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Mesoscopic Structural Profile ofa Syn-Tectonic Granite, Southwestern Nigeria

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Abstract:*Pan-African granites from Igarra area in southwestern Nigeria have a mesoscopicstructural profile which includes phenocrysts, xenoliths, joints, veins and different pluton shapes all in interesting orientations. The phenocrysts which are white or pink in colour show a preferred orientation of long axes in the NNW-SSE and N-S directions. The phenocrysts from the porphyritic granites show evidence of an early stage magmatic origin. The metasedimentary xenoliths frozen in these granites are strongly preferentially oriented in the NNW-SSE to N-S direction as well, for reasons related to the tectonics of the region. The xenoliths being poor strain markers are at best useful for inferring the direction of maximum extension. Joints in the granites are good and linear suggesting that fracture toughness was far exceeded by driving pressure during joint propagation. These joints, like the veins are preferentially oriented in the E-W and N-S directions, an indication that the fluids of pegmatite, quartz and aplite within this area took advantage of available fractures at the time, although favouring the E-W trending discontinuities. The E-W joints are interpreted as "ac" extension fractures that intruded the trajectory of the maximum principal stress (σ_1), while the N-S ones are "bc" tensile fractures, parallel to the minimum principal stress (σ_3). Two pluton types within this area are the ellipsoidal (Bell shaped) plutons and the elongated (Table top) plutons which are hosted by different metasedimentary rocks. The pluton shapes and phenocryst sizes suggest that magma of probably varying viscosities intruded different country rocks within this area.*
Keywords:*Plutons, Granite, Igarra, Phenocryst, Xenolith*

I. Introduction

The Pan – African mobile belt lies between the West African craton to the west and the Congo craton to the east and stretches from Hoggar to Brazil (Ferre, et al., 1995). This orogeny (Pan- African) which is the last tectonothermal event that affected the Nigerian basement complex, emplaced granitoids of different varieties within parts of the Nigerian basement (Oden 2012a; Oden and Udinmwen 2013; Oden and Igonor 2012a; Odeyemi 1976; Ike 1988; Oden et al., 2012; Ball 1980). Individual granite bodies consisting of many plutons occur within and around Igarra, these were called "Igarra Granites" for the sole purpose of easy reference in this work. The Pan-African granites within and around Igarra, south western Nigeria were studied mesoscopically to ascertain the structural profile of the granites. Phenocrysts, xenoliths, joints and veins are all found within these granites which are in two varieties viz: the porphyritic and non-porphyritic granite. The former variety is dominant, while the latter is almost featureless at the mesoscopic scale. The palaeostress configuration through the period tracked by these granites using strain markers and structures has been observed to have an E-W trending σ_1 (maximum compression) and a N-S direction of maximum elongation or σ_3 (Oden and Udinmwen, 2013; Oden and Udinmwen, 2014) conforming to other basement complex Older Granites in Nigeria (Oden, 2012a; Ball, 1980). The structural profile of these granite responded to the tectonic situation as observed by Oden and Udinmwen (2013). The physical characteristics of the plutons somewhat feed into the tectonic situation.

II. General Geology

The Igarra granites intruded the most easterly schist belts in southwestern Nigeria (Turner 1983). This region is underlain by rocks of the Precambrian basement complex and about four major groups have been observed within this area. These are the migmatite-gneiss complex, the metasediments (schists, calc-gneisses, quartzites and metaconglomerates), the porphyritic Older granite and the late, discordant, non-metamorphosed syenite dyke (Odeyemi 1976) (Fig 1). The Older granite has both porphyritic (Fig 2a) and non-prophyritic variety with the latter found around Dagbala, NE of Igarra (Fig 2b). The absence of conspicuous phenocrysts in the non-porphyritic granites makes it less important for extensive mesoscopic analysis, although it contains joints, xenoliths and veins. Three main porphyritic granite bodies are found within the mapped area. These are the "Igarra plutons" which intruded metasediments, the "Sebe-Ogbe/Ake" plutons which occur about 15km S/SW of the Igarra plutons and intruded metasediments (schist, metaconlomerateand calcgneiss) and the "Ososo plutons" which are about 10 km NE of the Igarra plutons and intruded gneisses to the west and south and migmatites to the northeast. The schist and gneisses are basically foliated in the NW-SE direction with some N-S trending foliation also occurring, joints within the granites trend E-W and N-S and the veins of pegmatite, quartz and aplite took advantage of these fractures.

