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Fracture Characterization, Mineral Vein Evolution and the Tectonic Pattern of Igarra Syn-Tectonic Granite, Southwestern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author OIM designed the study, wrote the protocol and managed the analyses of the study while Author UE wrote the first draft and managed the literature search. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Extensive outcrops of the pan-African granite were studied in detail with particular interest in the joint pattern and mineral vein characteristics. The attitude of 57 tectonic joints and 60 mineral veins were measured, the length and width of the veins documented. Rose diagrams and graphs representing fractures and veins were plotted and analysed based on their behavior and preferred orientations. Two (2) basic trends of mode I fractures(joints) and veins were observed in the granites, these are the E-W trending joints and veins parallel to the maximum principal stress ($\boldsymbol{\sigma}_1$) direction and the N-S trending joints and veins parallel to the minimum principal stress ($\boldsymbol{\sigma}_3$) direction. These granites contain mostly Mode I fractures which require lower stress to initiate and propagate relative to Mode II and Mode III fractures, although other trends (NW-SE and NE-SW) of joints and veins were mapped, they are highly insignificant compared to the major E-W and N-S trending joints and veins within the plutons. Mineral veins in these syn-tectonic granites developed apertures that were sensitive to the orientations of the stresses; the widest veins being those oriented approximately in the E-W direction, parallel to the maximum principal stress ($\boldsymbol{\sigma}_1$). Mineral veins in N-S orientation are generally thin and non-persistent; their formation indicates fluid pressure-build up in the course of the orogeny. The occurrence of sheet/exfoliation joints lends credence to the

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occurrence of some sort of near-surface deformation related to cooling and exhumation or unroofing within the granite. The simple pattern of surface joints and veins indicates a fairly constant orientation of the principal stresses $\boldsymbol{\sigma}_1$ and $\boldsymbol{\sigma}_3$ in the E-W and N-S directions respectively, through most part of the orogeny in this area. From this study, it would appear that the pan-African stress configuration did not change throughout the period tracked by the evolution of these granites. This work serves to elucidate the joint pattern and mineral vein evolution of the syn-tectonic granite to further discuss the history of Pan-African tectonics of the Igarra region in southwestern Nigeria and it was carried out in Igarra and environs with further analysis done at the Department of Geology, University of Calabar, Nigeria for a period of 18 months.

Keywords: Joint; vein; tectonic; mode I fracture; granite; Igarra.

1. INTRODUCTION

Nigeria sits at the hub of the Pan-African mobile belt which is part of a 4000Km long and several hundreds of kilometers wide orogenic province stretching from Hoggar to Brazil [1]. This orogeny is believed to be the last tectonic event to have affected the Nigerian basement complex (600±150my) which engendered the wide spread emplacement of syn-tectonic granitoids in different parts of the basement complex of Nigeria [1,2,3,4,5,6,7,8,9] and across the Atlantic ocean as far as Brazil where granitoids of similar age have been observed [10]. The Igarra region is part of the Precambrian southwestern basement complex of Nigeria and it host a series of rock types with the most conspicuous being plutons of pan-African granites which contain joints and mineral veins with some information on the tectonic history of the region. [11] have substantial information on the geology of the southwestern basement complex of Nigeria. Odeyemi has worked extensively in this region, producing a series of articles on the petrology and geochemistry of rocks in the region [3,12,13,14]. [3,12] attempted to document a generalized structural pattern of this region. [15] did an interesting work using both geological and geophysical methods to decipher the surface and subsurface fracture anisotropy within the Igarra region, but their work, although extensive, did not elucidate the tectonics responsible for the fracture patterns. Detailed structural analysis and the tectonics inferred from rocks in this region is scarce but most recently [5] used phenocryst data from the porphyritic pan-African granites in this area to estimate the strain intensity as well as the direction of the principal stresses that affected the pan-African granites. Joints are probably the most common structures exposed at the present day surface and seem to be featureless as mere cracks. Veins on the other hand are strongly related to joints as fluids tend to fill available cavities. The infilling of openings in rocks is not a radical process as studies have shown that fluids prefer to fill openings parallel to the maximum principal stress direction($\boldsymbol{\sigma}_1$) of a region [2,16,17,18,19,20]. Joints on its own give a subtle history of the stress and strain (tectonics) of a region, but analyzed concomitantly with mineral veins, they produce an absolutely phenomenal tectonic history of a region. This study serves to elucidate the joint pattern and mineral vein evolution of the syn-tectonic granite and a subtle history of pan-African tectonics of the Igarra region in southwestern Nigeria by focusing exclusively on the syn-tectonic granite, the authors exclude the effects of all earlier deformations in order to determine those of the pan-African alone.

