

*Full Length Research Paper*

## **Alteration of $\sigma_3$ field during the evolution of a polycyclic basement complex**

**Omosanya, K. O.<sup>1</sup>, Akinbodewa, E. A.<sup>1</sup>, Mosuro, G. O.<sup>1</sup> and Kaigama, U.<sup>2</sup>**

<sup>1</sup>Department of Earth Sciences, Olabisi Onabanjo, University, Ago-Iwoye, Ogun State, Nigeria.

<sup>2</sup>Department of Geology, Modibbo Adama University of Technology, Yola, Nigeria.

Accepted 5 January, 2013

The polycyclic nature of the Migmatized gneiss basement complex of South-western Nigeria is depicted by several tectonic imprints oriented in different manner; such setting is characterized by temporal adjustment of the minimum stress field. Attitude (strike and dip), length, width, average perpendicular distance and aspect ratios were taken for foliations, joints, veins, intrusions and boudinages. These parameters were analyzed on histograms, rose diagrams and stereo nets; outcrop maps were used to elucidate the heterogeneity of the stress field. Joints are the youngest tectonic structures in the study area; they include extensional and shear types, systematic, non-systematic and orthogonal sets with dihedral angle of  $<90^\circ$ . The boudinages occur in gneissic rocks; the veins and intrusions are metasome in the host rock and are made of quartz, feldspar and pegmatite minerals. The dominant orientation of structures are NNE-SSW for foliations, E-W, NE-SW, and NNW-SSE for joints, N-S, NNW-SSE and NNE-SSW for veins, and N-S for intrusions with dip direction of North-west and South-east for foliations and west for intrusions. Initial orientation of  $\sigma_3$  was east-west during the emplacement of the veins and pegmatite intrusions and then ENE-WSW for the quartz-rich intrusions. Joints oriented NE-SW commonly intersected the other structures suggesting they are juvenile and created by NW-SE oriented  $\sigma_3$ . Subsequently, shearing of the rocks and rotation of the least stress field produced the boudinages, conjugate joints, and tension gashes. Evidence for horizontally situated  $\sigma_1$  is shown by few slightly folded foliations seen in specific locations. In the study area, the joints were the product of multidirectional minimum stress which was dominantly oriented NW-SE prior to the Pan African orogeny.

**Key words:** Tectonic, stress,  $\sigma_3$ , joints, veins, boudinages, Pan African.

### **INTRODUCTION**

Tectonic stress applied to a rock is one or a combination of extension, compression or shearing (Ramsay, 1967). Extensional structures grow perpendicular to a minimum principal stress  $\sigma_3$  (Griggs and Handin, 1960; Kehle, 1964);  $\sigma_1$  is oriented perpendicular to compressional structures, and for strike-slip faults and other tectonic

structures produced by shearing, the intermediate stress is vertical (Anderson, 1936). Extensional structures include normal faults, joints, veins (including unsheared tension gashes), and intrusions, both pegmatite and quartz-feldspar rich. On the other hand, compressional structures are limited to ductile rock types producing folds and thrust faults in their brittle equivalents. Evidence for shearing most often includes the presence of LS tectonites characterized by S-C fabrics or Riedel shears along shear zones (Twiss and Moore, 2007).

Joints as palaeostress markers that provide the record

\*Corresponding author. E-mail: [kamaloomosanya@yahoo.com](mailto:kamaloomosanya@yahoo.com).  
Tel: +2348034454405.

of stress orientation at the time of propagation are often extensional in nature (Dyer, 1983; Pollard and Segall, 1980); shearing commonly generate conjugate joints sets characterized by dihedral angles (Muehlberger, 1961). This is symbolized by the rotation and subsequent change in direction of  $\sigma_3$ . Consequently, joints are ubiquitous and the most dangerous palaeostress markers (Pollard et al., 1982). Intrusions and veins are developed in the same manner as joints except that they are subsequently filled with precipitated minerals such as quartz, feldspar and pegmatite minerals. In addition, boudinages are created by the disruption of layers, bodies or foliation planes within a rock mass in response to bulk extension along the enveloping surfaces (Lloyd and Ferguson, 1981; Swanson, 1992, 1999). Similarly, a-slip boudinages are formed by bulk shear sense; progressive deformation of arrays of veins by shear stresses can lead to sigmoid tension gashes (Ramsay and Graham, 1970; Pollard et al., 1982; Coelho et al., 2006; Lisle, 2012).

The Nigerian basement is characterized by different histories of metamorphism, orogenies and structural modifications (Odeyemi, 1981; Rahaman et al., 1983; Caby, 1989) which is reflected in its complex petrological and structural composition. The polycyclic nature of the basement rock means earlier episodes of metamorphism, magmatism; orogenies and tectonism would have been overprinted, reworked and modified by younger events (De Swardt, 1947; Oyawoye, 1972; Woakes et al., 1987; Ajibade et al., 1987; Omosanya et al., 2010, 2011, 2012). To reconstruct the palaeostress in such a setting is very problematic, as earlier events are often annihilated by recent tectonics activities, for example, older joints sets could be rotated during subsequent shearing. In addition, relict of the older events is sometimes preserved and do co-exist with the juvenile tectonic activities.

Structural analysis of rocks is often done using orientation diagrams such as rosette and stereographic projections. These tools have invaluable application in geology and could unravel history of deformation in several geological setting. In this research, we aim to (a) identify tectonic structures in rocks of the study area (b) evaluate their spatial distribution using simple orientation diagrams (c) and decipher changes in the direction of the principal stresses with time. In this work, we simplify the study of palaeostresses direction associated with deformation observed in the rock using outcrop sketch maps. We start by discussing the geological settings, methods used for the research, results and conclusion on the importance of the study.

### Local geologic setting

Regionally, the study area is situated on the South-western portion of the Nigerian basement, an extension of the Dahomeyide shield of the West African

Craton (WAC). The eastern border of the craton is occupied by series of ancient gneisses, schists and quartzites (Burke et al., 1976). In addition, the metamorphic rocks of the shield are cut by a variety of mainly acid igneous rocks.

The Precambrian basement rocks of South-western Nigeria include the Migmatized gneissic complex (MGC) of Achaean to early Proterozoic age (Grant, 1970; Grant et al., 1972; Dada et al., 1993; Dada, 1999), N-S trending schist belts of Upper Proterozoic age (Rahaman, 1988) and the Older Granitoid of Pan African age (Fitches et al., 1985). The Nigerian basement rock is affected by four orogenic episodes, which include the Liberian ( $2700 \pm 200$  Ma, Oversby, 1976), Eburnean ( $2000 \pm 200$  Ma, Oversby, 1976), Kibaran ( $1100 \pm 200$  Ma, Ogezi, 1977; Ekwueme, 1987), and Pan African orogenies ( $600 \pm 150$  Ma, Van Breemen et al., 1997; Fitches et al., 1985); the Kibaran orogeny is not generally accepted to have affected the Nigerian basement rocks.

