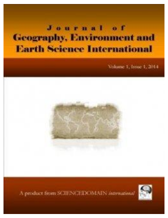

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Paleostress Analysis of Joints in Part of Basement Complex Area of Southwestern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Authors AJA and TAL designed the study. Author AJA carried out field mapping, structural analysis and interpreted the results. Authors AJA, TAL and OMO drafted the first draft of this manuscript. All authors read and approved the final manuscript.

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ABSTRACT

This study was carried out to understand structural features of joints of Owo area with the intention of unravelling the paleostress history of the area. The study area is a detachment of the Igarra schist belt, southwestern Nigeria. In this study, field mapping techniques and structural interpretations of joints using acceptable international methods were employed. The study was carried out in Owo, Ondo State, Nigeria from February, 2015 to July, 2016. Field mapping techniques involved the identification of joints and the measurement of strike and dip values using compass clinometer. A total of 623 joints were measured from nine mapping stations and their eigenvalues of $\sigma_1, \sigma_2 and\ \sigma_3$ with their trends and plunge values were plotted and input into the Win_Tensor Version: 5.8.4 software to determine the tensor direction. Three sets of joints that are gently to moderately dipping were observed in the area. They generally belong to radial and pure extensive regime. These joints were possibly formed under a stress condition of about 30-33 MPa. It further revealed that they were reactivated possibly during the pan-African orogeny. The radial and pure extensional tensor is similar to fracture trend related to major episodes of pan-African orogeny across Nigeria which generally NE-SW.

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1. INTRODUCTION

The state of stress in rocks is generally anisotropic and is defined by stress ellipsoid axes, which characterize the magnitudes of the principal stresses [1]. [2] Noted that stress analysis is a useful and popular tool for structural and seismological elements. If an ellipsoidal body undergo positive compression, the longest axis is the ellipsoid's major stress (S_1), the intermediate axis is the intermediate stress (S_2), and the shortest axis is the minimum stress (S_3) [3]. Several paleostress inversion methods have been developed using graphical ([4,5,6]) and analytical means ([7-19]). The orientation and shape of the stress ellipsoid with respect to earth's surface controls the type, orientation and slip sense of faults developed in an area [20]. Extensional structures grow perpendicular to a minimum principal stress S_3 ([21,22]); S_1 is oriented perpendicular to compressional structures, and for strike-slip faults and other tectonic structures produced by shearing, the intermediate stress is vertical [23]. Although paleostress analysis have proved to be empirically valid and successful, there are some limitations to its usage ([24,25,26]). Paleostress inversion studies are used to understand the effect of past slip events along active faults by making use of deflections in the orientations of the stress axes to recognize stress perturbations near the major faults ([27,28]). Standard paleostress inversion techniques are used only for determining the orientations and relative magnitudes (stress ratios) of the regional principal stress axes [20]. It is assumed that slip on the reactivated pre-existing planes of weaknesses and newly developed faults occur in accordance with the orientation and relative magnitudes of the principal stresses ([29,30]).

Where a fault cannot be observed for paleostress analysis, joints have been used in lieu of it [31]. Joints as palaeostress markers provide the record of stress orientation at the time of propagation are often extensional in nature ([32, 33]). Joints can be used separately or collectively with other structures such as contractional fractures such as stylolites to constrain the stress field that led to their formation [31]. The assumption being that the fractures formed in the same homogenous stress field i.e. related to the same deformational event, that the rocks themselves are fairly homogenous, the fractures do not significantly perturb the stress field in their vicinity and also that the structures have not rotated significantly since their initiation [34].

The schists Belts of Nigeria comprise of low grade metasediment trending in the N-S direction [35]. It is best developed in the western half of Nigeria, where the study area is located. They are considered to have been formed during the Upper Proterozoic [35]. It is believed that most parts of the belt include fragments of ocean floor material from small back-arc basin. Several studies have been carried out on the schists belts of Nigeria, though there are conflicting opinions on their formations. While [36] and [37] suggested that they were formed in several basins of deposition, [38] and [39] believed that they are supracrustal cover. Structurally, [40] reported that they are fault-controlled rift-like structures. Using structural and lithological relationships ([37,41,42]) suggested different ages for these metasediments. [43] Concluded that both series have similar deformation history. Many study had been carried out in schist belts across Nigeria but no detailed study had been carried in the Owo area to unravel the tectonic and deformational history of the area. This paper presents the structural features of joints of Owo area with the intention of unravelling the paleostress history of the area.

2. MATERIALS AND METHODS

2.1 Study Area

The study area is located in the northern part of Ondo State, Southwest Nigeria (Fig. 1). It lies between Latitudes 7°00' and 7°25'N and Longitudes 5°20' and 5°45'E. The area is accessible through asphaltic roads connecting the major towns, while minor roads connect settlements to the towns. The major road in the area links Ibadan, Akure and Benin together.

The study area consists typically of dendritic drainage pattern. The major rivers in the area are Rivers Eporo, and Ubeze which run from east to west and are major tributaries of the Ose River. Other major rivers in the study area are River Ogbesse and Aisenwen which runs from North to South. These rivers are perennial in nature and their tributaries are mostly seasonal, reaching their maximum dryness at the peak of the dry season. During the raining season, River Ogbesse overflow its bank causing floods that extends for about 300 meters on the either sides of the bank. The area is located within the tropical savannah belt of Nigeria. The soil belongs to the broad group Alfisol ([44, 45]) of the Basement Complex, though, locally classified as Okemesi Series [44]. The rainfall of is between 1100 mm to 1500 mm per annum and mean monthly temperature of 24-32°C [46].