1.1 Geology and Physiography

The Igarra area of the basement complex is located in the north of Edo State, Nigeria and it contains about four main groups of rocks. These are the migmatite-gneiss complex, the metasediments composed of schists, calc-gneisses, quartzites and metaconglomerates, the porphyritic Older Granites and the late discordant non-metamorphosed syenite dykes [3]. South of Igarra lie the non-metamorphosed syenite dyke which has a sharp contact with the folded metasediments and xenoliths of quartz-biotite schist and metaconglomerate with associated biotite pyroxenite [3,14]. It is probably one of the last events to affect this region [3]. The rocks shows a general NW-SE foliation trend which seems to lie parallel to the limbs of major folds while the migmatites had most major structural elements trend E-W [3]. The marked structural discordance between the migmatites and the metasediments/ Granites suite implies that the scale of deformation (and orogeny) in this part of the country was limited [3].

The Pan-African plutons in this area lie between Latitudes 7^o00^1 and 7^o30^1N and Longitudes 6^000^1 and 6^030^1E, alongside other rock types forming the lower-left quadrant of Lokoja Sheet 62 compiled and published by the Nigerian Geological Survey Agency (Fig. 1). These granites intruded schists and metaconglomerates at Igarra through Ogbe to Ogugu while S/SW of Igarra (Ake, Sebe-Ogbe) had them intruding metasediments (schist, gneiss and metaconglomerates). At Ososo (NE of Igarra) they intruded granite gneiss and migmatites (Fig. 1). The contact between the country rocks and the granite intrusion were sharp in most cases. The Igarra area falls within Nigeria's tropical rain forest belt, its hilly/undulating topography averages about 500m above sea level and the higher elevations expose the bell-shaped pan-African granites. This region is one of the most exposed parts of the pan-African domains of Nigeria.

