STRAIN PARTITIONING AND DIMENSIONAL PREFERRED ORIENTATION IN A SYN-TECTONIC GRANITOID, SOUTHEAST NIGERIA.

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ABSTRACT

Uwet granodiorite, a syn-tectonic granitoid of Pan-African age in south eastern Nigeria is partly porphyritic, containing megacrysts of K-feldspars, xenoliths and ellipsoidal bodies. The preferred orientations of the feldspar phenocrysts are in the NE-SW, NW-SE and N-S, the strongest being the NW-SE trend. The E-W sectors show minimum grain orientation. Calculated values of strain–arithmetic mean $\overline{R}$, geometric mean G and harmonic mean H, show minimum strain for grains in E-W orientation and maximum strain for grains in N-S orientation. Phenocrysts in NE-SW and NW-SE orientations showed intermediate values of strain, with the latter axis having higher values than the former. Generally, irrespective of orientation or axis, the relationship $\overline{R}$ > G>H was found to hold. The analysis favours the interpretation that when two simple shears and a pure shear operate simultaneously in a viscous/ductile matrix at high temperature, under a non-hydrostatic stress state, dimensional preferred orientation and strain are partitioned unequally along those axes. The paucity of phenocryst orientation and low strain values in the E-W axis are an indication that maximum compressive stress (σ_1) was oriented in this direction, during the Pan-African Orogeny.

Key words: Strain, Phenocrysts, orientation, arithmetic, geometric, harmonic.

INTRODUCTION

Dimensional preferred orientation of rigid particles in a viscous matrix is a subject that has received much attention either by way of theoretical treatment alone, a combination of both theoretical treatment and computer modeling or yet still a combination of theoretical treatment, computer modeling and presentation of supporting natural geological evidence. Prominent among publications on this subject is the work of Masuda *et al.,* (1995). Through a rigorous theoretical treatment based on the hydrodynamic equations of Ghosh & Ramberg (1976), combined with computer modeling, Masuda *et al.,*(1985) obtained several patterns of preferred orientation for different combinations of simultaneous pure shear and simple shear. Finally they compared preferred orientation and ellipticity patterns occurring naturally in two mylonites in Japan, to their computer models, and they noticed interesting similarities in the patterns. This enabled them to conclude that deformation within the two mylonites contains a simple shear component on which a certain amount of pure shear component is superimposed.

Ghosh & Ramberg's (1976) treatment of the subject of dimensional preferred orientation was both at the theoretical and experimental levels. Their theoretical treatment was based on the equations of Jeffery (1922) and Muskhelishvili (1953), for simple shear and pure shear, respectively. The model experiments, on the other hand, were performed only for simple shear using silicone putty in which were embedded rigid rectangular blocks and linear inclusions. Their experiments did prove that Jeffrey's (1922) equation for rigid ellipsoidal bodies was also applicable to rigid rectangular blocks. They also showed, among other things, that an elongate inclusion has the maximum rate of rotation when it is at a right angle to the simple shear direction and a minimum rate when

it is parallel to the shear direction. Equant inclusions were also shown to have a constant rate of rotation, while passive marker lines as well as very long rigid inclusions were shown to have no rotation when they are parallel to the direction of simple shear (Ghosh & Ramberg, 1976). This last observation appears as a sub-set of one of the later observations of Ghosh (1993), who showed that depending on the kinematical vorticity number and the aspect ratio R of ellipsoidal inclusions, they would rotate in all orientations when R is below a certain critical value. For values of R equal to or above the critical, the inclusions cannot rotate indefinitely, because there is a stable orientation at which their rotations cease.

Reed & Tryggvason (1974) presented a study of computer-simulated dimensional fabric development in pure shear and simple shear deformation, without recourse to any real geologic case studies. They showed from their simulations that whether in simple shear or pure shear, the higher the strain ratio (λ_1 / λ_2), the better is the resulting fabric. Also their patterns for simple shear and pure shear were quite different even for the same strain ratios. All studies of dimensional preferred orientation in viscous media tend to confirm the view of Passchier (1987) that populations of rigid objects in rocks that have undergone ductile deformation, store a good amount of information. Such information can provide a better understanding of the physical behaviour of both the rigid particles as well as the viscous media surrounding them.

