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Measurement of Pan-African Strain in Zaria Precambrian Granite Batholith, Northwestern Nigeria

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Abstract: *The Zaria granite batholith in northern Nigeria is an example of syn-tectonic batholith emplaced about 600 ± 150 Ma, ago during the Pan - African orogeny. Its strain history and strain marker behavior have been studied in order to further elucidate the tectonics of the Pan- African orogeny. Field observations, measurements and different methods of strain estimation were applied on 623 data to determine the strain intensity, direction of maximum elongation (σ_3) and compression direction (σ_1). The different methods produced strain values between 2.66 and 2.07, maximum elongation took place in the N - S direction while the σ_1 (maximum compression) trajectory was oriented E – W, making the direction the least favourable for strain marker (phenocryst and xenolith) growth. Strain partitioning revealed that the N - S direction experienced the highest strain while the NE - SW orientation showed a lower strain value than the NW - SE direction regardless of the number of markers preferring the directions. Xenoliths, faults and joints lend credence to the measured strain results. It would seem that the E - W compression during the Pan - African orogeny was widespread and fairly constant throughout most of the period tracked by the granites.*
Keywords: *Granite, Strain, Batholith, Pan-African, Phenocryst*

I. Introduction

The Zaira Granite batholith is a N – S oriented body, about 90 km long and 25 km wide and extends from me northern part of Zaria southward to the vicinity of Kaduna (Ike, 1988; Webb, 1972). It belongs to a suite of syn- and late- tectonic granites and granodiorites that marked the intrusive phase of the late Precambrian to early Paleozoic Pan-African Orogeny in Nigeria (McCurry, 1973). The Pan-African thermo-tectonic event which took place between 750 Ma - 450 Ma is believed to be the latest major orogenic event that affected the Nigerian Basement Complex. The activity resulted in structural modification and slight migmatization of the earlier units but most importantly in the emplacement of a suite of rocks referred to as Older granites. The batholith is dominated by the porphyritic biotite granite. In this rock, the Crystallization history closed with the appearance of the feldspar megacrysts. The assimilation of xenoliths is by the local metasomatic replacement through the generation of feldspar megacrysts. Age determinations from various parts of the country have shown that the granites were emplaced about 600 ± 150 Ma ago, a time that coincides with the Pan-African orogeny. Accounts of the Nigerian Older granites so far, present varying interpretations of their origin. Evidences have been found in support of magmatic (Russ, 1957) as well as metasomatic (De Swardt, 1953) origins for the granites. Some authors, however, share the opinion of Jones and Hockey (1964) that the emplacement of the granites involved both magmatic intrusion and metasomatism. The common view based almost exclusively on Rb-Sr dating, is that the Nigerian basement evolved during a long and polyphase tectono-metamorphic history. However, unequivocal geochronological and structural evidence in the post Archean is available only for the Pan-African event (Dada. 1998). Debate exists on whether the Pan-African event was so pervasive that it completely isotopically rehomogenized the older rocks, thereby obliterating all traces of earlier tectono-metamorphic events. According to Ferre et al., (1997), structural studies on plutonic bodies can be useful in deciphering the kinematic evolution of an orogenic belt. In this present work is aimed at appraising the Pan-African strain in the Zaria granite batholiths. Some of the conclusions, in this work show that an E - W compression operated through most of the orogeny tracked by these granites which resulted in the highest strain intensity in the N - S direction and the NW - SE trajectory. It is hoped that the findings from the study will shed more light on the tectonic character of the Nigerian Older granites which will in turn provide better understanding of the tectonic evolution of the Nigerian Pan-African basement complex.

II. Geological Setting And Methodology

The study area (data collection) spans about 70km of the 90km long Zaria granite batholith covering most parts of Zaria through Gabi to Togache (Fig. 1). This batholith belongs to a suite of syn- to late- tectonic granitoids (granites and granodiorites) which marked the intrusive phase of the Pan-African orogeny in Nigeria (McCurry, 1973). These granites intruded undifferentiated schists, gneisses and migmatites and are called "Older Granites" (Falconer, 1911) separating them from the Mesozoic "Younger Granites" of the Jos Plateau area. Radiometric dating of the Pan-African orogeny gives an age of about 600±150 Ma. Grant (1969) used Rb - Sr method to date the porphyritic Older granites and arrived at 618 to 467 Ma. The major rock unit within this batholith is the coarse grained, porphyritic biotite granite and biotite -hornblende granite which has a strong magmatic fabric with preferred alignment of closely packed, pink to white coloured feldspar phenocrysts. The strong preferred orientation of the phenocrysts is the same as the batholith itself.