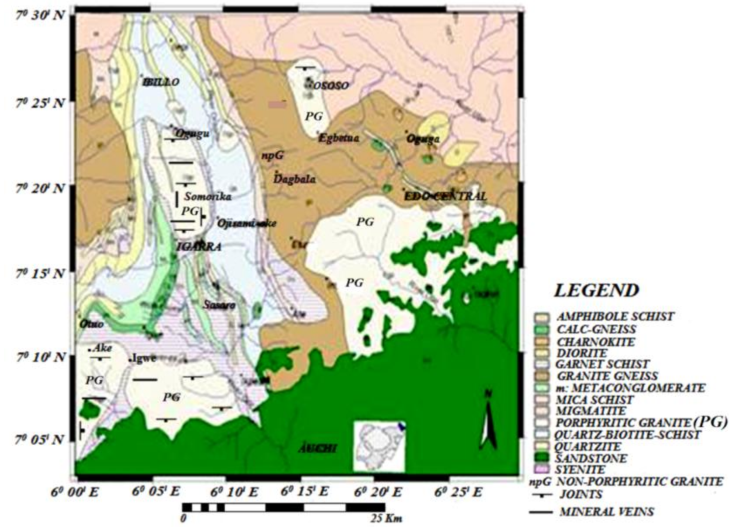

Fig 1.Geologic map of the study area. Modified after Anifowose et al., (2006)

Fig 2: Granites of Igarra area. (a) Porphyritic variety, with well-formed feldspar phenocrysts showing preferred orientation (b) Non-porphyritic variety, without well-formedphenocrysts, found around Dagbala area.

III. Structural Profile

Rocks of the Igarra area have an interesting structural profile, with the granites hosting the least of these structures when compared to the schists and other metamorphic rock types. The pluton shape and mesoscopic structures prove to be quite important to structural and tectonic analysis. The structures and strain markers which make up the profile include phenocryst, xenoliths, joints, mineral veins and pluton shapes.

3.1 Phenocrysts

Phenocrysts are numerous in the porphyritic variety of the Igarra granites. These pinkish to whitish phenocrysts (Fig 3 a and b) with rectangular shape range in length from 0.9cm to 12.5cm and width from 0.3cm to 4.8cm. This is similar to what was observed in the Uwetgranodiorite, SE Nigeria (Oden, 2012a; Oden and Igonor, 2012a; Oden &Igonor 2012b) although the phenocrysts here are slightly larger than those of the granodiorite.

Fig 3: Phenocrysts of the Igarra granites. (a) Pink coloured, large feldspar phenocrysts, found only in the elongated (Table top) Ososo plutons. (b) White coloured, relatively small feldspar phenocrysts which are dominant in the ellipsoidal (bell shaped) Igarra granites. In both cases, the phenocrysts have well defined euhedral shapes, without interference. They are conspicuously larger than the groundmass and show preferred orientation of long axes.

The whitish phenocrysts are smaller and they were observed around Igarra to Ogugu, Ake and Sebe-Ogbe while the pinkish variety is conspicuously larger and crowded as observed in Ososo. The phenocrysts are preferentially oriented strongly in the NNW-SSE and weakly in the N-S directions (Fig 4). Oden and Udinmwen (2013) used tablets of phenocrysts from the Igarra granites as strain makers to estimate strain intensity and determine the direction of maximum elongation of the Pan-African orogeny within this area. Their result showed a N-S direction of maximum elongation and an E- W direction of maximum compression (σ_1)which agrees with the tectonics of the Pan-African from other parts of the mobile belt (Ball, 1980; Ike, 1988; Oden, 2012a).The Igarraphenocrysts are perfect strain markers due to their origin (early stage magmatic crystals) and thus must have tracked a long period of Pan-African tectonics related to this area.