The basement complex in South-western, Nigeria is composed of MGC that is characterized by grey foliated Biotite Acid/Biotite Hornblende quartz feldspathic gneiss of tonalitic to granodioritic composition (Rahaman, 1988); Mafic to ultramafic component which outcrops as discontinuous boudinaged lenses or concordant sheet of amphibolites with minor amount of biotite-rich ultramafite; and Felsic component, a varied group comprised of pegmatite, aplite quartz-oligoclase veins, fine-grained granite gneiss, and porphyritic granite.

The MGC of South-western Nigeria is affected by 3 major geotectonic events (a) initiation of crust forming process during the Early Proterozoic (2000 Ma) typified by the Ibadan (South-western Nigeria) grey gneisses considered by Woakes et al. (1987) as to have been derived directly from the mantle; (b) emplacement of granites in Early Proterozoic (2000 Ma) and (c) the Pan African events (450 to 750 Ma) (Oyinloye, 2011). The schist belts represent N-S trending synformal troughs infolded into the MGCs which are best developed in the western part of the country. The schist belts are largely sediment-dominated in contrast to other schist belts of South Africa and Australia. The most important lithologies are pelrites, semi-pelrites and quartzite. This rock suite provides information on the structural pattern of the basement rocks.

The older granites correspond to the last rock types of the basement; these rocks are the most obvious manifestation of the Pan African orogeny and constitute about 40 to 50% of the basement complex outcrop. They vary in composition from tonalite through granodiorites to granite and syenite granodiorite composition is the most common (Oyinloye, 2011).

### METHODOLOGY

In order to accomplish the rationale of this research, 17 rock exposures/outcrops were studied. Mapping of the structures was

done by inventory; areas of complex structural architecture were gridded at outcrop locations. Attitudes (strike and dip) of foliation planes, joints, veins and intrusions were estimated using techniques of Barnes and Lisle (2008) and Omosanya et al. (2011). Other parameters measured on the field include the average perpendicular distance between joints sets, veins and intrusions. The average perpendicular distance is the mean of three separations taking diagonally between the structures (Omosanya et al., 2010). The important structural inquiries include a) whether the joints/veins/intrusions are systematic or non-systematic; b) the number of joints/veins/intrusions sets present, c) their cross-cutting relationship; d) the surface appearance of the joints/veins/intrusions; e) spacing and density; f) relationship of the joints/veins/intrusions to other geological structures and g) whether joints/veins/intrusions are isolated or connected to regional network. In addition, boudinages, foliations and intrusions were studied in order to describe the evolution of the entire outcrop and relate the interaction of the main extensional structures. For the purpose of description, the aspect ratio of the boudinages and veins were estimated as length/width.

Consequently, the data collected were plotted on histograms, rose diagrams and stereographic projections. The interaction of the structures at outcrop scale was studied using the outcrop sketch maps. Foliation were described as space and continuous if the shape or arrangement of rock components is greater or less than 0.001 m; for ease of description, joints were assigned letter J, intrusions, I and veins as V.

The principal stresses responsible for deformation in rocks are mutually perpendicular,  $\sigma_1$  is the maximum compressive stress,  $\sigma_2$  is intermediate, while  $\sigma_3$  is the maximum tensile stress and the least compressive (Anderson, 1936). The use of joint interaction and their cross cutting relationship with other structures have been previously applied for timing the evolution of joints (Omosanya et al., 2011, 2012). In this work, we use rose diagrams to elucidate the direction of minimum principal stress associated with the extension of the joints, consequently, the joint interaction with the other tectonic structures were studied on the sketch maps and used to define the change or variation in the position of this stress field through the history of each of the outcrops.

## RESULTS

### Description of rock types

Rock types in the study area include biotite-gneiss, banded-gneiss, (Migmatized in some parts and intruded by pegmatite) and granite (Figure 1). The Migmatized gneisses have similar composition with the gneisses, the minerals are dark colored and are dominantly composed of Mafic minerals such as biotite and hornblende. The banded gneisses are characterized by bands resulting from the segregation of Mafic and Felsic minerals during recrystallization (Figure 3a). The Mafic bands consist of biotite and hornblende; the Felsic bands are rich in quartz, muscovite, and orthoclase feldspars. In addition, the gneisses are presumably derived from granitic protolith.

Consequently, the granite gneisses consist of quartz, alkali feldspar, muscovite, and hornblende. The minerals are medium grained and coarse textured. These rocks are slightly foliated, with two kind of foliation planes, an obvious alignment of light colored minerals separated

~1.4 cm and a faint segregation of minerals characterized by very-thin foliation planes. The pegmatite contains large-coarse textured minerals with individual mineral grains ranging from ~2.2 to 5 cm (Figure 3e). They are composed primarily of plagioclase, muscovite, tourmaline, quartz and occasionally dark-colored minerals such as biotite. The pegmatites in the study area occurred as dykes, or irregular pockets in the other rock types.

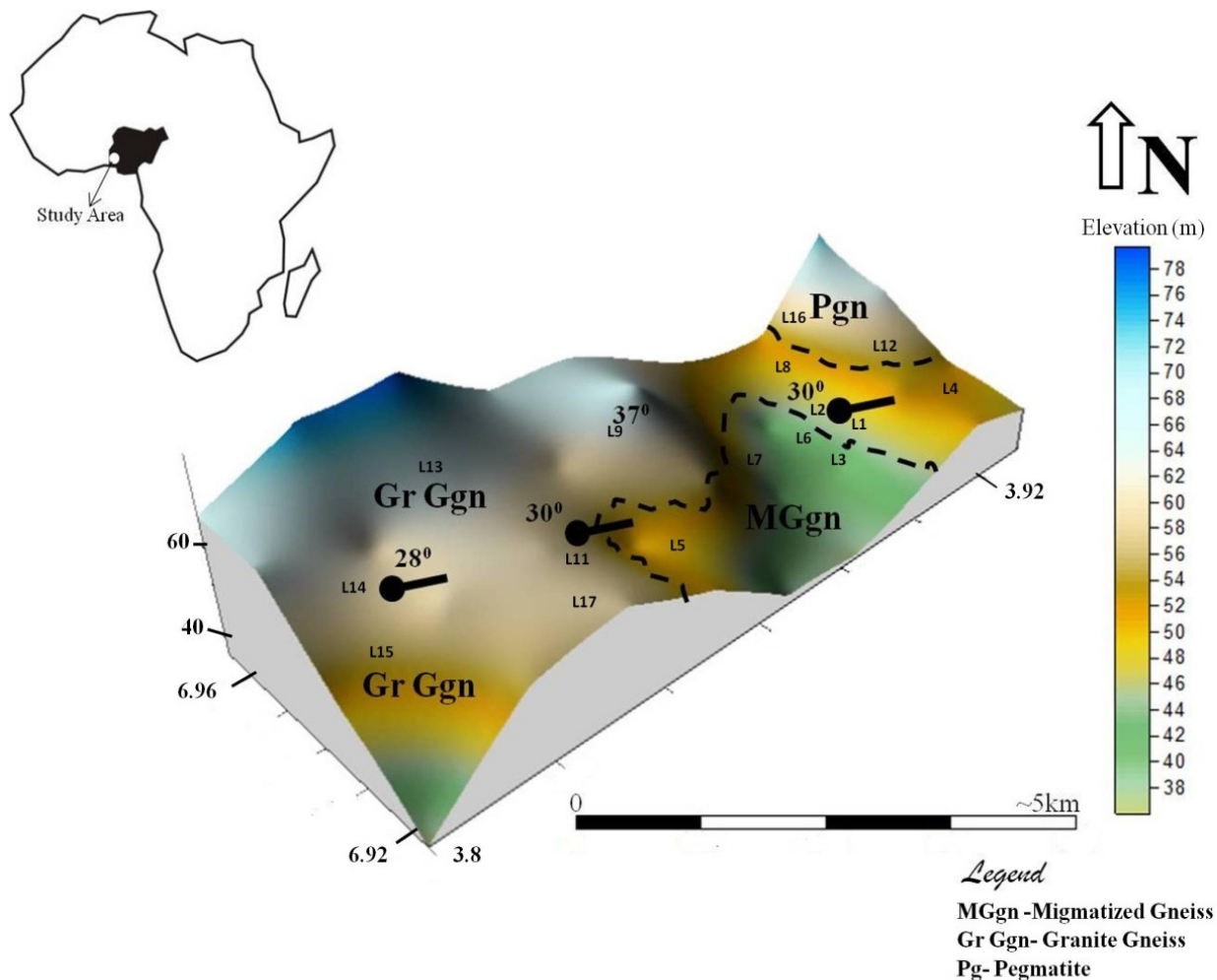
### Geometry and orientation of structures

