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Petrology, Geochemistry and Structural Attributes of the Irruan Basement Rocks, Southern Obudu Plateau, Southeastern Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. Author EOO designed the study, managed field mapping and geochemical and petrographic analyses as well as wrote the first draft of manuscript. Author EEU designed the study, managed geochemical analysis and literature searches as well as wrote the first draft of manuscript. Author OOOI managed the petrographic analysis and wrote the first draft of the manuscript. Author JEE managed the literature searches and wrote the first draft of manuscript. Author DPO managed the petrographic analysis and the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Very little research has been carried out and reported on the Irruan granitoids. Geological field mapping and laboratory analyses were carried out to ascertain the petrological, geochemical and structural attributes of the Irruan Basement Rocks in southern Obudu Plateau, southeastern Nigeria. Five petrological units: granite gneiss, banded gneiss, migmatite gneiss, granodiorite and biotite granite were identified in the area. The rocks are generally siliceous and quartzofeldspathic, recording ≥70.11 wt.% of SiO_2 except the biotite granite that records 61.10 wt.% of SiO_2; quartz ranges from 25 – 35%, 30%, 20 – 27%, 22 – 35% and 30% for granite gneiss, banded gneiss, migmatite gneiss, granodiorite and biotite granite respectively. Feldspar ranges from 20 – 35%, 22 – 25%, 20 – 27%, 20 – 30% and 25% respectively for the granite gneiss, banded gneiss, migmatite gneiss, granodiorite and biotite granite. Relative to plagioclase, orthoclase is more dominant in

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many of the samples. Biotite and muscovite range from 5 – 15%. The metamorphosed rocks are predominantly peraluminous, showing aluminum saturation index (ASI) ranging from 1.05 to 3.37 and (Na_2O + CaO)/Al_2O_3 ratios of 0.27 – 0.95 and average A/CNK of 1.13. Generally, there are marked variations in the distribution of trace elements with Rb/Nb, Rb/Zr and Rb/Sr ratios of ≤25,000, ≤0.5319 and ≤0.7377 respectively. The granitoids have resulted from the partial melting of the crust with possible contribution from mantle-derived, crust-contaminated magma. On the outcrop scale, fractures occur in NW-SE, NE-SW, NNE-SSW, E-W and N-S orientations. Evidences of primary and secondary structures were observed. The dominant NE-SW fractures were developed contemporaneously with the foliations and lineaments. The N-S and fairly weak E-W fracture sets were developed from a later episode.

Keywords: Petrology; geochemistry; structural attributes; Irruan basement rocks; Obudu Plateau.

1. INTRODUCTION

The polycyclic, basement rocks in Nigeria are part of the reworked Precambrian rocks of the West African craton. The tectonics and evolution of these rocks have been the focus of research interests over the last three decades [1]. It is widely believed that the Nigerian Basement Complex has been affected by 4 tectono-metamorphic events: Liberian (2700 ± 200 Ma), Eburnian (2000 ± 200 Ma), Kibaran (1100 ± 200 Ma) and Pan-African (600 ± 150 Ma), although the Liberian and Kibaran events are disputed by some workers [2].

Relative to their counterparts in northwestern and southwestern parts of the country, the basement rocks of southeastern Nigeria have attracted less research interests [3–4]. Prior to the work of [1], the area of the present study had been classified as part of the “Undifferentiated Basement”, “Granulites Terrain” and “Granitoids” in the 1994, 2004 and 2011 geological maps of the Nigerian Geological Survey Agency (NGSA) respectively (Fig. 1A). More so, most of the existing studies around the area of the study [e.g. 5–6] are largely regional in scale. Also, most of the studies in the area are either focused entirely on the geology of the area without giving adequate consideration to the structural attributes or they are focused on the mechanical (structural) attributes without paying proper attention to the geology. The work of [1] centered largely on the geochemistry of the unmetamorphosed granitoids in the area without paying much attention to the gneissic rocks. [4] recently reported on the petrogenesis and tectonic setting of the area.

Recently, efforts have been made to address the paucity of studies on the Irruan area. Prominent among such efforts are the published works of [1 and 4] reporting that the Irruan area is underlain by both igneous and metamorphic rocks. And relying on geochemical data, these rocks have been classified as peraluminous, alkali-calcic to calcic as well as ferroan [1]. Tectonic setting ranging from syn-collisional to post-collisional has been inferred for these rocks just as a sedimentary or metasedimetary protholith interpreted for the Irruan gneisses [4]. Considering their highly felsic nature (75.53% SiO_2 on the average) together with evidences from discriminant plots, parent magma for these granitoids have been interpreted to have largely evolved from the continental crust [4] with partial melting of the continental crust in a post-collisional tectonic setting playing a dominant role [1].

However, the overall evolution of these rocks remains vague. So far, there are no studies which combine both geochemical and petrological data with structural data for the purpose of reconstructing the geology of the area. According to [7–9], relying on only geological or mechanical data for analysis may not give the best results and interpretations compared to when such data are integrated or correlated. Despite the efforts by [1 and 4], the structural geology of the Irruan remains unreported. Whereas both studies relied largely on field observations and geochemical data, no attempts at discussing the structural attributes of these rocks have been made. More so, [4] mainly focused on the bulk rock geochemistry without considering the trace element geochemistry. The current paper therefore, is an attempt to combine the structural geology of the area with the existing knowledge on the area with a view to enhancing the understanding of the evolution of the basement rocks of the area. Also, efforts are made to discuss the trace element geochemistry in relation to the magma source for the rocks of the area. The present study, therefore, is aimed at initiating a discussion on the evolution of basement rocks in the Irruan araea using the integrated approach of combining petrological, geochemical and structural analyses.

1.1 Overview of the Geology of the Nigerian Basement Complex and Location of the area of the Study

The Nigerian Basement Complex is part of the Benin-Nigeria shield, located within the Pan-African mobile belt. The belt is situated between the West African and the Gabon-Congo cratons [10–11]. Lithologically, the Nigerian Basement Complex consists of four rock units: the Migmatite-gneiss-quartzite complex, the Schist belts, the charnockitic gabbroic and dioritic rocks as well as the Older Granites [11–14].

The Migmatite-gneiss-quartzite complex is a heterogeneous assemblage of dominantly orthogneisses, paragneisses and traces of basic to ultrabasic rocks. The petrological units consist of grey foliated quartzo-feldsparthic gneiss of tonalitic to granodioritic composition. The migmatite gneisses make up about 60% of the Nigerian Basement [11–13]. The Schist belt is otherwise regarded as the Younger Pan-African metasedimetary series and occupies north-south synclinoria in the Basement Complex. The Schist Belt is thought to overlie the Migmatite Gnesiss Complex and comprise of predominantly metasediments with inter-layered gneisses and in rare cases, amphibolites otherwise interpreted as metavolcanics. These are low grade, metasediment-dominated rocks with the lithological units consisting of semi-pelites, quartzites, marbles, amphibolites, ultramafic and minor felsic to intermediate metavocalnics and greywackes [11,14]

The Older Granites which are often referred to as the Pan-African granitoids consist of strongly granitic plutons and charnockites. Typically, the Older Granites intrude both the migmatite gneisses and the schists. Important lithologic units in the Pan-African granitoids include biotite-granite, biotite-muscovite granites, charnockite, diorites, monzonites, serpentinites and anorthosites [11–13].

The Nigerian Basement Complex is part of the reactivated Pan-African mobile belt [15], generally thought to have resulted from the collision of the West African Craton and the Tuareg Shield (Fig 1B). Otherwise known as the Trans-Saharan Pan-African Orogen, the collision orogeny is characterized by the development of thrust-nappe, high grade metamorphism and massive granitic rocks.