In this paper, the orientations of rectangular tablets of feldspar phenocrysts in a syn-tectonic (Pan-African) granitoid – Uwet granodiorite are presented. The orientations subdivide into pure shear and simple shear configurations and estimates of strain are made for each of the trends. Some of the conclusions arrived at emphasize the views of Ball (1980) and Rahaman *et al.,* (1988), that an E-W compression operated throughout most of the Pan-African Orogeny.

MATERIAS AND METHODS

Field work exercise spanning over a period of 40 days was carried out in the study area (Uwet). Field exposures of the dominant intrusive rock type (the porphyritic granodiorite) were studied attention paid to the relationship existing among the various lithology especially the physical characteristics of rigid objects like the xenoliths and phenocrysts present in the rocks. Their sizes and orientations were measured. Collected data were subjected to standard structural analytical methods.

RESULTS

Macroscopic analysis: The most dominant intrusive rock type in the western part of the Precambrian Oban Massif in S. E. Nigeria is the syn-tectonic granitoid-Uwet granodiorite. This is largely a porphyritic, sometimes non-porphyritic granodiorite (Fig. 1) which has yielded a Pan-African age of 617 ± 2 ma from radiometric dating (Ekwueme & Nganje, 2000). Raeburn (1927) mapped this rock as porphyritic biotite gneissose granite, but Rahman *et al.,* (1981), Odigi (1986), Ekwueme (1987, 1990) all recognize this unfoliated granitoid as a granodiorite. The porphyritic variety of this gray-coloured rock occurs in such areas as Igbofia Camp, Uyanga, Akwa Ibami and Ojor Nkonemba (Fig.1), while the non-porphyritic variety is found mostly around Iwuru Obiotan, Nde Okoro and Agbangana.

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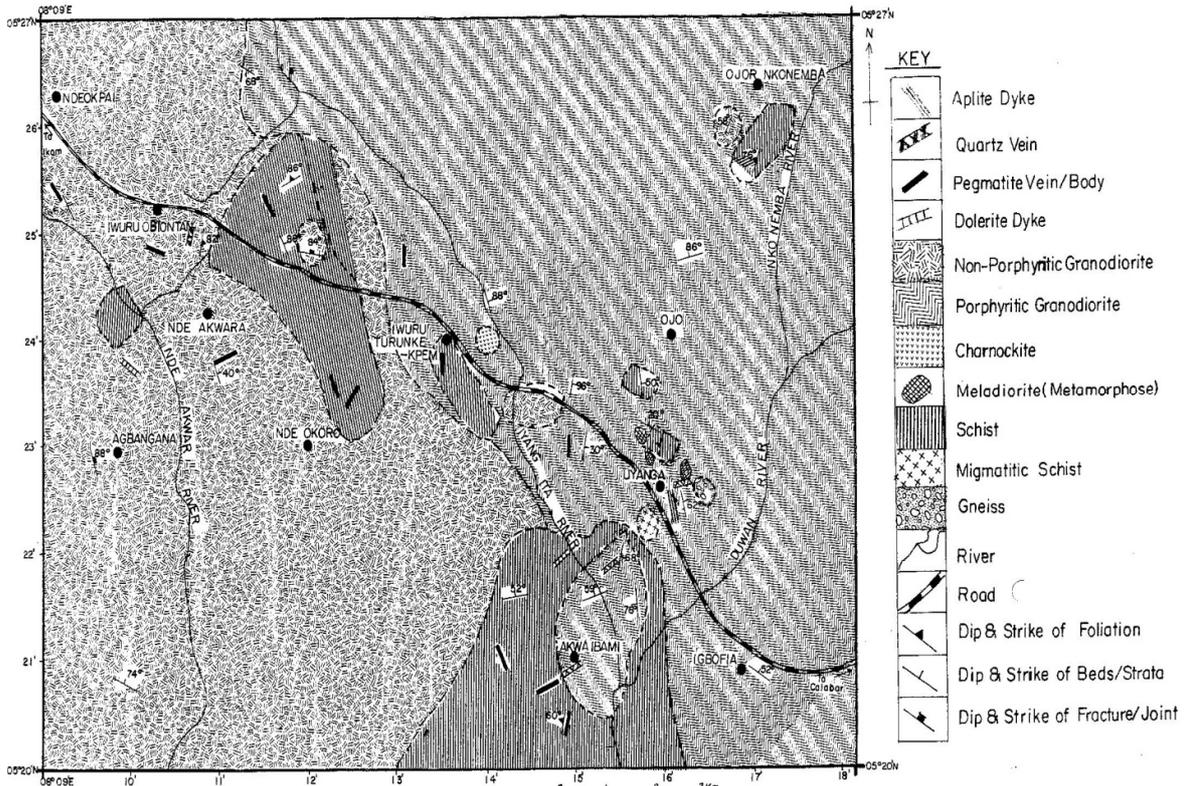
FIG. 1. THE GEOLOGIC MAP OF WESTERN OBAN MASSIF