The strike and dip of 79 individual foliations planes were measured in the study area; they are continuous, fine and dominantly oriented in the N-S, NNE-SSW and NNW-SSE direction with principal dip of east and west (Figure 2a and b). The foliation planes were measured in the migmatite, banded gneiss and the granite gneiss. The principal dip directions suggest the presence of a regional fold in the area. This fold is thought to have an average interlimb angle of ~60° (Figure 2a).

Joints found in the study area include both extensional fractures and shear joints. Three hundred and twenty-five (325) joints were mapped in the area; these structures are oriented in the E-W, N-S, NE-SW, NNW-SSE and ENE-WSW directions (Figure 4). The joint set includes systematic joints with average perpendicular distance of ~4 cm ( $J_{38}$  and  $J_{39}$ , LOC4) up to 67 cm ( $J_{11}$ ,  $J_{15}$ , LOC 15). The joints sets are parallel to sub-parallel in map view. The non-systematic joints have inconsistent average perpendicular spacing.

In general, the surfaces of the joints appear irregular, haphazard, and curved. The surfaces of the joints lacked common features associated (Figure 5) with shearing such as grooves, lines and plumose structures. Intersection geometry of the joints includes T-joints and conjugate joints (Figure 6a to c); some of the conjugate joints have dihedral angle of <90° (Figures 7b, d, and f). Tip geometries include gradual dyeing out, branch outs and y tips. Average length of joints is ~23 cm (LOC 5) to ~71.30 cm (LOC 1) (Table 1 and Figure 7). The longest joints are the master joints in most of the visited outcrops. In addition, joints cross cuts all the other structures in the study area; examples are shown in Figure 3.

The other kind of extensional structures includes the 37 veins oriented in the N-S, NNW-SSE and NNE-SSW directions. Average length of the vein in the area is ~156 cm (LOC 6) and ~303.14 cm (LOC 3) (Table 1 and Figure 7), while the average width is <2.29 cm. The vein type includes quartz, quartzo-feldspathic and in few migmatite, granitic veins; 25% of the veins are composed of quartz. Similarly, the intrusions are composed of quartz ( $I_8$ ,  $I_9$ ,  $I_{10}$ ; LOC 17), quartz-feldspars ( $I_2$ , LOC 4;  $I_3$ ,  $I_4$ ,  $I_5$ , LOC 9 and  $I_{11}$ , LOC 17), and pegmatite minerals ( $I_6$  and  $I_7$ , LOC 12 and  $I_1$  LOC 1), they trend N-S direction with dip dominantly West (Figure 2). Average length and width of



**Figure 1.** Map of the study area. The geology of area is dominated by Granitic gneiss, biotite gneiss and pegmatite. Major depressions on the map correspond to structurally-controlled drainage pathways. Contour values correspond to the elevation above sea level. Elevation data were derived from global positioning system (GPS) readings and data from the National Oceanographic and Atmospheric Association website ([www.noaa.gov](http://www.noaa.gov)). The index map shows the location of the study area in the context of Africa and Nigeria. NB: L is acronym for location of outcrops.

intrusion are ~211 and ~14 cm, respectively.

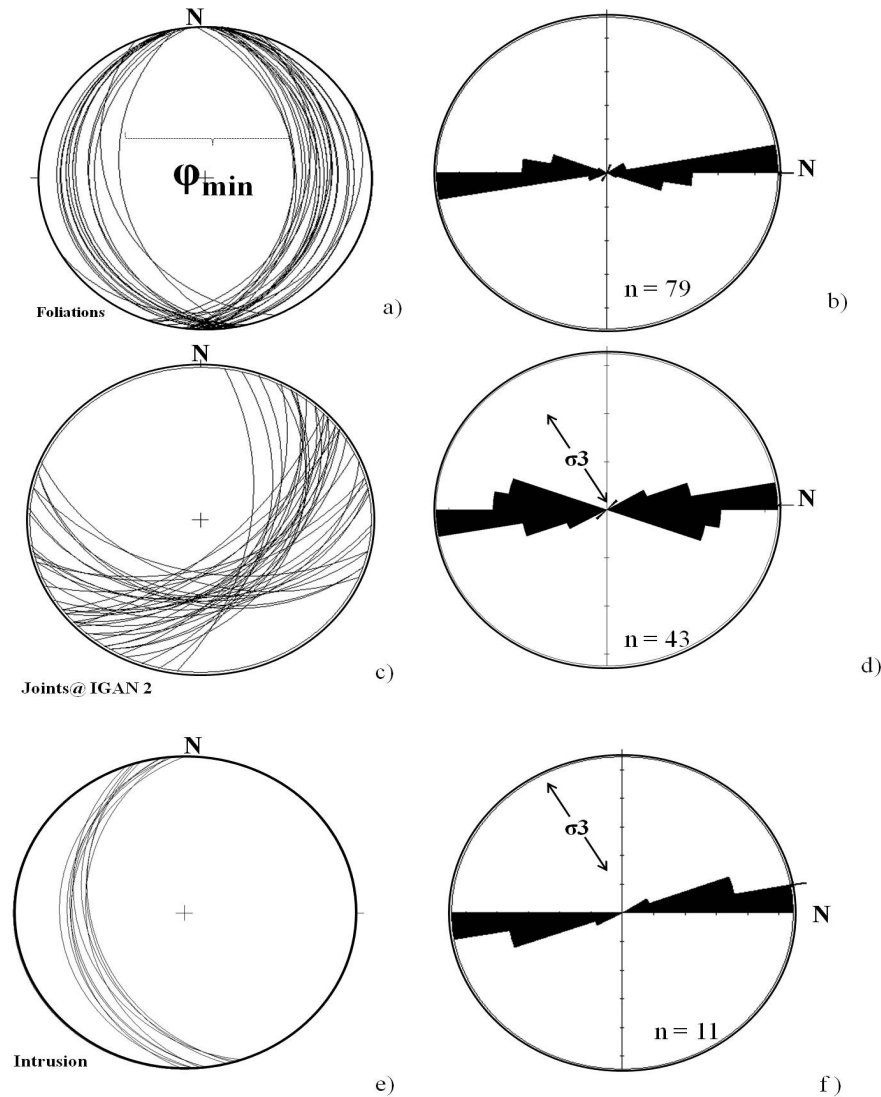
Boudinages are found in the gneissic rocks; they are foliation boudinages oriented in the E-W direction. Average length of the boudinages was ~834 cm, with width and aspect ratios of ~41.35 and ~0.026 cm, respectively. Boudinage in the study area are antithetic (A-slip) with respect to bulk shear sense (Figure 8); they were found at Locations 2, 4, 12, and 17. Other structures include sigmoidal tension gashes and minor folding that are both evidence of shearing and compression of the rocks (Figures 3b, d and f).

