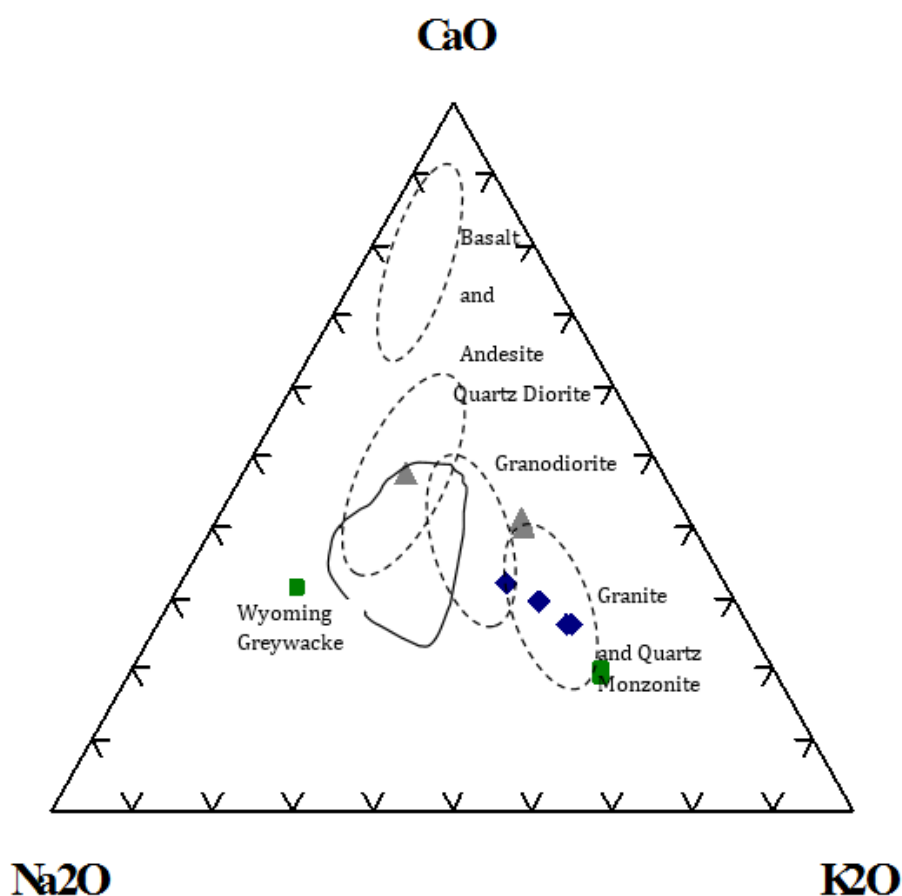


Figure 5. CaO-Na₂O-K₂O ternary diagram of the granitoids showing the granitoids plotting mainly within the field of granites (after Condie, 1967).

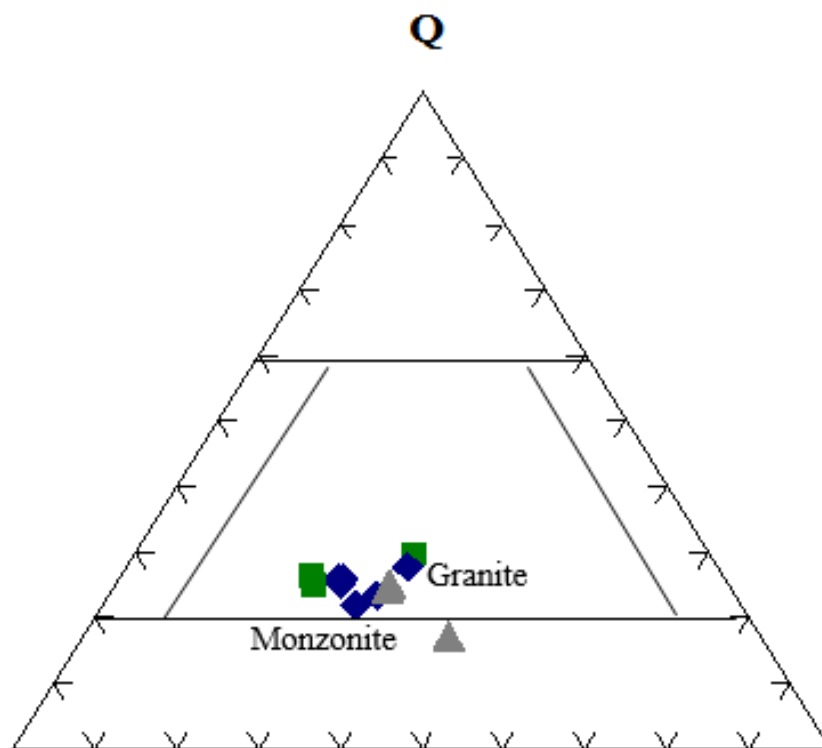


Figure 6. QAP ternary diagram of the granitoids showing the granitoids plotting in the field of granites (after Streckeisen, 1976)