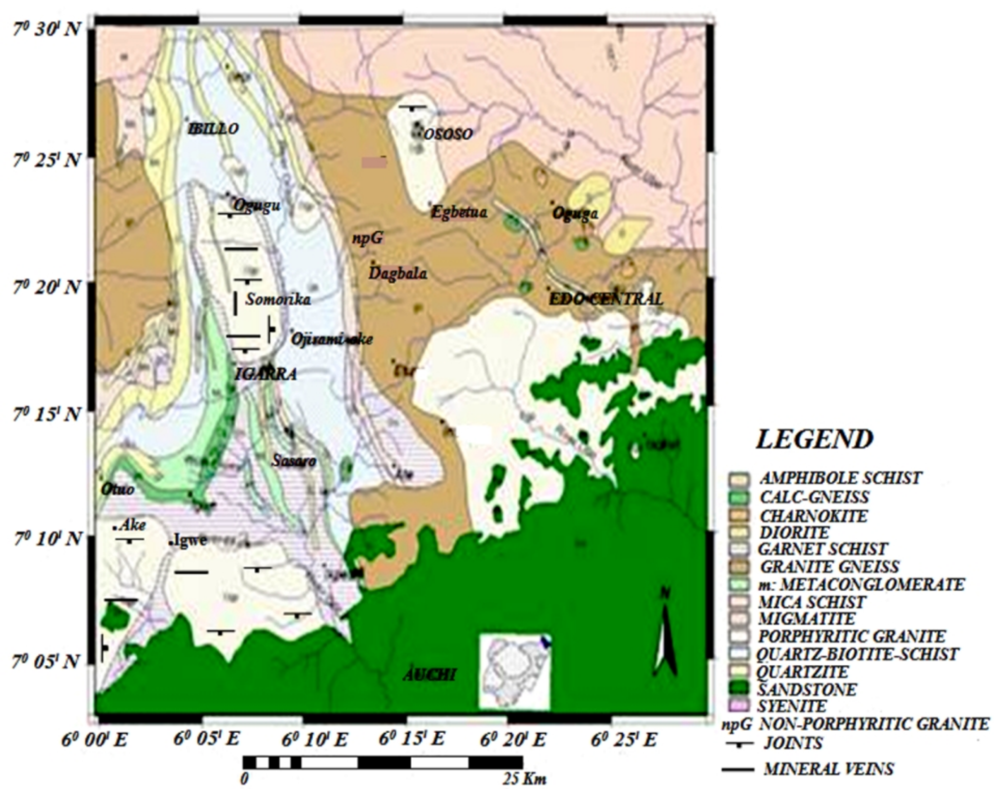

Fig. 1. Geologic map of the study area modified after [21]

2. MATERIALS AND METHODS

Extensive outcrops of the pan-African granite around Igarra were studied in detail with particular interest in the joint pattern and mineral vein characteristics. The attitude of joints and veins as well as the length and width of veins were measured using standard structural analytical methods and analyzed using simple computer statistical tools. The accurate positions of plutons were obtained using a Garmin 76 Global Positioning System (GPS). All data used in this work were obtained from small scale geological structures through direct observation and measurement.

3. RESULTS AND ANALYSIS

3.1 Joints

Joints are probably the most common and simplest structures exposed in the study area. At first glance, joints (e.g. Fig. 2) may seem to be simple and featureless geologic structures but they constitute an important element of structural patterns both locally and regionally [18] and they can provide a detailed, though subtle, history of stress and strain in a region [16], [22].

Fig. 2. Mode I fracture in the granite

The Igarra granites is a syn-tectonic granite emplaced during the pan-African orogeny [6], [3]. A study of the joint system in the Igarra granite using 57 data points shows two major joint patterns which are: a dominant E-W trending joint set and a less frequently occurring N-S trending set (Fig. 3a), with high angle dips between 60º and 90º (Fig. 3b). Also occurring within the area are special horizontal joints (sheet/exfoliation joints) (Fig. 4). Considering the tectonic pattern given by [5], the E-W trending joints are the 'ac' extension joints while the N-S trending joints are a bit younger 'bc'tensile joints, both of which are pure Mode I fractures [23] and [24]. There is no evidence of surface Mode II or Mode III fractures within the plutons. The sheet/exfoliation joints sub-horizontal joints approximately parallel to the ground surface. These sheet joints are strongly related to the N-S trending joints which mostly terminate at the slabs formed by the sheet joints. The tectonic process which produced the

E-W joints is responsible for the N-S joints as well, while the sheet joints are mainly cooling and exhumation-related. Surprisingly the N-S trending joints contain thin mineral veins, which probably formed through the sealing of open cavity by excess fluids. Sheet joints tend to form where horizontal stress is significantly greater than vertical load [16] and the N-S joints most likely supported the movement of the thin granite slabs formed by sheeting as the pluton was being unroofed. The N-S trending joints are relatively younger than the E-W joints because of the termination relationship as shown in Fig. 5. The N-S and sheet joints were observed in a few locations among the numerous plutons in the Igarra granite range. These plutons were about 3km away from each other. Studies of pan-African rocks and structures in other areas have revealed an E-W compressional axis ($\boldsymbol{\sigma}_1$ direction) through most part of the orogeny, a N-S $\boldsymbol{\sigma}_3$ direction as well as NW-SE and NE-SW simple shear directions [2].