### The direction of minimum principal stress

Foliation associated with regional metamorphism and compression are usually oriented perpendicular to the

maximum principal stress,  $\sigma_1$  (Blatt and Roberts, 1996; Vernon, 2004). The dominant orientation of foliation planes in the study area is normal to E-W and ENE-WSW oriented  $\sigma_1$ , which implies that  $\sigma_2$  was perpendicular to these orientation during the formation of the foliation planes.

The joints produced by tensile stress fields are oriented essentially E-W, N-S, and NE-SW, which coincide with the direction of  $\sigma_2$  during their formation. However,  $\sigma_3$  was oriented N-S, E-W and NW-SE, respectively; these joints therefore formed through mode I propagation. For the conjugate joint sets, they are thought to be formed in compressive stress fields, with  $\sigma_3$  oriented ENE-WSW and NNW-SSE. In addition, the direction of  $\sigma_1$  is NNE-SSW and NNW-SSE cutting the plane of the acute angle between the conjugate joints. In addition, the curved surface of the joints imply spatial and temporal difference



**Figure 2.** (a) Stereographic projections for foliations in the study area. The minimum interlimb angle for an inferred regional fold is shown in the figure. (b) Rose diagram for the orientation of foliations in the study area. (c) Stereographic projection for orientation of joints at location 2 joints and intrusion in the study area. (d) Rose diagram for the orientation of joints at Location 2. (e) Stereographic projection for orientation of intrusions in the study area. (f) The rose diagrams for the orientation of intrusions. The inferred direction of  $\sigma_3$  is shown with the arrow.

in the direction of  $\sigma_3$  during the growth of the joints (Blatts and Roberts, 1996).

## DISCUSSION

### Relative timing of structures

Using 9 representative sketch maps (Figure 10), we reconstructed the tectonic evolution of the study area. At Location 1a, the dominant orientation for the joints is NW-SE, only  $J_4$  and  $J_{15}$  are oriented E-W and NE-SW,

respectively. In contrast, the joint in Figure 9b are oriented in NE-SW, N-S and E-W directions. The NE-SW joints cross cut quartz vein ( $V_4$ ), and are presumably younger than the veins. Similarly,  $J_{15}$  was terminated on  $J_{14}$  (Figure 10a), while  $J_7$  and  $J_5$  are pruned on  $J_6$  (Figure 10b). Initial extension of the NW-SE veins was associated with  $\sigma_3$  NE-SW, which is older than the NE-SW oriented joints produced by NW-SE  $\sigma_3$ . In addition, the NE-SW joint are supposedly older than N-S and NW-SE oriented joint. However, the E-W joints predated the NE-SW joints but was unconnected with the NW-SE veins. Thus, it is difficult to establish a timing relationship





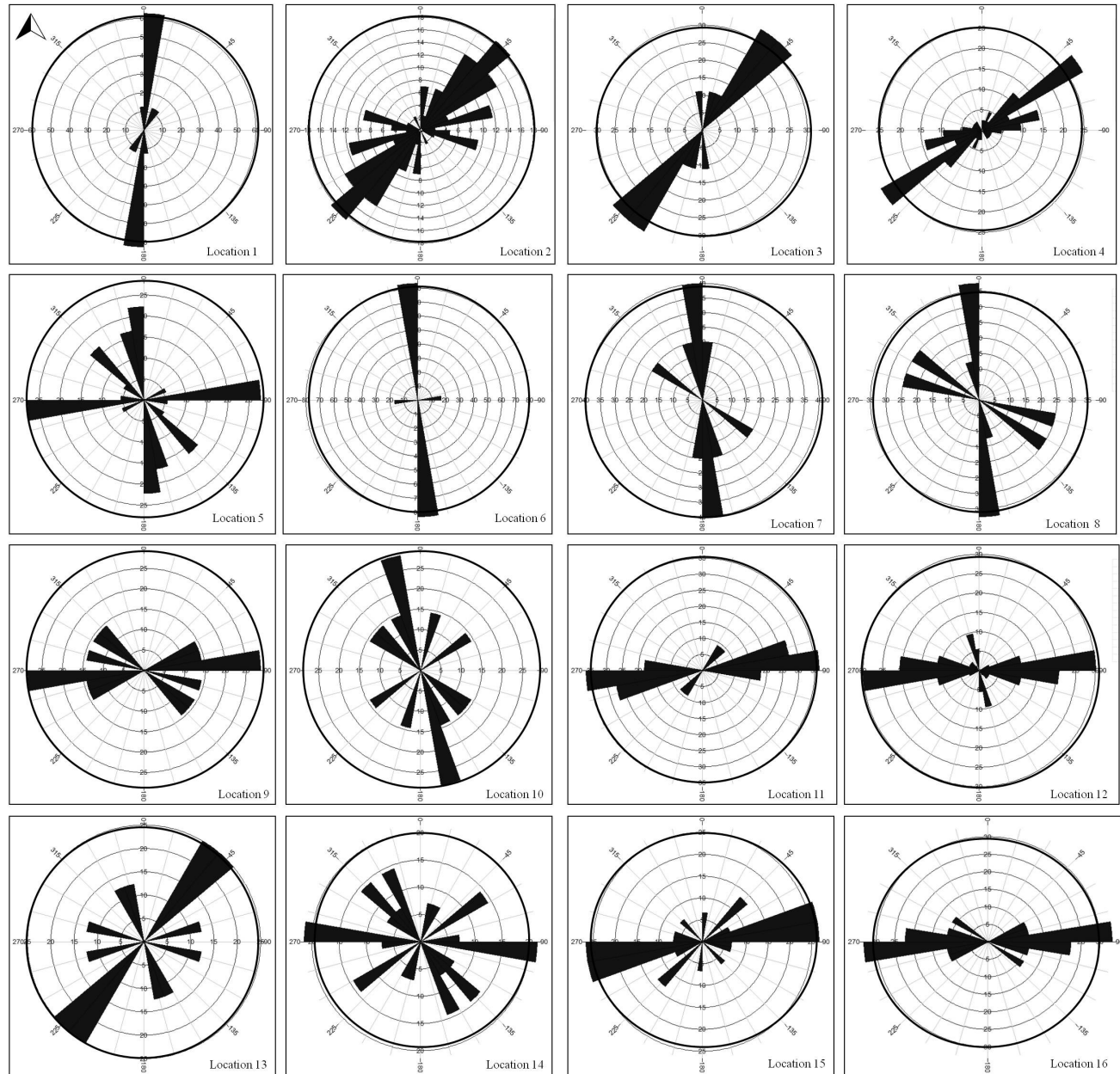
**Figure 3.** (a) Foliation found in the hornblende Gneiss is related to regional metamorphism and subsequent segregation of Mafic and Felsic minerals. (b) An asymmetric fold found in one of the localities. (c) Example of a quartzo-feldspathic vein found in the study area. (d) Tension gashes provided hints on the bulk sense of shear in some of the boudinaged gneisses. (e) An outcrop of a pegmatite. (f) A tension gash cross cut by a quartz vein at Location 7. NB: The direction of the North is shown by the red end of the compass.