Geologically, the area is underlain by the Basement Complex of Nigeria, which are generally classified as migmatite-gneiss-quartzite group [47] are Precambrian in age and is within the zone of Pan African reactivation [48]. Rocks outcropping in the area are quartzite, schist, granite gneiss and migmatite gneiss (Fig. 2). The quartzite/quartz schist are found in Owo and Emure, mostly trending from NW to SE [49]. Granite gneiss is observed in Ogbesse and Eporo which are generally low-lying. Migmatite gneiss covers the whole of Oba-Akoko peaking at 1000 meters and forming inselbergs [49].

2.2 Methodology

For this study, field mapping techniques and structural interpretations of joints were carried out in eight stations across the study area. They are designated as Achievers Hall 1A, Sawmill, Achievers Hall 1B, Poly 1, Poly 2, Osere, Ipele and Adafin camp. Field mapping techniques involved the identification of joints and the measurement of strike and dip values using compass clinometer. After the field mapping, the data were plotted on the stereonet using the "stereonet software" (an open source software). Lines were plotted using the strike and dip data obtained from the field. This was used to generate rose diagrams which was used to determine the trends of joints in the area.

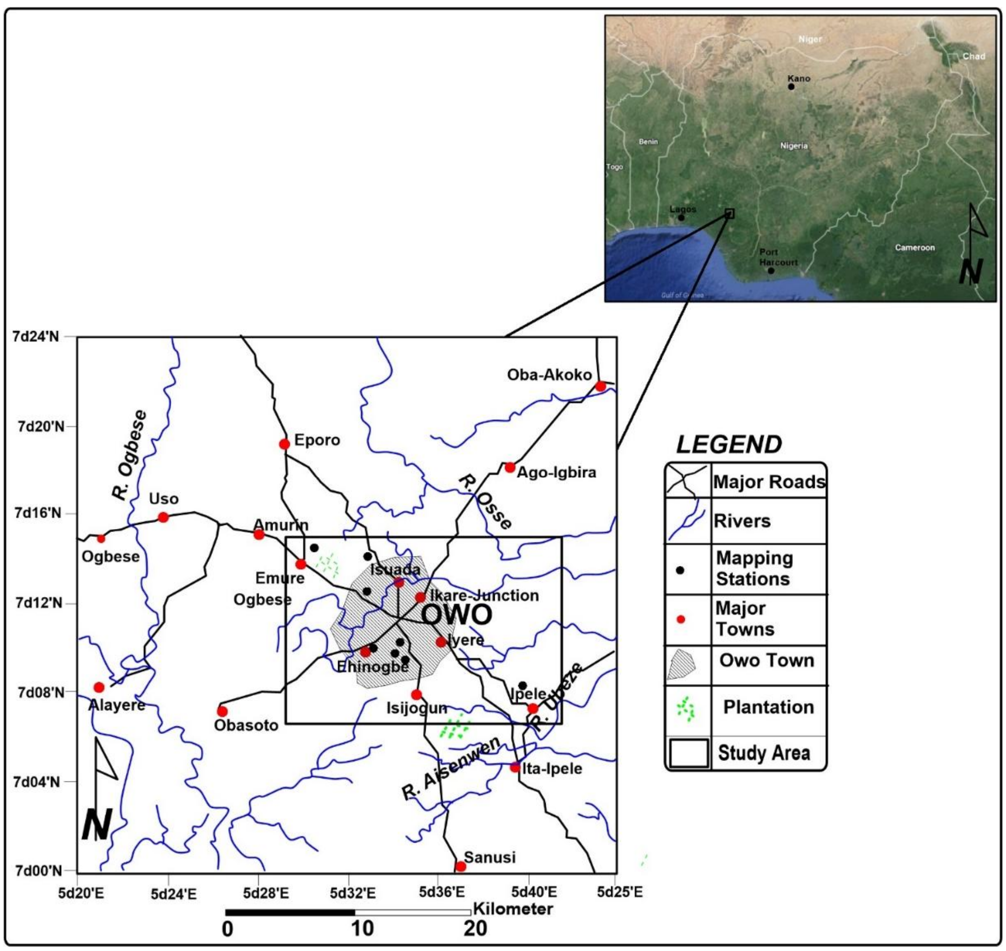

Fig. 1. Location map of the study area

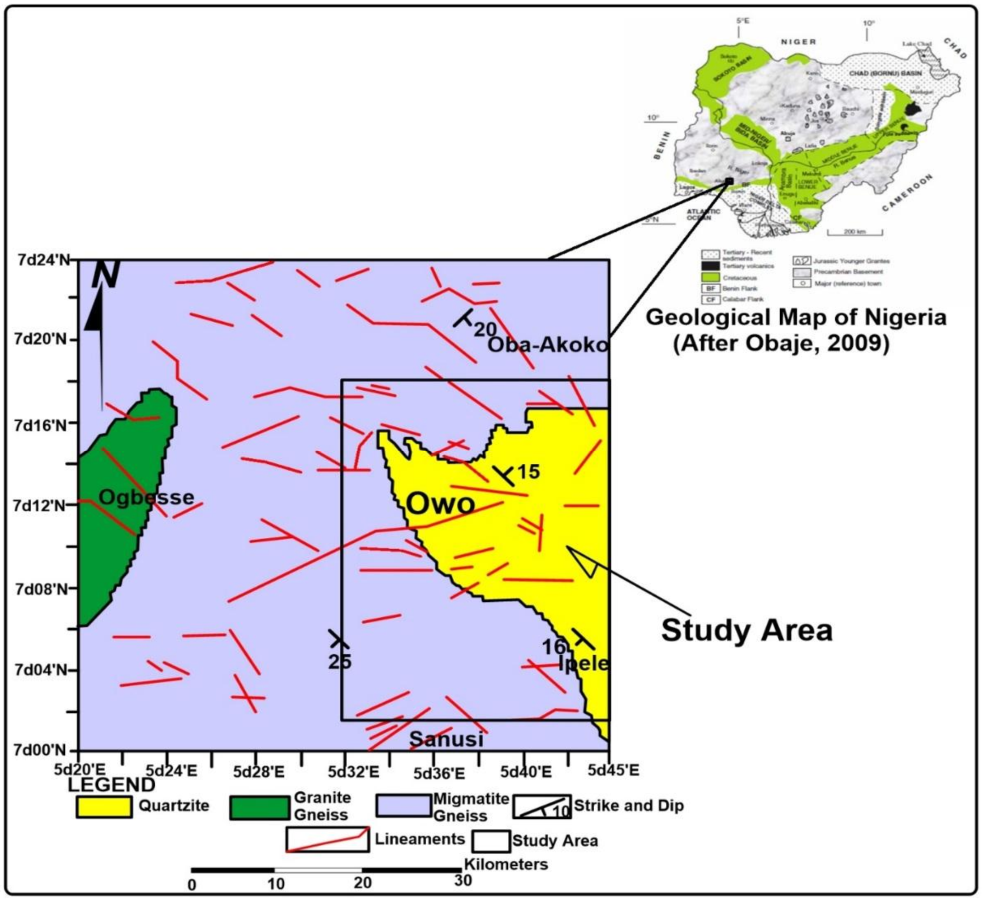

Fig. 2. Geological Map of Owo Area. Lineaments were mapped using LANDSAT^{TM} imagery after [49]

The planes and plane from poles diagram was also generated using the stereonet software using the strike, dip, and dip quadrant values. The cylindrical best fit gave the eigenvalues data of $\sigma_1, \sigma_2 and\, \sigma_3$ with their trends and plunge values. These data were then input into the Win_Tensor Version: 5.8.4 software to determine the tensor direction using the $\sigma_1, \sigma_2 and\, \sigma_3$ trend values. This showed the direction of stress on Schmidt diagram. The Mohr diagram for each station was obtained. Other important data generated include SH_{max}, Sh_{min} and R (tectonic regimes). R was calculated using equation 1.

$$R = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} \qquad (1)$$

Where $0 \leq R \leq 1$