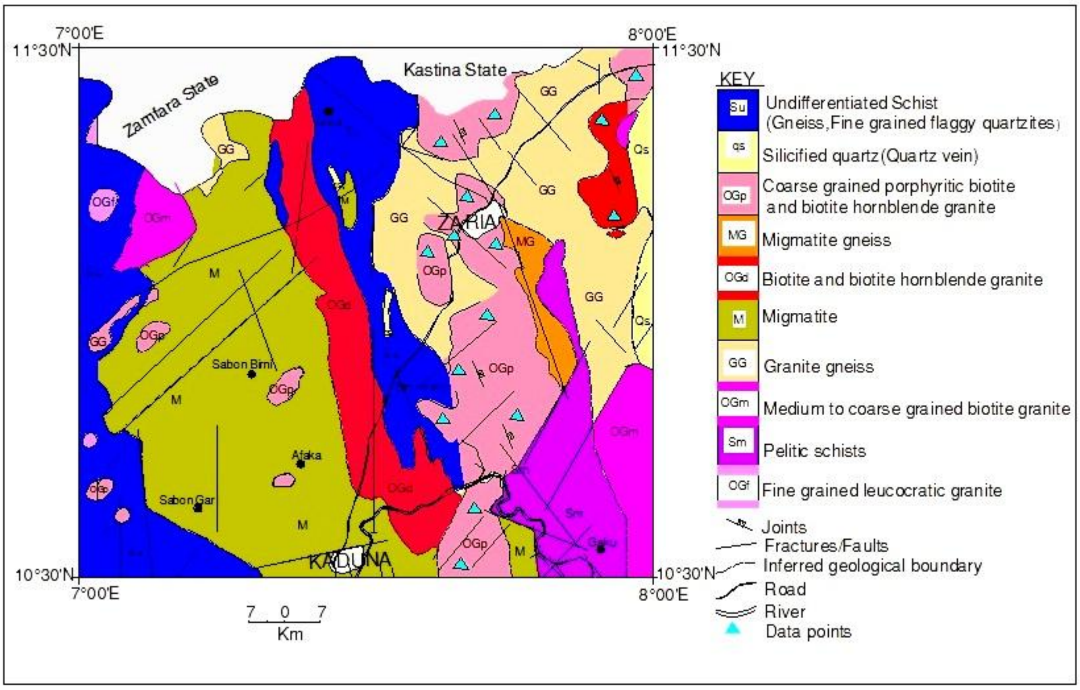

Fig 1. Geological map of the Zaria granite batholiths showing locations of the studied granites.

A total of 623 data were collected from different exposures within 15 locations in the study area (Fig. 1), with particular interest in the characteristic of feldspar phenocrysts, xenoliths and other structures such as Joint, faults, veins and igneous intrusions. The length and width of the phenocrysts (strain markers) and xenoliths as well as the orientation of their major minor axes were measured and subjected to standard strain analytical techniques. Three (3) methods were used to calculate strain from the measured data, these are; the length against width of grain method, the Arithmetic mean ($\bar{R}$); Geometric mean (G) and Harmonic mean (H) method and the R_f/ø technique.

III. Strain Analysis

Feldspar phenocrysts are good markers for the analysis of strain in igneous rocks. These rectangular feldspar tablets which are early stage magmatic crystals of igneous origin, tracked a long period of tectonic strain within the Zaria granite batholith which is probably the most prolific granitoid batholith within the Nigerian sector of the Pan-African domain. The alignment of igneous minerals records strain during flow and crystallization of a rheologically complex mush (Ildenfonse et al., 1997; Begrantz and Dawes, 1994). Regional deformation may play an important role in forming magmatic fabrics (Bouchez et al., 1990; Hutton, 1988). Given that magmatic fabrics are easily reset, they may reflect only the last increment of strain of comparatively weak materials thus providing a relatively direct record of palaeostress in orogenic belts (Paterson, et al., 1998). The widely used method, though not always the most accurate, is that of strain analysis by direct measurement of the principal axes of each marker. It is usual to take the arithmetic mean of individual observations (Ramsay, 1967), although the arithmetic mean of R_f is of little value for estimation of strain as it is strongly dependent on the initial shape factor (Lisle, 1977). Another method of recording the strain data is to represent each ellipse on a graph by plotting the length of the short axis as abscissa and that of the long axis as ordinate. The points should fall on or about a straight line passing through the origin, and the slope of this line gives the mean ratio of the principal strains (Ramsay, 1967; Ramsay and Huber, 1983). This method produced results close to those of the simple harmonic mean for parts of the southwestern basement complex of Nigeria (Oden and Udinmwen, 2013). R_f/ø plots of deformed elliptical markers is a good method of strain estimation using feldspar tablets as markers given that the fluctuation(F) which defines the ambiguity in the preferred orientation of strain marker long axes is usually high, which supports the application of this method (Lisle, 1979; Dunnet 1969; Matthews et al., 1974). Considering the inaccuracy in the application of some methods of strain measurements and the complex nature of the preferred orientation of markers in magmatic fabrics, data was collected from different parts of the prolific Zaria granite batholiths (Fig. 1) and a combination of methods was applied to estimate the strain recorded by this granite so as to get a truly composite and representative result.

Strain analysis was done in 2-dimensions using tablets of pink to white coloured K-feldspar phenocrysts as strain markers (Fig 2a). The long axis orientation and length as well as short axis orientation and width were measured for 623 feldspar phenocrysts within the batholith. The long axes of the markers show a strong preferred orientation (Fig. 2b). Their long axes vary from 1.0cm to 6cm, while the grain width varies from 0.5 to 3.5cm with R_f of between 2 and 3 (Fig. 2c), although markers as long as 12.5cm and 5cm with were recorded and R_f as high as 7.5 was calculated. This is similar to the observation by Oden (2012a) and Oden and Udinmwen (2013) for other Older Granite suites in Nigeria. Xenoliths are less frequently occurring features in fee Zaria granite batholith. The xenoliths are much larger than the phenocrysts and both are usually in alignment save for one location (Jim Harrison), where the phenocrysts preferred the NE - SW orientation (Fig. 2d) and this location accounts for over 90% of the NE - SW trending markers within the study area; nevertheless, the xenoliths in most locations were trending in the general N - S trajectory (Fig. 2e). The length of the xenoliths ranges between 14cm and 54cm and the width is between 3cm and 22cm. The ratio of long axis to short axis has a cluster between 2.0 and 3.0 (Fig. 2f) just as was observed for the phenocrysts (Fig. 2c). The distribution of phenocrysts (Table 1) and the rose diagram (Fig. 2b) shows a very strong N-S orientation of grains similar to those of the xenoliths (Fig. 2e). Phenocryst oriented in the NW- SE and NE - SW directions are rather scanty and interestingly E – W oriented phenocrysts are very scarce or non-existent (Fig. 2c). This has been reported for Older granites in southeastern and southwestern parts of the basement complex of Nigeria (Oden, 2012a; Oden and Udinmwen 2013).