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Both varieties contain a lot of xenoliths of schist and meladiorite, the parent rocks of which were most probably in place prior to the intrusion of the granodiorite. In–situ (non-xenolith) varieties of the meladiorite and schist are highly deformed, containing foliations of low to high angle dips. The area has a high density of pegmatite, quartz and aplite veins, with small occurrences of anatectic gneiss and greenish charnockite near Uyanga and Iwuru Turunkekpen, respectively. Dolerite occurs in dykes, of various sizes intruded into the granodiorite, mostly, while late-stage fractures and faults are also visible in most of the rock types, including the granodiorite (Fig. 2).
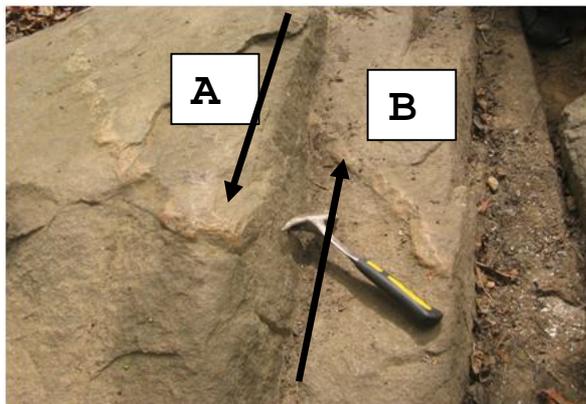
FIG. 2. FIELD EXPOSURE RELATIONSHIPS OF GRANODIORITE, DOLERITE AND FAULTS (SLAB A HAS MOVED WITH REFERENCE TO B DISPLAYING A FAULT STRUCTURE)
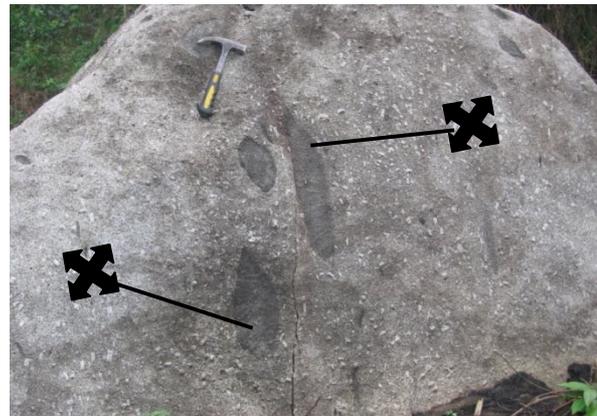
FIG. 3. XENOLITHS (X) AND ELLIPSOIDAL BODIES ARE COMMON IN THE GRANODIORITE

Mesoscopic observations: At the level of the exposure and hand specimen, the porphyritic granodiorite is much more interesting than the non-porphyritic variety. Apart from xenoliths and ellipsoidal bodies (Fig. 3), the porphyritic granodiorite also incorporates feldspar phenocrysts of different sizes and orientations (Figs. 4 & 5). Sometimes the phenocrysts are in such good alignment as to give a linear fabric to the rock, but this preferred orientation tends to vary a little from place to place. For an analysis of the general preferred orientation and dimensional ratios of these grains, samples were randomly selected and measured from Igbofia, Akwa Ibami, Iwuru Central, Ojor and Iwuru Obiontan (Fig. 1)