The stress regime is determined by the nature of the vertical stress axes: extensional when σ_1 is vertical, strike-slip when σ_2 is vertical and compressional when σ_3 is vertical. The stress regimes also vary, within these three main types, as a function of the stress ratio R: Radial extension ($\sigma_1$vertical, 0 < R < 0.25), Pure extension (σ_1 vertical, 0.25 < R < 0.75), Transtension (σ_2 vertical, 0.75 < R < 1 or σ_2 vertical, 1 > R > 0.75), Pure strike-slip (σ_2 vertical, 0.75 > R > 0.25), Transpression (σ_2 vertical, 0.25 > R > 0 or σ_3 vertical, 0 < R < 0.25), Pure compression (σ_3, vertical, 0.25 < R < 0.75) and Radial compression (σ_3 vertical, 0.75 < R < l) ([50,51]). The type of stress regime can be expressed numerically using an index R', ranging from 0.0 to 3.0 and defined as follows:

R' = R when (σ_1 is vertical; extensional stress regime)
R' = 2 - R when (σ_2 is vertical; strike-slip stress regime)
R' = 2 + R when (σ_3 is vertical; compressional stress regime)

3. RESULTS AND DISCUSSION

3.1 Results

A total of 623 joints were mapped in all the stations. The breakdown for each station is Achievers Hall 1A (55), Sawmill (45), Achievers Hall 1B (49), Poly 1 (116), Poly 2 (49), Osere (89), Ipele (111) and Adafin camp (109) (Fig. 3). The joints in the study area are subparallel, parallel and cross-cutting each other at different parts of the study area. The broad trend analysis of the joints revealed that the joints are trending from NE-SW and NW-SE. However, majority of the joints tends to prefer the NE-SW direction as revealed by the Fig. 5. Paleostress data are presented in Table 1.

At Achievers Hall 1A station, 20.41% of the joints trends in the north-northeastern direction, 30.61% in the south-southwest direction, 30.61% in the east-southeast direction and 28.57% in the north-northeastern direction (Fig. 4). The average length of the joints is 11.04 cm. The joints in this station belongs to pure extensive regime and a Normal fault region according to the Andersonian classification (Fig. 6). This stress regime is classified by $\delta_1 = 88/118$, $\delta_2 = 02/297$and $\delta_3 = 00/027$ and the NNE-SSW direction of maximum extension, characterized the gently to moderately dipping joints.

