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Structural evolution and tectonic setting of Pan-African igneous rocks around Boki, Bamenda Massif, southeastern Nigeria.

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Abstract

The Pan-African syntectonic felsic and mafic rocks of Boki region in southeastern Nigeria were comprehensively studied with focus on their chemical compositions and structural characteristics, the goal was to ascertain their tectonic setting and the impact of Pan-African thermotectonic events on the rocks. The intricate tectonic history of the area is reflected in the structural and mineralogical characteristics of these granitic bodies, which were created during the Pan-African orogeny. Extensive field investigations and structural examinations reveal that the granitoids have experienced notable deformation, manifesting as fractures and shear zones. High tectonic stress regimes that fostered the crystallization and evolution of mineral veins inside the rocks are indicated by these deformation characteristics. The attitude of more than 180 mode-I fractures and over 120 mineral veins were measured and documented. Rose diagrams and stereographic projections of the various structures were plotted and analyzed to show the impact of tectonic stress on the preferred orientation of the joints and veins. The granitic bodies include garnetiferous granite and granodiorites, which consist of quartz, biotite, k-feldspars, and subordinate muscovite, and tourmaline. They exhibit two major trends of fractures, which include the E –W trending mode-I fracture and the N – S trending fractures and veins. The E – W fractures (ac extensional fractures) and veins are oriented in the direction of the maximum principal stress (σ_1) while the N – S fractures (bc tensile fractures) are oriented in the direction of minimum principal stress (σ_3). The mode-I fractures are pervasive in the granitoids since they require less stress for their initiation and propagation relative to mode-II and mode-III factures. The widest veins are those oriented in the direction of the σ_1. The mineral veins are very narrow and thins out easily in the N –S direction of σ_3. The orientations of these veins is a reflection of the pattern of fluid pressure build-up during the Pan-African orogeny, which initiated the crystallization of the minerals in the veins. This study explains the configurations of the principal stresses and indicates E – W direction for σ_1 and N – S direction for σ_3 during the most part of the Pan-African orogeny.

Keywords: *Stress configuration, Mode I fractures, Conjugate fractures, Mineral vein, Crack and seal mechanism.*

1. Introduction

The southeastern Nigerian basement region is part the Bamenda massif of West Africa which extends from Cameroun to Nigeria. It occurs within the Pan-African (600+ 20my) mobile belt and forms part of a widespread orogenic province that stretches from Hoggar to Brazil (Ferre et al., 1995). This is the latest tectonic event that affected the Nigerian Basement Complex. It initiated the emplacement of several syn-tectonic igneous bodies in the basement complex of Nigeria, Cameroun, and other West African countries as well as eastern Brazil where igneous rocks of similar age and features have been studied (Ike, 1988; Archanjo et al., 2007; Oden, 2012a.). The crystalline basement complex rocks within Boki region inclde: migmatitic banded gneiss, porphyroblastic/augen gneiss, biotite gneiss, garnet-mica schist, garnetiferous granite, granodiorite and such igneous rocks as basalt, dolerite, and gabbro. The various rock units are shown in the geological map of northwest Boki area (Fig. 1) and these rocks are petrologically described in Ibegbulam and Ukwang (2014).

The granites and granodirites of southeastern basement complex of Nigeria have several fractures and minerals veins whose characteristics bear information on tectonic history of the region. Ekwueme and Nganje (2000) and Ephraim et al., (2008) have carried out extensive works on the geochronology, geology, and P-T evolution of various crystalline rocks of Oban massif which is a southward extension of the basement complex. However, there works did not elucidate much on the structural characterization of the rocks this region. In this study we are interested in utilizing the geochemical data of the various igneous rocks of the study area and the fracture pattern stress configuration to decipher the petrogenetic and tectonic settings as well as structural evolution of this segment of the Nigerian Basement Complex within the Bemenda Massif.

1.1 Geology of the Study Area

The study area constitutes part of the Southeastern Nigerian basement complex and lies within latitudes 6° 15′N - 6° 30′N and longitudes 8° 45′E - 9° 00′E. It is a metamorphic terrain with impacts of several igneous intrusions. The rocks generally exhibit prominent N–S trending foliation and some NW –SE trend of foliation. The contact between the garnetiferous granite and the metasediments is quite sharp in many areas. The presence of garnet within granitic rock depicts some degree of metasomatic interaction between the country rock (metasediments) and the intruding granitic body. Physiographically the region lies within Nigeria's tropically rain forest belt exhibiting an undulating topography with an average height of 600-800m above sea level. Among the highest elevation is the bell-shaped garnetiferous granite at Agba. This region, which constitutes part of the extension of Cameroun Mountain into Nigeria is among the most exposed parts of the Pan-African basement domains in Southeastern Nigeria.

2. Material and Methods

The Pan-African basement rocks around the study area were extensively observed by means of detailed field mapping. The accurate positions of exposures of various plutonic bodies and other rock units were obtained using a Garmin 76CxS Global positioning system (GPS).

