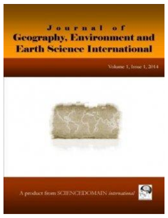

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Finite Strain Analysis of Xenoliths and Phenocrysts in Akure Granitoids, Ondo State, Southwestern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aim: This study was carried out to measure the strain conditions in the Akure granitiods with a goal to understand the impact of the pan-African orogenic cycle on this granitic body that extends from Ore through Akure to Ado-Ekiti axis.
Methods: Lengths, strike, and dips of the principal stress directions, σ_1, σ_2 and σ_3 in 101 xenoliths and 887 phenocrysts were measured. The length of the principal axes were measured using a centimeter rule while the strike and dip of xenoliths and trends of phenocrysts were measured using a compass clinometers. The extent of elongation and shortening, stretch and quadratic elongations were also determined. The Flinn's, logarithmic Flinn's and the Hsu diagrams were employed to understand the impact of the tectonism on rocks in the area. A total of 101 xenoliths and 887 phenocrysts were measured on the field. The lengths and trends of the maximum, intermediate and minimum directions were measured.
Results: The data obtained from the field analysis revealed that the maximum strain direction

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trends from NE-SW which corresponds to the direction of the stress field of the Pan-African orogeny. The original shape of these geological bodies ranges between 14.38 and 36.83 cm. Furthermore, the results showed that there is a correlation between the length and width of the xenoliths which confirms that they must have been acted upon by tectonic activity. The study further revealed that the xenoliths and phenocrysts trend in the NE-SW and NW-SE directions which correspond to the principal directions of the Pan-African Orogeny. The elongation of xenoliths in the maximum, intermediate and minimum strain directions ranges between 1.05 and 37.38, -1.94 and -1.14 and -3.15 and -0.20 respectively. The quadratic elongation is between 1.90 and 2.66 for the maximum strain direction while it ranges between 0.39 and 0.60 in the intermediate strain direction. In minimum strain direction, quadratic elongation ranges between 0.51 and 0.61. Flinn's plot revealed that 100% of the xenoliths were strained by tectonism while logarithmic Flinn's and Hsu plots revealed that 97% and 3% of the xenoliths were deformed by constrictional and flattened strain respectively.

Conclusion: This study revealed that the pan-African orogeny played a significant role in deforming the xenoliths in the porphyritic granite. The investigation further revealed that the stress that acted on the Akure granitoids produced a constrictional change in most of the xenoliths while only a few of them were flattened.

Keywords: Akure; granitoid; Pan-African Orogeny; phenocrysts; strain; xenoliths.

1. INTRODUCTION

Rocks during tectonism are subjected to the operations of both external and internal forces, such as magmatism and fracturing, that tend to change the orientation and shape of their outlook [1,2,3,4]. During tectonism rocks adjust in response to the applied stress [1,2,3,5]. These responses generally referred to as strain is observable in rock bodies and are visible as folds, faults, joints, foliation and micro adjustments in the sizes and arrangements of their grains and magmatic structures such as xenoliths [1,2,4]. Strain analysis in rocks may be problematic where strain markers such as xenoliths, pebbles, and other ellipsoidal bodies are not available [1,2] In the presence of these markers, strain analysis provides a useful technique to understand and unravel the tectonics that might have affected an area [1,2,3,5]. The direction of the principal stresses, σ_1, σ_2 and σ_3 which is also known as the maximum, intermediate and minimum stress directions are of great importance to unravel the tectonic history of an area [1,2].

The pan-African thermos-tectonic event which took place between 750 and 450 Ma is believed to be the latest major orogenic event that affected the whole Africa continent [2]. This event is thought to have obliterated to extent evidence of preceding orogenic activities such as the Liberian, Kibaran, and Eburnean [2,6,7,8, 9,10,11]. It is believed that structural modification and migmitization of the older granites accompanied these activities. Oden et al. [3] concluded that the crystallization history of the Zaria batholiths is closely associated with the appearance of feldspar megacrysts. They also believed that the xenoliths observed in these pan-African granitoids are by local metasomatic replacement through the generations of feldspar megacrysts. Isotopic age determinations of the granitoids showed that they were emplaced during the pan-African tectonism. Similar studies relating to strain analysis in rocks include [4,5,6]. Three models have been presented to prove that these granitoids were emplaced during the pan-African tectonism [2,3,5,6,7,8, 9,10,11]. These are; the ones which were formed due to a magmatic process [12]; some that were emplaced by metasomatic process [3]; and the ones which is a combination of both magmatic and metasomatic processes played essential roles in their formation [13].

Several geochemical data exist to understand the impact of tectonic processes on the Nigerian Basement Complex [14,15,16,17,18,19] but only a few studies have focused on understanding the kinematics that accompanied the pan-African orogeny. Oden et al. [3], Oden and Udinmwen [5] studied these granitoids exposed in both Zaria and Igarra northwest and southwest parts of Nigeria respectively. The paleostress analysis of joints carried out in Owo area by Adewumi et al. [20] revealed that the stress field trending NW-SE during the pre-Pan-African age was shifted to NE-SW during the Pan-African tectonism. Although these give clues to the impact of the orogenic activities on the stress-strain relationship in the rocks, they are too small to understand such events on a regional scale in a country like Nigeria [20].

Although no work had been done to unravel the kinematic history of the Akure porphyritic granite, [21] resolved strain conditions of adjacent charnockite using petrographic and field techniques. Therefore, the aim of this study is to measure the strain conditions in the Akure porphyritic granite with a goal to understand the impact of the pan-African orogenic cycle on this granitic body that extends from Ore to Ondo through Akure to Ado Ekiti axis. To achieve this goal, the lengths, strike, and dips of the principal stress directions, $\sigma_1, \sigma_2\ and\ \sigma_3$ in one hundred and one (101) xenoliths were measured. The extent of elongation and shortening, stretch, quadratic elongations and angular shear were also determined. The Flinn's, logarithmic Flinn's and the Hsu diagrams were used to understand the impact of the tectonism on rocks in the study area.