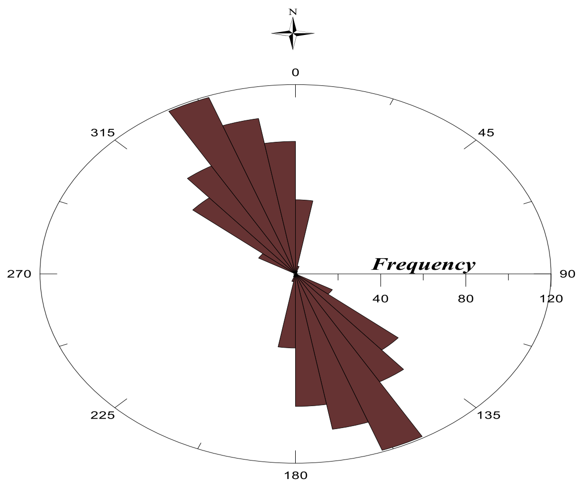

Fig 4: Rose diagram of phenocryst long axes, showing a strong preferred orientation dominantly in the NNW-SSE direction and less occurring in the N-S orientation. (523 data point).

3.2 Xenoliths

The xenoliths of the Igarra granites are metasedimentary (Egbuniwe and Ocan, 2009) and are much larger than the phenocrysts (Fig 5a). Their lengths vary from 2cm to 34cm while they are between 0.5cm to 27cm wide. The orientations of the long axes of the elliptical xenoliths show a strong preferred orientation in the NNW-SSE to N-S directions (Fig 6). This preferred orientation is related to their physical properties and the Pan-African palaeostress system and does not differ much from that of the phenocrysts. Some of the metasedimenary xenoliths that occur close to the sharp contact between the schist and the granites still retain their foliation, though weak and rotated (Fig 5b), while those further away from the contact do not show such characteristics (Fig 5a).

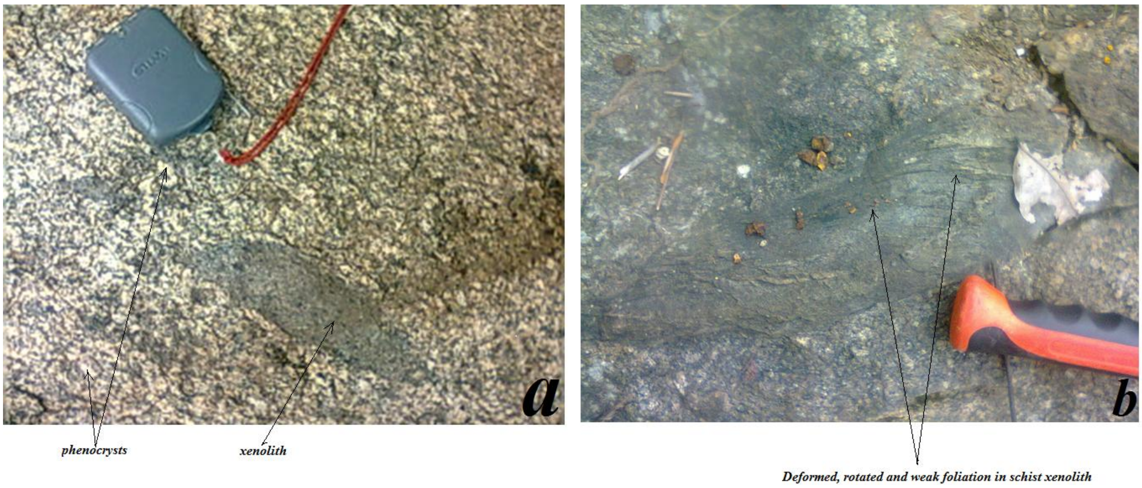

Fig 5: Xenolith in the Igarra Granites. (a) Xenolith and phenocrystassociation showing a common orientation of long axis. (b) Elliptical schistose xenolith close to a sharp contact between granite and schist with its foliation still preserved, although weak, rotated and deformed.