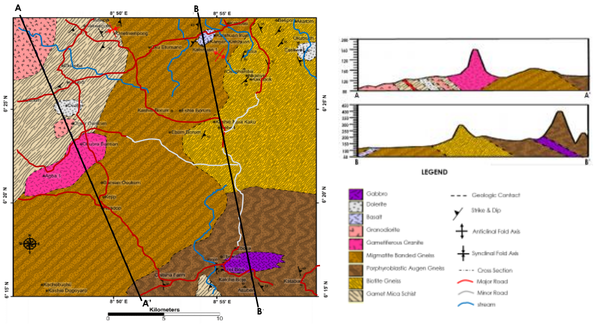

Fig. 1: Geologic map of study area (modified after: Ibegbulam and Ukwang, 2014).

The attitude of structures such as joints, and mineral veins as well as the dimension of veins were obtained using standard structural measurement and analytical methods involving the use of silver compass and meter rule. The data were analyzed by using simple computer statistical tools. All structural data analyzed in this work were obtained from thorough investigation of small-scale observable geological structures. Representative samples of the various rock were analyzed for major trace and rare earth elements in Geosciences Laboratories (GEOLABS), Canada. The Inductively Coupled Plasma Mass Spectrometry (ICP – MS) method was used for the analyses of the rock samples. About 100mg of each sample was analyzed. The detection limits were calculated and set from six times the square root of the blank solution counts divided by the sensitivity of the standard solutions. The operating parameters of the instrument include; forward power = 1300w, reflected power is < 5w, argon flow rate = 14L/min, auxiliary gas (Ar) flow rate = 0.75 L/min, plasma temperature = 10,000k, nebulizer gas (Ar) flow rate = 0.85L/min, radio frequency = 27.12 million cycles per second, resolution is 0.85amu, detector mode is by pulse counting, number of scan sweep = 100. This method is capable of detecting metals and non-metals at concentrations as low as one part in 10^{12} (part per trillion). This is achieved by ionizing the sample with inductively coupled plasma and then using mass spectrometer to separate and quantify the ions. The ions are obtained by inductively heating the nebulized sample gas with an electrical coil to make the gas electrically conductive.

3. Analysis and Result

3.1 Joints.

The most observable structures evident in the study area are joints (mode I fractures), which include conjugate fractures and single fractures (Fig.2 a-d). Fractures/joints as well as veins are among the most commonly observable structures at the surface of these rocks. At first glance they seem as mere cracks and cavity fillings, however, filling of openings in rocks is not just a random process. Rather crystal growth in cavities resulting from mineral-laden fluids is a process directly related to the orientation of the principal stresses, which determine the trend of fractures and fluid dynamics in the rock. Fracture cavities that are parallel to the direction of maximum principal stress (σ_1) are preferentially filled (Oden, 2012; Van der Pluijm & Marshak, 1997; Davis and Reynolds 1996; Wilson, 1982). This category of fractures/cavities are referred to as 'ac' extension fractures (Hobbs et al., 1976). Though their ubiquitous nature makes them appear as simple and featureless geologic structures, however, they constitute a very important element of structural patterns that can grant insight into the history of stress and strain in a region (Van der Pluijm, Marshak, 1997; Hills, 1972; Ramsay, Huber, 1987). The Boki area bears the imprint of Pan-African orogeny which brought about the metamorphism of rocks of pelitic protoliths (Ibegbulam and Ukwang, 2014) and emplacement of Syn-tectonic igneous rocks (Fig.1). Two major fracture patterns were observed from the study of the joint system in the igneous rocks using 184 data points.

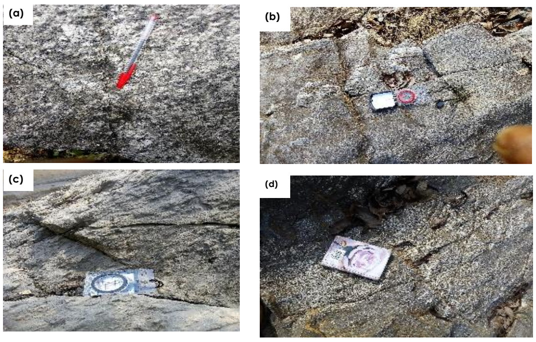

Fig.2: Joints in igneous rocks of Boki (a, and c are single fractures while b and d is are conjugate fracture).