10

FIG. 4. PHENOCRYSTS VARY IN SIZE AND ORIENTATION, BUT SOME EXPOSURES SHOW A GOOD PREFERRED ORIENTATION

FIG. 5. PHENOCRYSTS AND XENOLITHS ARE OFTEN IN GOOD ALIGNMENT

Analysis of dimensional preferred orientation: Measurements of long axis orientation and length as well as short axis orientation and width were made for 249 feldspar phenocrysts within the map area. Grain lengths vary from 1.0 cm to 4.0 cm, while grain widths vary from 0.4 to 2.8 cm. A graph of major axis against minor axis of phenocrysts shows a good positive correlation (Fig. 6). This indicates that generally dimensional growth or shrinkage of the grains was constrained and correlated in such a way that any alteration (+ve or -ve) in the long axis was simultaneous with that in the short axis. Fig. 6 is like Ramsay's (1967) Figs. 5-8, as well as Ghosh's (1993) Fig. 10. The straight line through the points as suggested by the computer is of the form y= 0.897x+ 1.064. This does not pass through the origin and also implies that when grains have zero width, they would still have a length up to 1.064 units. This is unrealistic, hence there was need to impose another straight line on the data set, which passed through the origin. This second straight line has the equation y = 1.617x and slope = 1.617 is closer to the average value of the harmonic mean, as shown by Ramsay (1967) and Ghosh (1993). The orientation distribution of the long axes of the phenocrysts is shown in Fig. 7. Both the distribution table (Table 1) and the rose diagram (Fig. 7) show very strong grain orientation in the NW–SE (130^0 - 160^0) corridor. Other directions of preferred orientation are the N – S (160^0 - 180^0 - 190^0) as well as the NE–SW (030^0 - 060^0). Interestingly, the east–west corridor (90^0-120^0) is the least preferred for grain orientation, while the NW–SE orientation is the most preferred direction, from this investigation (Fig. 7).

Only 5.64% of all the phenocrysts measured are orientated approximately in the E–W direction, while the N – S corridor takes about 22%. The NE–SW and NW–SE orientations account for about 19% and 26% respectively (Table 1).
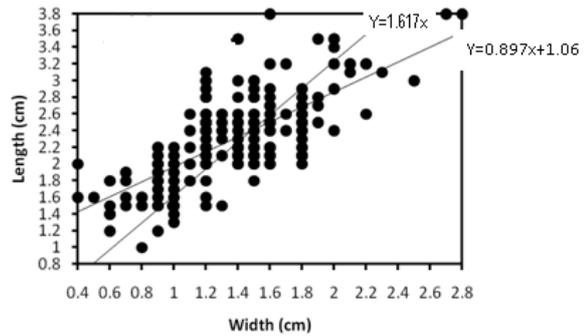
FIG. 6. GRAPH OF LENGTH AGAINST WIDTH OF PHENOCRYSTS IN UWET GRANODIORITE
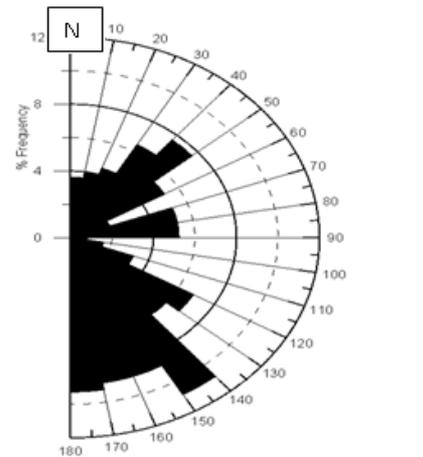
FIG. 7. ORIENTATION ROSE DIAGRAM SHOWING DISTRIBUTION OF LONG AXES OF PHENOCRYSTS IN UWET GRANODIORITE

TABLE 1. DISTRIBUTION OF PHENOCRYSTS AND STRAIN PARAMETERS IN THE DIFFERENT SECTORS OF ORIENTATION

	ORIENTATION			
	E - W	NE - SW	NW - SE	N - S
n = number of pheniocrysts measured	14	47	64	54
Percentage Grain Distribution	5.64	19.0	26.0	22.0
Arithmetic Mean ($\overline{R}$)	1.63	1.69	1.72	1.78
Geometric Mean (G)	1.61	1.64	1.68	1.75
Harmonic Mean (H)	1.58	1.60	1.65	1.72