between these particular joints and the veins. In terms of relative chronology, the oldest extensional joints at Location 1 are the E-W oriented joints, then NE-SW, N-S and NW-SE which were product of  $\sigma_3$  presumably oriented N-S, NW-SE, E-W and NE-SW, respectively.

The sigmoidal tension gashes were produced by NW-

SE oriented  $\sigma_3$ .

The intersection of  $J_{15}$  and  $J_{13}$  at Location 1 produced a conjugate intersection geometry with  $\sim 60^\circ$  dihedral angle. South of the outcrop in grid 2 (Figure 10c), the same geometry was also observed though with an acute angle of  $\sim 74^\circ$ . Conjugate intersection was in addition observed



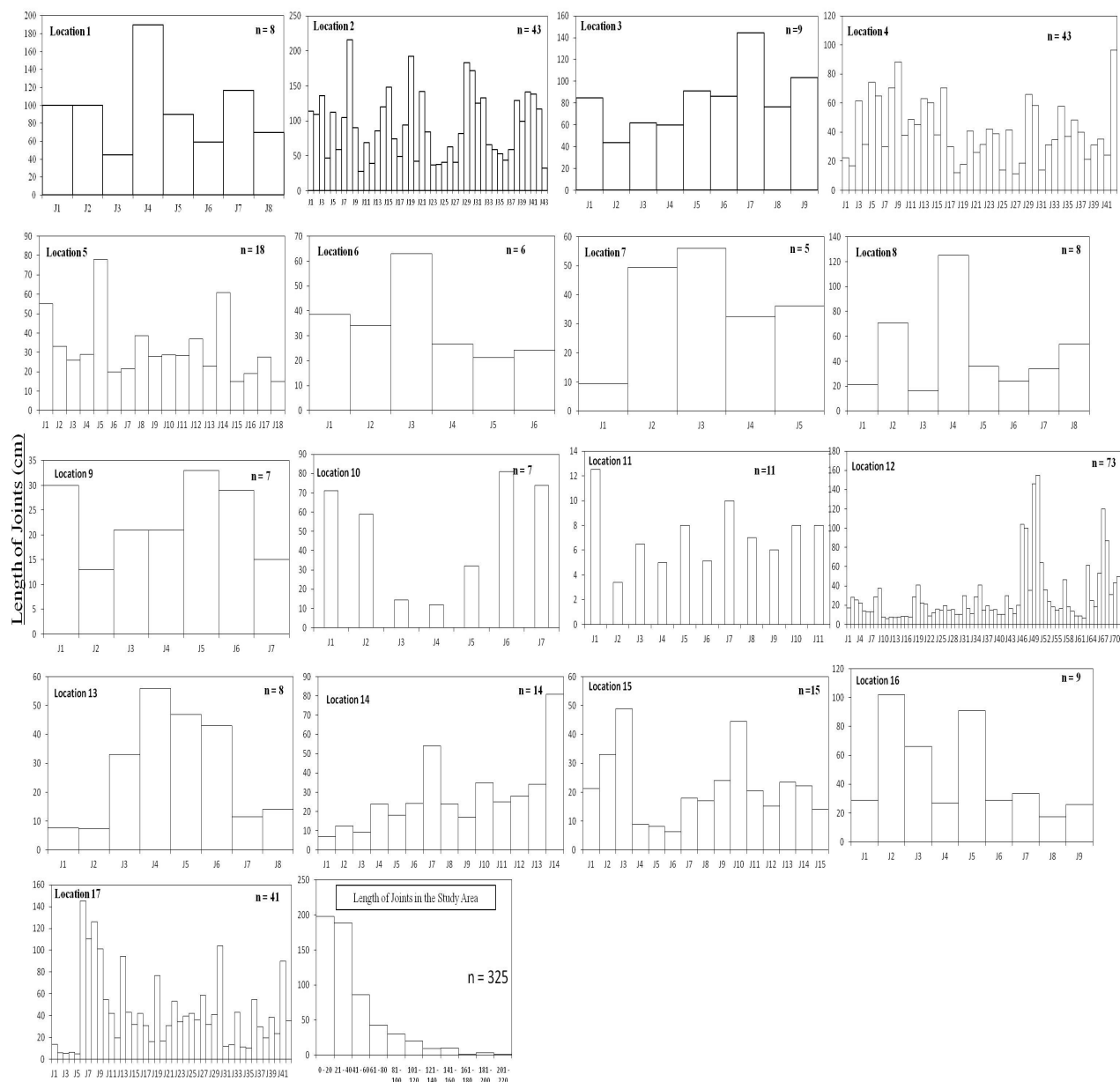
**Figure 4.** Rose diagram for the orientation of Joints in Locations 1 to 16; dominant orientations are E-W, NE-SW, and NNW-SSE.

between  $J_2$  and  $J_6$  at location 2, these joints were master joints oriented  $N02^\circ E$  and  $N22^\circ W$ , respectively (Figure 7). The dihedral angle between these joints is  $\sim 68^\circ$ . In addition, the extension was produced by  $\sigma_3$  oriented E-W and N-S directions.

Consequently, at Location 2, the E-W and NE-SW joints were truncated on the NW-SE joints  $J_4$ . The E-W joints taper into the intrusion 1 and 2 and terminated at  $J_4$  (Figure 10c). This complex orientation of the joint relative to the intrusions may suggest extension of the joints predated the emergence of the intrusion. This assertion invalidates all geologic reasoning, as it is often the case

to find intrusion being older than joints in any setting. However, the presence of the conjugate joints sets at Location 2 (Figure 6a) signifies that the intrusion had been sheared in the plane of the conjugate joints. The relative timing of the joints in this setup is cumbersome except in place where the joints are unconnected with intrusions. Furthermore, the oldest joints are NW-SE oriented, then NE-SW and E-W joints. These events were preceded by N-S directed  $\sigma_3$  related to the emplacement of the intrusions.