The joint sets include a dominant E-W oriented joint set and less frequently occurring N-S oriented joint set with angle dips between 65^o and 90^o. The rose diagram and the stereographic projection of the attitude of the various joints buttress their high dip. This pattern is similarly exhibited in other major rock units occurring in the study area which include gneisses and schist. (Fig. 3a-e). Exfoliation/horizontal sheet joints also occur in the study area. From the tectonic pattern given by Oden (2012), the 'ac' extension fractures are represented by the E-W trending joints while the N-S trending joints represent the 'bc' tensile fractures. These are pure mode 1 fractures (Price, 1966; Twiss and Moores, 1993). The sub-horizontal sheet joints are strongly related to the N-S trending joints in that they mostly terminate at the slab formed by the sheet joints. The sheet joints result mainly from exhumation and cooling-related processes. However, the same tectonic process is responsible for the formation of E-W and N-S trending joints respectively. Several of the N-S trending joints contain thin mineral veins. These probably formed by the process of sealing of open fracture by excess mineral-laden fluids. On the other hand, exfoliation joints tend to form where horizontal stress is significantly greater than vertical load (Van der Pluijm and Marshak, 1997) resulting in the movement of the thin granitic slabs formed by sheeting during the exhumation and unroofing of the pluton. Studies of Pan-African structures and tectonic imprints on rocks in other areas of the Nigerian basement complex have shown an E-W compression axis (σ_1 direction) and a N-S orientation of minimum compressional stress (σ_3) as well as NW-SE and NE- SW simple shear directions (Oden, 2012) through most part of the Pan-African orogenic activity.

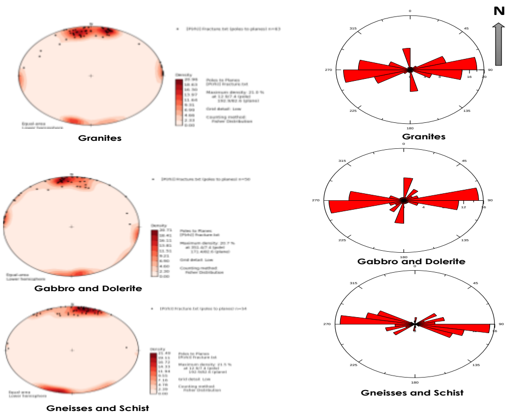

Fig. 3 Stereographic projections of mode 1 fractures and their rose diagrams in the igneous and other rocks of the study area.

The main tectonic axes of the Pan-African orogeny were an E-W direction of compression and a N-S pure shear direction as well as two simple shear directions of NW-SE and NE - SW. This conclusion was draw from consideration of strain partitioning using feldspar phenocrysts as strain makers from granodiorite rocks of Oban Massif southeastern Nigeria by Oden (2012). Also from the strain analysis in the granitic rocks of Igarra area southwestern Nigeria, Oden and Udinmwen (2013) confirmed the tectonic axes of the Pan-African orogeny.

3.2 Veins

Several mineral veins occur mainly in the granitoid plutons as well as the migmatitic gneiss of the study area. These basically consist of quartzo-feldspathic, veins, which may be aplitic or pegmatitc. The data obtained from the study of about 120 veins in the area showed two dominant orientations (Fig.4). The N-S trending veins perpendicular to σ_1 (maximum principal compressional stress) orientation and E-W trending veins, parallel to σ_1. Veins in the E – W corridor whose orientations range between 78^o and 130^o from the north are the widest in size while most of those that trend between 0^o- 40^o and 150^o -180^o are relatively thinner.

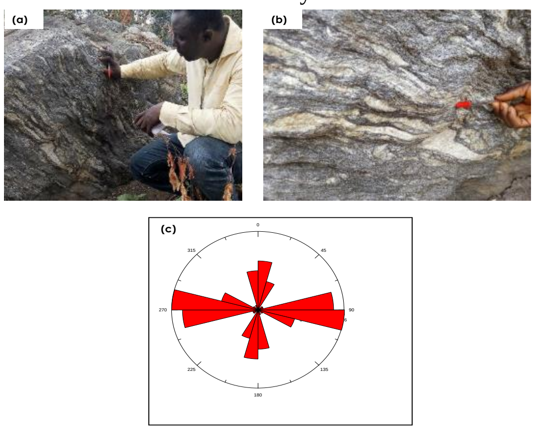

Fig. 4: (a-b) Fracture fillings (veins) in the migmatized rocks of the study area and (c) rose diagram of vein orientations in the rocks.

The Pan–African orogeny is characterized by E – W trending σ_1 (Oden, 2012). Field observation in Boki area reveals that the E-W trending veins contain more mineral crystals whose growth direction is perpendicular to the long axis of the vein. This is the axis of the minimum principal stress orientation (σ_3). This shows that these are syn-tectonic veins that were developed at depth and progressively widened over time by crack and seal mechanism. This is based on the fact that crystal growth is enhanced more in the direction of minimum principal compressional stress (σ_3). However, the narrow nature of the N-S veins is due to the fact that growth of crystals in them occurred in the direction of σ_1, hence the opposing stress inhibited their growth and elongation thereby developing thin veins. The N-S veins were probably filled at a period when there was slightly higher fluid pressure and more volume of mineral laden fluids such that the excess mineral

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laden fluid filled these veins. The horizontal to sub-horizontal exfoliation joints in the gradnitoids are parallel to the free surface. They form thin slabs in response to the decompression resulting from unroofing of the pluton (Van der Pluijim and Marshak, 1997).