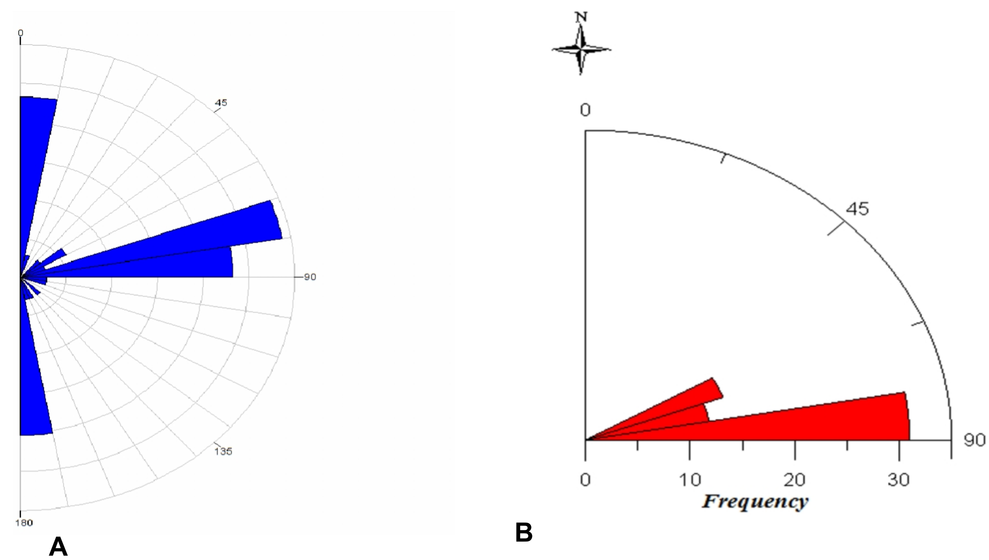

Fig. 3. (a) Rose diagram of joint orientations; (57 data points, 0º indicates the north direction); (b) Dip diagram of joints dominantly between 60º - 90º.

Fig. 4. Sheet/Exfoliation joints in granites around Igarra/Somorika

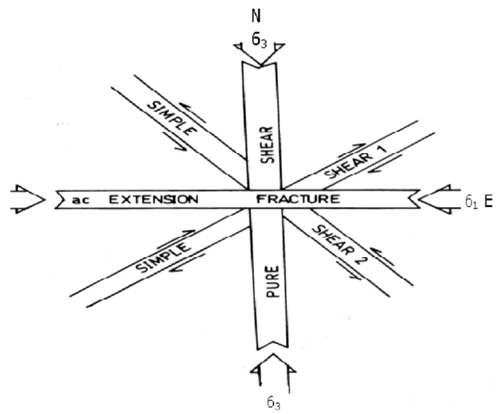

Fig. 4a. The main tectonic axes of the pan-African orogeny (After Oden [2])

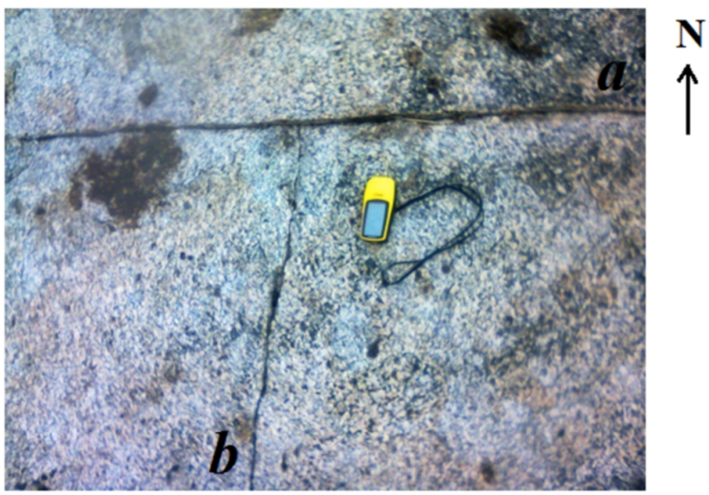

Fig. 5. Termination relationship between 'a'(E-W) and 'b'(N-S) joints in the granite. The 'b'(weaker) joint could not propagate across the void space already created by the 'a' joint which is older, stronger and wider

[15] using geophysical methods recognized the occurrence of NW-SE trending fractures in the sub-surface of the general Igarra area, although this was scarcely available on the surface. This is expected, given that the main tectonic axes of the Pan-African orogeny were one pure shear direction (N-S), two simple shear directions (NW-SE and NE-SW) and an E-W direction of compression, see Fig. 4a. [2] arrived at his conclusions from consideration of strain partitioning using tablets of feldspar phenocryst as strain markers from Uwet granodiorite in southeastern Nigeria among others. [5] from strain analysis in the Igarra granite, southwestern Nigeria also confirmed the tectonic axes of the Pan-African orogeny as shown in Fig. 4a. The data from [15] are acceptable but their interpretation which places NW-SE trending structures as pre Pan-African is not. Considering the simple fact that some of the rocks hosting these NW-SE trending structures from their data are confirmed syn-tectonic Pan-African rocks, e.g. granites, the same rocks cannot also host pre-Pan-African structures.