At Adafin station, 26.61% of the joints trends in the north-northeastern direction, 20.18% in the south-southwest direction, 40.37% in the east-southeast direction and 12.84% in the north-northeastern direction (Fig. 4). Their average length is 10.5 cm. The joints in this station belongs to pure extensive regime and a Normal fault region of the Andersonian classification (Fig. 6). This stress regime is classified by$\delta_1 = 88/126$, $\delta_2 = 02/336$ and $\delta_3 = 01/246$ and ENE-WSW direction of maximum extension, characterized by the gently dipping joints.

At Sawmill station, 25% of the joints trends in the north-northeastern direction, 29.16% in the south-southwest direction, 20.83% in the east-southeast direction and 25% in the north-northeastern direction (Fig. 4). Their average length is 27.26 cm. The joints in this station belongs to radial extensive regime and a Normal fault region of the Andersonian classification (Fig. 6). This stress regime is classified by$\delta_1 = 83/285$, $\delta_2 = 01/118$ and $\delta_3 = 07/094$ and NNE-SSW direction of maximum extension characterized by gently to moderately dipping joints.

At Osere station, 26.04% of the joints trends in the north-northeastern direction, 28.13% in the south-southwest direction, 33.33% in the east-southeast direction and 12.5% in the north-northeastern direction (Fig. 4). Their average length is 24.56 cm. The joints in this station belongs to pure extensive regime and a Normal fault region of the Andersonian classification (Fig. 6). This stress regime is classified by$\delta_1 = 87/000$, $\delta_2 = 00/308$ and $\delta_3 = 03/218$ and NE-SW direction of maximum extension, characterized by gently to moderately dipping joints.

At Achievers Hall 1B station, 52% of the joints trends in the north-northeastern direction, 14% in the south-southwest direction, 20% in the east-southeast direction and 14% in the north-northeastern direction (Fig. 4). The average length of the joints is 20.67 cm. The joints in this station belongs to pure extensive regime and a Normal fault region of the Andersonian classification (Fig. 6). This stress regime is classified by $\delta_1 = 83/327$, $\delta_2 = 06/121$ and $\delta_3 = 03/211$ and NNE-SSW direction of maximum extension, characterized by gently to moderately dipping joints.

At Poly 1 station, 28.45% of the joints trends in the north-northeastern direction, 25.86% in the south-southwest direction, 32.76% in the east-southeast direction and 13% in the north-northeastern direction. The average length of the joints is 18.65 cm. The joints in this station belongs to radial extensive regime and a Normal fault region of the Andersonian classification. This stress regime is classified by$\delta_1 = 82/252$, $\delta_2 = 03/360$ and $\delta_3 = 08/090$ and ENE-WSW direction of maximum extension, characterized by gently to moderately dipping joints.

At Ipele station, 36.94% of the joints trends in the north-northeastern direction, 32.43% in the south-southwest direction, 10.82% in the east-southeast direction and 19.81% in the north-northeastern direction. The average length of the joints is 25.50 cm. The joints in this station belongs to radial extensive regime and a Normal fault region of the Andersonian classification. This stress regime is classified by$\delta_1 = 86/285$, $\delta_2 = 01/76$ and $\delta_3 = 04/086$ and E-W direction of maximum extension, characterized by gently to moderately dipping joints.

Fig. 3. Joints in parts of the study area. Some of the joints are subparallel, parallel and cross-cutting each other

At Poly 2 station, 30.61% of the joints trends in the north-northeastern direction, 32.43% in the south-southwest direction, 28.57% in the east-southeast direction and 34.69% in the north-northeastern direction. The average length of the joints is 18.26 cm. The joints in this station belongs to radial extensive regime and a Normal fault region of the Andersonian classification. This stress regime is classified by $\delta_1 = 83/067$, $\delta_2 = 06/273$ and $\delta_3 = 03/183$ and N-S direction of maximum extension, characterized by gently to moderately dipping joints.

3.2 Discussion

Paleostress inversion techniques have been used in several parts of the world to unravel the tectonic history of many geological environments ([1,2,31]). Although there are limitations to the use of paleostress inversion techniques, it is still widely acceptable method to understand tectonic histories of any geological settings ([31]). Studies within the Basement Complex of Nigeria revealed that NW – SE trending lineaments are possibly pre-Pan African and might have been overprinted by a set of NE – SW fracture system cut obliquely by an E-W ([52,53]). Joints of Owo area revealed these trends. In all the stations where field measurements were carried out, three sets of joints were observed. These are the NW-SE, NE-SW and the E-W trending lineaments (Fig. 4 and 5). This is in consonance with lineament mapping of this area by [49] where he used LANDSAT^{TM} to study lineaments in the area. It is widely believed that lineaments trending NE-SW, N-S and E-W were possibly formed during the pan-African orogeny ([52,54,55]). Therefore ages can be assigned to joints in Owo area based on the aforementioned theories. Joints trending NW-SE are possibly pre Pan-African [56]. Some other authors have assigned an Eburnean age to these set of joints within the schist belt, where this area is located. The joints trending NE-SW are assigned the pan-African age [56]. The pan African orogeny is believed to have occurred some 500 million years ago [57].