Both ductile and brittle deformational structures have been mapped in Nigerian basement rocks. Mineralization within the basement rocks have been identified as structurally controlled [16]. Four fracture lineament trends, NW-SE, NW-SE, E-W and N-S have been reported in the basement rocks of the Oban massif and Obudu Plateau, both in southeastern Nigeria [17]. According to them, the NW-SE fracture trend predominates with a disorientation of 10^{o} among the NW-SE fractures in both areas. They also reported the N-S trending to be the least frequent in both areas but this trend (N-S) recorded the longest fractures. The most frequently occurring fracture length in the basement rocks of southeastern Nigeria is about 2 km and the frequency decreases with increasing length [17].

This study was carried out around Irruan and neighbouring communities in Boki Local Government Area of Cross River State, southeastern Nigeria (Fig. 1). Specifically, the area of the study falls within the Bansara NE (Sheet 304NE) of the NGSA, covering between Latitude N06°23′00.0″ and N06°30′00.0″ and Longitude E008°46′46.0″ and E009°01′00.0″. Irruan is situated at the southern part of the Obudu Plateau. The Obudu Plateau forms the western extension of the Bamenda Massif of the northern Cameroon in southeastern Nigeria. The Obudu Plateau and the Oban Massif constitute the Precambrian basement horsts flanked by the Cameroon Volcanic Line on the southeast and the Benue Trough to the northwest [10]. Notable petrological units in the Obudu Plateau as identified from previous studies include dolerite, granodiorite, migmatite gneisses [15,18].

Topographically, the area is undulating with altitude reaching over 400m above sea level in places. To the east, there is a long mountain ridge stretching from Ndemenchang southward up to Boje. This north-south trending Ndemenchang Hill represents the highest point in the study area and is considered to be part of the Afi Mountain belt [19]. The area is generally served by road networks prominent among which are the Okundi-Katchuan Irruan road, the Akaton Irruan-Ndemenchang road as well as the Borum road among others. However, most of the outcrops in the study area are located within the forest and were only accessible by foot using footpaths and tracks used by farmers.

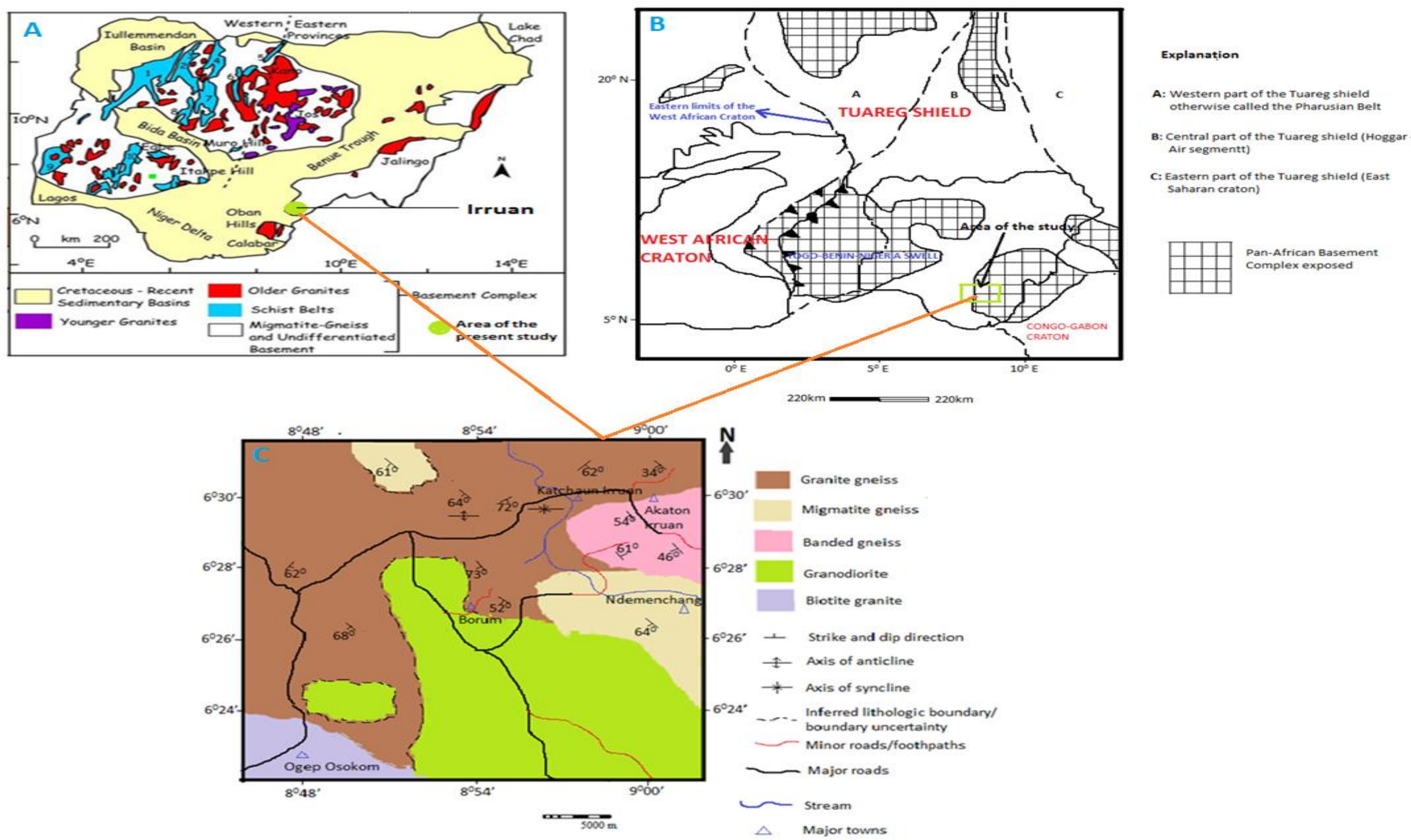

Fig. 1. A = Geological map of the Nigerian Basement Complex rocks [modified after 20]; B = Geological map of parts of West African showing the position of Nigeria and its Pan-African basement, the Congo-Gabon craton, the West Africa Craton and the Tuareg Shield [modified after 21]; C = Simplified geological map of the study area

2. RESEARCH METHODOLOGY

The study was carried out in two phases – geological field mapping and laboratory analyses. The field mapping was carried out using the geological survey-mapping method described by [22]. Rocks were observed in their field conditions, emphasizing their field relationship, mineralogical and structural characteristics. A total of 20 samples were taken for laboratory analyses. Laboratory analysis to determine the major and trace elements geochemistry of the rock was done at the National Geosciences Laboratory of the NGSA, Kaduna using the X-Ray Fluorescence (XRF) technique. The XRF analyses were carried out using the standard procedures of [23]. Thin sections were prepared from the rock samples at the Department of Geology, University of Calabar. Microscopic analysis was done at the Department of Earth Sciences, Federal University of Petroleum Resources, Effurun, Nigeria.

3. RESULTS

3.1 Field Occurrence and Petrography

Five distinct petrological units: granite gneiss, banded gneiss, migmatite gneiss, granodiorite and biotite granite were mapped in the area (Fig. 1C).

3.1.1 The granite gneiss

The granite gneiss is the most abundant rock type, accounting for over 40% of the outcropping basement rocks in the Irruan area. The granite gneiss outcrops along Okundi-Katchuan Irruan Road and Buyian Irruan, in the northern and western parts of the study area (Fig. 1C). The granite gneiss occurs as large elongated blocks and dome-shaped in some places. Texturally, these rocks are predominantly fine-grained to medium-grained. Angular, largely leucocratic boulders were visible around the granite gneiss at Katchuan Irruan. Feldspar and quartz are the dominant felsic minerals whereas biotite is the major mafic mineral identified on mesoscopic scale. The feldspar identified in the hand specimen is orthoclase as indicated by the pinkish colour of the mineral.