2. MATERIALS AND METHODS

2.1 Study Area

Akure is a significant and the capital city of Ondo State, South-western Nigeria. It is located between latitudes 7º 15′ and 7º17′ north of the Equator, and between longitudes 5º14′ and 5º 15′ east of the Greenwich Meridian (Fig. 1). It is about 204 km east of Ibadan, the capital city of Oyo state; 168 km west of Benin City, capital of Edo State; 311 km north-east of Lagos; and 323 km south-west of Abuja, the Federal Capital Territory of Nigeria. It covers a land area of approximately 15,500 km^2 with a topographic elevation of about 370 m above the sea level. The city had a population of 484,798 as at the 2006 population census. Major towns surrounding the study area include Ilesha, Ado-Ekiti, Ikere, and Owo.

Geologically, the area is located on the Nigerian Basement Complex (Fig. 1) which lies within the remobilized zone of the West African Basement. The dominant rock types in the area as classified by Adekoya et al. [22] are; the gneiss-migmatite-quartzite complex the schist belts which are low to medium grade supracrustal and meta-igneous rocks; the Pan African granitoids (Older Granites) and other related rocks such as charnockitic rocks and syenites and minor felsic and mafic intrusives. The rocks intruded into the migmatite-gneiss-quartzite complex.

It is believed that tectonic joints are quantitative and directional manifestations of operative forces that can give a clue to possible stress distribution in a deformed rock [4]. Research studies within the basement complex include but not limited to the works [6,7,8,9,10,11,23,24]. Shitta [24] described the three types of charnockitic rocks in Akure area based on their textural characteristics such as; coarse-grained as exemplified by the

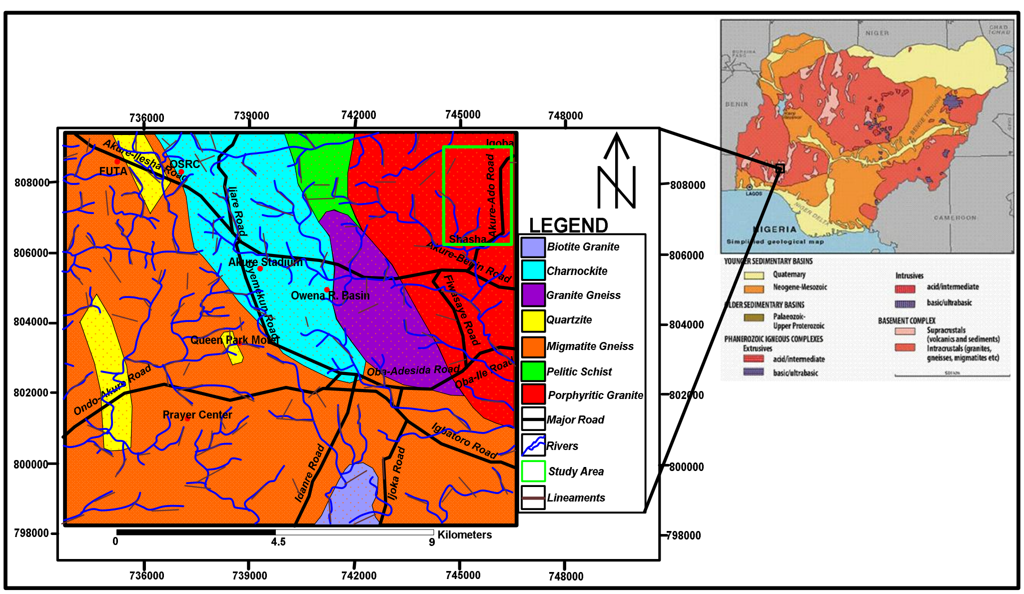

Fig. 1. Location and geological map of Akure showing the study area the study area (After [10], Lineaments after [25])

Akure body; massive fine-grained which form along the margins of the granitic bodies as seen in Ijare, Uro and Edemo-Idemo; and the gneissic fine-grained types which were recognized within the bodies of the gneisses in Ilara and Iju. The charnockitic rocks of Akure-Ikerre-Ado Ekiti have earlier been described as an association [19]. It is concluded that alteration pathways from fresh to weathered charnokitic rocks are different under each climate conditions. In addition, [20] described the deformation traits in the charnockites of Akure area. He suggested that the directions of maximum compressional and tensional stresses in the area were in agreement with the general directions of the Pan-African orogenic events that had great impacts on the basement complex rocks in Africa [8,9].

2.2 Research Methods

In this study, the geological field mapping techniques as proposed by Davis and Reynolds [1] was used to analyze the strains in xenoliths granitoids of Akure area, Southwest Nigeria as shown in Fig. 2. On the field, the lengths of the maximum, intermediate and minimum stress directions were measured using a centimeter ruler, while the trends of these stress directions were measured using compass clinometer. A total of 101 xenoliths and 877 phenocrysts were estimated from four stations namely Benin Garage, Igoba, Shasha 1 and Shasha 2. The field data were organized and plotted on a rose diagram using rockwork software version 16 [26]. Also, the breadth and width of the phenocrysts and xenoliths were plotted on decipher to ascertain any relationship between these two parameters measured on the field. In addition, strain equations (equations 1 to 6) outlined by Davis and Reynolds [1] were used to unravel the original shape of the xenoliths and the types of strain that is in operation in the area [1]. The Flinn's chart was plotted by plotting $1 + \varepsilon_1$ along the horizontal axis and $1 + \varepsilon_3$ along the vertical