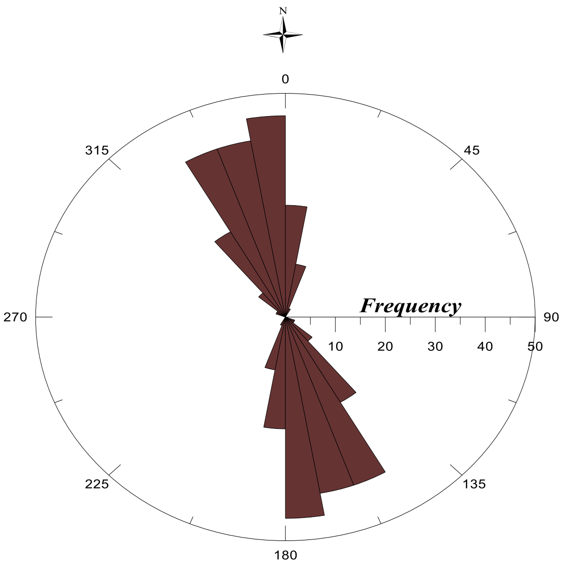

Fig 6:Rose diagram of xenolith long axis showing a strong preferred orientation in the NNW-SSE to N-S directions. (197 data points).

3.3 Joints and Veins

Joints and veins are exposed throughout the granite plutons within and around Igarra. These joints are linear with straight propagation paths. Two basic joint sets are found within the study area, these are a dominant, stronger and wider E-W trending set and a less occurring, weaker N-S trending set (Fig. 7 a, b and c). The joints were filled with fluid during or immediately after formation, these fluids deposited pegmatite, aplites and quartz. Like the joints, the veins has two major sets which are a wider E-W trending set and a narrower N-S trending set (Fig 8 a, b and c). The unambiguous relationship between the joints and the veins is most likely a product of the Pan-African tectonics that affected these granites.

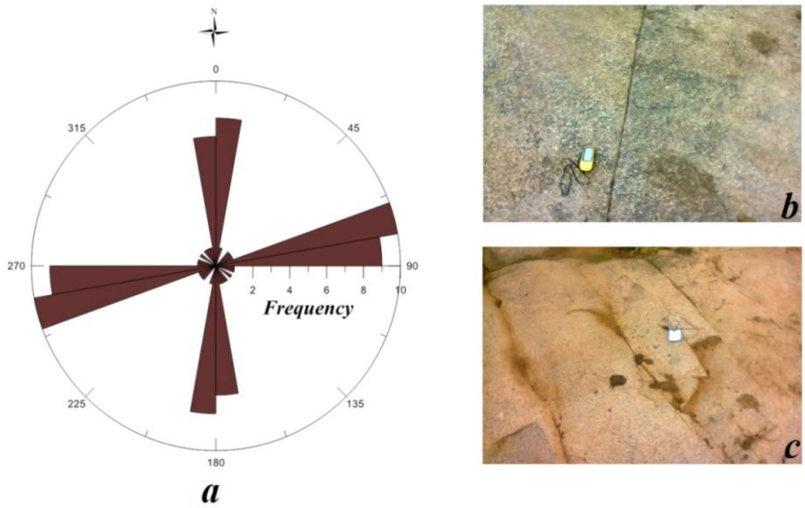

Fig 7: Joints inIgarra granites. (a) Rose diagram of joint orientation showing two sets of joints (E-W and N-S). (44 data points). (b) Joint with a good linear propagation in the N-S direction (c) Parallel E-W trending joint set at Igwe-Oke.