Modal composition for the granite gneiss as determined from thin sections indicate that quartz ranges from 25 to 35%. K-feldspar, predominantly occurring as orthoclase varies in modal composition from 20 to 35% whereas plagioclase ranges from 20 to 25% (Table 1). With the exception of samples GGN2 and GGN7, orthoclase is more abundant relative to the plagioclase in the granite gneisses. Similarly, muscovite (8 – 15%) generally exceeds biotite (5 – 13%). The quartz crystals are generally subhedral to anhedral with relatively low undulose extinction (Fig. 1B). The edges of the quartz are serrated in many samples. The mica (muscovite) typically occurs as lenticular. Intra-grain fractures are generally rare in the quartz crystals but rather restricted to the feldspars. Albite twinning was observed in the plagioclase.

3.1.2 The banded gneiss

The banded gneiss is restricted to Akaton Irruan community, northeast of the area of study (Fig. 1C). The banded gneiss occurs as an elongated block as well as in-situ boulders. The elongated rock mass measures about 25 x 13m on the exposed surface whereas the surrounding boulders measure about 9 x 4.4m on the average. The banded gneiss is mesocratic on the outcrop scale, with alternating bands of leucocratic (feldspar and quartz) and melanocratic (biotite) minerals. The mafic bands are about 8cm – 12cm thick and constitute about 45% of this rock. The bands are fine-grained in texture. On the other hand, the felsic bands are relatively thinner (generally ≤10cm) but more pervasive, making up about 55% of the rock. The feldspar appears grey to pinkish in colour, which is suggestive of k-feldspar. Also, the felsic band is texturally made up of medium grained minerals. Like the granite gneiss, the banded gneiss is fractured and with quartz veins. Unlike the granite gneiss however, the veins are fewer with the largest vein measuring about 0.13m in width.

Like the granitic gneiss, the banded gneiss is quartzofeldspathic with modal composition as estimated from thin sections as follows: quartz (30%), k-feldpsar (23 – 25%), plagioclase (22%), biotite (10 – 12%), muscovite (10 – 11%) and hornblende (2%). Quartz occurs both as groundmass and as porphyroblastic crystals. Undulose extinction and simple twinning were observed in the quartz and plagioclase crystals respectively.

3.1.3 Migmatite gneiss

The migmatite gneiss in the Irruan area crops out at the northern end (foot) of the Ndemenchang Hill in the eastern part of the study area. The rock comprises of medium-grained to coarse-grained crystals. The rock is fractured in different directions with boulders of various sizes. The felsic minerals (feldspar and quartz) are more prominent relative to their mafic (biotite) counterpart. The migmatite gneiss differs from the banded gneiss in that they contain garnet. Similarly, under the microscope, the migmatite gneiss contains markedly higher percentage of hornblende than the banded. The migmatite gneisses are mesocratic on the outcrop scale, comprising of both felsic (quartz and feldspar) and mafic (biotite) minerals, although the felsic minerals are relatively more prominent. The feldspathic minerals are pinkish in colour. The alternating felsic and mafic bands are thinner in the magmatic gneisses compared to the banded gneiss, occurring mainly as streaks of minerals.

The modal composition of the migmatite gneiss estimated from the thin sections are as shown in Table 1 includes: quartz (25 – 30%), k-feldspar (20 – 27%), plagioclase (20 -25%), biotite (10 – 15%), muscovite (5 – 12%). Hornblende ≤ 6% were also observed in the migmatites. Quartz crystals occur largely as rectangular and subhedral (Fig. 2). The muscovite is lenticular in shape with the plagioclase showing traces of albite twinning. Traces of weak zoning were also observed here.

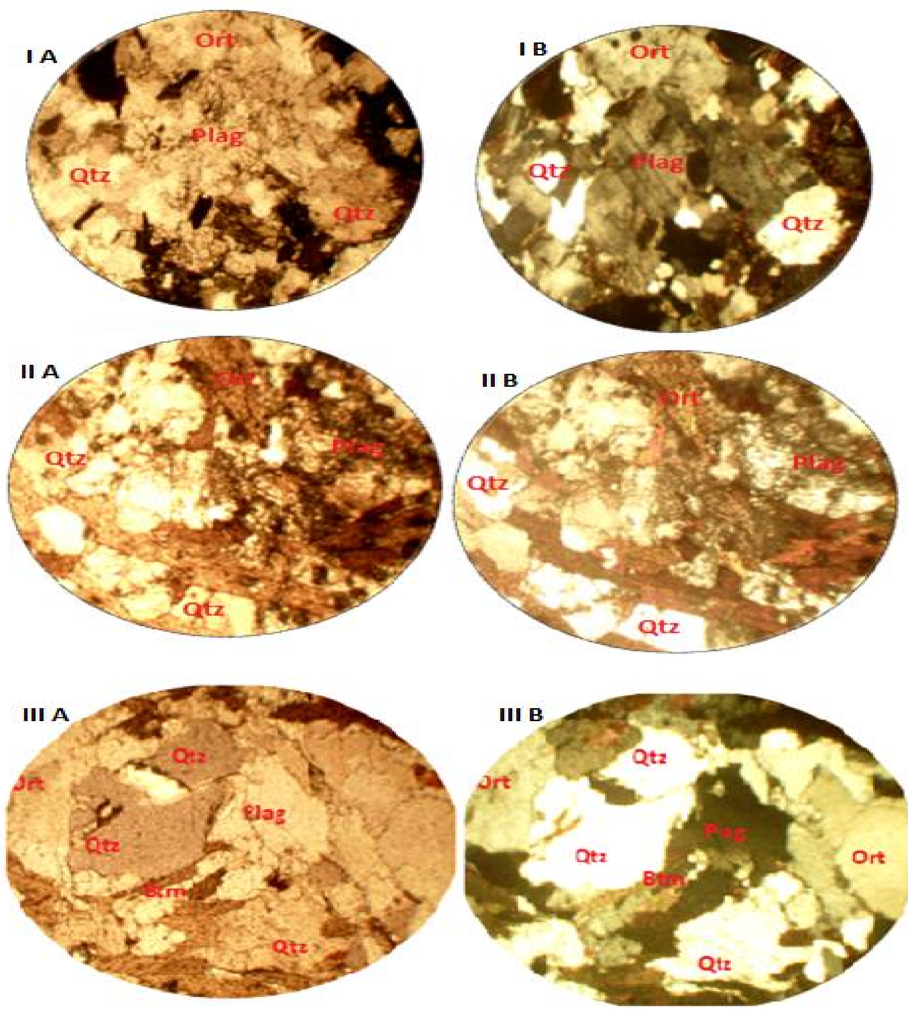

Fig. 2. Photomicrographs of basement rocks from the Irruan area. I = granite gneiss, II = migmatite gneiss, III = granodiorite; A = plane polarized light (PPL), B = crossed polarized light (XPL). Qtz = quartz, Ort = orthoclase feldspar, Plag = plagioclase feldspar, Btm = biotite mica (magnification = x 40)