Fig. 2. Xenoliths and phenocrysts studied in porphyritic granite of the study area

axis of scaled coordinate systems, while the logarithmic Flinn's diagram was generated by plotting the logarithm values of the ratio of X (maximum strain direction) to Y (intermediate strain direction) against the logarithmic value of Y (intermediate strain direction) to Z (minimum strain direction). The Hsu diagram was used to determine the strain magnitude by plotting the strain magnitude which ranges between 0 and 5 against shape ellipsoid which ranges between 0 and 1 for flattened ellipsoids and 0 to -1 for constricted ellipsoid.

$$r^2 = a^2 + b^2 \quad (1)$$

$$r = \sqrt{a + b} \quad (2)$$

Where r = is the radius of the xenoliths
a = the maximum length of xenoliths
b = the minimum length of xenoliths

$$Elongation\ along\ the\ maximum\ length\ \ (e_A) = \frac{2a + 2r}{2r} \quad (3)$$

$$Elongation\ along\ the\ minimum\ length\ (e_b) = \frac{2b + 2r}{2r} \quad (4)$$

$$Stretch\ along\ the\ maximum\ length\ \ (S_A) = \frac{2a - 2r}{2r} \quad (5)$$

$$Stretch\ along\ the\ minimum\ length\ (S_b) = \frac{2b - 2r}{2r} \quad (6)$$

3. RESULTS AND DISCUSSION

3.1 Trends of Strain Direction

3.1.1 Benin garage area

A total of 320 phenocrysts were measured in the study area with a mean length of 2.75 cm and mean width of 1.10 cm. The azimuthal direction for the phenocrysts in the maximum and minimum stress directions σ_1 and σ_3 is shown in the Fig. 3. The result revealed that the phenocrysts maximum stress directions (X) σ_2 trend mostly in the NW-SE direction with few phenocrysts trending towards the NE-SW direction while in the minimum direction (Z) σ_3 the trends were mainly in the NE-SW direction (Fig. 3). The graph of length against width (Fig. 8) indicated possible correlation between the maximum and minimum stress directions in the phenocrysts of this study area. This probably implies that both sides were deformed during the tectonic regime (possibly Pan-African orogeny) under which they were formed.

3.1.2 Igoba area

A total of 164 phenocrysts were measured in Igoba area with a mean length of 2.75 cm and a mean breadth of 1.10 cm. The rose diagram for the phenocrysts of this area (Fig. 4) shows that the maximum direction (σ_1) trend mostly in the NW-SE and NNE-SSE directions, while the phenocrysts in the minimum direction σ_3 trend mainly in the E-W direction. The graph of length against width (Fig. 8) indicated possible correlation between the maximum and minimum stress directions in phenocrysts of this study area.

3.1.3 Shasha 1

A total of 200 phenocrysts were measured in Shasha 1 area. The mean length was 3.53 cm while the mean breadth was 1.28 cm. The rose diagram for the phenocrysts of this study area (Fig. 5) revealed that the maximum direction (σ_1) trends mostly in the NW-SE and NE-SW directions with the NW-SE directions predominating. Phenocrysts in the minimum direction (Z) sigma σ_3 trends predominantly in the NE-SW direction while few of them trends in the NW-SE direction. The graph of length against width (Fig. 8) revealed possible correlations between the maximum and minimum stress directions in the phenocrysts of the study area.

3.1.4 Shasha 2

A total of 193 phenocrysts were measured in Shasha 1 area. The mean length is 3.35cm while the mean breadth was 1.17cm. The rose diagram for the phenocrysts of this area (Fig. 6) revealed that the maximum direction (σ_1) trends mostly in the NW-SE direction while only a few trend in the NE-SW directions. The phenocrysts in the minimum direction (Z) sigma σ_3 trends predominantly in the NE-SW directions. The graph of length against width (Fig. 8) showed possible correlations between the maximum and minimum stress directions in phenocrysts of the study area (Fig. 8).

3.2 Xenoliths

A total of 101 xenoliths were measured in the study area. The mean length is 44.8cm while the mean breadth is 6.1cm. The rose diagram for the xenoliths in the maximum (σ_1) and intermediate

(σ_2) directions shows that they both trend mostly in the NE-SW direction, while those in the minimum direction (σ_3) trend mainly in the NW-SE direction (Fig. 7). The graph of length against width (Fig. 9) indicated possible correlations between the maximum and minimum stress directions in the xenoliths of the study area. This implied that both sides were deformed

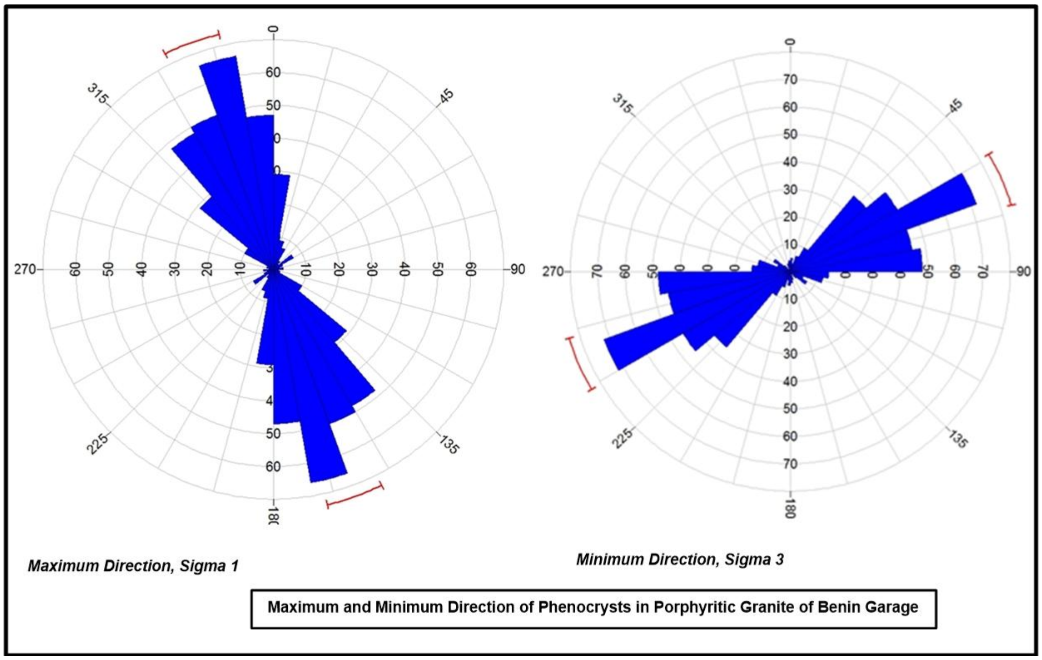

Fig. 3. Rose diagram for the maximum and minimum directions for phenocrysts in porphyritic granite in Benin Garage study area