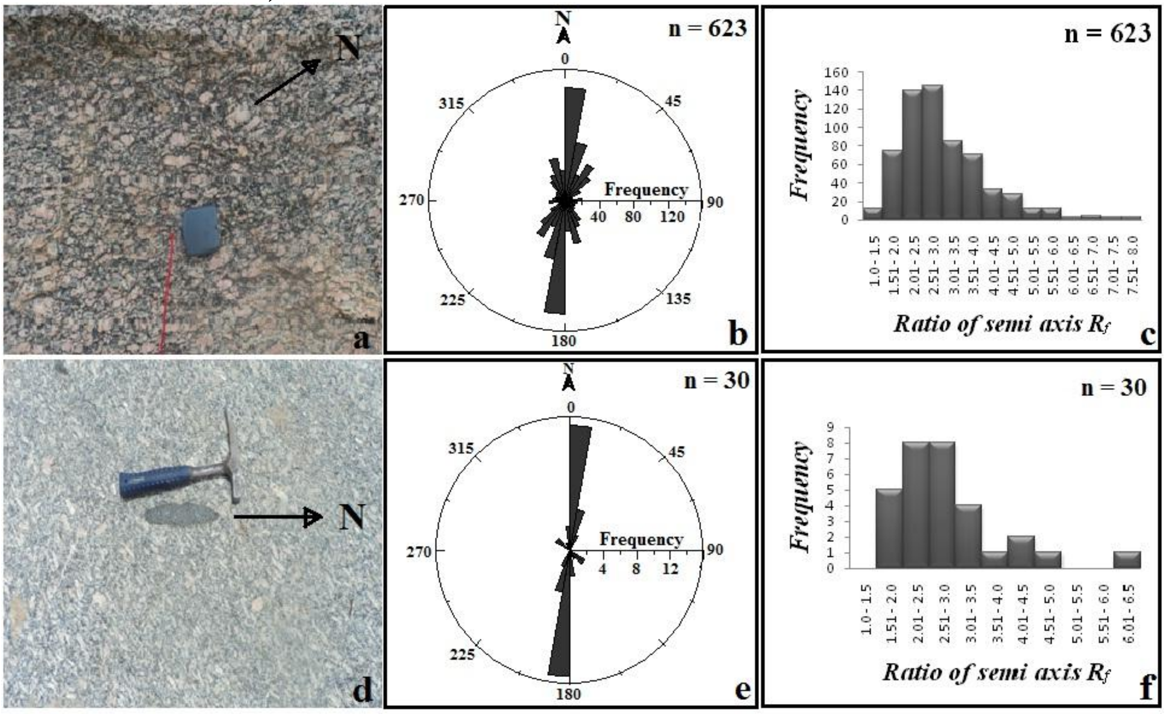

Fig. 2 Photographs and plots of phenocrysts and xenoliths data of the granite batholith. (a) phenocrysts of the batholith showing a strong preferred orientation at Ban ZauZau, the average dimension of the markers is 4cm by 2cm (b) Rose diagram of phenocryst long axes orientation (c) Histogram showing the frequency of occurrence of the ratio of semi axes of phenocrysts (d) Discordance relationship between phenocrysts and xenolith. Note that this occurred only at Jim Harrison; other locations had both markers in alignment (e) Rose diagram of xenolith long axes orientation (f) Histogram showing the frequency of occurrence of the ratio of semi axes of xenoliths. There is a preponderance of R_f values between 2 and 3 for both phenocrysts and xenoliths.

A plot of major axis (abscissa) against minor axis (ordinate) of phenocryst markers shows a positive correlation. The data points lie about a straight line passing through the origin (Fig 3) and the slope of the line gives the mean ratio of the principal strain (Ramsay, 1967). The equation from Fig. 3 is $y = 2.65x$ and the slope, 2.65 is closest to the average harmonic mean of 2.66 (Table 1).

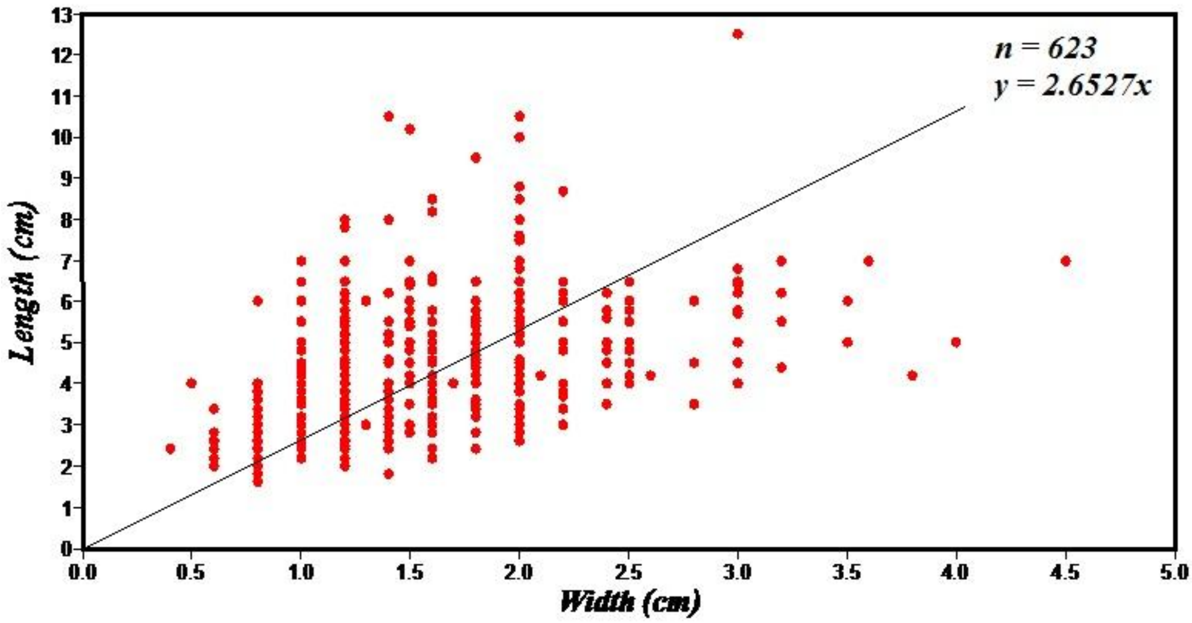

Fig 3 Graph of length against width of phenocrysts. Length of phenocrysts climaxed at 12.5cm, while the maximum width recorded was 4.5cm.