Table 1. Modal mineral composition of the Irruan Basement Rocks

Rock-type	Migmatite Gneiss		Granite gneiss										Banded gneiss		Granodiorite					Biotite granite
Sample label	**MG**	**MG1**	**GGN1**	**GGN2**	**GGN3**	**GGN4**	**GGN5**	**GGN6**	**GGN7**	**GGN8**	**GGN9**	**GGN10**	**AKBG**	**AKBG2**	**GD**	**GD1**	**GD2**	**GD3**	**GD4**	**BG**
Minerals																				
Quartz	30	25	30	35	28	30	25	35	25	28	25	30	30	30	25	25	23	22	35	20
K-feldspar	20	27	25	20	25	25	35	20	20	25	28	20	23	25	20	25	20	20	20	25
Plagioclase	20	22	20	25	20	25	20	20	25	22	25	20	22	22	25	25	34	32	20	30
Biotite	10	13	10	7	10	8	5	13	10	8	12	7	12	10	11	15	5	6	10	20
Muscovite	12	5	13	8	15	10	10	12	15	12	8	15	11	10	15	7	15	15	15	5
Hornblende	6	8		5	1		3		5	5		5	2	2	4	3	2	5		
Opaque Minerals	2		2			2	1				2	2		1			1			
Total	100	100	100	100	99	100	99	100	100	100	100	99	100	100	100	100	100	100	100	100

AKBG = banded gneiss, GGN = granite gneiss, MG = migmatite gneiss, GD = granodiorite, BG = biotite granite

3.1.4 Granodiorite

The granodiorite constitutes the second most abundant rock type after the granite gneiss. This rock occurs both as large in-situ, isolated boulders and occasionally as large massive rock. The granodiorites were seen at Kakubok, Bitiah and NjuaKakue, southeast of the area (Fig. 1C). Like the biotite granite, the granodiorites occur as massive, dome-shaped intrusives and as several boulders of various sizes. These rocks are fine- to medium grained in texture and mesocratic in colour. In hand specimen, identifiable minerals include quartz and feldspar (felsic minerals) and biotite. In a few places, clasts of mafic minerals were also seen. The k-feldspar is easily recognizable with its characteristic grey to pink colour.

As shown in Table 1, from the thin sections, the granodiorites in the area have modal compositions as follows: quartz (22 – 35%), k-feldspar (20 – 30%), plagioclase (20 – 30%), biotite (5 – 15%), muscovite (5 – 15%) and hornblende ≤ 5%. The dominant k-feldspar is orthoclase. Biotite occurs mainly as lenticular. Like the biotite granite, the Na-plagioclase is more dominant than the k-feldspar. Quartz occurs predominantly as phenocryst and largely anhedral (Fig. 2).

3.1.5 Biotite granite

Unlike the granodiorite, the biotite granite is relatively scarce with the only visible outcrop seen at Ogep Osokom, southwest of the study area. The biotite granite occurs as dome-shaped massive rock and as boulders. On the outcrop scale, notable minerals seen in the biotite granite include biotite, feldspar and quartz. The boulders vary in sizes and are largely rounded in shape with a few showing angular edges. Relative to the granodiorite, the biotite granite is higher in percentage of mafic minerals. Just as the name implies, biotite is the dominant mafic mineral in this rock. Texturally, the rock ranges from medium- to coarse-grained.

From the thin section, the biotite granite has a modal composition estimated as follow: 20% for quartz with Na-plagioclase (30%) exceeding K-feldspar (25%). Quartz occurs mainly as groundmass, although the occurrence of well developed crystals of quartz (phenocrysts) was also observed. Biotite is present as relatively brownish in colour and anhedral morphologically. The k-feldpsar (orthoclase) occurs rectangular in shape. The overall petrographic attributes presented here are comparable to those reported by [1].

3.2 Geochemistry

As shown in Table 2, the rocks are highly siliceous with an average SiO_2 composition of 75.53 (wt. %). Apart from the biotite granite (61.10 wt. %), all the other samples contain well over 70 wt. % of SiO_2 in their averages with the granite gneiss (75.88 wt. %), banded gneiss (81.55 wt. %), migmatite gneiss (83.05 wt. %) and granodiorite (72.30 wt. %). The biotite granite recorded the highest FeO_3 content (12. 46 wt. %), followed by the granodiorite (2.00 – 6.06 wt. %). The granite gneiss, banded gneiss and migmatite gneiss are relatively low in FeO_3 with values of 0.86 – 3.84; 0.78 – 2.10 and

1.60 – 2.10 respectively. The sampled rocks are generally low in MnO (≤ 0.45). Like the FeO_3, significant Al_2O_3 enrichment is observed in biotite granite and granodiorite with both rock types showing average Al_2O_3 wt. % of 12.00 and 12.46 respectively. The granite gneiss, banded gneiss and migmatite gneiss show relatively lower values of 11.87, 7.8 and 8.6 respectively.

The $(Na_2O + K_2O + CaO)/Al_2O_3$ ratios are consistently less than one (0.27 – 0.95) and the aluminium saturation index (ASI) generally greater than one which are indicative of peraluminous attribute of the rocks [24]. However, the A/CNK range of 0.74 – 1.46 (average of 1.13) clearly suggests the presence of slightly metaluminous rocks in the area, even though the peraluminous rocks predominate. According to [25], rocks with wt. % SiO_2 less than 70% are typically metaluminous whereas those that are more silica-rich (> 70 wt. % SiO_2) are commonly peraluminous. As pointed out by [24], low CaO, MgO and FeO_3 are characteristic of peraluminous and S-type granitoids. Based on the foregoing and the geochemical data obtained from this study, the metamorphic rocks present in the Irruan area have been classified as peraluminous. The classification of the rocks of the area as being predominantly peraluminous is further supported by the A/NK vs. A/CNK classification plot (Fig. 3) which shows most of the samples plotting in the peraluminous field with the exception of three which clearly fall within the metaluminous field.

As shown in Table 3, the Irruan basement rocks are characterized by high variability in their trace elements compositions. Generally, the concentrations of Sb, U, Th, Tn, and Sn are negligible in most of the rocks. The Ge concentrations are also negligible for the gneissic rocks but fairly enriched in the granodiorite and biotite granite. V, Cr, Cu, Zr, Sr and Zn are present in virtually all the rocks in significant concentrations. With a value of 5630 ppm, the biotite granite records the highest concentration of Zr. Rb varies from <0.01 to 250 ppm with the granite gneisses having the higher concentrations.

The igneous rocks are acidic (Fig. 4), as indicated by the high SiO_2 content and have also been classified as S-type granitoids (Fig. 5). The fairly potassic and high silica content of the rocks are characteristic of the S-type granitoids [25]. The gneissic rocks of the Irruan area are thought to have metamorphosed from sedimentary protoliths (Fig. 6).

3.3 Structural Attributes

3.3.1 Spatial distribution and orientation of structures

Both primary and secondary structures were mapped in the rocks. The primary structures occur predominantly as foliations and lineations whereas secondary structures exist mainly as fractures and folds. The foliation planes are continuous, consisting of alternating bands of felsic and mafic minerals in most places. Foliations seen in the Irruan basement rocks are concentrated mainly in the granite gneiss and the banded gneiss and vary in attitude from almost horizontal to near-vertical in places. Similarly, the foliation dips vary from low to medium in the sampled rocks. Like the fractures, the foliations are oriented in different directions, the most dominant being the SE and E-W directions with the N-S less prominent (Fig. 7). Joints occur in parallel and sub-parallel orientations to the foliation planes.