Conjugate shear fractures in the syn-tectonic igneous rocks of the study area (Fig. 2b and d) were very useful in the determination of the plunge magnitude and direction of the maximum principal stress (σ_1), intermediate principal stress (σ_2) and minimum principal stress (σ_3) that were active during the tectonic episode that affected the area. Conjugate shear fractures are co-genetically developed in conjugate sets with dihedral angle (2ɵ) > 45˚ (Singhal and Gupta, 2010). The acute angle between the conjugate shear fractures is the dihedral angle (2ɵ). These fractures, which represent complementary shear sets usually formed at an acute angle to the maximum principal stress (σ_1) (Hills, 1972; Hubbert and Willis, 1957). The acute bisectrix of the angle between the conjugate pair is parallel to the direction of the active maximum principal stress (σ_1) in the area. This is also normal to the trends of local fold axes (Shainin, 1950; Wilson, 1982). According to Billings (1972), actual shear fractures make an angle of less than 45˚ with the maximum principal stress (σ_1) axis. Dihedral angle that is approximately equal to 60˚ indicates a brittle deformation that took place at shallow depth while those with higher values close to 90˚ is indicative of ductile deformation at great depth (Singhal and Gupta, 2010). Twenty (20) pairs of conjugate shear fractures from these igneous rocks were studied, their attitudes plunge magnitude and direction of the principal stresses as well as the dihedral angles (2ɵ) were determined by stereographic projection (Table 1). The plunge magnitude and direction of these stresses ($\sigma_{1,}$ σ_2 & σ_3) being further projected on stereonet as poles yielded a major E – W trending σ_1 orientation and a N – S trending σ_3 orientation. The dihedral angle generally range between 60˚ to 88˚. This indicates that the area bears imprints of both ductile and brittle deformations.

3.3 Geochemistry:

The results of the major elements concentrations as oxides and the CIPW norms are shown in Table 2. In the granites, the SiO_2 content varies from 65.62 to 72.37 wt. %. Whereas in the gabbro, dolerite, and basalts, SiO_2 varies from 49.89 to 53.61 wt. %. Similarly, the total alkali is higher in the granite family, ranging from 5.39 to 7.35 wt. %. However, the total alkali values for mafic rocks are low, 1.30 to 4.41 wt. %. The granite family members with high K_2O have K_2O/Na_2O ratios exceeding 1 except sample 1. These samples equally have higher molecular ACNK and ANK ratios are greater than 1.3, an indication that these rocks are peraluminous. The peraluminous nature is further confirmed by the discrimination plot of ANK against ACNK (Maniar and Piccoli, 1985; Fig. 5a). TiO_2 for the granitic rocks is less than one except sample 4. Values of TiO_2 ranges between 1.24 and 2.67wt. % for the basic rocks. The granitic rocks exhibit MgO > 1 except sample 4. The mafic rocks of the study area have MgO values ranging between 4.60 and 6.97wt. %. Geochemically these igneous rocks range from primitive to relatively fractionated variety as reflected by the concentrations of SiO_2, MgO, and variable concentrations of mantle compatible elements. These rocks display sub-alkaline affinity in the discrimination plot of (Na_2O) + K_2O) versus SiO_2 (Irvine and Baragar, 1971; Fig. 5b). The basic rocks are all tholeiitic in character as depicted in the discrimination diagram of FeOt/MgO against SiO_2 (after Peacock, 1931; Fig. 5c).

Table 1. Principal Stresses and dihedral angles of conjugate shear fractures.

	Lithology	**PM of $\sigma_{1.}$ (˚)**	**PD of σ_1(˚)**	**PM of σ_2(˚)**	**PD of σ_2(˚)**	**PM of σ_3(˚)**	**PD σ_3(˚)**	**2ɵ(˚)**
1	Granitic Gneiss	27	166	61	004	08	261	88
2		47	078	40	234	12	334	80
3		48	070	40	230	11	328	65
4		49	072	36	220	16	322	76
5		46	075	40	228	14	330	78
6		62	060	28	242	01	151	58
7		43	066	40	206	20	315	60
8		67	277	23	101	01	010	69
9		46	073	36	222	15	327	88
10		47	034	42	199	08	267	75
11		68	032	22	210	01	300	70
12		49	073	36	221	16	324	76

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13		43	072	42	270	15	177	70
14	Granite and Granodiorite	54	043	35	238	07	142	75
15		51	107	36	263	12	001	68
16		57	041	37	240	08	144	67
17		49	056	40	253	09	155	60
18		52	109	37	227	07	011	75
19		48	031	38	238	14	136	67
20		50	045	38	245	10	147	65