A comparative analysis of strain was performed along the axes of preferred orientation of phenocrysts so as to study the strain behaviour within preferred orientations. The total population of markers within each axes considered was used to determine the strain parameters, $\bar{R}$(Arithmetic mean), G(Geometric mean) and H(Harmonic mean) (Table 1). The average values of $\bar{R}$, G and H were determined to ascertain a composite result as the average harmonic mean (H) is usually closest to strain values derived from the more accurate $R_f/ø$ method (Lisle 1977).

$\bar{R}$ is the arithmetic mean of the R_{factor} (R_f) of the markers, and it was given by (Lisle, 1977; Ramsay and Huber, 1983; Ramsay, 1967 and Ghosh, 1993) as

$$\bar{R} = \frac{\Sigma R_f}{n} \text{ -- (1)}$$

G and H are the Geometric mean and Harmonic mean, respectively and they are given by Lisle (1977) as

$$G = \sqrt{R_{f1} . R_{f2} . R_{f3} \ldots\ldots\ldots\ldots R_{fn}} \text{ ------------------------------ (2)}$$

$$H = \frac{n}{\Sigma 1/R_f} \text{ -- (3)}$$

Where R_f (R_{factor}) is the ratio of major to minor semi axes [$R_f = (I+e_1)/(I+e_3)$], and n is the population of data being considered.

The phenocrysts (markers) of Zaria granite batholith have a strong preferred orientation in the N-S direction and this account for 57.7% of the total data population. Other available orientations of markers are NW-SE (11.7%) and NE-SW (21.0%). Phenocryst orientations are scarce or non-existent in the E-W direction (9.5%), a situation which has been observed in other granitoid batholiths of the basement complex of Nigeria (Oden, 2012a; Oden and Udinmwen, 2013). Taking cognizance of marker orientations in the N-S (n = 291), NW-SE (n = 59), NE-SW (n = 106) and E-W (n = 48), the Arithmetic mean ($\bar{R}$) values computed for these axes are 3.19, 3.16, 2.85 and 2.83 respectively. The geometric mean (G) values range from 3.01 through 3.00, 2.67 to 2.62 while the harmonic mean (H) values range from 2.80 through 2.80, 2.53 to 2.53 (Table I) the same axes. The average values of $\bar{R}$, G and H considering all axes are 3.00, 2.82 and 2.66 respectively. The average harmonic mean which is closest to values from $R_f/ø$ method (Lisle 1977) is 2.66 and this value is very close to the slope (2.65) of the length against width graph (Fig. 3). The relationship between calculated values of strain parameters is of the form; $\bar{R} \geq G \geq H$, which was demonstrated by Lisle (1977).

3.1 $R_f/ø$ plot

$R_f/ø$ plots are the key to the analysis of the geometry of deformed elliptical markers, and provide an excellent way of separating the components of tectonic strain from the initial shapes of the markers (Ramsay and Huber, 1983; Ramsay, 1967). One good way of finding the tectonic strain depends on establishing the graphs which determine how the ratios of the axes of the deformed phenocrysts vary with the orientations of their major and minor axes (Fig. 4). First a line is drawn on the section as a reference azimuth (90° for this work) and men the angle (ø) between the longest axes of each marker and the reference azimuth is recorded together with the ratios of their major and minor axes (R_f). These are plotted on a graph and the points should all lie on or about a curve which is symmetrical about a line of some fixed value "orn" and concentrated around the maximum value of R_f (Fig. 4). This value of "orn" gives the angle between the principal tectonic extension (long axis of strain ellipsoid) and the reference azimuth. Different equations are used to calculate different strain parameters depending on the behaviour of the plot. The behaviour of the curve determines the strain situation i.e $R_i > R_s$ or $R_s > R_i$. Generally where $R_i > R_s$, the data envelop is symmetrical about the orientation of the long axis of the strain ellipse but where $R_s > R_i$, the data envelop is closed and the data points show a limited range of orientations (Ragan, 1968, Ramsay and Huber, 1983). The R_f/ø plot of strain markers (Fig. 4) from Zaria granite batholiths suggests that $R_i > R_s$ thus the equations (4) and (5) given by Ramsey and Huber (1983) are applicable.

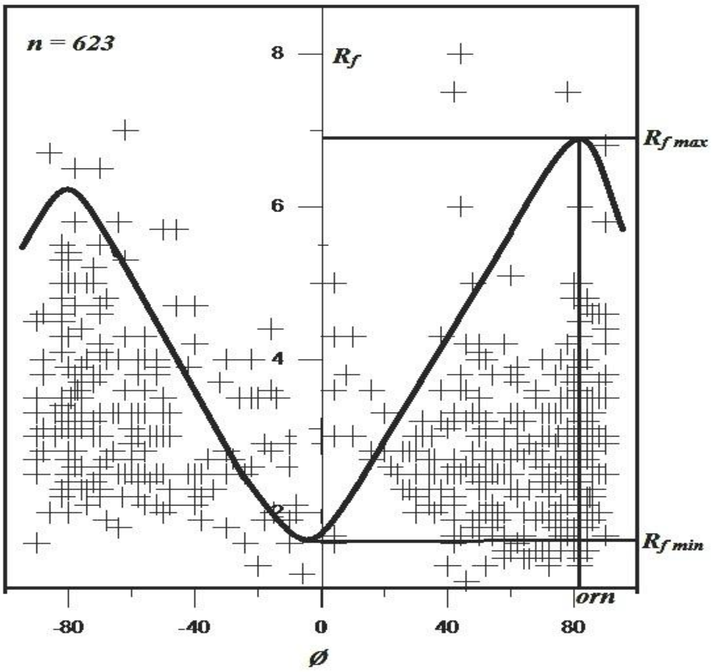

Fig. 4 R_f/ø plot with the maximum and minimum R_f values for the combined data points and the direction of maximum elongation.

$R_{i\,max} = (R_{f\,max} \, . \, R_{f\,min})^{1/2}$ --- (4)
$R_f = (R_{f\,max} / R_{f\,min})^{1/2}$ --- (5)
From Fig 4.
$R_{f\,max} = 6.9$
$R_{f\,min} = 1.8$

For this work, the reference azimuth is fixed at 90° and ø for each data point was gotten by subtracting the orientation of its long axis from the arbitrary reference azimuth (90°). "Orn", which is the angle between the principal tectonic extension and the reference azimuth, is 84° (Fig. 4) thus the principal tectonic extension orientation is gotten by subtracting this angle (orn) from the reference azimuth value.