Table 1. Paleostress data of the study area

S/N	Locations	σ_1 Trend/Plunge	σ_2 Trend/Plunge	σ_3 Trend/Plunge	R'	SHmax	SHmin	Andersonian region	Shear stress magnitude
1.	Achievers Hall1A	118/88	297/02	027/000	0.5	117	27	NF	33
2.	Adafin Camp	88/126	02/336	01/246	0.5	156	66	NF	33
3.	Sawmill	83/285	01/88	07/094	0	105	15	NF	30
4.	Osere	87/00	00/308	03/218	0.5	128	38	NF	31
5.	Achievers Hall1B	83/327	06/121	03/211	0.5	121	31	NF	30
6.	Poly 1	82/252	03/360	08/090	0	72	162	NF	31
7.	Ipele	86/285	01/076	04/086	0.5	176	86	NF	32
8.	Poly 2	83/067	06/273	03/183	0.5	128	03	NF	32

NF = Normal Fault.

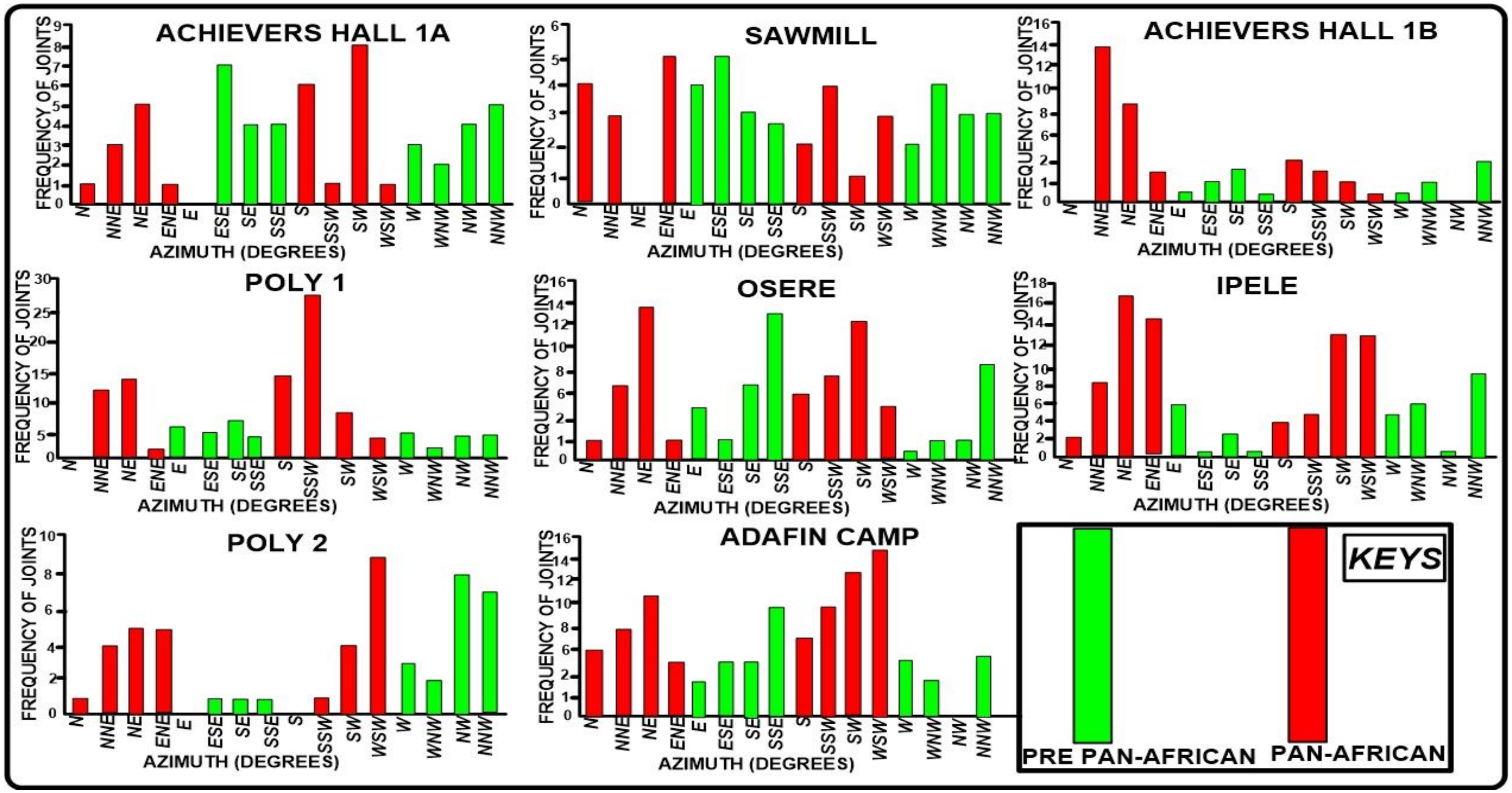

Fig. 4. Bar chart showing the distribution of joints into sixteen different azimuths