PM = Plunge Magnitude. PD = Plunge Direction. Dihedral Angle = **2ɵ**

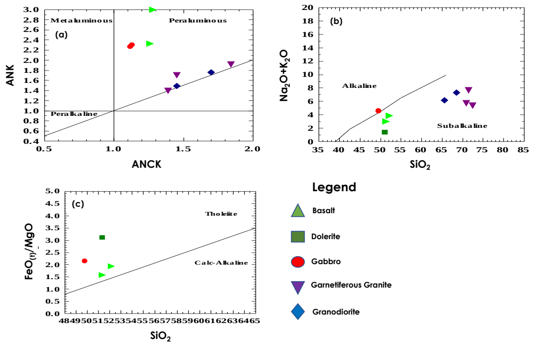

Fig. 5: (a) ANK – ACNK discrimination diagram (after Maniar and Piccoli, 1989) (b) Alkali – SiO_2 discrimination diagram (after Irvine and Baragar, 1971) (c) $FeO_{(t)}/MgO$–SiO_2 discrimination diagram (after Peacock, 1931) for rocks from Boki area.

There is a strong correlation between TiO_2, Fe_2O_3, MgO, CaO, and SiO_2 (Fig. 6). Positive correlation exist between Rb and SiO_2 but faintly for K_2O. Oxides like Na_2O and Al_2O_3 show no obvious trend. The igneous rocks of granitic composition are saturated with normative SiO_2 up to 37.97% (Table 2). The basic rocks on the other hand are deficient in normative SiO_2 which range from < 1 to 5.93%. Normative orthoclase and plagioclase range in values between 13.65 to 32.65% and from 23.38 to 35.94% respectively. These rocks contain no diopside in the norm but hypersthene ranges from 4.64 to 10.53%. The basic rocks contain both diopside and hypersthene in the norm. (Table 1). Normative corundum occurs minimally in the granitic rocks. As expected, the granitic rocks have MgO far less than what is tenable in the basic rocks. The LOI values of most samples range from 0.68 to 2.20 wt.%. The trace and rare earth elements (REE) compositions for the igneous rocks from Boki, Bamenda Massif show high concentrations of Ba, Rb, and Sr in granitic rocks. The compatible elements (Cr, Ni, and Sr) consistently decrease with increasing SiO_2. The igneous rocks from NW Boki therefore shows increase in Zr/Yratio with increasing SiO_2. Except for the granitic rocks, the basic rocks show high La/Nb and Sr/Y < 1 for the basic rocks. Zr/Ba ratios are greater than 0.2 except for gabbro and two samples of garnetiferous granite (Table 2).

Table 2: TRACE ELEMEMT GEOCHEMISTRY OF IGNEOUS ROCKS OF BOKI AREA.

	1	2	3	4	5	6	7	8	9	10	11
Zr/Ba	0.16	0.21	0.16	0.25	0.37	0.06	0.06	0.15	0.14	0.58	0.57
La/Nb	4.04	4.37	1.97	2.05	1.68	0.24	0.25	5.32	4.36	4.71	4.87
La/Ta	51.60	52.36	38.63	37.93	26.96	4.36	4.28	29.43	27.36	70.09	50.53
Sr/ Y	5.99	12.73	12.78	9.77	3.99	6.01	5.84	0.75	2.64	1.81	0.15

1 - 3 = garnetiferous granite: 4 - 5 = granodiorite; 6 -7 = gabbro; 8 - 9-= dolerite; 10 - 11 = basalt.

The trace and REE element abundances are as illustrated in Fig. 7 and 8. The composition ranges broadly but all are enriched in LREE and depleted in HREE. The Chondrite and primitive mantle plots for the rocks from Boki region display strong negative anomalies in Eu, U, Li, and Sr (Fig. 7 a and b). Strong Eu and Sr negative anomalies are in consonance with the high proportion of normative feldspar minerals in the rocks. Dolerite, gabbro, and basalts from Boki have Zr/Ba > 0.2. The LREE are of comparatively higher significant values than those of HREE.

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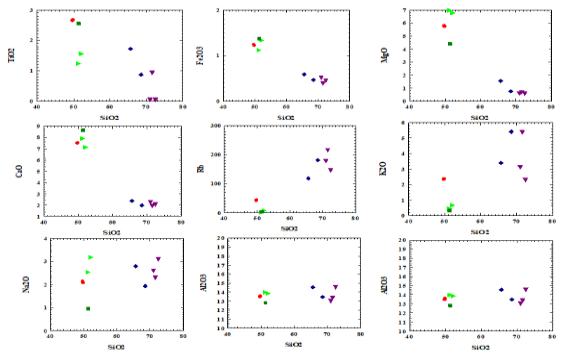
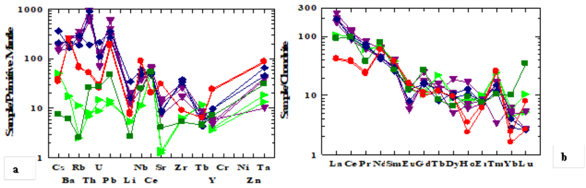


Fig. 6: Harker variation plots for igneous rocks from Boki, Bamenda Massif Southeastern Nigeria. (Symbols as shown in Fig. 5).