Long axis of strain ellipsoid = reference azimuth - orn
Reference azimuth = 90°
"Orn" = 84°
MED = 90^0-84^0
Maximum extension direction (MED) = 006° which is approximately N-S

A North - South maximum extension direction would suggest an approximately E-W orientation of σ_1 (direction of maximum compression) and it agrees with Ball, (1980); Oden, (2012a); Oden and Udinmwen, (2013) and Udinmwen, et al., (2013), all of which observed an E-W compressional axis for most parts of the Pan-African mobile belt. Strain can be estimated from xenolith data but measurement of strain using this method is problematic due to the large initial shape variation and most methods of strain analysis emphasize a regular/constant initial shape of markers (Ramsay, 1967; Ramsay and Huber, 1983). Therefore there are limits to the accuracy of strain determination from xenohths. Some methods of strain analysis which derived initial shape and tectonic strain from measurements of final shape and axis orientation of markers ($R_f/ø$) are difficult to apply for xenolith markers. Due to these difficulties the geometric mean (G) of xenoliths has been used in granitoids as an estimate of strain (Barriere, 1977; Holder, 1979; Ramsay, 1981). However the use of this method alone is a measure of the mean deformed shape and will be an over estimate of the actual tectonic strain (Hutton 1982). Most important of the xenoliths is the preferred orientation of their long axes which is strictly in the N-S direction (Fig 2e). This is most probably the direction of maximum extension, as xenoliths orientations, in deformed granitoids can be used to infer the direction of maximum elongation (Hutton 1982). The xenoliths obviously responded to the E-W compression that prevailed in this area, during the orogeny.

3.2 Response of other Structures to measured strain

Joints are the second most abundant feature in these granites, after phenocrysts. Simple and seemingly featureless geologic structures such as joints constitute an important element of structural patterns which can provide confirmation of stress and strain in a region (Hills, 1972; Ramsey and Huber, 1987). To this end, joint data from the batholith were analysed with respect to the known joint mechanics, measured strain and inferred stress. A stereoplot of 50 tectonic joint data shows two directions of orientation; these are the N-S and ESE-WNW directions (Fig. 5a).These joints have high angle dips (Fig. 5b) which is a feature of 'ac' extension and 'bc' tensile fractures. Generally, 'ac' extension fractures are expected propagate parallel to σ_1 direction while the 'bc' tensile fractures grow perpendicular to σ_1 (Muehlberger, 1961; Price, 1966; Engelder and Geiser. 1980; Ike, 1988).

Mineral veins which are strongly related to joints (Oden, 2012b) are found in this area but hardly available. They are mainly quartz, pegmatite and feldspathic veins. Steeply dipping sinistral strike-slip faults occur within the batholiths (Fig. 5c and d). These have a N-S trend, an indication that the E-W compression slipped the faults along tensile or shear fractures. Observations of the offset of V_1 and V_2 compared with V_2 and V_3 (Fig. 5c) show that a greater displacement occurred along F_2 than F_1 which binds blocks A/B and B/C respectively. Other structures associated with this area are microgranite intrusion and exfoliation joints (Fig 5e) which are mainly cooling and exhumation related. Similar exfoliation joints have been reported in the southwestern basement complex of Nigeria (Oden and Udinmwen, 2014).

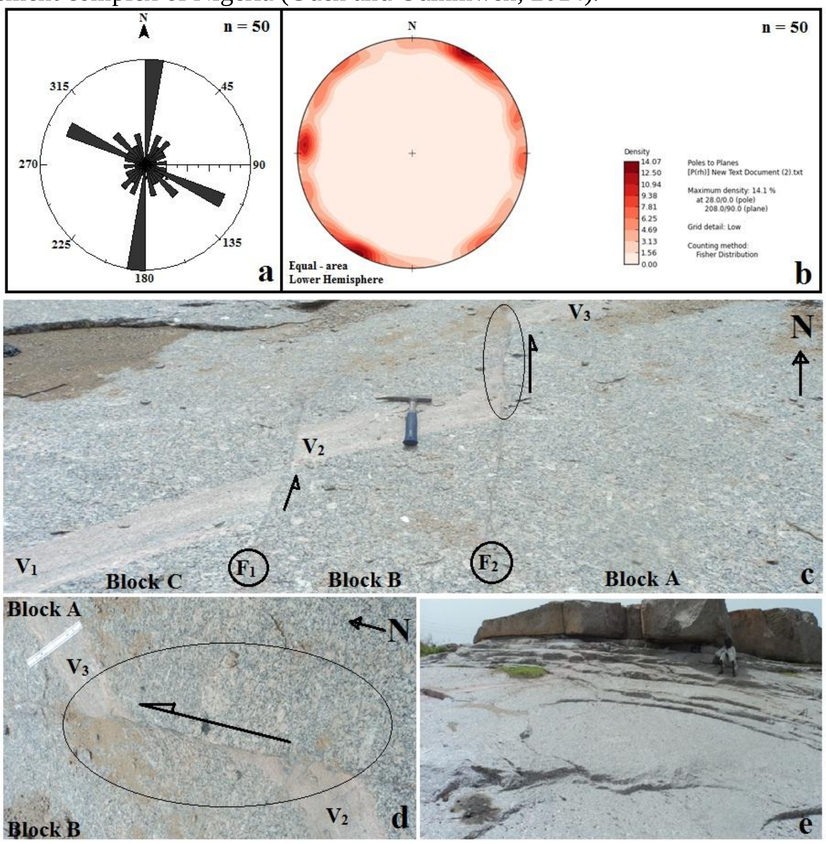

Fig. 5 Photographs and plots of joints and faults (a) Rose diagram of joints showing preferred orientation in two directions (b) Stereographic projection of joints poles (contour density) with information on their dips and dip

direction (c - d) Photograph of schlieren offset along sinistral strike-slip magmatic faults in the Zaria granite batholith. The fault occurred by melt-assisted grain boundary sliding and stopped before final crystallization (e) Exfoliation joints related to late stage cooling and exhumation of the batholith.