The intrusions and some veins are oriented N-S, these structures formed presumably by mode I propagation like



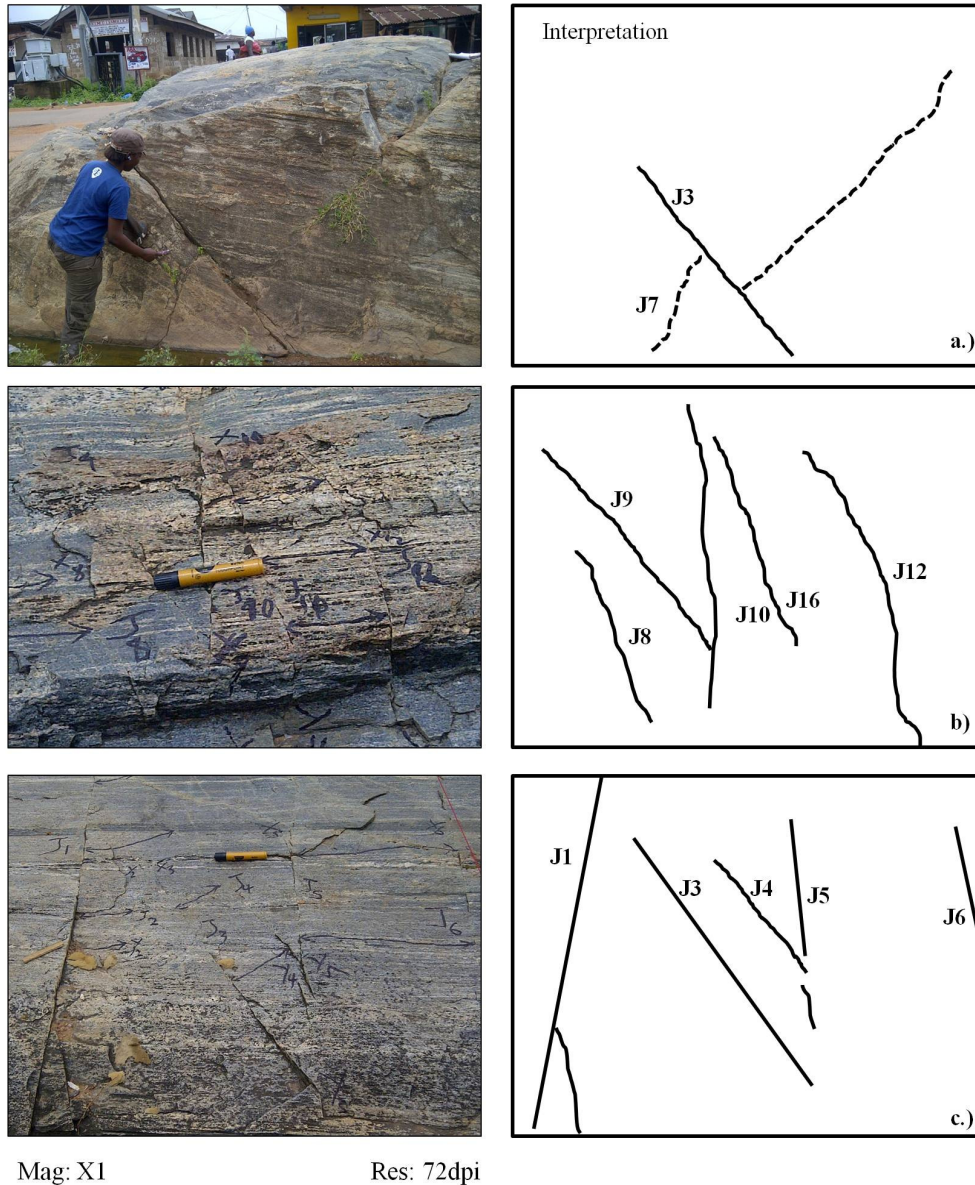
**Figure 5.** Histogram for the length of joints at outcrop locations in the study area. 325 joints were mapped in the entire study area; the maximum length of joint is ~220 cm. The longer joints at each location are the master joints.

the extensional joints sets. The direction of  $\sigma_3$  for these structures is E-W. For other veins types oriented NNW-SSE and NNE-SSW, they were produced by ENE-WSW minimum principal stresses. The boudinages oriented E-W are aligned in the direction of  $\sigma_3$  but perpendicular to  $\sigma_1$ .

The dominant orientation of joints is E-W at Location 4 (Figure 10d and e). The veins ( $V_1$ ) and pegmatites intrusions ( $Pg_1$  and  $Pg_2$ ) are in the N-S direction. These older structures are cross cuts by the joints. Relative chronology of extension is E-W  $\sigma_3$  for  $V_1$ ,  $Pg_1$  and  $Pg_2$ , and predominantly N-S  $\sigma_3$  for the joints. The NW-SE

joints truncated against the  $J_5$ . Nonetheless, the sketch covers a section of the location dominated by E-W oriented joints. Consequently, joints in Figure 10f are diagonal to the veins and the intrusion. The latter were produced by presumably NE-SW  $\sigma_3$  and the joints by NE-SW oriented  $\sigma_3$ . Conversely, the joints in Figure 10g are parallel to the Quartzo feldspathic intrusion, which signifies that they were produced by N-S oriented  $\sigma_3$ . Timing, ideally may preclude the intrusion being older than the joints but this is an oversimplification of the actual evolutionary history of the structures. In terms of geometry and orientation, these structures can be