Chondrite normalized rare earth element diagram for intrusive and extrusive rocks from Boki, Bamenda massif southeastern Nigeria from. (Symbols as shown in Fig. 5)

3.4 Tectonic Discrimination

The igneous rocks of Boki region, southeastern Nigeria in the Bamenda Massif plots in the arc and the within plate fields of Rb – (Y+Nb) discrimination diagram after Pearce et al. (1984) (Fig. 8a). The basalt, dolerite, and garnetiferous granite show affinity for arc field, while granodiorite and gabbro show affinity for within plate environment. This affinity for arc and within plate fields is further buttressed by the discrimination plot of Nb against Y after Pearce et al (1984) (Fig. 8b) and in the R2 against R1 discrimination plot of Bachelor and Bowden (1985) (Fig. 18c). Apart from the dolerite, the igneous rocks all plot in the pre-plate collision field. The Hf/3 – Th – Ta Ternary plot of Wood (1980) (Fig. 8d), show that the rocks of the map area are tholeiitic within plate differentiates.

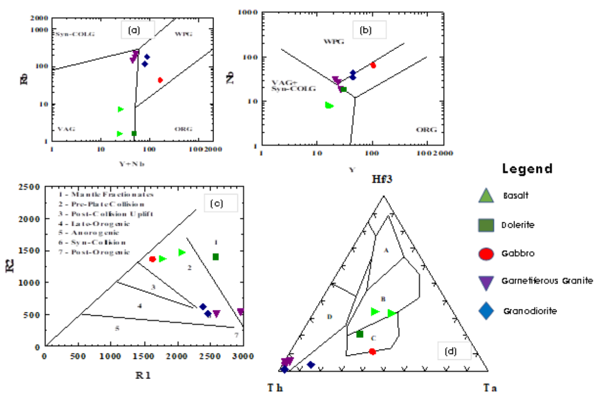


Fig. 8: (a) Rb – (Y+Nb) discrimination diagram after Pearce et al. (1984). Syn-COLG = Syn-collision granites; VAG = volcanic arc granites; WPG = within plate granites; ORG = ocean ridge granites. (b) Nb – Y discrimination diagram after Pearce et al. (1984). (c) R1 – R2 tectonic discrimination plot after Batchelor and Bowden, (1985). R1 = 4Si – 11(a + k) – 2(Fe + Ti); R2 = 6Ca + 2Mg + Al). (d) Tectonic discrimination diagram after Wood (1980). A = N-type MORB; B = E-type MORB & Tholeiitic WPB differentiates; C = Alkaline WPB & WPB differentiates; D = destructive plate-margin basalts & differentiates for igneous rocks from Bokia area.

4.1 Discussion

At first glance, the several mode 1 fractures the igneous rocks of Boki may seem simple and of no significant geologic consequence. However, they are relevant features that can provide a subtle though important detailed information on pattern of stress and strain distribution during the tectonic process that a given region (Van der Pluijm & Marshak, 1997; Oden, 2012a), they also aid mineral exploration in an area as vein consist of joints that were filled/sealed by mineral bearing fluids (Oden, 2012b). The igneous rocks in southeastern basement complex of Nigerian (migmatitc gneisses and granitoids) contain joints and vein which bear syn-tectonic imprints of Pan-African orogeny with prominent N – S trending bc tensile mode I fracture and E – W trending ac extension mode 1 fractures. These must have been associated with the E – W trending maximum compressional stress (σ_1) of Pan-African tectonic episode. The 'ac' extension joints, which form parallel to maximum principal stress (σ_1), occur when the tensile strength of a rock is exceeded due to the stress on it (Davis & Reynolds, 1996). Rocks usually break perpendicular to the direction of maximum stress and in the direction of minimum stress σ_3 (Price, 1966). The orientation of σ_1 during the Pan–African tectonic episode is in the E–W corridor. This is most probably the reason for the development of E – W trending ac extensional joints in the basement rocks Boki area. Rock failure usually occur by shearing rather than tension because extension is required in failure by tension but this is usually impeded by confining pressure (Wilson, 1982).