Comparative strain analysis along the axes of preferred orientation: The sub-total population of phenocrysts within each of the axes considered in the last section was used to determine the strain parameters, $\overline{R}$, G and H. $\overline{R}$, which is the arithmetic mean of the ratios of long axes to short axes of the phenocrysts, is given by Ramsay (1967), Lisle (1977), Ramsay & Huber (1983) and Ghosh (1993) as:

$$\overline{R} = \frac{\sum Rf}{n} \qquad \ldots (1)$$

The geometric mean G and harmonic mean H are given by the equations:

11

$$G = n\sqrt{Rf_1 \, x Rf_2 \, x Rf_3 \, x --- Rf_n} \qquad \text{... (2)}$$

and

$$H = \frac{n}{\sum \frac{1}{Rf}} \qquad \text{... (3)}$$

Note: Rf in each equation is the ratio of long axis to short axis of a phenocryst, while n is the population of phenocrysts in a particular orientation.

Considering orientations in the E – W where n = 14, NE –SW (n = 47), NW – SE (n = 64) and N – S (n = 54), the arithmetic mean ($\overline{R}$) values calculated for these axes are 1.63, 1.69, 1.72 and 1.78 respectively (Table 1). G values range from 1.61 through 1.64, 1.68 to 1.75, while H values range from 1.58 through 1.60, 1.65, to 1.72 for the same axes referred to above. The strain in the granodiorite system has been partitioned in such a way that the maximum compression axis (E - W) showed the least grain growth, with the least values of $\overline{R}$, G and H, while the N – S direction, where grains are in pure shear configuration, shows the maximum value of the strain parameters. The simple shear axes NE – SW and NW – SE show intermediate values of strain, with the NW – SE being the stronger of the two axes. Whether the strain partitioning produced by the phenocrysts is the same as that in the granodiorite matrix has not been proved by this work, nor is it the aim of the exercise. It is interesting to note from Table 1 that the few grains oriented closest to the maximum compression (б₁) which is approximately E – W (Ball, 1980), are those that approach equant shapes the most. Grains oriented in the general N – S direction, on the other hand, are the most oblong in shapes. Also the relationship between the calculated values of the strain parameters is of the form: $\overline{R}$ > G> H, which was shown by Lisle (1977) and Ramsay (1967) to be the case.

DISCUSSION
Uwet granodiorite, a syn-tectonic, porphyritic granitoid, shows very interesting structural features viz: the way rigid particles rotate and orient themselves in a viscous matrix and the growth or elongation of such particles once they are favourably oriented. The N–SW and NW–SE simple shear orientations of phenocrysts in the viscous matrix are equivalent to Ball's (1980) and Ike's (1988) NE-SW and NW–SE conjugate strike-slip fault system in the Pan-African mobile belt. The N–S (pure shear) trend of phenocrysts is equivalent to Ball's (1980) N–S trending vertical mylonitic shear zones, where higher strains are obtained.
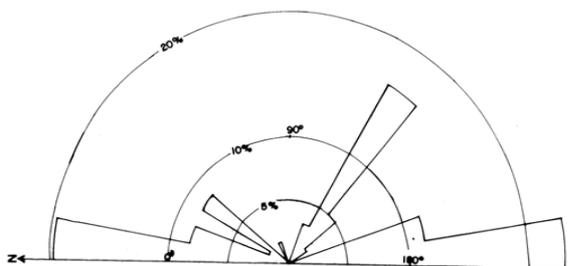
Since the N–S and vertical orientations are perpendicular to σ₁ - the maximum compressive stress-all crystallizing and recrystallizing crystals in these two orientations will, according to Kamb (1959a), tend to elongate fastest. But grain growth in the vertical direction (parallel to б₂ direction) is prevented by the lithostatic load (ρgz- Pf) – which is quite substantial (Lacomb, 2007). Hence grain elongation in the N–S direction is partly a result of E–W compression as well as compensation for absence of growth in the vertical direction. This is probably what $\overline{R}$ = 1.78 in the N–S orientation shows (Table 1). The very poor preferred orientation and grain elongation in the E–W direction add credence to Tanner and Radchiffe's (1962) observation that the kinetics of grain initiation and growth are retarded by pressure. Also Kaufman et al., (1961) showed that pressure retards the thermally activated processes of recovery, recrystallization and grain growth. Based on these observations, the most probable orientation of (б₁) – the maximum principal compressive stress – during Pan-African times, is the present day 90⁰ to 120⁰ corridor from the north, (Fig. 7). This is the corridor with the least number of grains, as well as the least values of the strain parameters in the entire distribution and it occurs in the E–W orientation.