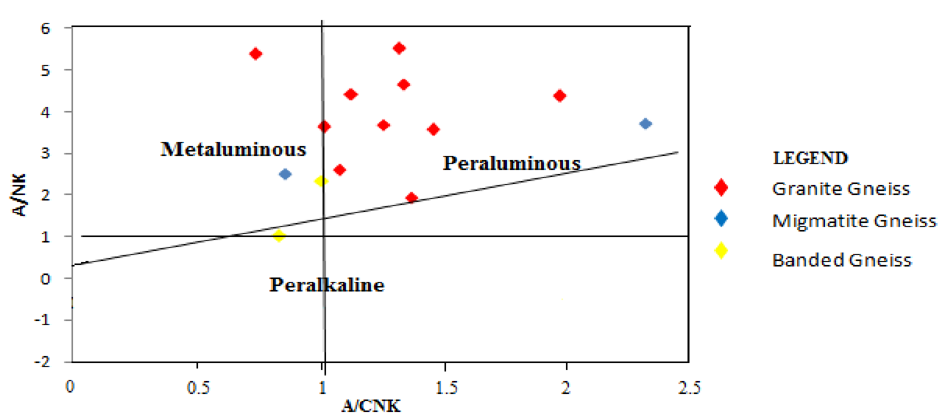

Fig. 3. A/NK vs. A/CNK classification diagram [adapted from 4]

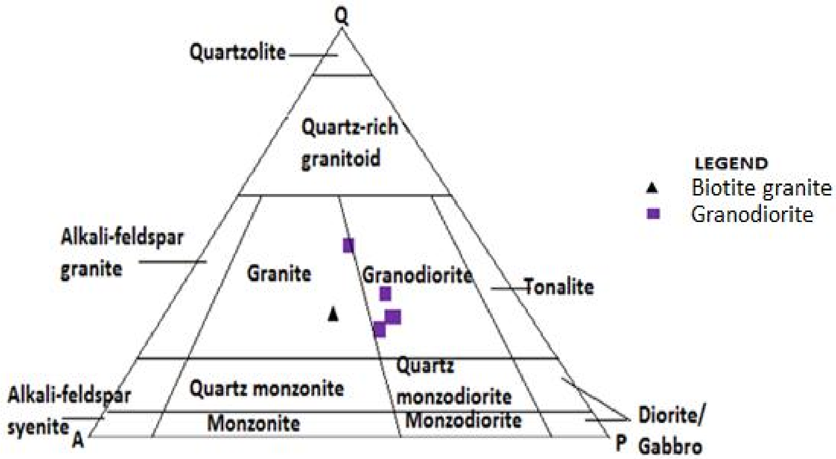

Fig. 4. QAP classification of the Irruan granitic rocks [boundaries modified after 26]

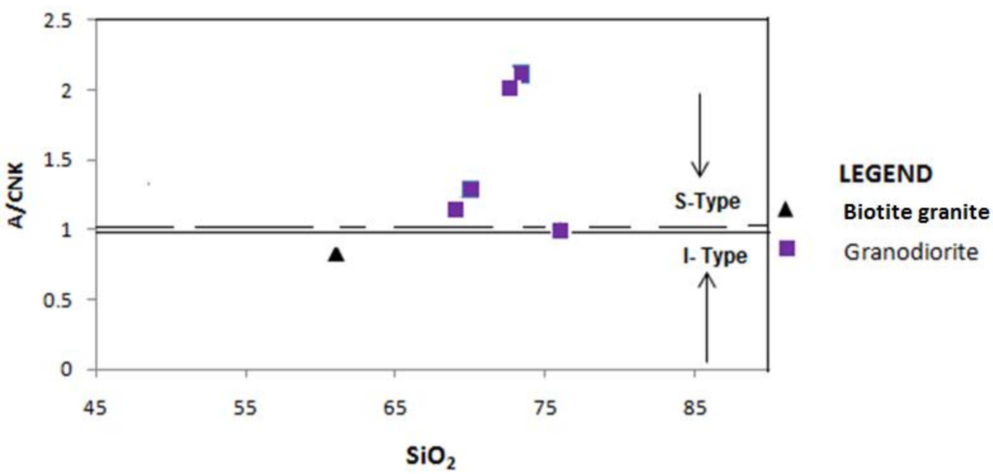

Fig. 5. A/CNK vs. SiO_2 classification plot for the Irruan Basement Rocks [boundaries modified after 27]

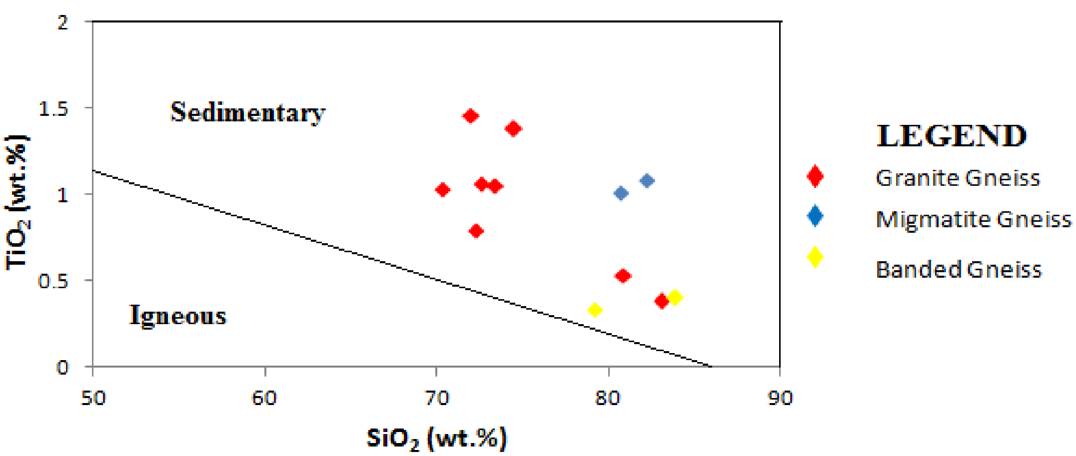

Fig. 6. TiO_2 vs. SiO_2 Discriminant Plot [adapted from 4]

Table 2. Major oxides composition of the Irruan basement rocks

Oxides (wt%)	AKBG	AKBG2	GGN1	GGN2	GGN3	GGN4	GGN5	GGN6	GGN7	GGN8	GGN9	GGN10	GD	GD1	GD2	GD3	GD4	BG	MG	MG1
SiO_2	79.20	83.90	80.90	79.00	72.30	74.50	73.40	72.00	83.10	70.30	72.60	80.70	73.00	69.30	73.40	75.70	70.11	61.10	82.30	83.80
CaO	0.88	2.30	1.07	3.00	5.07	2.00	4.32	5.50	5.01	4.03	3.80	2.21	1.00	1.25	0.68	3.80	1.40	4.58	3.00	0.89
MgO	0.06	0.61	0.62	0.64	1.00	0.84	1.21	0.87	0.77	2.11	1.07	1.24	0.76	0.84	0.21	1.42	0.70	0.88	0.50	0.24
SO_3	ND	0.06	ND	0.40	0.21	0.21	0.17	0.07	ND	0.63	0.64	0.08	0.02	ND	ND	ND	0.21	ND	ND	0.06
K_2O	5.71	0.80	3.02	2.00	0.70	0.63	0.70	1.00	0.43	1.02	1.00	0.94	2.06	4.43	3.00	2.34	4.01	3.07	1.60	0.60
Na_2O	1.20	1.40	0.84	1.01	1.48	1.40	1.04	1.70	0.60	1.65	1.04	1.09	1.32	2.00	1.02	1.06	2.00	1.68	0.70	1.24
TiO_2	0.33	0.40	0.53	0.37	0.79	1.38	1.05	1.46	0.38	1.03	1.06	1.01	1.03	1.81	1.68	1.37	1.55	1.06	1.08	0.84
MnO	0.02	0.06	0.10	0.07	0.16	0.25	0.16	0.27	0.07	0.17	0.15	0.11	0.12	0.45	0.24	0.34	0.43	0.11	0.06	0.14
P_2O_5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.02	ND	ND	0.03	0.03	ND	ND
Fe_2O_3	0.78	2.10	1.55	2.10	2.06	2.40	1.43	1.30	0.86	2.84	3.84	1.08	5.40	6.06	4.70	2.00	4.00	12.46	1.60	2.10
Al_2O_3	8.20	7.40	9.01	10.00	14.08	13.06	13.60	14.10	7.81	14.06	13.01	10.00	13.10	12.13	13.02	11.06	13.00	12.00	7.20	10.00
LOI	1.60	0.60	2.01	0.72	2.30	1.76	1.06	1.30	0.73	2.14	1.81	1.00	2.10	2.41	1.84	0.98	2.42	3.24	1.40	0.58
TOTAL	97.98	99.63	99.65	99.31	100.15	98.43	98.14	99.57	99.76	99.98	100.02	99.46	99.91	100.70	99.79	100.07	99.86	100.21	99.44	100.49
$(Na_2O+ K_2O + CaO)/ Al_2O_3$	0.95	0.61	0.55	0.60	0.51	0.31	0.45	0.58	0.77	0.48	0.45	0.42							0.74	0.27
ASI	1.05	1.64	1.83	1.66	1.94	3.37	2.21	1.72	1.29	2.10	2.23	2.36							1.36	3.66
A/CNK	0.84	1.01	1.37	1.08	1.13	1.97	1.32	1.02	0.74	1.26	1.34	1.46	2.11	1.17	0.83	2.11	0.99	1.28	0.86	2.32
(A/NK)/ (A/CNK)	1.20	2.32	1.42	2.42	3.90	2.22	4.17	3.56	7.27	2.92	3.48	2.44	1.41	1.28	2.37	1.25	2.62	1.33	2.91	1.60