IV. Discussion

The Zaria granite batholith is a syn-tectonic, Pan-African granitoid which holds good information on the Pan-African deformation through the period tracked by these granites. The strain markers in these granite (phenocryst) and xenoliths show strong preferred orientation in the N – S, NW - SE and NE- SW trends are relatively weaker (Fig 2b). The scarcity of phenocrysts oriented in the E - W direction is an indication that this direction inhibited grain growth as it is the direction of maximum principal (σ_1), while the strong alignment of phenocryst long axes perpendicular to the E - W direction (i.e N - S) is expected as the perpendicular direction to σ_1 produces crystals which elongate fastest (Kamb, 1959) and crystals in the ductile state tend to rotate such that their largest faces are perpendicular to σ_1 (DeVore, 1969). The operation of Pan-African tectonics produced one pure shear and two simple shear directions (Oden, 20l2a). The strength of the NW - SE simple shear has been shown to be stronger than the NE – SW, during the pan-African deformation (Oden,2012a; Oden and Udinmwen, 2013;Ike 1988). Although, phenocrysts in the Zaria granite favoured the NE - SW over the NW – SE direction in terms of orientation of long axis, the operation of the NE - SW simple shear direction in the Zaria granite is of local effect as over 90% of the NE - SW trending phenocrsyts were collected from one location (Jim Harrison). Strain analysis (Table 1) shows that despite the preferred orientation of phenocrysts in the NE - SW direction relative to the NW - SE direction, strain intensity, was higher in the NW - SE direction showing that the strength of the NW - SE simple shear is higher in terms of strain than that of the NE - SW simple shear as observed in other Pan-African basement areas in Nigeria. The graph of length against width of markers has a slope of 2.65 which is very close to the average Harmonic mean (2.66). The Arithmetic mean ($\bar{R}$) Geometric mean (G) and Harmonic mean (H) methods of strain analysis (Table 1) partitioned strain in the Zaria granite batholith such that the N - S direction and NW – SE orientation show similar values of higher strain than the E - W and the NE - SW directions of lower strain. This shows that straining was highest in the N - S and NW - SE directions. A more reliable method of strain analysis which derives initial shape and tectonic strain from measurements of final shape and axis of orientation (ie R_f/ø method) was used in the determination of strain in the Zaria granite. This method gives a strain value of 2.07 which is considerably lower than the average harmonic mean (2.66) and the slope of the length against of grains (2.65). Similar situation was observed by Oden and Udinmwen (2013) for the southwestern basement complex of Nigeria. Hutton (1982) considered the use of geometric mean alone to determine the estimate of strain an inappropriate procedure which would give an over estimate of the actual strain value, since it is essentially a measure of the mean deformed shape of the markers. The orientation of the long axis of the strain ellipsoid "orn" is 006° (N - S) from which an E - W comprssional axis is deduced. Xenoliths are strictly oriented in this direction as non-random initial distribution of xenolith long axes is expected in the analysis of their strain and in many cases; the preferred orientation will initially be parallel to the maximum extension direction (Hutton, 1982). Considering a strictly co-axial (pure shear) deformation, "orn" (006°) value would be used to derive the specific orientation of σ_1 (maximum principal stress), but complication exist where there is a combination of co-axial (pure shear) and non-co-axial (simple shear) deformation as in the case of the pan-African deformations (Oden, 2012a). Fractures can be used for inferring palaeostress directions and if properly studied and they give a subtle tectonic history of an area (Gudmundsson, 1983; Olson and Pollard, 1989; Oden and Udinmwen, 2014). The fractures in this prolific Precambrian batholith show a preferred orientation in the N - S and ESE - WNW directions (Fig 5a). The N - S trending fractures are interpreted as the 'bc' tensile joints perpendicular to σ_1 direction while the ESE - WNW fracture set has a 10^0 deviation in the clock wise direction from the expected orientation of 'ac' extension fractures parallel to σ_1. Considering the 90° - 120° corridor from the north given by Oden (2012a) as the maximum stress corridor during the pan-African orogeny, these ESE - WNW fracture sets are thus interpreted as "ac" extension fractures which would propagate parallel to σ_1 direction (Muehlbeger,1961; Olson and Pollard, 1989; Price, 1966). The higher slip distance which occurred along F_2 relative to F_1 of the strike slip faults probably caused the re-orientation of crystals along the fault plane (Fig. 5d) and implies that block A has slipped further relative to blocks B and C (Fig. 5c). This greater slippage of block A is probably responsible for the re-orientation of crystals around F_2 which binds blocks A and B, as such re-orientation is not found around F_1 which slipped a shorter distance

It is worth noting that of the three pan-African granitoids so far studied in Nigeria, the Zaria Granite shows higher strain from all parameters than the others. For instance the $\bar{R}$, G and H Measured along the N-S axis in this study are 3.19, 3.01 and 2.80 respectively, while Igarra porphyritic granite produced values of 2.91 2.73 and 2.65 (Oden and Udinmwen 2013). Uwet granodiorite on the other hand gave values of 1.78, 1.75 and 1.72 for the three parameters respectively on the same N-S axis (Oden, 2012). Strain analysis requires the combination of methods with data from widely distributed areas to get a truly composite and representative result.

V. Conclusion

Rigid definite shape objects, like feldspar phenocrysts from different parts of a deformed granite can produce the history of strain intensity and direction, maximum elongation that operated during the deformation. The phenocrsyts of the Precambrian Zaria granite batholith are preferentially oriented in the N - S direction, a direction which also recorded the highest strain value. The E - W orientation inhibited the growth of grains and recorded the lowest strain values hence it is the direction of maximum compression (σ_1). Preferred orientation of strain markers requires careful study as it does relate with the intensity of strain. Strain analysis of simple shear orientations (NW - SE and NE – SW) showed the NW - SE dominating over the NE - SW direction in terms of strain intensity. From strain partitioning, strain intensity and dimensional preferred orientation, the pan- African tectonics seems to have operated on constant axes throughout the period tracked by these granites.