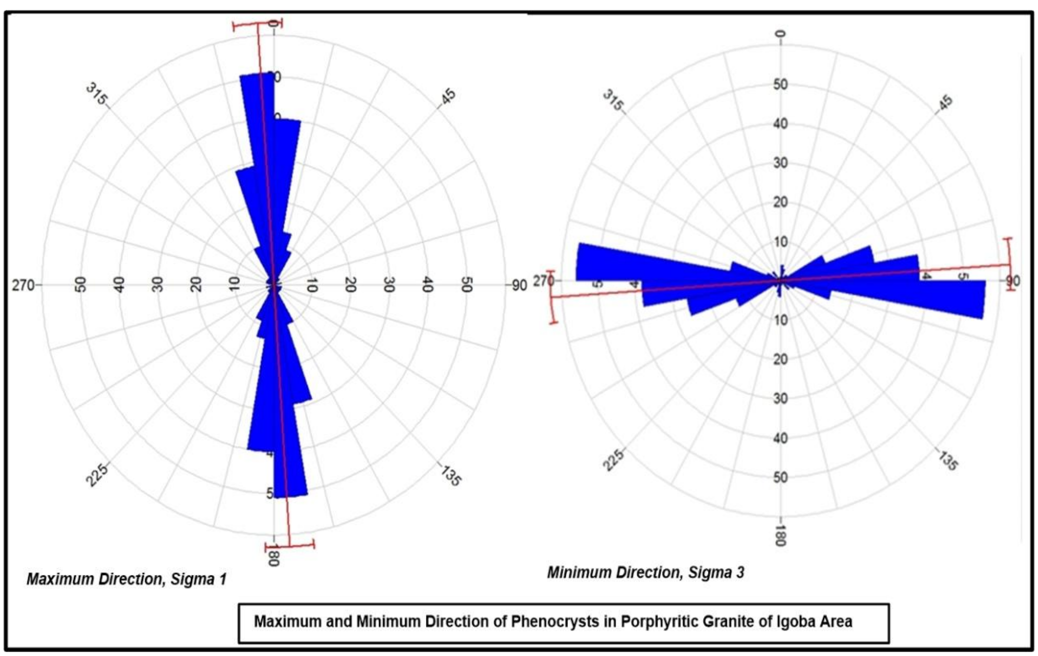

Fig. 4. Rose diagram for the maximum and minimum directions for phenocrysts in porphyritic granite in Igoba study area

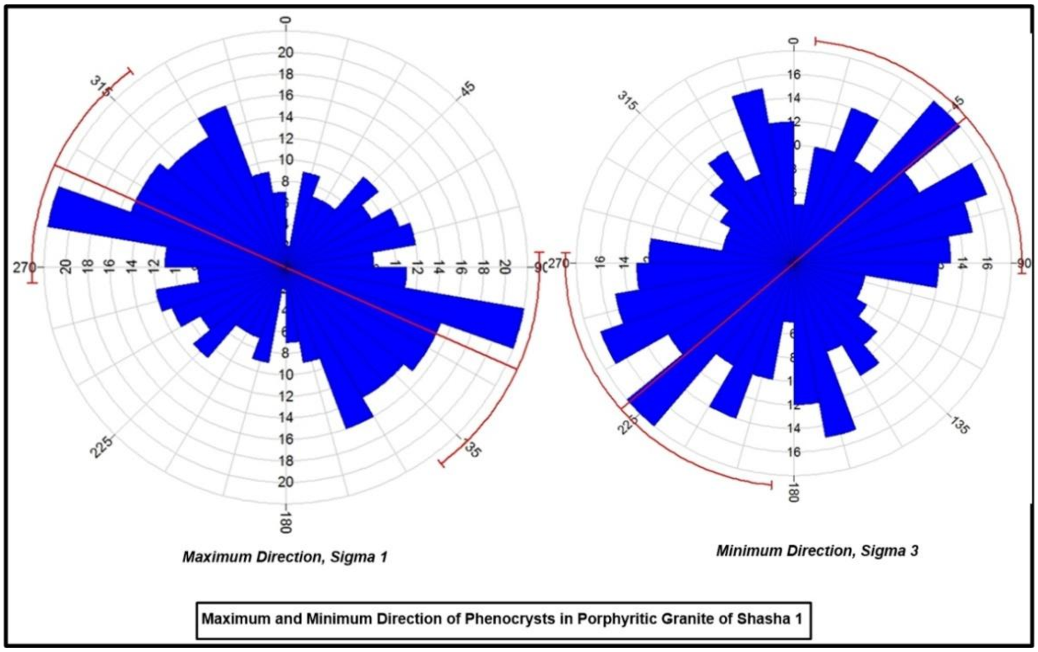

Fig. 5. Rose diagram for the maximum and minimum directions for phenocrysts in porphyritic granite in Shasha 1 study area