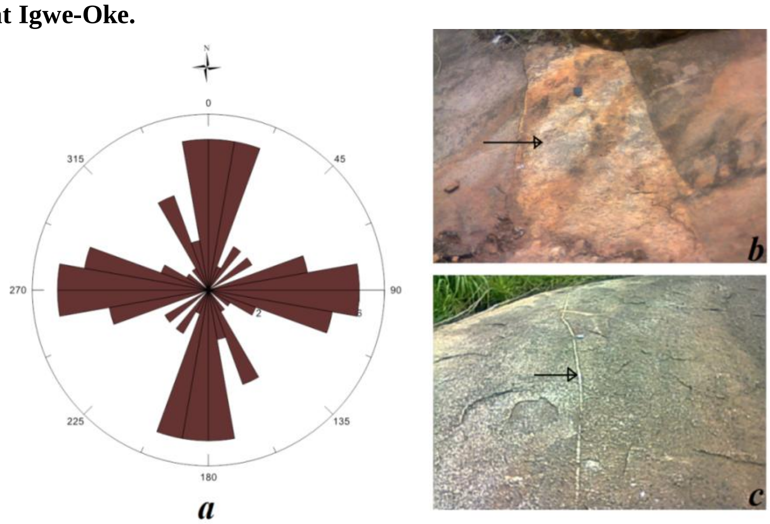

Fig 8: Veins of Igarra granite. (a) Rose diagram of vein orientations showing two basic sets (E-W and N-S) an indication that the veins basically took advantage of existing fractures or they were both the product of hydraulic fracturing.(54 data points). (b) Wider, E-W trending pegmatite vein. (c) Thin N-S trendingaplite vein

3.4 Granite Plutons

Individual granite bodies consisting of many granite plutons occur within and around Igarra. Three of these individual granite bodies were mapped mesoscopically for structures. These are the plutons around Igarra through Somorika to Ogugu (Igarra plutons), the plutons around Ake (Sebe-Ogbe/Ake plutons) and the plutons centered in Ososo (Ososo plutons). The Igarra plutons are approximately 12km x 5km, N-S trending, bell-shaped granite range with white colouredphenocrysts (Figs. 1, 3b and 9 a & b). These granites average about 500m above sea level (Oden and Udinmwen, 2013) and intruded schists, metaconglomerates and quartzites. Around Igarra, the rocks are fairly well exposed with the level of exposure approaching 60% in some places (Egbuniwe and Ocan, 2009). Approximately 10km-15km, south to southwest of the Igarra plutons is the Sebe-Ogbe/Ake plutons. These like the Igarra plutons are bell shaped and contain small whitish phenocrysts intruding basically schist and rarely metaconglomerate and calc-gneiss. About 15km NE of the Igarra plutons are the Ososo plutons which have different characteristics from other granites within this region. Against the usual bell shaped/ellipsoidal plutons (Igarra, Sebe-Ogbe/Ake), the Ososo plutons are elongated table-topped shaped (Fig. 10 a and b), they are approximately 10km x 7Km, N-S/NNE-SSW trending pluton range which contains large, pink colouredphenocrysts (Fig. 3a), giving the rock a general light colour (Figs. 3a, 10 and 11). It intruded granite gneiss to the south and west and migmatite to the east and north. The occurrence discordance between the Ososo plutons and other plutons within this area seem to be related to the terrain of emplacement (Odeyemi, 1976). These plutons (Ososo) also contain dykes of a late stage igneous material (most likely basaltic) (Fig 11) which are not wide spread over the plutons and are not found in any other granite around the region. Other structures such as joints, veins and preferred orientations of phenocrysts are consistent throughout the Igarra granites.

Fig 9: Ellipsoidal (Bell shaped) plutonic inselbergs along Igarra/Somorika road.

Fig 10: Elongated (Table top) plutons found along the road to Ososo main town.

Fig 11: Late-stage igneous intrusive in the Ososo granites along the road to Ososo main town. The dyke is most likely a basaltic rock.

Associated with the plutonism in this area is the "space" issue. Very large volumes of country rock were either digested, shoved aside or both, to make space for the granite. The presence of xenoliths of the country rock in the granite is an indication that the former process operated largely all over the place (Fig. 12b). This also implies that the original granitic magma must have undergone enormous contamination by engulfing and digesting such large volumes of country rocks.

IV. Discussion

Feldspar phenocrysts are one of the most important features within these granites as their magmatic origin placed them in a convenient position to track a long tectonic history of the Pan-African orogeny which affected this area. The origin of K-feldspar phenocrysts in granitic rocks has been a subject of conflict. While some believe that phenocrysts crystallized directly from a magmatic melt at an early stage (Kerric, 1969; Nemec, 1975), others think that they are porphyroblast that must have grown from a water rich fluid under sub-solidus conditions (Dickson, 1967; Emmermann, 1968). Johnson et al. (2006) recognised that K-feldspar phenocrysts are younger than the ground mass but Piwinskii (1968) and Whitney (1975) believe that phenocrysts grew earlier in liguidus and liquidus-solidus temperatures. Mesoscopic structural characteristics support an early stage igneous origin for phenocrysts of the Igarra granite, but they must have continued in growth and rotation to attain an optimum preferred orientation.