Acknowledgement

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Explanation Of Plates

Plate 1/Fig. 2: (a) Photograph showing the preferred orientation of closely packed, pinkish phenocrysts strictly in the N - S direction with little variation. Despite the close association of phenocrysts, they never interfered with each other. (b) A rose diagram showing the preferred orientation of phenocrysts long axes in the N - S direction. The NE - SW and NW - SE trajectories are barely available while the E - W orientation is almost non-existent, (c) Histogram showing the distribution of the ratio of semi axes (R_f) and their frequency. This reveals that most of the markers are not very much longer than they are wide. R_f values less than 1.5 are scarce while those greater than 5 are almost unavailable. They are dominant between 2 and 3. (d) Photograph showing the preferred orientation of phenocryst long axes in the NE - SW direction which differs from the direction of the xenolith (N - S). This was observed in one location (Jim Harrison) of the 15 locations studied within the batholith. The markers in this environment might have responded to some sort of local stress thus their orientation, (e) Rose diagram showing xenolith long axes preferred orientation strictly in the N - S direction and sparingly in the NW - SE direction. This is in response to the calculated N - S direction of maximum elongation for this batholith. (I) Histogram showing the distribution of the R_f of xenoliths. Though the xenoliths are much larger than the phenocrysts, their R_f values are similar which indicates that both markers were subjected to similar strain conditions irrespective of their sizes.

Plate 2/Fig. 3: This figure shows the graph of length against width of phenocrysts. A straight line passing through the origin was inserted and the data points plot around the line which gives an equation ($y = 2.6527x$), the slope of which is an estimate of the strain experienced by the markers. From this plot, the strain value is 2.65.

Plate 3/Fig. 4: This plate shows the plot of $R_f/ø$. The R_f values is the ratio of length and width of each marker while the ø is the angle between the orientation of the long axes of markers and a chosen reference line (90° for this work) The ø values are positive or negative depending on the orientation of the long axis of the marker. Markers with orientation greater than 90° will have a negative value while those less than 90° will show a positive figure. The fit tine which defines R_{fmax} and R_{fmin} was inserted to the plot considering the population density of data points with an attempt to accommodate as many points as possible so as to get a truly composite result. The line that defines "orn" was inserted considering the area of greatest cluster of points which shows the direction of maximum elongation.

Plate/Fig. 5 (a) A rose plot showing the orientation of joints within the study area which is basically in the N - S and ESE - WNW directions. Considering the calculated maximum elongation direction, the former are interpreted as "bc" tensile joints which grow parallel to σ_3 while the latter are "ac" extension fractures which develop parallel to σ_1 (b) This is a contour density stereographic projection of joint poles within the batholith. By concentration of the contour densities around the periphery of the stereonet, the joints have high angle dips which is a characteristic of extension and tensile fractures. The contour density is strongest in the E, W, NNE and SSW directions. These are the dip directions for the fractures which show that the fractures had preferred orientations. (c and d) Photograph of offset along magmatic faults in the Zaria granite batholith. The offset is between 5cm and 25cm with a preferred orientation of minerals close to F_2. Some igneous crystals grow across the fault suggesting that the offset occurred by melt-assisted grain boundary sliding and stopped before final crystallization. The sinistral strike-slip faults occurs along two parallel fault planes trending in the N - S direction with high angle dips which indicates that they were probably initiated along tensile fractures. The offset along F_1 binding blocks B and C is about 5cm while that of F_2 binding blocks A and B is about 20cm. The distance between V_1 and V_2 is 5cm while that of V_2 and V_3 is 15cm. This indicates that a greater slip occurred along F_2 than F_1 thus displacing block A which hosts V_3 further than blocks B and C which hosts V_2 and V_1 respectively. This may account for the re-orientation of magmatic crystals along F_2 (between V_2 and V_3) as similar situation was not observed along F_1. Phenocrysts occurring in the vicinity of the faults were not used for strain analysis as the block displacement had a local effect on the orientation of their long axes, (e) Photograph showing exfoliation joints in the granites. This shows that a late stage, near surface process related to cooling and exhumation occurred.