A comparison of the two simple shear trajectories: NE–SW and NW–SE (Fig. 7) shows that the latter is the stronger, both in percentage grain distribution and the $\overline{R}$,G and H factors (Table 1), than the former. This was also observed by Ike (1988) from consideration of fracture lineaments and joints in the syntectonic Zaria granite batholith of northern Nigeria. Exactly why the NW–SE trajectory is stronger than the NE–SW is not immediately clear, but it should be remembered that the distribution in question is a high temperature/high pressure one. Probably the operation of the NW–SE distribution is favoured in rocks at high temperature and pressure. That seems to be the view depicted in figures 8 and 9. In the map area, (Fig. 1) deformed meladiorite and schist are regarded as primary host rocks, the xenoliths of which are carried in the granodiorite. Small outcrops of foliated meladiorite occur in Uyanga village. Rose diagrams depicting foliation trends in meladiorite (Fig. 8) and schist (Fig. 9) show that the former rock type deformed in a manner that produced mainly N-S and NW–SE foliations. The NE–SW trend is either non-existent or very weak. In the schist, on the other hand, stress was transmitted by shearing predominantly in the NE–SW direction. The NW–SE trend is weak comparatively, while the N–S foliation trend is non-existent (Fig. 9). The conclusion is inevitable that shearing predominantly in the NE-SW direction was probably favoured in low temperature/low pressure media, while the operation of NW–SE and N–S shears was dominant in high temperature /high pressure rocks, in this pan-

FIG. 8. ROSE DIAGRAM DEPICTING ORIENTATION OF FOLLATION PLANES IN DEFORMED MELADIORITH, UYANGA-AREA
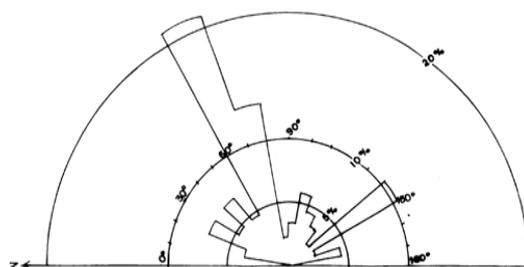
FIG. 9. ROSE DIAGRAM DEPICTING ORIENTATION OF FOLLATION PLANES IN DEFORMED MELADIORITH, SHIST, UYANGA-AKWA IBAMI AREA

12

African terrain. This seems to run against the views of Ekwueme (1987) who recognized only N-S-and NE-SW trending structures as pan-African, while the ENE-WSW and NW-SE trending structures he attributed to a pre-pan-African deformation event. There was obvious lack of understanding of pan-African stress configuration in the analysis by Ekwueme (1987), which resulted in his conclusions.

A synthesis of structural orientations of pan-African origin, having in mind the stress configuration that operated at that time, is shown in Fig. 10. This synthesis puts together the observations of Ball (1980), Ekwueme (1987), Oluyide (1988), Danbatta (2003) in conjunction with the findings from Uyanga–Akwa Ibami area (this project).

There were five main axes by which stress was transmitted through the pan-African tectonites during deformation. The E-W axis, approximately paralleled to maximum compression, was that along which 'ac' extension fractures developed.