(a) **PhenocrystEuhedral Shapes**: The phenocrysts of the Igarra granites possess euhedral shapes, which is characteristic of an Igneous-origin K-feldspar phenocrysts in granitoids (Bateman et al., 1963; Schermerhorn, 1956). This is different from porphyroblasts in metamorphic rocks where euhedral shapes are rather uncommon (Vernon, 1983).

(b) **Preferred Phenocryst Orientation**: The phenocryst of the Igarra granites are preferentially oriented in the N-S and NNW-SSE directions (Fig 4). This gives the rock a strong stress-controlled magmatic fabric which is different from free flow structures in igneous rocks commonly related to the local turbulent fluid patterns (Quinn, 1944; Larsen, 1948). This suggests that the phenocrysts were only free to “flow” and grow in a certain direction, at a high angle to the prevailing maximum compressive stress (σ_1). This was a high viscosity flow, very much unlike the free flow of water, which was further constrained by the principal stresses that acted during the orogeny.

(c) **Phenocryst and Xenolith Relationship**: The association of xenoliths and phenocrysts in the Igarra granites (Fig 5a) may represent a crowding of solid materials in the early stages of magma crystallization which rules out the possibility of a late stage porphyroblastic origin for these phenocrysts. The close orientation relationship between phenocrysts and xenoliths in the viscous matrix (Figs. 4 and 6) is an indication that although they differ in size, the forces that rotated them were the same and the sense of rotation for both was also the same for both. Marques and Burlini (2008) showed experimentally that rigid inclusions (spheres, cubes and circular cylinders) embedded in a synthetic viscous matrix, rotate in simple shear or combinations of pure and simple shears. This is because rocks behave as continua, allowing the principles of fluid mechanics to be applied to them.

(d) **Phenocryst Interference:** The phenocrysts do not interfere with each other (ie they do not grow into each other) even in areas where they are large, crowded and closely related (Figs. 2a, 3a and 3b). This suggests that the phenocrysts were “assembled after completion” as a simultaneous growth of phenocrysts at solidus stage would cause them to grow into each other (Gilbert, 1906).

(e) **Phenocryst Size Relative to Groundmass:** The phenocrysts of the Igarra granite vary in size relative to the size of the groundmass. The larger Ososophenocrysts have a coarser groundmass than the smaller phenocrysts of Igarra and Sebe-Ogbe/Ake plutons (Fig 3a and 3b). It appears that smaller the phenocrysts, the finer the groundmass. This has been recognized in other parts of the world (Exley and Stone, 1964; Wallace, 1956) and it suggests an igneous origin (Stone and Austin, 1961).