The chemical data, several co-variance diagrams and parameters applied to the analyzed major element data of the rocks of the area indicate a wide range of relationship in their protoliths and evolution. The abundance of potash feldspar and myrmekites with little plagioclase indicates that these migmatites are alkaline in nature. On the $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$

vs $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ diagram (Fig.7), the biotite-garnet-sillimanite gneisses and biotite-garnet gneisses plot within the sedimentary field. To confirm this, Discrimination Factor (DF) of Shaw (1972) defined as $\text{DF} = 10.44 - 0.21\text{SiO}_2 - 0.32\text{Fe}_2\text{O}_{3\text{tot}} - 0.48\text{MgO} + 0.55\text{CaO} + 1.46\text{Na}_2\text{O} + 0.54\text{K}_2\text{O}$ was applied to establish whether the rocks are really of sedimentary or igneous origins. This factor shows that the biotite-garnet-sillimanite gneisses and biotite-garnet gneisses with values for the gneisses are similar to the values obtained for Igbeta gneisses (Emofurieta, 1985). Also the presence of very high SiO_2 , sillimanite, abundance of biotite and the preference for sedimentary fields of the biotite-garnet-sillimanite gneisses and biotite-garnet gneisses argue in favour of sedimentary progenitor for these gneisses. Thus, the gneisses have metasedimentary protoliths.

The paragneisses show $\text{K}_2\text{O} > \text{Na}_2\text{O}$ (pelitic origin) and $\text{K}_2\text{O} < \text{Na}_2\text{O}$ (greywacke origin) (Crichton and Condie, 1993). In general, argillaceous rocks especially those containing appreciable amounts of illite and montmorillonite, show $\text{K}_2\text{O} > \text{Na}_2\text{O}$ but where $\text{K}_2\text{O} < \text{Na}_2\text{O}$, Pettijohn (1975) suggested that volcanic materials and shales may have mixed or there is association of greywackes with shales. Biotite (K-mica) and, probably K-

feldspar in some of the gneisses, account for the high K in most of the gneisses. The changing trend in soda/potash ratio may be ascribed to different source lithologies (shale-greywacke). Thus, the protolith of the biotite-garnet-sillimanite gneisses and biotite-garnet gneisses was a greywacke-shale sequence. The ranges of K_2O/Na_2O and Al_2O_3/Na_2O in the biotite-garnet-sillimanite gneisses and biotite-garnet gneisses are 0.6 to 1.4 and 4.97 to 6.14 respectively. These values are consistent with values obtained for migmatitic gneisses from Obudu Plateau area and also high-grade metagreywacke-pelite turbidite (McLennan and Taylor, 1991). Furthermore, the low fm (<37) and high al-alk value (18-23) for the biotite-garnet-sillimanite gneisses indicate derivation from greywacke-clay rich protoliths. This view is supported by the general $Na_2O > K_2O$ values.

The high TiO_2 and P_2O_5 contents in the enderbites indicate high temperature of formation (Green and Pearson, 1986). The occurrence of perthite and exsolution textures suggests initial crystallization at elevated temperature. The fractionation pattern in Mukuru area is similar to patterns of late Pan-African Older Granites and charnockites in the Trans-Saharan belt of Eastern Nigeria (Rahman, 1981). The enderbites of Mukuru area plot in igneous to sedimentary fields on the SiO_2 vs TiO_2 variation diagram. However, the igneous origin of both rock types is apparent from field relations such as outcrop pattern, random orientation of phenocrysts with contact metamorphic aureole; petrology such as granitic textures and mineralogy, and distinct geochemical characteristics. The uncertainty about the parentage of the enderbites was resolved by applying the Discrimination Factor (DF) of Shaw (1972). The enderbites showed average DF value of 2.21. Thus, the enderbites are igneous in origin.