However, the high fluid pressure in the rocks of Boki area must have helped to reduce the effect of confining pressure by weakening the normal stress and thereby strongly favoring the propagation of mode 1 fractures. On the other hand, mode II and mode III fractures will require much higher stress to propagate. The process by which veins are re-opened and sealed is crack and seal mechanism. This involves the sealing of a joint with mineral crystallizing from mineral-laden fluid with crystals growing perpendicular to the direction of propagation of the joints, and the reopening of the joints due to the impact of continuous stress. Evidence of this occur in the region which contributed to the occurrence of E - W trending composite veins of muscovititc mica and quartzofeldspatic minerals that are parallel to σ_1. This affirms the syn-tectonic origin of the veins. Veins in this orientation enhances mineral crystal growth and vein expansion in the direction of minimum principal stress (σ_3), which is a low energy direction (Oden, 2012a). Usually, mineral grains growing in this direction tend to elongate fastest (Kamb, 1959). This is due to the available space created by extension fracture. Hence the many E – W trending veins in the study area are wider and follow the trend of natural vein evolution. The few narrow N – S veins which are not so common in these Pan-African rock bodies might have resulted from excessive mineral-laden fluid that filled some of the 'bc' tensile fractures. The reason for their very narrow size is that mineral crystal growth is them tend to elongate in the direction of maximum compressive stress (σ_1) (E – W direction), which naturally inhibits their growth thereby making the veins thin and limited in size. Presence of mineral-rich fluid in the crystalline rocks of the study area is evidenced by the abundant quartzofeldsparthic veins and pegmatites in the surrounding igneous bodies. Other crystalline rocks such as the granitic gneisses in the area show paucity of E – W trending foliation, this along with very few mineral vein system trending in this direction suggests that the region experienced a fairly constant E – W compression during most parts of the Pan-African orogeny. This correlates with the assertion by (Oden, 2012a) and (Oden & Udinmwen, 2013) who considered the structural imprints of Pan-African orogeny on basement roots of Oban Massif southeastern Nigerian and Igarra granites of southwestern Nigeria respectively. Also, Oden (2012a) has shown that the impact Pan-African orogeny produced structures with different orientations this buttresses the fact that a single phase deformation could produce structures with different structural trends though with a dominant trend among them. Wilson (1982) explains that 'ac' extension fractures which, result from simple compression usually occur parallel to maximum principal stress (σ_1) and perpendicular to the axes of folds in folded rocks.

Also geochemically, the igneous rocks of Boki region are peraluminous. The Harker plots show linear to near-linear geochemical variations of TiO_2, Fe_2O_3, MgO, and CaO with increasing SiO_2. Also, the depletion in heavy REE and increase in the Zr/Y ratio with increasing SiO_2 suggests magmatic evolution through fractional crystallization. The relatively high MgO content of the basic rocks ranging from 4.60 to 6.78 wt % and the moderately low compatible element contents (Cr 47 – 163ppm; Co 34.64 – 67.90ppm; Ni 89.50 – 237ppm) suggest the rocks were probably derived from an evolved magma (Li et al., 2003). The rocks equally show decrease in MgO and CaO with increasing SiO_2 in the Harker diagrams (Fig. 6). This probably indicate that the fractional crystallization of olivine and clinopyroxene played a major role in magma crystallization. The low Cr and Ni values supports the fact that most primitive samples were already fractionated. Ba in the granitic rocks is comparable to the Ba values (< 1000) in the granitic rocks from SW Obudu Plateau (Ukwang and Ekwueme, 2009), the rocks of Boki has much higher values. The Sr/Y is < 7 in the basic rocks from Boki and this probably preclude slab melting during magma genesis. The rocks of the map area are characterized by low U, Li, Sr, and Tb in the primitive mantle normalized trace element diagram (Fig. 7a). The diagram for the primitive mantle normalized trace elements) shows positive anomalies for Nb, Th, Pb, Zr and Ta. This is consistent with the within-plate tectonic environments of these rocks. The scatter in Ba and Rb may probably indicate secondary process that enhanced mobility of these elements during metamorphism and /or alteration (Li et al., 2003). La/Nb ratio for the basalt on the average is 4.79, for gabbro and dolerite the values are 0.25 and 4.84 respectively. The values for basalt and dolerite are higher than that obtained for Shekou and Yaunzhuang basalts from SE China by Li et al (2003). The higher values may be attributed to metasomatic enrichment or partial melting. The values of LOI in these rocks clearly suggest that the rocks from Boki region must have experienced some degrees of alteration (Zhu et al., 2012). These rocks show close similarities with the rocks of the SW Obudu reported in Ukwang and Ekwueme (2009).

4.2 CONCLUSIONS

Generally, geochemical data of igneous rocks of Boki region depicts a transitional tectonic setting that ranges from arc to within plate environment. Structural evidence from joints, and mineral vein study has shown the impact of Pan-African tectonic event on the basement rocks of southeastern Nigeria. Through most part of the orogeny, the principal stresses σ_1 and σ_3 (maximum and minimum principal stresses) apparently maintained a constant orientation in the E – W, and N – S direction respectively as indicated by the joint pattern of observable mode 1 fractures in the rocks. Mineral veins oriented in the direction of maximum principal stress (σ_1) are better disposed for expansion in width, which favors mineral crystal growth and should be the main focus for exploration for solid mineral deposit in the study area. Hence understanding of paleostress configuration in an area is important for the purpose of exploring for mineral veins as this will determine the orientation of veins of greater proficiency, which should be the main focus of explorers.