AKBG = banded gneiss, GGN = granite gneiss, MG = migmatite gneiss, GD = granodiorite, BG = biotite granite

Table 3. Trace elements composition of the Irruan basement rocks

Elements (ppm)	AKBG	AKBG2	GGN1	MG	MG1	GGN2	GGN3	GGN4	GGN5	GGN6	GGN7	GGN8	GGN9	GGN10	GD	GD1	GD2	GD3	GD4	BG
V	24.00	4.00	20.46	490.00	8.00	0.70	180.00	400.00	290.00	540.00	100.00	280.40	250.30	190.00	720.20	1000.24	630.00	400.60	400.00	100.50
Cr	36.30	<0.01	31.00	340.00	0.12	<0.01	217.60	430.60	16.00	310.23	55.73	220.00	120.44	12.07	310.00	870.00	500.00	240.00	390.10	40.60
Cu	260.00	210.00	200.00	290.00	190.00	280.00	330.00	750.76	360.00	870.00	160.00	360.00	190.00	180.00	460.00	1100.08	730.38	670.00	650.00	500.21
Sr	1170.00	1800.00	660.30	1050.20	650.00	790.00	2170.33	2001.03	1760.00	5010.00	2310.00	244.00	2430.00	1790.00	1400.00	4700.00	2800.00	2500.00	2800.00	2990.00
Zr	290.42	490.00	2250.00	1500.00	2980.00	2100.00	790.40	3400.00	470.00	1400.00	340.11	870.00	800.00	500.20	1500.00	4800.00	2801.38	3600.00	5200.00	5630.00
Ba	7100.00	300.00	6400.00	300.00	3300.00	2500.00	<0.01	2000.00	<0.01	1000.00	<0.01	300.00	<0.01	<0.01	900.00	3000.00	2700.00	<0.01	370.00	6900.00
Zn	2820.00	50.00	250.00	200.00	250.21	430.00	180.70	573.40	290.00	530.30	20.40	170.76	194.06	140.00	380.00	2300.00	840.00	730.30	990.00	550.00
Pb	70.00	100.00	<0.01	<0.01	<0.01	<0.01	<0.01	860.00	140.00	0.73	230.00	0.47	<0.01	<0.01	1400.00	<0.01	130.00	<0.01	150.00	<0.01
Ga	4.24	<0.01	1.40	8.01	0.80	20.00	<0.01	10.23	6.20	26.06	4.00	<0.01	<0.01	<0.01	<0.01	<0.01	5.48	<0.01	<0.01	<0.01
As	21.23	6.80	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1.06	<0.01	0.01	<0.01	200.00	<0.01	20.00	30.00	26.13	<0.01
Y	3.03	4.00	22.00	<0.01	26.40	53.10	<0.01	4.60	<0.01	<0.01	<0.01	17.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ni	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	12.03	<0.01	<0.01	<0.01	<0.01	12.46	<0.01	<0.01	22.00	70.00	43.30	72.03	74.00	6.60
Rb	37.70	<0.01	200.00	180.00	130.11	100.30	183.00	71.37	250.00	88.81	120.00	180.00	<0.01	<0.01	<0.01	50.06	0.43	24.42	<0.01	<0.01
Nb	<0.01	140.00	<0.01	<0.01	<0.01	16.00	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	230.00	190.00	480.30	350.70	110.34	96.81	19.40	480.22
Sn	<0.01	180.20	<0.01	<0.01	<0.01	<0.01	0.46	0.76	0.02	0.72	0.02	0.76	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	75.00
Ta	<0.01	0.24	<0.01	<0.01	<0.01	1.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.13	0.12	1.42	15.40	12.68	4.24	30.00	1.07
W	79.36	60.20	<0.01	<0.01	<0.01	54.00	<0.01	<0.01	<0.01	<0.01	0.45	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	60.33
Hf	40.30	48.00	51.32	48.10	38.30	40.30	36.00	76.00	36.21	70.33	43.60	38.12	<0.01	<0.01	<0.01	46.24	<0.01	<0.01	<0.01	24.00
U	<0.01	21.20	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	41.30	43.00	49.60	60.20	64.63	70.70	44.14	71.06
Th	0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.09
Sb	<0.01	0.24	<0.01	<0.01	<0.01	<0.01	9.20	2.43	7.01	2.30	0.30	1.10	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.03
Ge	<0.01	<0.01	<0.01	20.00	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.95	0.53	8.10	130.00	86.00	11.01	610.20	3.20
Rb/Sr	0.0322	<0.0001	0.3029	0.1714	0.2002	0.1270	0.0843	0.0357	0.1420	0.0177	0.0519	0.7377	<0.0001	<0.0001	<0.0001	0.0117	0.0002	0.0997	<0.0001	<0.0001
Rb/Nb	3770	0.0001	20000	18000	13011	6.2688	18300	7137	25000	8881	12000	18000	<0.0001	0.0001	<0.0001	0.1427	0.0039	0.2522	0.0001	<0.0001
Rb/Zr	0.1298	<0.0001	0.0889	0.1200	0.0437	0.0478	0.2315	0.0210	0.5319	0.0634	0.3528	0.2069	<0.0001	<0.0001	<0.0001	0.0104	0.0002	0.0068	<0.0001	<0.0001

AKBG = banded gneiss, GGN = granite gneiss, MG = migmatite gneiss, GD = granodiorite, BG = biotite granite