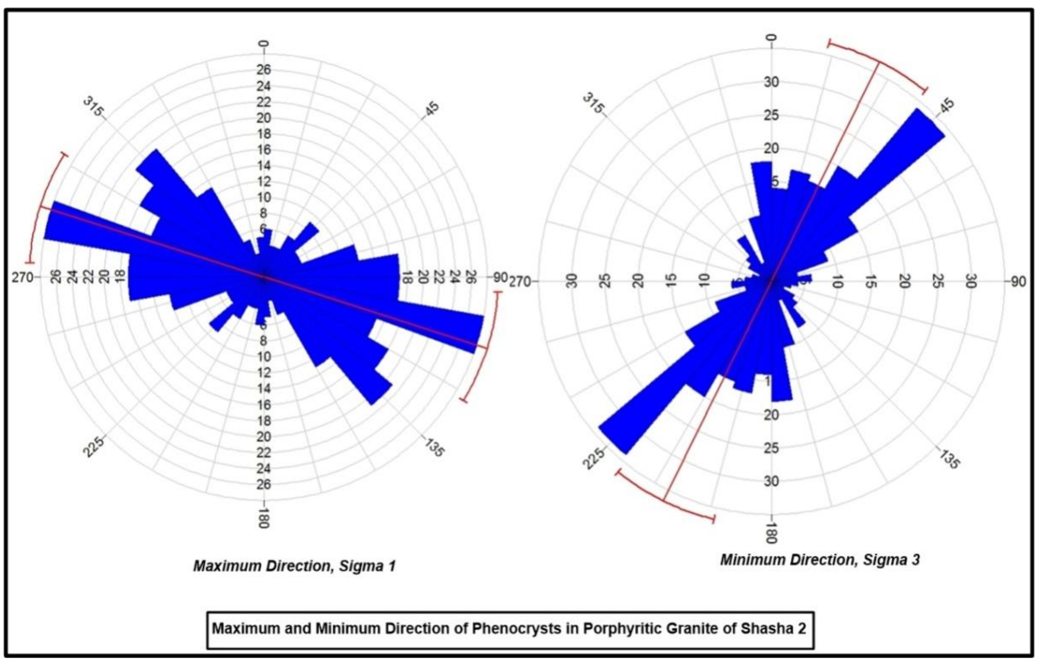

Fig. 6. Rose diagram for the maximum and minimum directions for phenocrysts in porphyritic granite in Shasha 2 study area

during the tectonic regime (possibly during Pan-African orogeny) under which they were formed. One of the main reasons for strain analysis in rocks is to unraveled the original shape of geological bodies before under-going various forms of deformation. In this study, it was observed that the original form of the xenoliths varied from 14.38 to 36.83 cm.

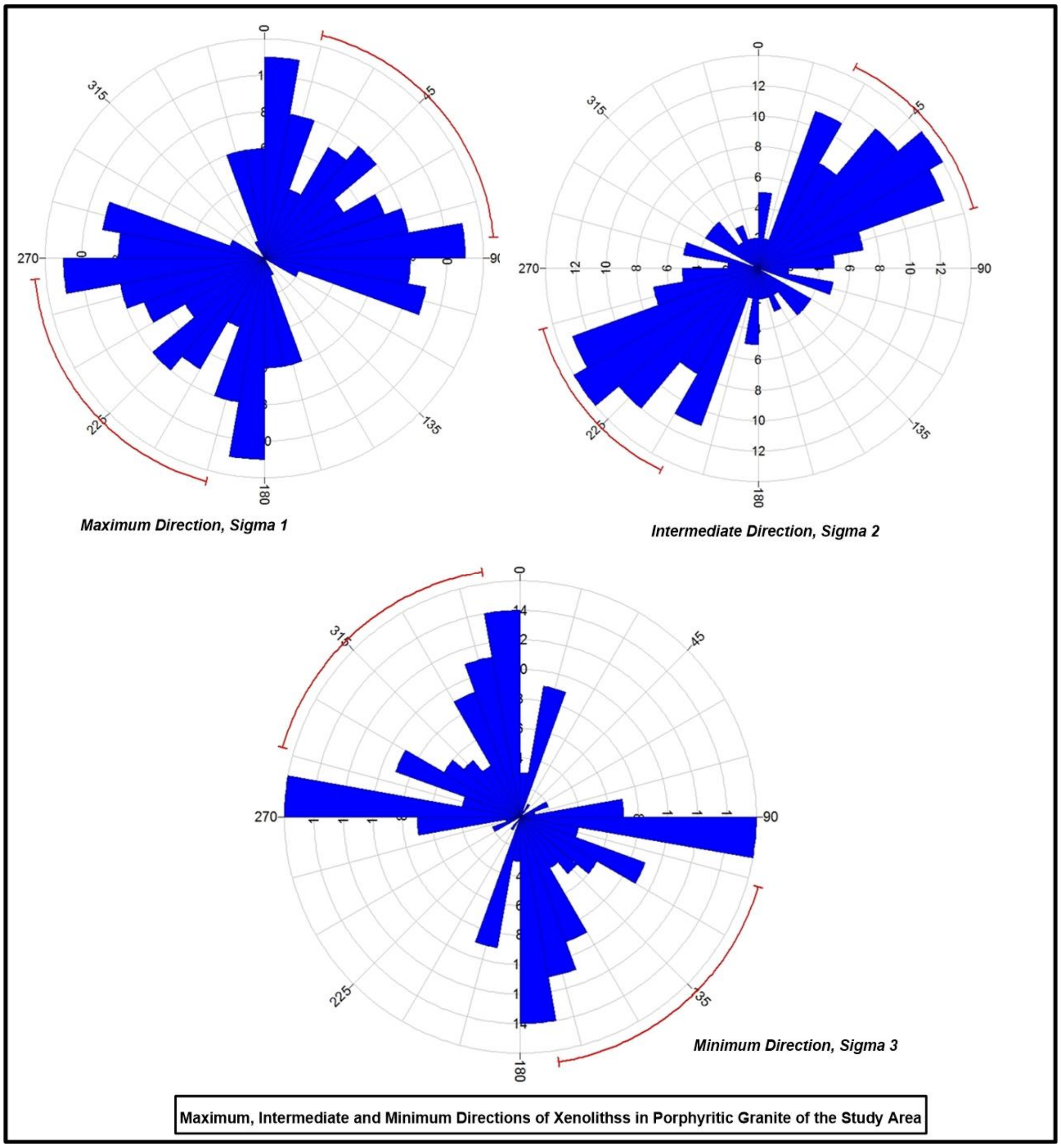

Fig. 7. Rose diagram for the maximum, intermediate and minimum directions for xenoliths in porphyritic granite of the study area