Phenocrysts of the granites are usually high temperature magmatic crystals which according to the University of Sydney School of Geosciences (USSD, 2006) form early below the First Rheological Threshold (FRT), where the crystals were oriented randomly due to their size and the turbulent nature of magma below FRT, above the FRT and below SRT (Second Rheological Threshold), the magma is a non-Newtonian fluid (USSD, 2006) and the flow of the melt combined with simple shear stresses generated by the long range compressive Pan-African stresses, trigged the rotation of crystals (feldspars) and enclaves (xenolith). This led to the development of a strong magmatic fabric marked by the preferred orientation of phenocrysts and xenoliths. This somewhat explains the preferential orientation of phenocryst and xenolith long axes in the Igarra granites (Fig 4 and 6). Oden andUdinmwen (2013) recognized an E-W maximum compressional stress axis (σ_1) for the Pan-African orogeny within the Igarra area, using phenocrysts from granites as strain markers. This stress orientation is responsible for the scarcity of E-W trending phenocrysts (Fig 4), because it is the most unfavourable direction for crystal growth within the granites, as crystals elongate fastest perpendicular to σ_1 and parallel to σ_3 direction (Kamb, 1959). The xenoliths show a very strong NNW-SSE to N-S orientation (Fig 6). This is expected in syn-tectonic intrusions irrespective of the degree of ductile stain that occurred as xenoliths will initially rotate to alignment in the early stages of deformation due to their high ductility contrast with the magmatic host (Hutton, 1982). Despite this good orientation, xenoliths are very poor strain markers for reasons basically related to their initial random shapes and at best, their geometric mean shape ratio can be used to estimate strain (Barrier, 1977; Holder, 1979; Ramsay 1981). Hutton (1982) however argued that the measure of the mean deformed shape will be an overestimate of tectonic strain. The most important aspect of these xenoliths is that their orientations can be used to infer the direction of maximum elongation as their preferred orientation in many cases will initially be parallel to the maximum extension direction (Hutton 1982). Joints and veins are good tools for the determination and confirmation of palaeostress and strain (Gudmundsson, 1983; Segall and Pollard, 1983; Olson and pollard, 1989; Oden and Udinmwen 2014). Considering the E-W compression which operated during the Pan-African orogeny in the Igarra region and other parts of Nigeria (Ball, 1980; Oden, 2012; Oden and Udinmwen, 2013; Rahaman et al., 1988), the dominant E-W trending joints are the 'ac' extension fractures which propagated parallel to σ_1 (Engelder and Gneiser, 1980; Price, 1966; Oden and Udinmwen, 2014; Olson and pollard, 1989). They are the most favoured fractures for vein formation as mineral grains would grow perpendicular to the walls of the fractures (Hills, 1972; Davis and Reynolds, 1966; Oden, 2012b; Oden, 2012c). The strong linear nature of the fractures in these granites shows that the fracture driving pressure during fracture initiation in the Pan-African orogeny within this area was well higher than the fracture toughness (K_{IC}) of the granites.The unique shapes of the granite intrusions in the Igarra region are quite significant. This granite is in sharp contact with the country rocks (Fig 12a) and in some areas displays squeezing or intermingling of schist and granite (Fig 12b). Flat (Table top) intrusions such as those found in Ososo (Fig10 a and b) are thought to be characterised by low viscosity magma and thick overburden (USSD, 2006). The phenocrysts within this granite (Ososo) are conspicuously larger than others in the Igarra region (Fig. 3) and K-feldspar phenocrysts are known to grow to large grains in the presence of enough liquid (Wegner, et al. 2005; Moore and Sisson, 2008; Bacon, et al., 1981). This observation suggests that the Ososo plutons probably crystallized from a lower viscosity melt relative to the Igarra and Sebe-Ogbe/Ake plutons and possibly, the migmatite and granite gneiss which the Ososo plutons intruded are thicker than the schist intruded by the other plutons within this area. Nevertheless, geophysical and other methods for determination of the country rock thickness around these granites are recommended so as to get an estimate of the depth of intrusion emplacement and the actual nature of the melt within this region as the nature of host rock and tectonic context are fairly well known. Some of the major and minor granite intrusions within this area are somewhat oriented/elongated in the N-S direction (Fig. 1), which is also the preferred direction for phenocryst long axes (Fig 4). This may reflect or support the assumption by Davis (1963) and Vigneresse (1990) that magmatic fabrics are mostly parallel to the wall of the magma chambers.

Fig 12: Sharp contact between granite (x) and schist (y). (a) Sharp contact between granite and schist with a well-defined boundary and the foliation of the schist is partially preserved. (b) Squeezing or mixing of granite and schist with no definite boundary and the foliation of the schist is completely destroyed, possibly at a digestion boundary.

V. Conclusion

The structural profile of the Igarra granite holds sufficient information on the physical characteristics and palaeostress configuration at the time of emplacement. The magmatic phenocryst tracked a long period of tectonic strain, thus they are good tool for strain analysis. The xenoliths, being poor markers, are at best good for inferring the direction of maximum elongation. The similarity in orientation of the phenocrysts and the xenoliths, despite their size differences, is an indication that the same rotational stresses with the same sense of rotation acted on these rigid inclusions during the viscous to plastic states of the granites. Joints and veins are good tools for palaeostress determination but are better for palaeostress confirmation. The shapes of the intrusions, size of phenocrysts and the intruded country rocks seem to be important in estimating the general viscosity condition of the magma that produced these granites.

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