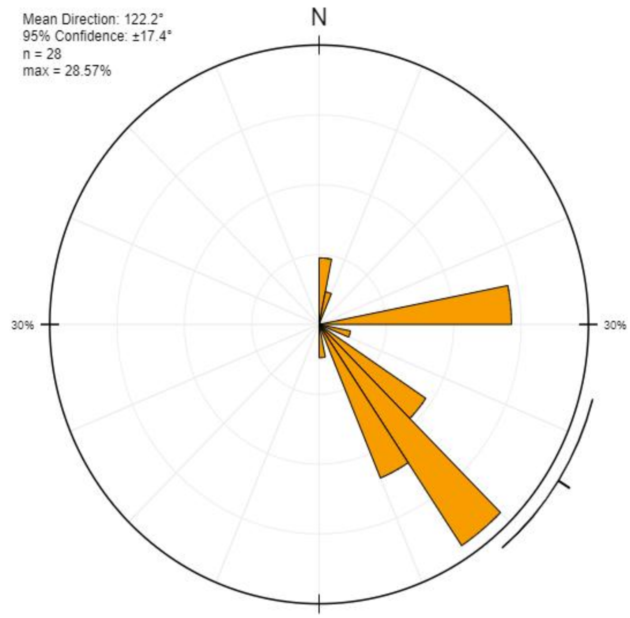

Fig. 7. Rose diagram of foliation trends for the Irruan basement rocks

Joints of various dispositions and attributes were observed in the area, ranging from straight to curvilinear and chaotic in places (Fig. 8). All the rocks in the area are fractured although these fractures are mainly concentrated in the gneisses. Generally, the average distances between adjacent joints are heterogeneous and non-systematic. Jointing in the biotite granite and granodiorite are relatively few and randomly oriented. Thus, emphasis is placed on the gneisses. The fractures in the metamorphic rocks are both shear and tensional fractures as shown by the stereographic projection (Fig. 9B). Conjugate fractures are common in the granite gneiss, especially around the outcrops at Katchuan Irruan (Fig. 8d). Fracturing in the rocks is generally pervasive without noticeable zoning or concentration in particular sections of the rocks. In both the granite gneiss and the migmatite gneiss, the NE-SW, N-S and NW-SE fracture lineaments were observed. In some places, E-W and NNE-SSW fractures were also observed. Generally, the NE-SW fractures were the most abundant fracture set in the area. The N-S fractures were the next most frequently occurring set after the NE-SW. Sealed joints in the granite gneiss are present as series of quartz veins measuring about 0.2m in width on the average (Fig. 8a). The largest of these veins measures 5 x 0.3m. The average fracture spacing between the dominant NE-SW joints is about 120cm. There are series of clataclasites in the granite gneisses which suggests brittle deformation of the rocks. The preferred mineralization trends as shown by the quartz veins are the NE-SW and N-S orientations. Also, some of the mineral veins occur along cross-joints of tensional fractures (conjugate fractures), sealing preexisting joints.

Although fractures of different dimensions and orientations are common in the gneissic rocks, large scale faults are rare in the area. The general difficulty in discernible, mappable faults from outcrops in the Obudu Plateau has been attributed to the dense vegetation cover of the area [17]. However, a few minor normal faults were mapped in the granite gneiss along Katchuan Irruan/Okundi road. The faults here are characterized by millimeters (mm) to centimeters (cm) scale displacements, generally ≤15cm apart (Fig. 10). The most prominent displacement direction of the minor faults mapped in the area is NE – SW.

Folding in the Irruan basement rocks are readily seen in the granite gneiss and are mainly in the form of asymmetrical, close and minor folds (Fig. 11). The folds vary in sizes from minor to large scale folds. The minor folds here occur as drag folds. The minor folds are generally asymmetrical folds produced in the weaker beds by differential movements of the more resistant rocks above and below [28]. The minor folds were concentrated around the flanks of the major asymmetrical folds in the granite gneisses.

Fig. 8. Fractures and fractured veins in the gneissic rocks around Irruan (a = sealed fracture; b = fractured vein; c = truncation of foliation by fractures; d = conjuagte fracture)

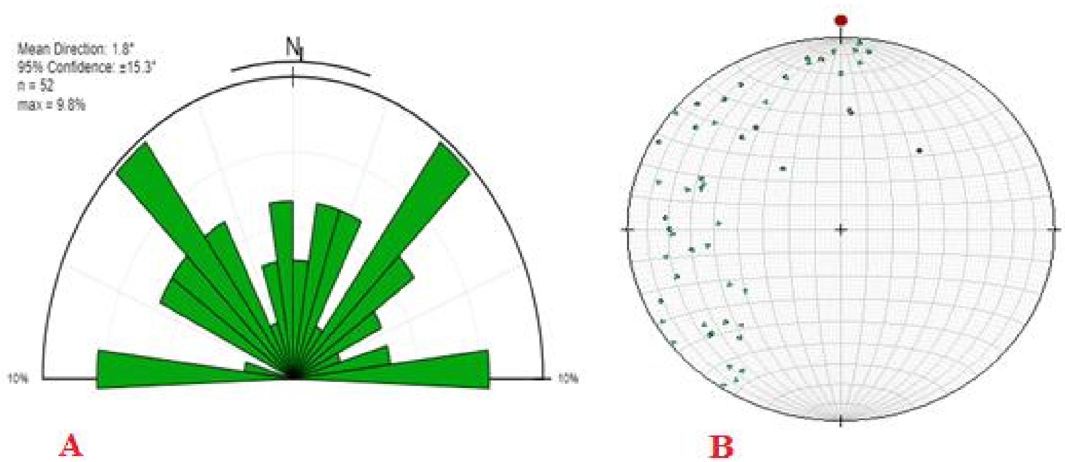

Fig. 9. Composite rose diagram of the gneissic rocks at Irruan

3.3.2 Implications for rock deformation

The occurrence of conjugate (NE-SW and NW-SE) fractures suggests that these fractures were congenital. The conformity of these fractures with the dip of the foliation planes (NE-SW) is interpreted to imply that they developed contemporaneously with the foliations in the gneissic rocks. However, the truncation of the quartz veins by the N-S and E-W fractures in some places (Fig. 8b & c) suggests that the N-S and E-W fractures were developed from a different episode of deformation. The field investigations indicate that the NE-SW fractures are chronologically older than their N-S counterparts.

The restriction of the poles to the core and middle of the stereographic projection (Fig. 9b) is an indication that the angles of dip for the gneisses range from medium to low. According to [29], shear fractures typically have their poles plotting on the peripheral edges on a stereographic plot. Typically, the NW-SE fractures cut across those of NE-SW thereby forming conjugate joints. Some of these conjugate fractures are tensional and occur in form of lenticular veins filled with quartz mineralization.

Fig. 10. Minor fault in the granite gneiss along Katchuan Irruan/Okundi road

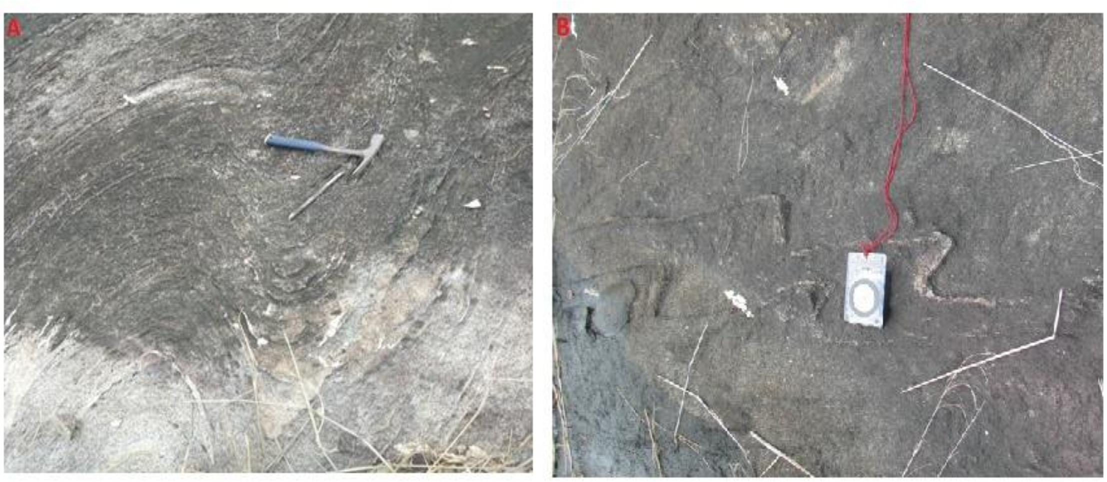

Fig. 11. Folds in the granite gneiss along Okundi-Irruan road (A = meso-scale assymetrical fold; B = minor fold)