3.3 Finite Strain Pattern

In strain analysis, it has been generally accepted that an elliptical strain marker was in circular from before it was deformed by stress. In this study, the results revealed that the radius of the original shape of the xenoliths in the porphyritic granite range between 14.38 to 36.83 cm (Table 1). Also, the mean extension value for the maximum strain direction (σ_1) is 1.30 with a mean percentage extension of 130 % while the mean extension value for the intermediate strain direction (σ_2) is -1.78 with a percentage extension value of -178 %, and the mean extension value for the minimum strain (σ_3) direction was -0.69 with a percentage value -69%. The negative values observed in the extension values in the intermediate and minimum directions implied that the stress that acted on the xenoliths led to their constriction while the maximum strain direction was expanded. The mean stretch value for the maximum strain direction (σ_1) was 2.30 with a mean percentage stretch of 230 % while the mean stretch value for the intermediate strain direction (σ_2) was 0.46 with a percentage extension value of 46 % and the mean extension value for the minimum strain (σ_3) direction was 0.46 with a percentage value of 31 %. This revealed that the xenoliths in the porphyritic granite of Akure region were positively stretched in the direction of the Pan-African tectonic forces which trends mostly in the NE-SW directions.

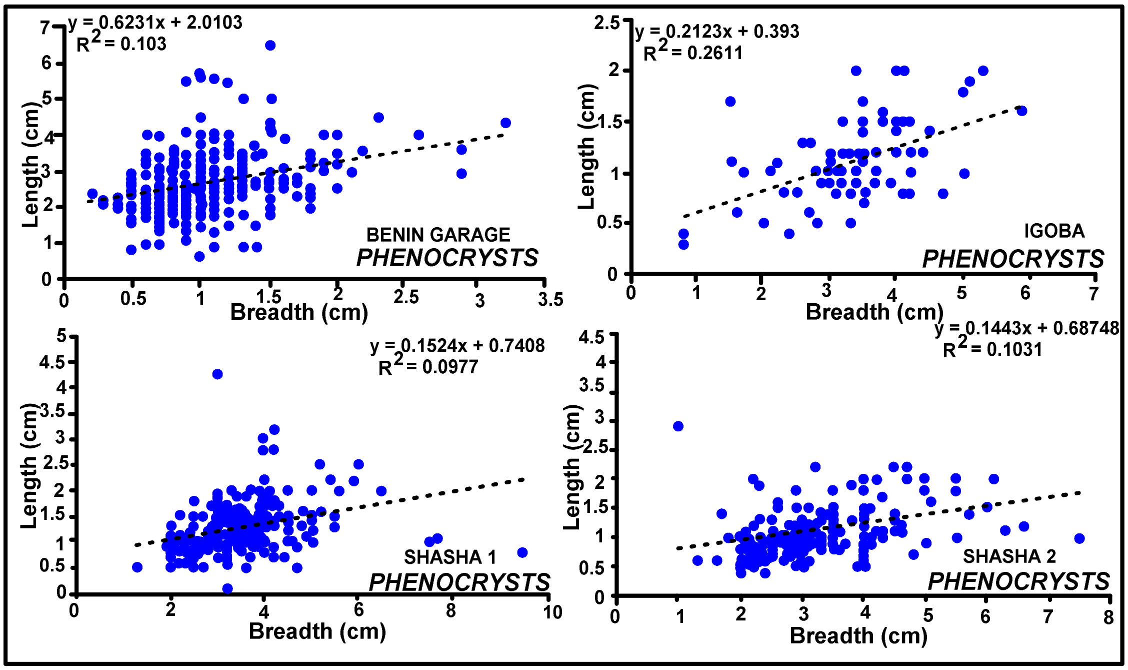

Fig. 8. Graph of length against the breadth of Phenocrysts in Benin Garage, Igoba, Shasha 1, and Shasha 2 study areas

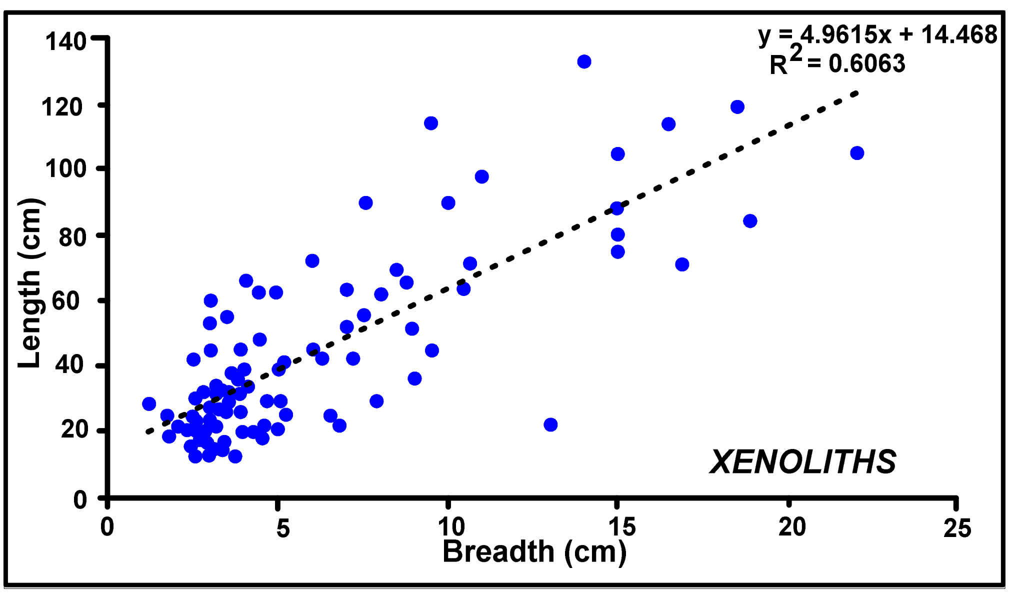

Fig. 9. Graph of length against the breadth of Phenocrysts in Benin Garage, Igoba, Shasha 1, and Shasha 2 study areas