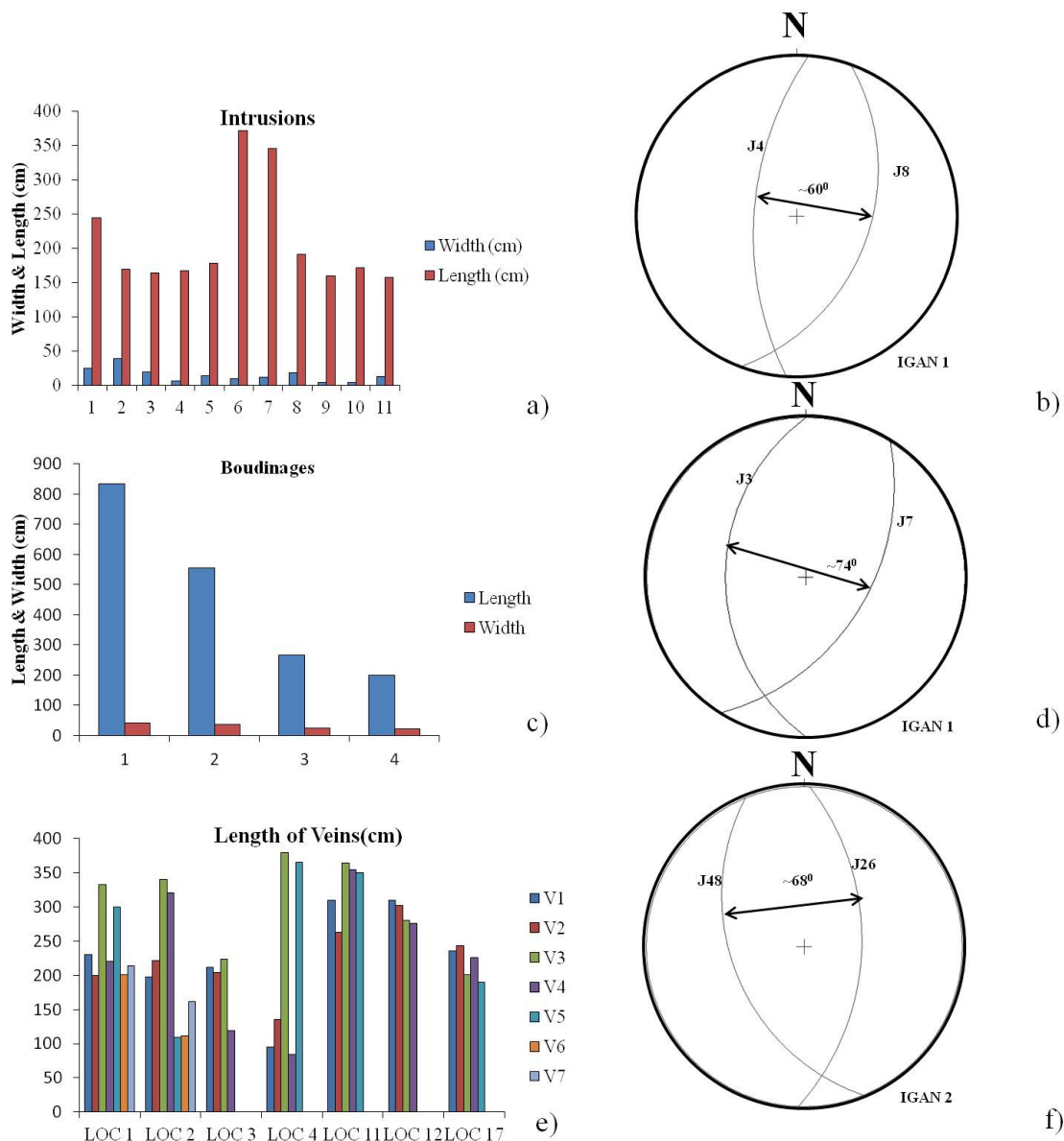
**Figure 6.** Conjugate joint sets at Locations 1 and 3. These joints are characterized by acute angle of  $<90^\circ$  between them. The joints surfaces are rugged and haphazard suggesting spatial and temporal variation in the direction of the minimum principal stress,  $\sigma_3$ . NB: Joints numbers are specific to different locations and not used continuously, for example  $J_1$  represent the first joint in each of the locations.

thought of as contemporaneous extensional fractures related to a similar stress field.

Subsequently, the joints are oriented NE-SW and NW-SE (Figure 10h) at location  $1_2$ ;  $J_1$  and  $J_2$  are terminated on the intrusions, while  $J_{27}$  and  $J_{29}$  were pruned on the NNW-SSE  $J_{14}$ . Thus,  $J_{14}$  is older than the other joint sets. The  $\sigma_3$  direction was supposedly N-S for veins, ENE-WSW, NW-SE and NE-SW for the joints.

The intrusion and veins were formed by initial extension of the host rock in a tensile stress field. The opening created during these extensions were infilled by mineral

precipitates. The extensional regimes associated with these structures thus indicate the pristine orientation of the  $\sigma_3$  only in places where the intrusions were cross cuts by joints. Similarly, the sigmoidal tension gashes at some of the locations revealed that initial extensions of the veins were succeeded by shearing along the orientation of the veins (Figures 10a and 3e). Some of the gashes were later intersected by joints and veins, which show that the deformation involved several phases of extension and invariably diversity of the  $\sigma_3$  direction through time. In the special cases of boudinages, the



**Figure 7a, c, and e.** Histogram for length and width of intrusions, boudinages and veins. (b), (d) and (f) show the stereographic projections for the conjugate joints in the study area.

joints parallel to the axis of the Boudin were presumably contemporaneous with the extension of the Boudin (Figure 8b). Obliquely oriented joints sets are younger than the boudinages (Figure 8d). Boudinages are formed by the disruption of layers, bodies or foliation planes within a rock mass in response to bulk extension along the enveloping surface (Goscombe et al., 2004).

### Joints as complicated palaeostress indicators

Joints in the study area occur as either tensile joints or conjugate shear joints. The shear joints are restricted to

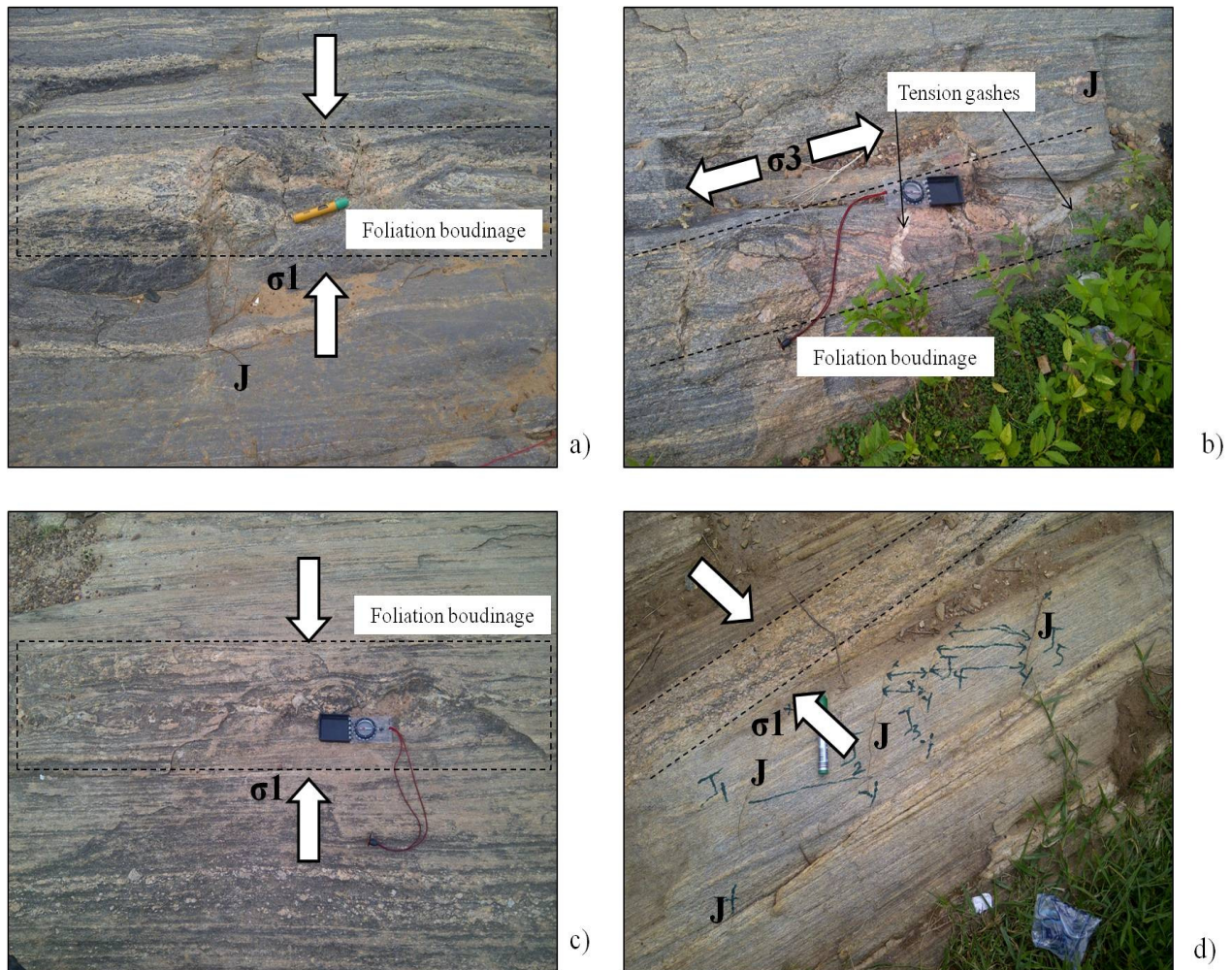
specific locations. Unlike, other conjugate sets, the surfaces of the shear joints in the study area are not striated or slicken sided. This may be related to the nature and mechanical competency of the associated host rock. In addition, the conjugate joints thus form in a compressive stress field; the joints develop with the orientation of symmetric fracture planes (the conjugate direction) making the lower angle with the principal stress direction,  $\sigma_1$ . The extensional joints are the dominant joints sets, as a rule of thumb; they extend by stretching normal to the tensile stress direction which is usually the minor principal stress,  $\sigma_3$ . In the study area, the tension joints are rough and weathered. The shear joints are