Compression of the rocks produced the major and minor asymmetrical folds respectively are recorded in the area. It is likely that these compressions were followed by extensional events resulting in the developments of joints and veins. Their cross-cutting relationship indicates obviously that the quartzofeldspathic veins are older than the fractures (Fig. 8b & c), and segregation of minerals into felsic and mafic bands presents chronologically the oldest deformation event. Ductile deformation is manifested by the presence of banding – mineral segregation into leucrocratic and melanocratic bands and the folding. Similar widespread plastic deformation and shear flow have also been identified in the crystalline basement rocks of southwestern Nigeria [30]. As pointed out by [31], banding in the migmatite-gneisses within the Nigerian basement could be attributed to the recrystalization of minerals during regional metamorphic event within the basement.

4. DISCUSSION

The variations in trace element distribution among the rocks (particularly the granodiorite and biotite granite) suggest the likelihood of multiple sources of magma. Similar heterogeneity in the basement rocks around the southwestern Obudu area had been interpreted to imply mantle-crust interaction [15]. The highly siliceous nature of the rocks is indicative crustal magma origin. However, the possibility of such felsic rocks originating from the partial melting of the basic granulites from the mantle before crustal contamination that produced their silica enrichment has been reported in the Bamenda Mountains in western Cameroon [32]. Considering the ratios of Rb against the selected trace elements (Table 3), it is our view that the primary magma source for these rocks was from the lithospheric crust. Most of the rocks show high Rb/Nb (≤ 25,000) and Rb/Zr ratios (≤ 0.5319). These ratios together with those of Rb/Sr (≤ 0.7377) support the inference of crustal magma source. As pointed out by [32], basic granulite (mantle-derived) magmas are characterized by very low Rb/Sr ratios, typically about 0.023.

Inferring from the heterogeneous geochemical and tectonic setting of the southwestern Obudu Plateau, [15] have concluded that petrogenesis in the area must have been largely influenced by crustal recycling processes, with orogenesis contemporaneous with metamorphism. This does not however, completely rule out the possible contribution of mantle-derived magma. According to [33], very high concentrations of Sr (>660 ppm) and Ba (1,854 ppm on the average) as shown by the rocks are characteristic of less differentiated sanukitoids. They opine that such less differentiated sanukitoids are derived from the partial melting of the enriched mantle. Clearly, there are a significant number of the rocks (samples AKBG2, GGN9, GGN10, GD1, GD4 and BG) that gave very low Rb/Sr ratios of <0.0001. Hence, it is our view that although most of the magma source must have been derived from the crust, there may have also been a significant contribution from the partial melting of the underlying mantle. In course of magma upwelling, such mantle-derived magma underwent crustal contamination giving the rocks their present felsic attributes. This inference is comparable with those of [33] on the granitoids of the Mandara Hills, north of the present study area as well as those of [15] on the southwestern Obudu Plateau.

The Nigerian basement is thought to have been affected and reworked by at least, four orogenic events – (Liberian, 2700Ma ±200; Eburnean, 2000Ma ±200; Kiberian, 1100Ma ± 100 and the Pan-African, 650 Ma ±150), the Pan-African being the most widespread and intense of these orogenies [11]. The Pan-African event caused the reworking of preexisting terranes through widespread migmatization, granitization, intrusion and deformation resulting in the development of structural elements, predominantly in the N-S, NE-SW and E-W directions [34]. The polygenic petrogenetic and tectonic attributes of these rocks [4], no doubt, suggest that active thermo-metamorphic processes must have affected these rocks. The broad petrological and geochemical characteristics of the rocks indicate that the granitoids in the area must have been derived from crustal and mantle sources with anatexis playing a key role. The quartz mineralization of the fractures and the ductile deformational structures in the area must have developed from such fluid-assisted thermo-metamorphic activities. The occurrence of garnet in the migmatite gneisses in the area has been attributed to the absorption of water into migmatitic partial melts for low-H_2O pressure conditions to stabilize anhydrous minerals such as garnets and orthopyroxene [3]

Previous studies of the basement rocks in southeastern Nigeria generally support the idea that the Oban Massif and the Obudu Plateau have both undergone widespread regional metamorphism resulting in the development of granulite facies and similar structural imprints in both areas. [3,35] have reported single zircon ages of 584.5 (±10Ma) and 574.1 (±10Ma) for charnockitic rocks in the Oban massif and Obudu Plateau respectively. [17] have also carried out comparative studies on the structural attributes of the Oban and Obudu areas. According to them, the fracture lineaments in both areas are identical with the NW – SE fractures and fracture length of about 2km being the most dominant. The shift from NW–SE to NE–SW trending fractures in the area of the present may have been as a result of block rotation. The adjoining E–W Ikom-Mamfe embayment has been interpreted to have resulted from a clockwise rotation between the Obudu and Oban areas [17]. The NE–SW fractures in the Irruan area may have been induced by this rotational event.

Findings from this study correlate with previous studies on the southeastern Nigerian basement rocks [e.g. 1, 36–37]. The findings here are also comparable to those of other parts of the Nigerian Basement Complex such as Hubbard [30–33] on the granitoids of southwestern Nigeria and the Mandara Hills, northeastern Nigeria respectively. The findings however differ slightly from other earlier works [e.g. 18 and 38]. Whereas the Irruan rocks are generally enriched in SiO_2 (≥ 61.1 wt.%), the granitoids around Oyioba-Uganga area, northeast of the present study area have been reported to be fairly lower in SiO_2 (≤ 59.5 wt.%). The Uyioba-Uganga as reported by [38] are also fairly rich in Al_2O_3 (15.64 – 19.27 wt.%) compared to the Irruan granitoids with an average Al_2O_3 weight percent of 12.

5. CONCLUSIONS

Igneous and metamorphic rocks outcropping around the Irruan area in southeastern Nigeria are the focus of this study. The rocks are quartzofeldspathic and range from fine-grained to coarse-grained. Apart from the biotite granite, the Irruan basement rocks are generally siliceous. The rocks have been classified as peraluminous and S-type granites. The gneisses metamorphosed from sedimentary protholiths. This inference is supported by discriminant plot and the high silica content as well as the calculated ASI and the low CaO and FeO_3 attributes of the rocks. The primary magmas for the granitoids are thought to have originated from the partial melting of the lower crust with significant contribution from the upper mantle. The mantle-derived magma must have been subjected to crustal contamination during ascent therefore giving the overall siliceous character of the rocks.

Evidences of primary and secondary geological structures were observed in the rocks. It is suggested that the dominant NE-SW fractures were developed contemporaneously with the foliations and lineaments (the ductile deformation). A latter episode of deformation resulted in the N-S and fairly weak E-W fractures. The present structural configuration of the Irruan basement rocks may have been influenced by the E–W block rotation that resulted in the formation of the Ikom-Mamfe Embayment. The findings from this study are comparable with similar studies on the Precambrian basement rocks in Nigeria.

Going forward, micro-structural studies (including micro-structural geochronology) and trace element stratigraphy are recommended for these rocks as a way of further correlating their relationships and spatial extent. It is hoped that such studies will further enhance the general understanding of the evolution of the basement rocks of southeastern Nigeria.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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