Table 1. Summary of data obtained from the field analysis of xenoliths

	X (cm)	Y (cm)	Z (cm)	Radius (cm)	eA (cm)	eB (cm)	eC (cm)	S_A (cm)	S_B (cm)	S_C (cm)	Quadratic elongation (λA)	Quadratic elongation (λB)	Quadratic elongation (λC)
1-10	42.78	6.93	5.00	16.79	1.66	-1.70	-0.72	2.66	0.39	0.27	1.63	0.63	0.52
11-20	34.61	6.49	4.30	14.79	1.22	-1.88	-0.70	2.22	0.46	0.29	1.49	0.68	0.54
21-30	41.92	6.61	4.73	16.32	1.60	-1.70	-0.71	2.60	0.40	0.28	1.61	0.63	0.53
31-40	49.49	12.18	8.37	24.13	1.05	-2.09	-0.63	2.05	0.50	0.36	1.43	0.71	0.60
41-50	48.18	8.38	7.01	19.51	1.43	-1.94	-0.62	2.43	0.44	0.37	1.55	0.67	0.61
51-60	64.50	26.1	8.58	36.83	1.01	-0.20	-0.74	1.97	0.60	0.26	1.40	0.78	0.51
61-70	67.85	13.15	9.25	29.37	1.39	-1.77	-0.69	2.39	0.42	0.30	1.55	0.65	0.55
71-80	39.11	7.37	5.13	16.74	1.26	-1.88	-0.69	2.26	0.45	0.30	1.51	0.67	0.55
81-90	37.46	6.00	4.71	14.38	1.60	-1.91	-0.67	2.60	0.41	0.32	1.61	0.64	0.57
91-101	35.55	10.28	5.77	18.69	37.38	1.14	-3.15	1.90	0.54	0.30	1.37	0.74	0.55

X: Maximum Strain Direction; Y: Intermediate Strain Direction; Z: Minimum Strain Direction; eA: Extension of Maximum Strain Direction; eB: Extension of Intermediate Strain Direction: eC: Extension of Minimum Strain Direction; SA: Stretch of Maximum Strain Direction; SB: Stretch of Intermediate Strain Direction: SC: Stretch of Minimum Strain Direction

3.4 Graphical Representation of Strain Data

Different methods have been designed to estimate the finite strain of strain markers. These include the Flinn's diagram (Fig. 10), and the Hsu diagram (Fig. 12). The Flinn's and the logarithmic Flinn diagrams for xenoliths in the Porphyritic Granite of Akure Region are shown in Figs. 10 and 11. The Flinn plot indicates that the long and short axes of 99% of the xenoliths studied (Fig. 10) were affected by positive elongations and negative shortenings respectively. This implied that the maximum strain direction was affected by stress that stretched it, and the minimum strain direction was affected by stress that shrinked it. Only 1% of the xenoliths were affected totally by negative shortenings. The Flinn's plot further revealed that 100% of the xenoliths in the area have been strained by tectonic activities that affected the area possibly during the Pan-African Orogeny. The logarithmic Flinn's diagram (Fig. 11) revealed that 96% of the all the xenoliths studied undergone uniaxial constrictional strain which changes their original shape to a prolate cigar shaped ellipsoid with strain intensities between 0.1 and 1.48. The remaining 4% are flattened by stress that acted on them forming an oblate pan-cake shape with strain intensities between 0.3 and 1.5. It further showed that about 96% of these xenoliths were under the influence of a constrictional strain and the remaining 4% under the control of flattening strain. Fig. 11 further revealed that 3% of the xenoliths were deformed under a high constrictional strain (D = 1.5) while 2% were deformed under high flattened strain (D = 1.5). Also, 32% of the xenoliths were deformed under a medium constrictional strain (D = 1). Futhermore, 65% of the xenoliths were deformed under a low constrictional strain (D = 0.5) while only 2% were deformed under low flattened strain (D = 0.5). The Hsu diagram (Fig. 12) revealed that strain of magnitudes between 0 and 1.7 affected the xenoliths. It further confirmed that 97% of the xenoliths were affected by low to medium constrictional strain while only 3% were affected by low flattened strain.