3.2 Mineral Veins

The mineral veins in the granite plutons are basically pegmatite, aplite and quartz veins, the evolution of which is very interesting yet challenging at times. A total of 60 veins were studied within the area and the data showed two dominant trends viz: wider E-W trending veins, parallel to the direction of the maximum principal stress (σ_1) and narrow or thin N-S trending veins perpendicular to σ_1 (Figs. 6a and b).

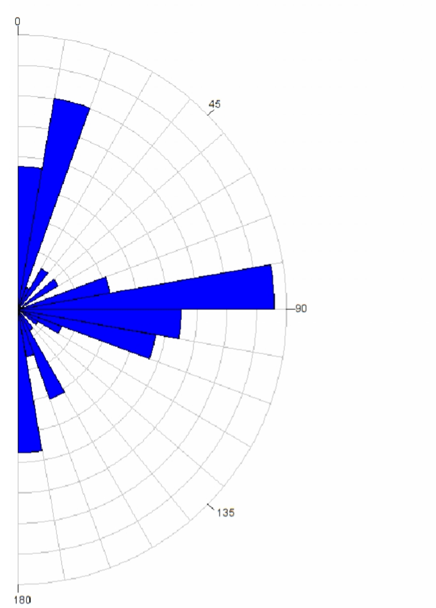

Fig. 6a. Rose diagram of mineral vein orientations; (60 data points, 0 indicates the north direction)

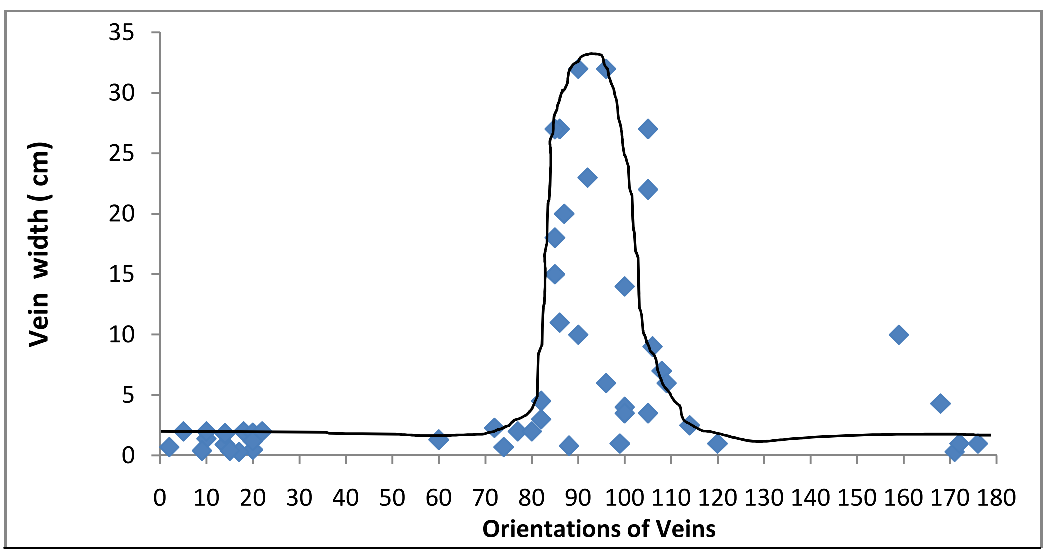

Fig. 6b. Graph of vein width against vein orientations or strike (60 data points)

Fig. 6c. Unsealed N-S trending Mode I Fracture

From Fig 6b, veins with orientations between 80º and 110º from the north are the widest while those with orientations between 0º-20º and 170º-180º are relatively narrow. That is, mineral veins in these syn-tectonic granites developed apertures that were sensitive to the orientations of the veins; the widest veins being those oriented approximately in the E-W direction. At a first glance, prior to detailed investigation, this situation aroused our curiosity and a question came to mind "Even though the N-S veins are thin/narrow, why did they open at all" ?