Those high angle, E-W fractures were noticed by Oluyide (1988) to be of limited extent, both in the western and eastern parts of the Nigerian basement complex. He also interpreted these fractures as the oldest. Similar E –W fractures have been observed near Ikot Ana (by the Cross River) at the western margin of Oban Massif. Some pegmatite veins are also oriented in this direction taking advantage of the existing fractures.
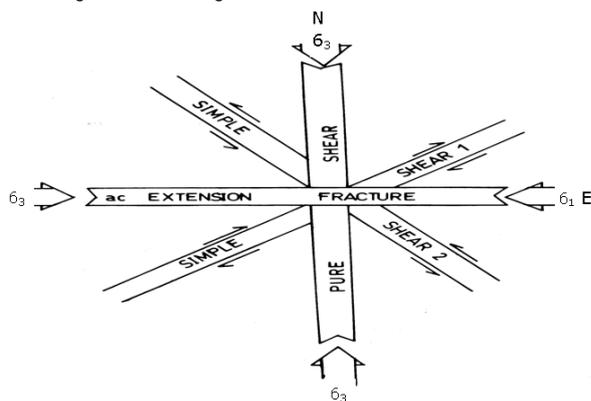
FIG. 10. THE MAIN TECTONIC AXES OF THE PAN-AFRICAN OROGENY. Б$_2$ OPERATED IN THE VERTICAL DIRECTION PERPENDICULAR TO Б$_1$ AND Б$_3$. THIS WAS THE FIFTH AXIS

The NE-SW and NW-SE simple shear axes are orientations of foliations, shear fractures and faults, extension lineations, shear zones and most pegmatite veins (Ball, 1980; Oluyide, 1988; Ekwueme, 1987, Ike, 1988, Danbatta, 2003 and this work). That the NW-SE structural trend is stronger than its NE-SW equivalent has not only been shown by this work, but was also reported by Ike (1988). The N-S structures developed along the pure shear axis, approximately perpendicular to the maximum principal stress (Б$_1$). These include mineral reorientation and growth lineations, mylonitic foliations (Ball, 1980), non-mylonitic foliations (Fig.8 and Ekwueme, 1987) as well as joints and fracture lineaments (Ike, 1988; Oluyide, 1988; Danbatta, 2003).

The fifth axis of material deformation during the pan-African orogeny was the vertical axis. This is also the axis of intermediate principal compressive stress (Б$_2$). The value of this stress at any level is the weight of the lithostatic load less the fluid pressure. This is a crushing and prohibitive load at the level of emplacement of the granitoid. It is for this reason that phenocrysts were not seen oriented parallel to the vertical axis, in the field. All other structural trends in true Pan African tectonites (like NNE-SSW or NNW-SSE) are interpreted as those in rotational transition.

CONCLUSION

Sizeable populations of rigid objects, like feldspar megacrysts, from different parts of a deformed, viscous medium, can produce significant information on the strain and strain paths that operated during the deformation. Simultaneous rigid body rotations into simple shear and pure shear configurations as well as grain growth, characterized the deformation of Uwet granodiorite in its viscous/ductile states, during the Pan-African orogeny. From consideration of both the magnitude of the strain factors and the percentage grain distributions, it could be inferred that there were two simple shear axes and one pure shear axis operating simultaneously. The NW-SE simple shear trajectory was stronger than the NE-SW, for reasons that may be related to the physical properties of the deformation. Structural studies in the pan-African granite batholith of Kaduna-Zaria area in northern Nigeria had indicated similar results earlier. While the NW-SE simple shear trajectory tracked the greatest number of phenocrysts, the N-S pure shear trajectory was the highest strain axis during the deformation. This combination of axes in a natural deforming rock body to share its material load and partition its strain is designed to transmit the stress imposed on it.

The N-S axis is not only a direction of strong preferred orientation, but also that of greatest grain elongation in this matrix. Compared to the E-W direction, grains that initiated along or rotated into the N-S direction experienced minimum pressure-induced inhibition to growth or elongation. Those that initiated in the E-W direction experienced maximum pressure – induced retardation to growth or elongation. The corridor from 090^0 to 120^0 from N is that with minimum grain orientation in the entire distribution, and is interpreted as the maximum stress corridor during the Pan African orogeny. Different parts of the granodiorite viscous matrix responded differently to stress during the period of active deformation. Hence it is not enough to collect a large population of data only, but also to sample as extensively over the intrusion as possible. Combinations of rigid rotations, plastic deformation and grain growth by diffusion could have produced the dimensional preferred orientation of and strain in feldspar phenocrysts in Uwet granodiorite, at a time that the medium was very viscous or ductile.

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13

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