REFERENCES

1. Archanjo C. J., Hollanda, M.H.B. M., Rodrigues S.W.O., Neves, B.B.B. and Armstrong, R. (2007). Fabrics of pre and syntectonic granite plutons and chronology of shear zones in the Eastern Borborema province, NE Brazil. *Journal of Structural Geology*. 30:310-326.
2. Billings, M. P. (1972). Structural Geology. PHI Learning Limited, New Delhi-110001.
3. Davis, G. H. and Reynolds, S. J. (1996). Structural Geology of Rocks and Regions. John Wiley and Sons. New Jersey.
4. Ekwueme, B. N. and Nganje T. N. (2000). Geochemistry and geochronology of Uwet granodiorite, SE. Nigeria. *Global Journal of Pure and Applied Sciences*.6(2):249-253.
5. Ephraim, B. E., Ekwueme, B. N., Mohssen, M. and Monir, M., (2008). P – T condition of Pan–African orogeny in southeastern Nigeria. *Central European Geology*, 51 (4) pp. 359 – 378.
6. Ferre, E., Gleizes, G. and Bouchez, J. L. (1995). Internal Fabric and strike-slip emplacement to Pan-African granties of Solli Hills, Northern Nigeria. *Tectonics*. 14:1205- 1219.

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7. Hills SE. (1972). Elements of Structural Geology. Chapman and Hall. London.
8. Hobbs B. E., Means W. D. and Williams P. F. (1976). An Outline of Structural Geology. John Wiley & Sons.
9. Hubbert, M. K. and Willis, D. G. (1957). Mechanics of Hydraulic Fracturing. *Journal of Petrology and Technol.* 210, 153-163
10. Ibegbulam, E. O. and Ukwang, E. E. (2014) The Petrology of Northwestern region of Boki, Bamenda massif, southeastern Nigeria. *International Journal of Nature and Applied Sciences* (IJNAS), vol. 9, Nos 1&2 p 23-38
11. Ike, E. C. (1988). Late-stage Geological phenomena in the Zaria Basement granites. Precambrian Geological of Nigeria, *Geological Survey of Nigeria*. 83-89.
12. Irvine, T. N. and Baragar, W. R. A. (1971). A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences,* 8, 523-548.
13. Kamb, W. B. (1959) Theory of Preferred Crystal Orientation developed by Crystallization under Stress. *Journal of Geology*.;67:153-170.
14. Maniar, P.D. and Piccoli, P.M. (1989). Tectonic discrimination of granitoids*. Geological Society of American Bulletin,*101, 635 – 643.
15. Oden, M. I. (2012) Strain Partitioning and Dimensional Preferred Orientation in a Syn-tectonic Granitoid, Southeast, Nigeria. *Science World Journal*. 7(1):9-14.
16. Oden, M. I. (2012b). Barite Veins in the Benue Trough: Field Characteristics, the Quality Issue and some Tectonic Implications. *Environment and Natural Resources Research*. 2(2):21-31.
17. Oden, M. I. and Udinmwen, E. (2013). The Behaviour of K-feldspar Phenocryst and Strain Anisotropy in Igarra Syn-Tectonic Granite, Southwestern, Nigeria. *Current Advances in Environmental Science*. 1(2):9-15.
18. Oden, M.I. (2012a). The Pegmatite Veins of Western Oban Massif: Tectonic and Lithological Controls on Physical Properties. *Research Journal of Environmental and Earth Sciences*. 4(4):381-389.
19. Peacock, M. A. (1931). Classification of igneous rock series. *Journal of Geology* 39:54-57.
20. Pearce, J. A., Wharris, N. B. and Tindle, A. G. (1984). Trace element discrimination diagram for the tectonic interpretation of granitic rocks. *Journal of Petrology,* 25, 956-983.
21. Price, N. J. (1966) Fault and Joint Development in Brittle and Semi–Brittle Rock. Oxford: Pergamon Press.
22. Ramsay, J. G. and Huber M.I. (1987). The Techniques of Modern Structural Geology, Folds and Fractures. Academic Press London.
23. Shainin, V. E. (1950) Conjugate set of en echelon tension fractures in the Athens limestone at Riverton Virginia Bull. Geol. Ecol. Am. 61. 509.
24. Singhal, B. B. S., and Gupta, R. P. (2010). Applied hydrogeology of rocks (2^{nd} ed.). *Springer*, Dordrecht. 401p.
25. Twiss, R. J. and Moores, E. M. (1993). Structural Geology. W. H. Freeman and Company, New York. 532p.
26. Ukwang, E. E. and Ekwueme, B. N. (2009a). Trace element geochemistry and tectonic characterization of the granulites facies rocks from southwest Obudu plateau, southeastern Nigeria. *Chinese Journal of Geochemistry,* 28, 248-257.
27. Van der Pluijm, B.A. and Marshak, S. (1997) Earth Structure: An Introduction to Structural Geology and Tectonics. WCB/McGraw Hill, New York.
28. Wilson G. (1982). Introduction to Small-Scale Geological Structures.George Allen and Unwin, London.128p.

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