A closer investigation of both the E-W and N-S trending veins revealed that the E-W trending veins are fibrous in nature (Fig. 7a) with crystals trending parallel to the short axis of the vein which is the least principal stress ($\boldsymbol{\sigma}_3$) direction. This suggests that they are natural tectonic veins, formed at depth and progressively widened with time (Fig. 7a). The N-S veins on the other hand are thin and blocky (Fig. 7b), probably because they tried to grow grains parallel to $\boldsymbol{\sigma}_1$ and the stress in that direction inhibited their growth and destroyed their elongation. This may suggest that the N-S veins were probably formed at a slightly later period when there was enough build-up of fluids.

A

B

Fig. 7. Mineral veins in the granite (a) E-W trending vein (notice the length-parallel crack at the left side of the vein, maybe part of a crack-seal process), (b) N-S trending aplite vein (notice the width of the vein)

The exfoliation joints (Fig. 4) which are horizontal to sub-horizontal and tend to be parallel to the free surface, formed thin slabs of granite (about 20 to 30cm thick) at the roof of the pluton, as doming and unroofing of the pluton occurred. The N-S joints formed and terminated at each slab formed by sheeting, they probably would have supported movements of the slabs as unroofing continued but because the horizontal stress was significantly greater than the vertical load which is usually the condition at near surface and probably the rate of uplift was not high, the horizontal movement of the slabs along the N-S joints delayed long enough for this aperture to be sealed up with excess fluids. Nevertheless, some of the N-S joints whose slabs had drifted significantly, created wide gaps or openings which were not sealed (Fig 6c), but are presently observed as a mode I fracture along which sufficient movement occurred. The occurrence of thin slabs (about 25cm thick) at the top of the pluton suggests that a few slabs had moved prior to the sealing of the joints. [6], from observation of roof pendants and meta-sedimentary xenoliths, suggested that the Igarra pluton is still being unroofed. It would require a large stress to re-open and drift slabs along the already sealed N-S joints and even a larger stress to initiate and propagate a fresh joint. It must be noted that the occurrence of sheet joints and N-S veins was local as they were only observed between Igarra and Somorika communities which host the most exposed plutons in the Igarra region. Both communities are about 3km from each other. Outside this limited zone, those structures were not observed.