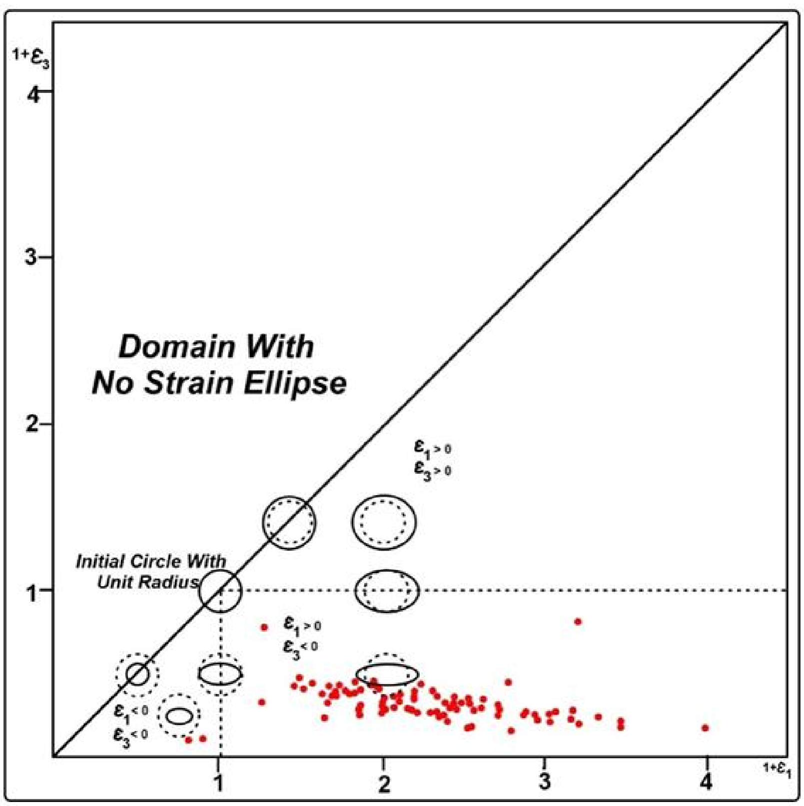

Fig. 10. Flinn's diagram for xenoliths in the porphyritic granite of Akure area

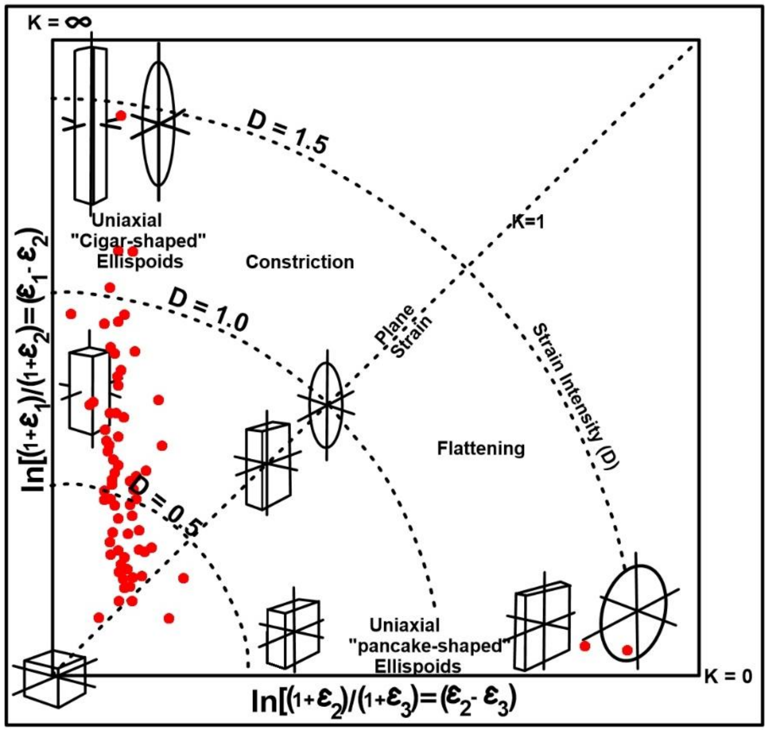

Fig. 11. Logarithmic Flinn diagram for xenoliths in the porphyritic granite of Akure area

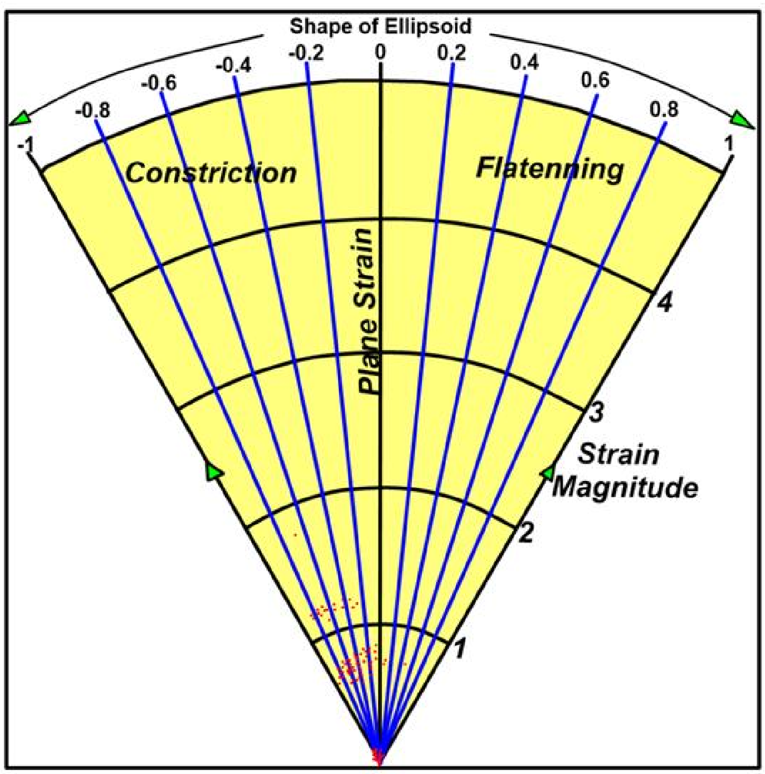

Fig. 12. Hsu diagram for xenoliths in the porphyritic granite of Akure area

4. CONCLUSIONS

The study was carried out to unravel the strain pattern that affected the Akure Porphyritic granite during the Pan-African orogeny. From the analysis of 101 Xenoliths and 877 Phenocrysts, it was observed that the maximum strain directions in both the xenoliths and the phenocryst trends in the NNE-SSW direction, which corresponds to the stress direction of the Pan-African orogeny. This revealed that the pan-African orogeny played a significant role in deforming the xenoliths in the porphyritic granite. The study further showed that the stress that acted on the Akure granitoids produced a constrictional change in most of the xenoliths while only a few of them were flattened. It is recommended that petrographic, geophysical and geochemical studies should be carried out on the xenoliths to ascertain the geological conditions under which they were formed.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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