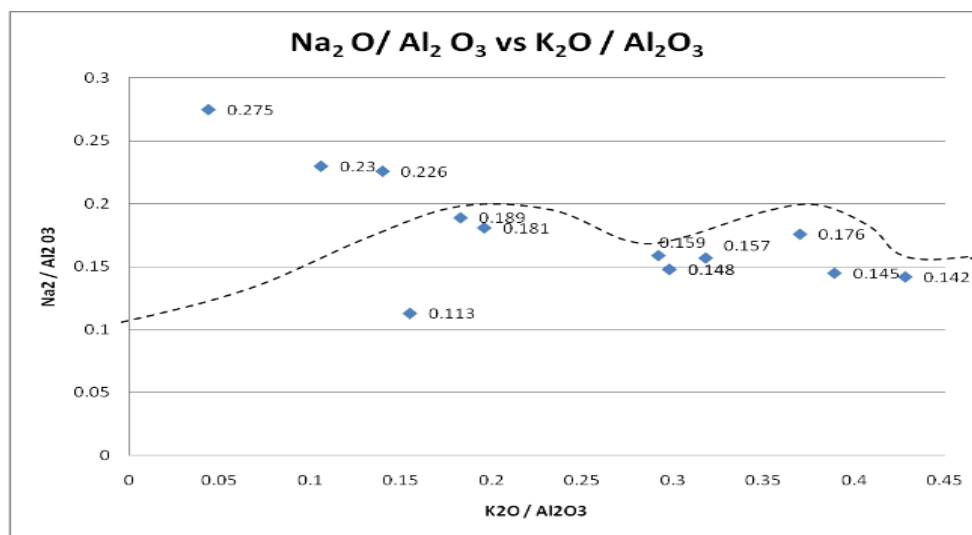


Figure 7. Na_2O/Al_2O_3 vs K_2O/Al_2O_3 for Precambrian rocks of the study area (Garrels and Mackenzie, 1971)

The enderbites plot within the igneous field on the $Na_2O/Al_2O_3 - K_2O/Al_2O_3$ variation diagram (Fig.7), and within the 1-type field on the QAP variation diagram and on the A/CNK vs A/NK discrimination diagram peraluminous (Fig.8). The dark-green colour and the yellowish fracture coating which characterize charnockites are due to crystallization in a water deficient environment during plutonic crystallization, probably due to very low water content in the source magma or from a high CO_2 content in or associated with

the magma (Janardhan *et al* 1982; Haslam 1989; Olarewaju, 1988). The fact that plagioclase and pyroxene are the main solid phases in the enderbites of the study area, suggests that crystallizing magma was under-saturated with respect to water. The fact that the enderbites are dioritic in composition suggests the role of magmatic differentiation from the mantle in the process of emplacement. However, basaltic magmas are also known to be hybridized with anatectic granitic melt to produce magma of intermediate composition within the crust.

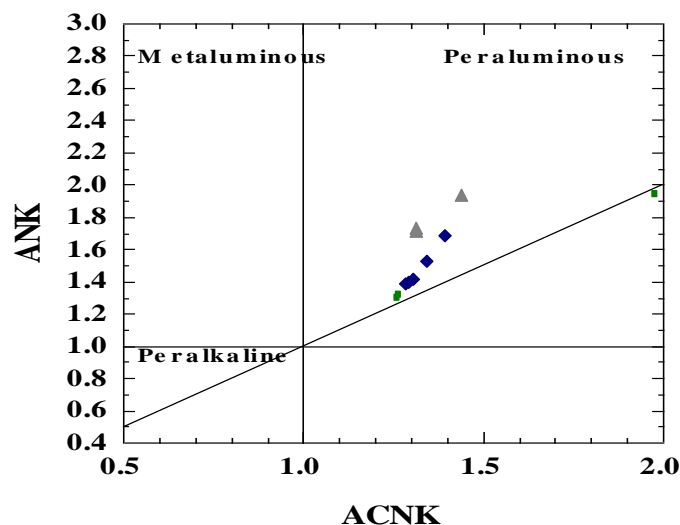


Figure 8. A/CNK vs A/NK binary variation diagram showing the peraluminous nature of the granitoids (after Manier and Piccoli, 1989) showing that the granitoids are peraluminous