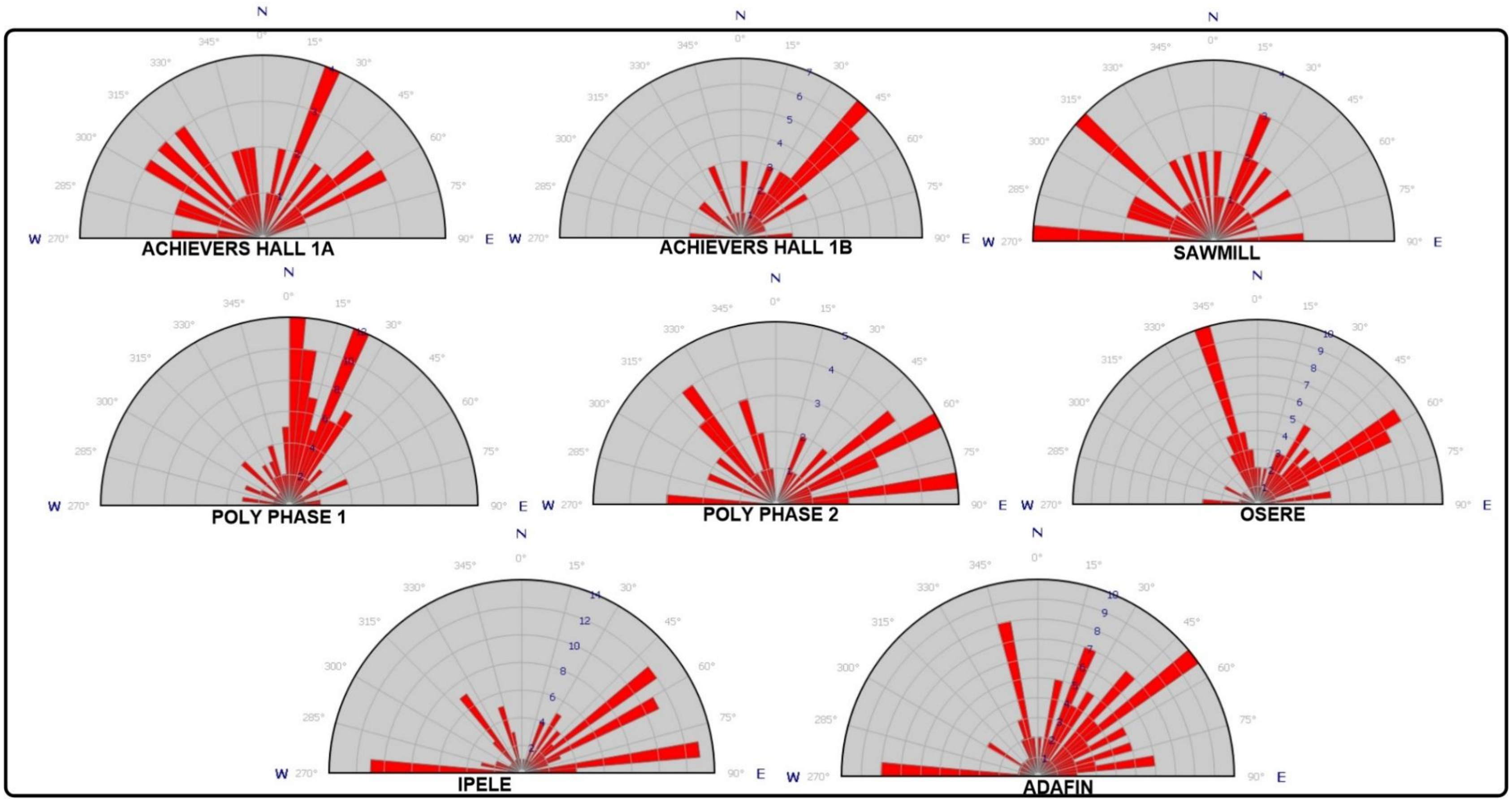

Fig. 5. Rose diagrams of joints in the study area

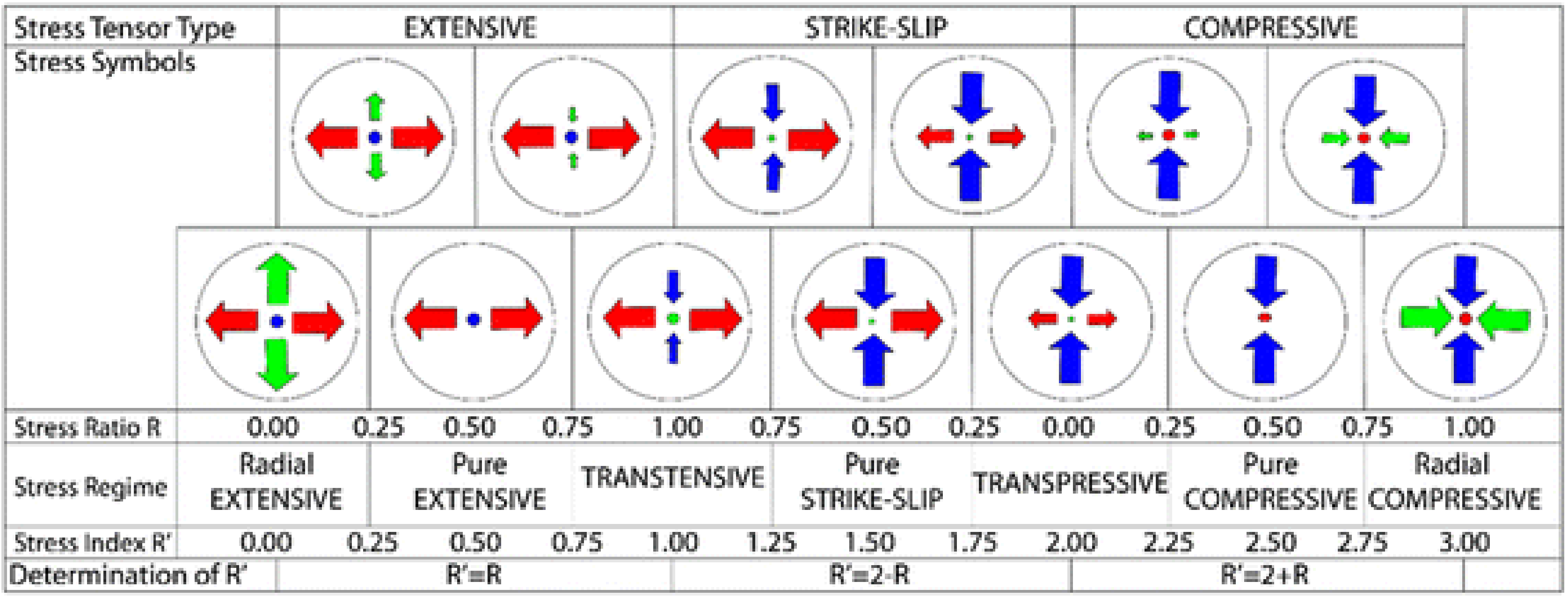

Fig. 6. Stress tensor representation for different stress regimes [60]