3.3 DISCUSSION

Joints may seem to be simple and featureless geologic structures but they are important because they can provide a detailed and subtle history of the stress and strain distribution in a region [16]. Veins on the other hand are structures which are strongly related to joints [25]. The Igarra granites exhibit a simple joint and vein relationship which indicates a syn-tectonic genesis for both of them. When the tensile strength of a rock is exceeded, the rock breaks perpendicular to the direction of tension. 'ac' extension joints are formed parallel to $\boldsymbol{\sigma}_1$ (E-W for the Igarra area) and perpendicular to $\boldsymbol{\sigma}_3$ [19] and [23]. This seems to be the condition responsible for the development of E-W trending joints in the Igarra granites. Though rocks are much weaker in tension than in shear, they often fail by shearing as by tension because failure by tension necessitates extension which is usually inhibited by confining pressure [20]. The situation in the Igarra granite plutons excludes the occurrence of surface shear fractures but these shear fractures (NW-SE and NE-SW trending joints) have been recognized by [2] and [14] in pan-African granitoids of both the eastern and western basement complex respectively. It must also be noted that the confining pressure was weakened by the high fluid pressure in the granite which reduced the normal stress thereby favouring the propagation of strictly Mode I fractures, as Mode II and Mode III fractures (shear fractures) require a higher level of stress to propagate. The occurrence of sheet joints in the granites suggests a near surface, post-tectonic deformation related to upliftment and unroofing. The earlier deep-seated tectonic deformation initiated and propagated extension joints and veins parallel to the maximum compressive stress (E-W trending). The crack-seal mechanism, which is a process by which veins are re-opened and sealed was probably not strong in this region, but could have contributed to the E-W trending veins, parallel to the maximum compressive stress ($\boldsymbol{\sigma}_1$) thereby confirming their syn-tectonic origin. This seems to be a general situation with veins irrespective of the geology, as barite veins in the Benue trough of Nigeria were shown to be strongly structurally controlled parallel to the prevalent maximum compressive stress direction ($\boldsymbol{\sigma}_1$). Such orientations enable grain growth and vein expansion to take place parallel to the least principal stress direction ($\boldsymbol{\sigma}_3$)- a low energy orientation [26]. Veins in extension fractures are expected to trend parallel to the direction of maximum principal stress [18] and mineral grains are expected to grow perpendicular to the walls of such structures [19]. According to [27] grains growing parallel to $\boldsymbol{\sigma}_3$ tend to elongate fastest. The E-W trending veins parallel to $\boldsymbol{\sigma}_1$ are expected from natural vein evolution while the N-S veins though narrow and limited are not so common especially in this pan-African granite. This is because the N-S veins would try to grow grains parallel to the maximum principal stress direction ($\boldsymbol{\sigma}_1$), which would strongly inhibit their growth. As cracking and sealing of the east-west veins continued in response to stress pulses during the orogeny, fluid pressure and volume must have built up and the excess residual fluids flowed into the less-favoured N-S joints. The mineral vein situation in the Igarra granite is unique with a local effect and is not expected in any part of this basement complex except all conditions of tectonic magnitude, fluid availability and pressure as well as structures is the same. The fluid availability in this region is evident from the abundant pegmatite and quartz veins in the surrounding schist and other rock types.

The simple joint characteristics, mineral vein system and the scarcity of E-W trending phenocrysts in the porphyritic granites [5], suggest that a fairly constant E-W compression prevailed in this region through most part of the pan-African orogeny. The interpretation of [15] that NW-SE trending “structures” are pre Pan-African is erroneous, as they obviously did not consider the tectonics and strain regime within the area prior to their conclusion. A similar interpretation which grouped NW-SE trending structures as pre Pan-African was given for western Oban massif in southeastern Nigeria by [28]. This was dismissed by [2] with evidence from strain analysis. [2,5] from consideration of strain analysis, stress configuration and the tectonics of southeastern and southwestern basement complex of Nigeria respectively, have shown that the Pan-African orogeny could produce structures with different orientations as shown in Fig. 4a thus the conclusion by [28,15] that NW-SE trending “structures” are pre Pan-African is obviously a mis-interpretation of Pan-African structural trends as NW-SE trending fractures, foliations, mineral lineations, dykes and lineaments have been reported in Pan-African regions [2,5,9,29,30,31,32,33]. A single phase deformation could also produce different structural trends depending on the structure and rock type considered. For instance, secondary foliations so commonly occur parallel or sub-parallel to the axial surfaces of folds [24] but extension fractures which result from simple compression usually appear at right angles to the axes of folds [20] and these fractures (“ac” extension) form parallel to σ_1 (maximum principal stress) direction [9,23,34,35].

4. CONCLUSIONS

The effects of the pan-African tectonics on the granites of this region have been unraveled from joint and mineral vein study. The simple pattern of surface joints and veins indicates a fairly constant orientation of the principal stresses $\boldsymbol{\sigma}_1$and$\boldsymbol{\sigma}_3$ in the E-W and N-S directions respectively, through most part of the orogeny. Only mineral veins oriented parallel to the maximum stress ($\boldsymbol{\sigma}_1$) direction are favoured for expansion in width. Mineral veins in the N-S orientation are generally thin and non-persistent; that they opened at all against prevailing E-W compression is an indication of fluid pressure build up in the course of the orogeny. These observations show that when exploring for mineral veins there is need to determine the paleostress configuration in the area, as this would enable the direction of veins of greater pay to be unraveled. Shear fracturing was very scarce or non-existent among the fracture data collected from these syn-tectonic granites. From this study, it would appear that the pan-African stress configuration did not change throughout the period tracked by the evolution of these granites.

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COMPETING INTEREST

The authors have declared that no competing interest exists.

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