Mafic enclaves in the enderbites further suggests the role of hybridization of mafic mantle derived magma with SiO₂ rich melts derived from old crustal sources. These enderbites are probably a hybrid product of anatectic melting and evolving magma at a thermal peak of a granulite facies metamorphism following crustal collision between the West African and Benin-Nigerian plates (Attoh, 1998, Affaton *et al.*, (1991). The geochemistry of these charnockites points probably to a complex origin, involving crystallization and crustal contamination. The enderbites exhibit some distinctive differences from average upper crustal rocks, which is consistent with the character of most medium pressure granulite terrains (Pride and Muecke, 1980). These differences include very low abundances of Rb, high K/Rb ratios, and more intermediate chemistry than average upper crustal rocks. The very high K/Rb range for the enderbites may also be due to contamination. The enderbites, therefore, represent fairly fractionated rocks. The mantle derivation of the pre-contaminated magma of the study area is consistent with the derivation of most of the late-stage Pan-African magmas from the mantle (Umeji, 1991). The magma that fractionated to produce the high-K, I-type calc alkaline enderbites in the crust was contaminated probably during stoping by crustally derived magma. The enderbites are comparable in many respects to some post-collisional Variscan granitoids of Western Europe that were generated long after ocean closure in a post-collisional setting predominantly by crustal melting (Gerdes *et al.*

2000). The enderbites are spatially closely associated with granulites, (Egesi and Ukaegbu, 2010) suggesting that they might have been contaminated hybrid product at apparently low water pressure at anatexis conditions, which produced in the process, abundant dense and dry minerals (eg. hypersthene and plagioclase) from decomposed micas and transformed hornblende (Ukaegbu, 2003). Thus, it seems that the enderbites in the area may be explained as a hybrid product of anatexis melting and evolving magma at a thermal peak of a granulite facies metamorphism following crustal collision between the West African and Benin-Nigerian plates (Attoh and Ekwueme, 1997). Todt *et al.* (1995) suggested that such intrusion could have taken place before or close to the end of thermal peak of metamorphism. The rocks plot mostly in calc-alkaline field on the AFM variation diagram, although the compositions of some of the enderbites are rich in iron and so they plot within the tholeiitic field. The rock types have chemical compositions typical of granitoids from dry magma source (O'Nions and Pankhurst, 1974). The dominance of orthopyroxene, plagioclase, quartz and K-feldspar as the main solid phases in the rocks suggests that the source was undersaturated with water.

The discriminating diagram of the rocks suggests a dominantly syn-collisional setting with subordinate late orogenic to post-collision settings for the enderbites. For instance, the enderbites show wide range of settings on the multicationic R1 vs R2 discrimination variation diagrams (Fig.9); from syn-collision setting to post-collision setting. This collision-type tectonic setting involved mixing of anatexis crustal material with juvenile material. Antignano and Tollo (2001) observed that orthopyroxene-bearing granitic mineral assemblages are common constituents of cratonic basement complexes worldwide.

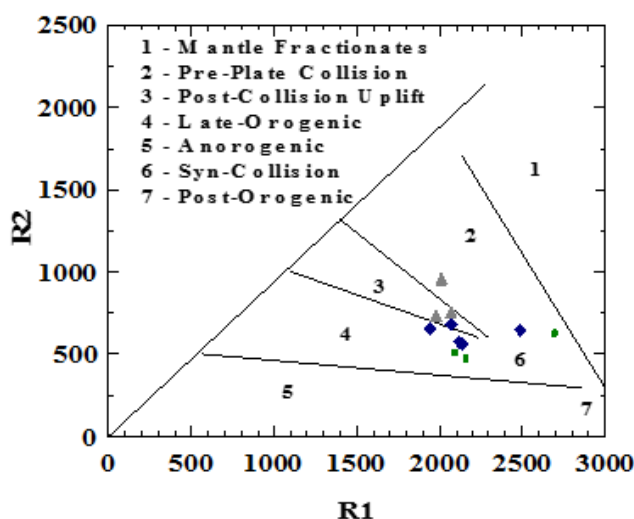


Figure 9. R1 vs R2 binary variation diagram of the granitoids (after Batchelor and Bowden, 1985) indicating that the granitoids are essentially of Late-orogenic to Post-collision uplift setting. $R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$; $R2 = 6Ca + 2Mg + Al$

5. Conclusion

The major elements contents of the enderbites suggest that the granitic protoliths intruded along an active continental margin. The low peraluminous values in the charnockites than in the enderbites probably indicates that they formed at deeper levels; an attribute suggested by the plutonic nature of the enderbites in the field. The rocks were probably emplaced in similar conditions during crystallization. The metamorphosed rocks indicates only three samples plotted in the metaigneous field pointing to the fact that most rocks analyzed in the area are metasedimentary in origin.

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