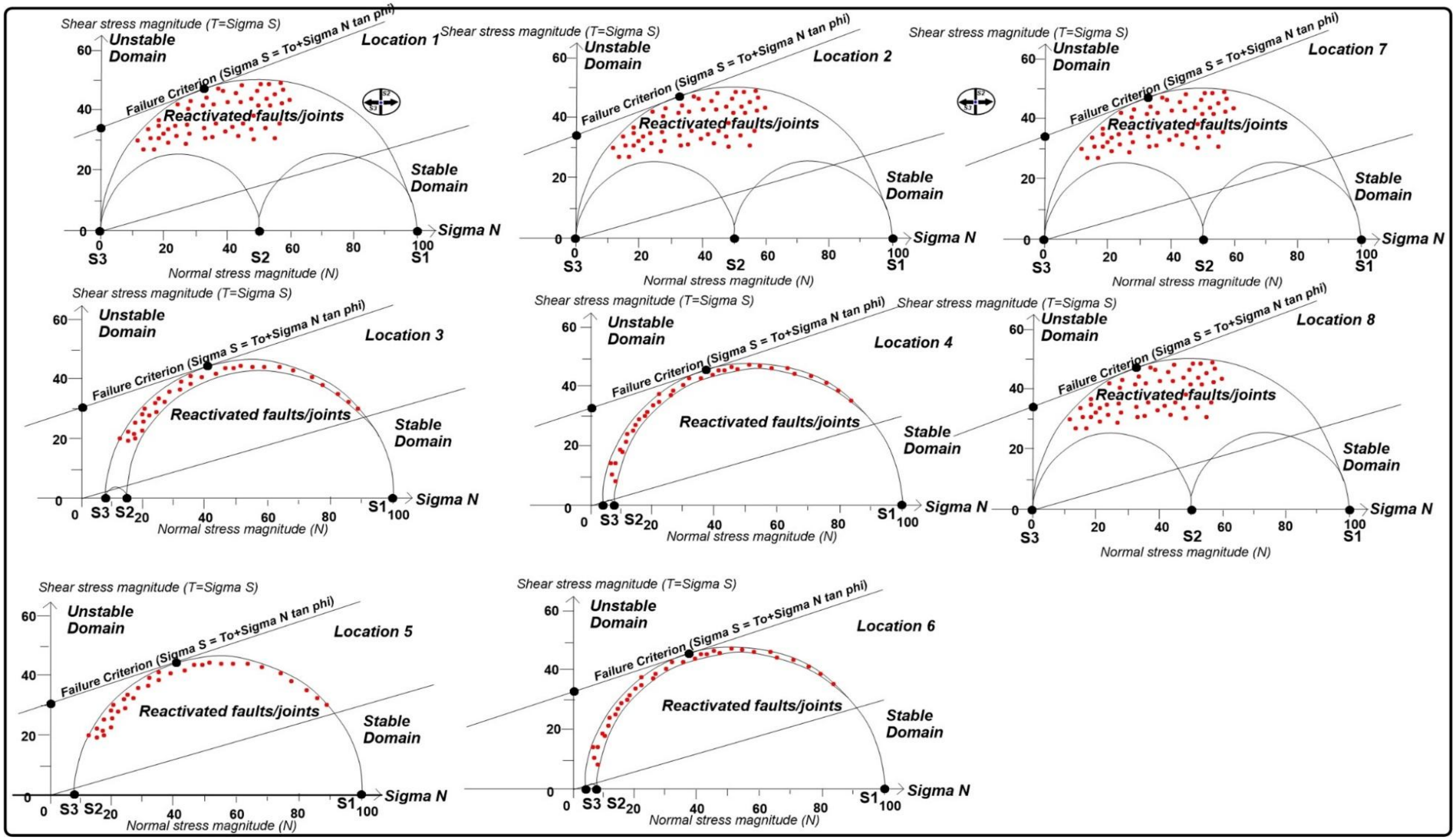

Fig. 7. Mohr strain diagram for rocks in the study area

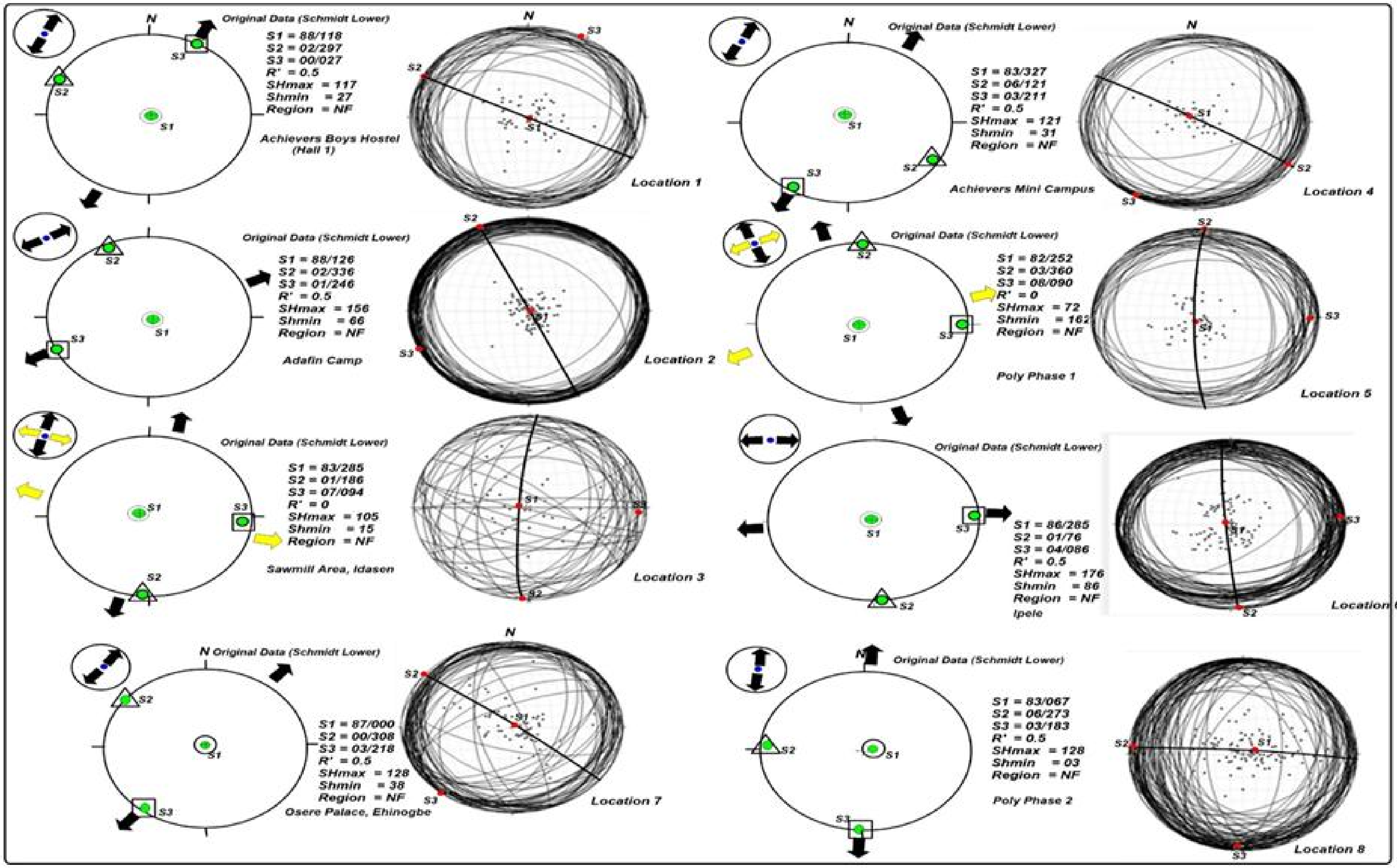

Fig. 8. Direction of paleostress in the study area

Paleostress inversion revealed that the NE-SW, N-S and the E-W oriented stress field occur in the area although the NE-SW is the most dominant (Fig. 6) and were formed by normal faulting according to the Andersonian classification of tectonic regimes (Fig. 6). This is in consonance with the idea that Nigeria schist belts are fault-controlled rift-like structures [58] which are extensional in nature. Mohr strain diagram (Fig. 7) shows that these joints were possibly formed under a stress condition of about 30-33 MPa. The further revealed that the joints are mostly reactivated. This reactivation may be linked to a shift of the stress field from NW-SE direction to NE-SW directions that accompanies the formation of these joints. These joints were possibly reactivated during the pan-African orogeny. The reactivated joints were possibly formed during the Eburnean when the schist belts across Nigeria were being formed. This study conforms to other related works in the Basement Complex of Nigeria. The reactivation of similar structures have also been reported in Ghana [59].

4. CONCLUSION

This research undertook the structural analysis of brittle structures within the Owo schist area to ascertain the paleostress conditions during their formations. Detailed field-based structural and paleostress analysis using the software Win_TENSOR™ have enabled three stress regime phases to be characterized for the study area for Eburnean and pan-African age. A possibly Eburnean and pan-African stress fields trending NW-SE and NE-SW respectively have been uncovered. These stress regimes are related to regional tectonism that affected West African craton before the separation of South America from Africa. The study revealed that the first sets of joints trending in the NW-SE were first formed, were healed and were reactivated by the NE-SW trending joints.

The radial and pure extensional tensor, with a general NE-SW maximum extension (SHmax) is strikingly similar to fracture trend related to major episodes of pan-African orogeny across Nigeria. The study also revealed that joints in the area are related to normal faulting that affected the area, which might be the possible cause of the separation of the Owo schist area from the Igarra schist belt.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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