References

[1]. Ball E., 1980. An example of very consistent brittle deformation over a wide intercontinental area: the late Pan-African Fracture system of the Tuareg and Nigerian shield. Tectonophysics, 61, 363-379.
[2]. Barrier M., 1977. Deformation associated with the Ploumanac'h Intrusive complex, Brittany J. Geol Soc. London, 134: 311-324.
[3]. Begrantz, G.W., Dawes. R. 1994. Aspects of magma generation and ascent in the continental lithosphere. In: Ryan, M.. ed.. Magmatic Systems. Academic Press, San Diego, CA. 291 - 317.
[4]. Dada. S.S., 1998. Crust forming ages and Proterozoic crustal evolution in Nigeria. A Reappraisal of current interpretations. Precambrian Research, 87: 65 - 74.
[5]. De Swardt, A.M., 1953. The Geology of the country around Ilesha Nigeria. Geol. Surv. Nigeria Bull. No 23, 54pp.
[6]. DeVore, G.W., 1969. Preferred mineral distributions of polymineralic rocks related to non-hydrostatic stresses as expressions of mechanical equilibrium. J. Geol. 77: 26 - 38.
[7]. Dunnet, D., 1969. A technique of finite strain analysis using elliptical particles. Tectonophysics, 7: 117- 136.
[8]. Engelder, T., Geiser, P., 1980. On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian plateau, New York. J. Geophys. Res., 85(11), 6319-6341.
[9]. Falconer. J. D., 1911. The Geology and Geography of Northern Nigeria. MacMillan, London.
[10]. Ferre, E.G., Gleizes, G, Djouadi, M.T., et al., 1997. Drainage and emplacement of magmas along an inclined transcurrent shear zone: petrophysical evidence from a granite-charnockite pluton (Rahama, Nigeria), In: Bouchez, J.L., Stephens, W.E.S. and Hutton, D.H,W. Granites: from magma segregation to emplacement fabrics. Kluwer Pub. Co, 253-273.
[11]. Ghosh, S. K., 1993. Structural Geology, Fundamentals and Modern Development. Pergamon Press. 598p
[12]. Grant, N. K., 1969. The Late Precambrian to Early Paleozoic Pan-African Orogeny in Ghana, Togo, Dahomey and Nigeria. J. Geol. Soc. Am., 80.45—55.
[13]. Gudmundsson, A., 1983. Stress estimates from length/width ratios of fractures. Journal of structural Geology. 5 (6) 623-626.
[14]. Hills, S.E., 1972. Elements of Structural Geology. Chapman and Hall. London, 502p
[15]. Holder, M. T., 1979. An emplacement mechanism for post tectonic granites and its implication for the geochemical features. In M. P. Atherton, and J. Tamey (editors), Origin of Granite Batholiths, Geochemical evidence. Shiva Publishing Ltd., Kent, 116-128.
[16]. Hutton, D.H.W., 1988. Granite emplacement mechanisms and tectonic control interference from deformation studies. Trans. Geol. Soc. Edinburgh: Earth Science, 79: 245 - 255.
[17]. Hutton, D.H.W., 1982. A method for the determination of the initial shapes of deformed xenoliths in granitoids. Tectonophysics, 85: 45-50.
[18]. Ike, E. C., 1988. Late stage geological phenomena in the Zaria Basement granites. Precambrian Geology of Nigeria, 83-89. Publication of the Geological Survey of Nigeria.
[19]. Ildenfonse, B., Arbaret, L., Diot, H., 1997. Rigid particles in simple shear flow: is their preferred orientation periodic or steady - state? In: Bouchez, J.L., Hutton, D.H.W, Stephens, W.E., eds., Granite: From Segregation of Melt to Emplacement Fabrics. Kluwer Academic Publishers, Netherlands. 177 - 185.
[20]. Jones, H.A., Hockey, R.D., 1964. The geology of part of southwestern Nigeria. Geol. Surv. Nigeria, Bull. No 31, 87pp.
[21]. Kamb. W.B., 1959. Theory of Preferred Crystal Orientation develop by Crystallization under Stress. Journal of Geology, 67: 153-1 70.
[22]. Lisle. R.J., 1977. Estimation of the Tectonic strain ratio from the mean shape of deformed elliptical markers. Geologie enMijnbouw, 56(2), 140-144.
[23]. Lisle, R.J., 1979. Strain analysis using deformed pebbles: the influence of initial pebble shape. Tectonophysics, 60: 263 - 277.
[24]. Matthews, P.E., Bond, R.A.B., van den Berg, J.J., 1974. An algebraic method of strain analysis using elliptical markers. Tectonophysics, 24: 31- 67.
[25]. McCurry, P., 1973. Geology of Degree Sheet 21, Zaria, Nigeria. Overseas Geol. Mineral Res., 10 (45): 1-45.
[26]. Muehlberger, W. R, 1961. Conjugate Joint sets of small dihedral angle. Journal of Geology, 69: 211-219.
[27]. Oden, M.I., Udinmwen, E., 2013. The Behaviour of K-feldspar Phenocrysts and Strain Anisotropy in Igarra Syn-Tectonic Granite, Southwestern, Nigeria. Current Advances in Environmental Science, 1(2), 9-15.
[28]. Oden, M.I., 2012a. Strain Partitioning and Dimensional Preferred Orientation in a Syn-Tectonic Granitoid, Southeast, Nigeria. Science World Journal, 7(1), 9-14.
[29]. Oden, M.I., 2012b. 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.
[30]. Oden, M.I., Udinmwen, E., 2014. Fracture Characterization, Mineral Vein Evolution and the Tectonic Pattern of Igarra Syn-Tectonic Granite, Southwestern Nigeria. British Journal of Science and Technology. 4(17), 2417 – 2429.
[31]. Olson, J., Pollard D. D., 1989. Inferring palaeostresses from natural fracture patterns: A new method -Geology. 17: 345-348.
[32]. Paterson, S.R., Fowler, T.K., Schmidt, K.L., et al., 1998. Interpreting magmatic fabric patterns in plutons. Lithos, 44, 53 - 82.Price, N J., 1966. Fault and Joint Development in Brittle and Semi -Brittle Rock. Oxford: Pergamon Press, 180p
[33]. Ragan D.M., 1968. Structural Geology: An Introduction to Geometrical Techniques. John Wiley and Sons. New York. 208p
[34]. Ramsay. J. G., 1967. Folding and Fracturing of rocks. McGraw-Hill, New York. 568p
[35]. Ramsay, J. G., 1981. Emplacement mechanism of the Chindamora Batholith, Zimbabwe. In M. P, Coward (Editor), Diapirism and Gravity Tectonics. J. Struct. Geol, 3. 93 (abstr.)

[36]. Ramsay, J.G., Huber, M.I., 1983. The Techniques of Modern Structural Geology, Vol.1, Strain Analysis. Academic press. 307p
[37]. Ramsay, J.G., Huber, M.I., 1987. The Techniques of Modern Structural Geology, Vol 2. Folds and Fractures. Academic Press London. 700p
[38]. Russ, W., 1957. The Geology of parts of Niger, Zaria and Sokoto Provinces with special references to the occurrence of gold. Geol. Surv. Nigeria, Bull. No 27. 42p
[39]. Udinmwen, E., Ayuba, R., Oden, M.I., 2013. Structural Geometry of Pan-African Gneiss in Osara, North Central Nigeria. International Journal of Science and Technology. 2(11): 822-831.
[40]. Webb, P. K., 1972. Recent research on Ihe geology between Zaria and Kaduna. Savannah, 2, 241-243.

Table 1. Distribution of phenocrysts and strain parameters.

Component	Direction of compression	Simple Shears		Pure shear	Average
Orientation	**E-W**	**NE-SW**	**NW-SE**	**N-S**	
No of data (n)	48	106	59	291	
Arithmetic mean ($\bar{R}$)	2.83	2.85	3.16	3.19	3.00
Geometric mean (G)	2.62	2.67	3.00	3.01	2.82
Harmonic mean (H)	2.53	2.53	2.80	2.80	2.66