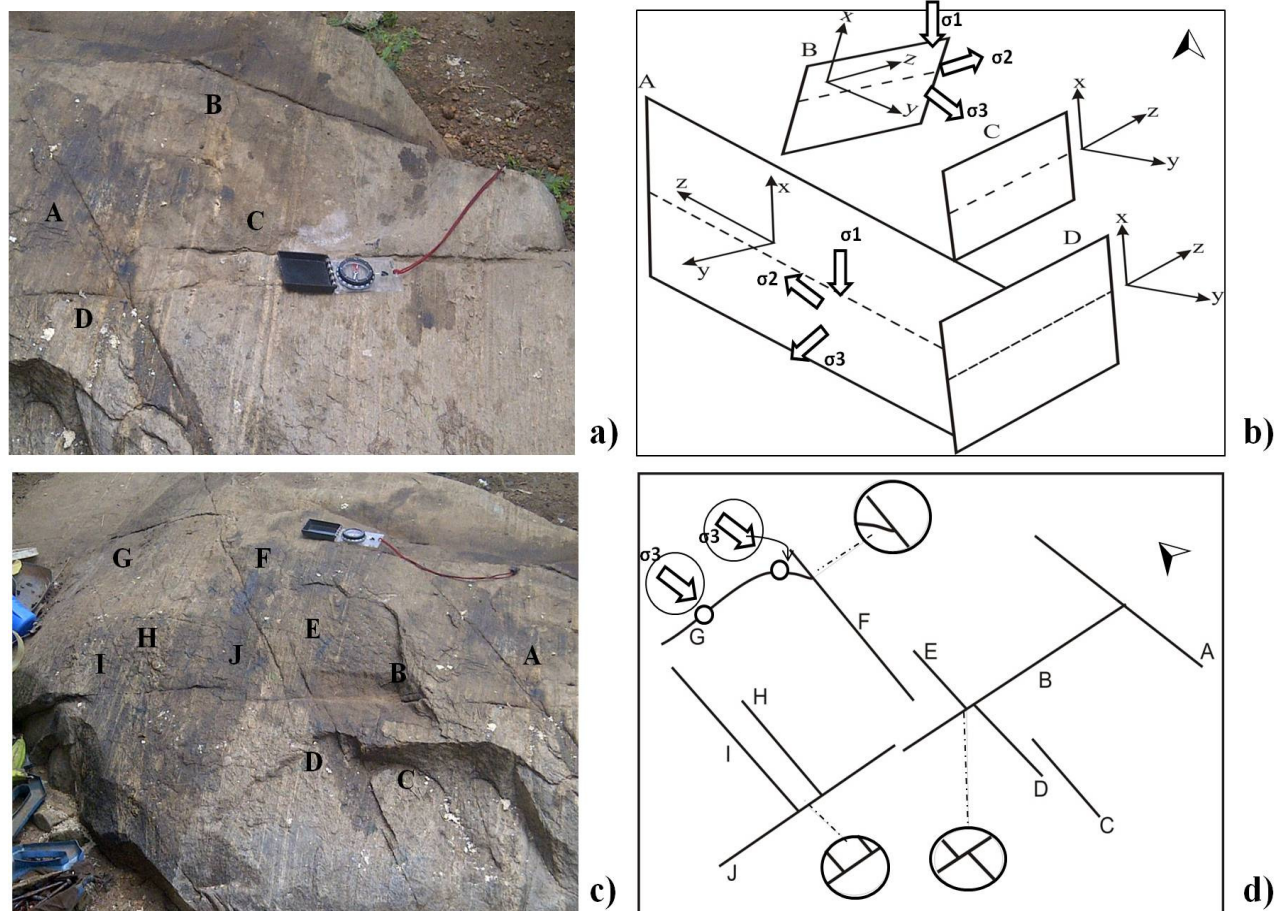
**Table 1.** Descriptive statistics for joints, and veins mapped at Locations 1 to 7.

Length of joints (cm)	LOC1	LOC2	LOC3	LOC4	LOC5	LOC6	LOC7
Mean	71.30	32.43	34.58	36.74	47.63	23.14	49.07
Standard deviation	44.493	16.694	15.315	17.986	36.104	7.712	29.101
Range	205	63	42	47	109	20	69
<b>Width of veins (cm)</b>							
Mean	1.93	2.29	1.94	2.10	2.04	1.33	1.36
Standard deviation	0.643	0.212	0.250	0.141	0.167	0.150	0.404
Range	2	1	1	0	0	0	1
<b>Length of veins (cm)</b>							
Mean	227.29	224.29	303.14	228.57	262.80	156.00	188.00
Standard deviation	73.436	52.741	69.633	99.592	109.985	63.640	36.770
Range	215	166	179	270	256	90	52

Mean is the average length of joints in the different locations. The standard deviation provides information on the spread of the length. Range is the difference between the minimum and maximum length estimated in each of the locations.



**Figure 8.** Boudinages at Locations 4, 9, 12, and 17. The boudinages are foliation boudinages characterized by (a) Composite (b) and (c) Single layer (d) Multiple layer boudins. NB: J is joint in the figure.



**Figure 9 a and c.** Types of complex intersection geometry of joints an evidence for over simplification of timing. (b) The idealised joint zone and its associated stress field (d) the way in which the state of stress may rotate to accommodate a free surface at a joint zone.

found in areas where the foliations are prominent. It suffices to think of the conjugate shear joints were formed by compression or rotation of the initial tension joints which is synonymous with anti plane shear (Mode III) (Dyer, 1983). In contrast, the tensile joints formed by opening (Mode I) propagation (Engelder and Geiser, 1980).

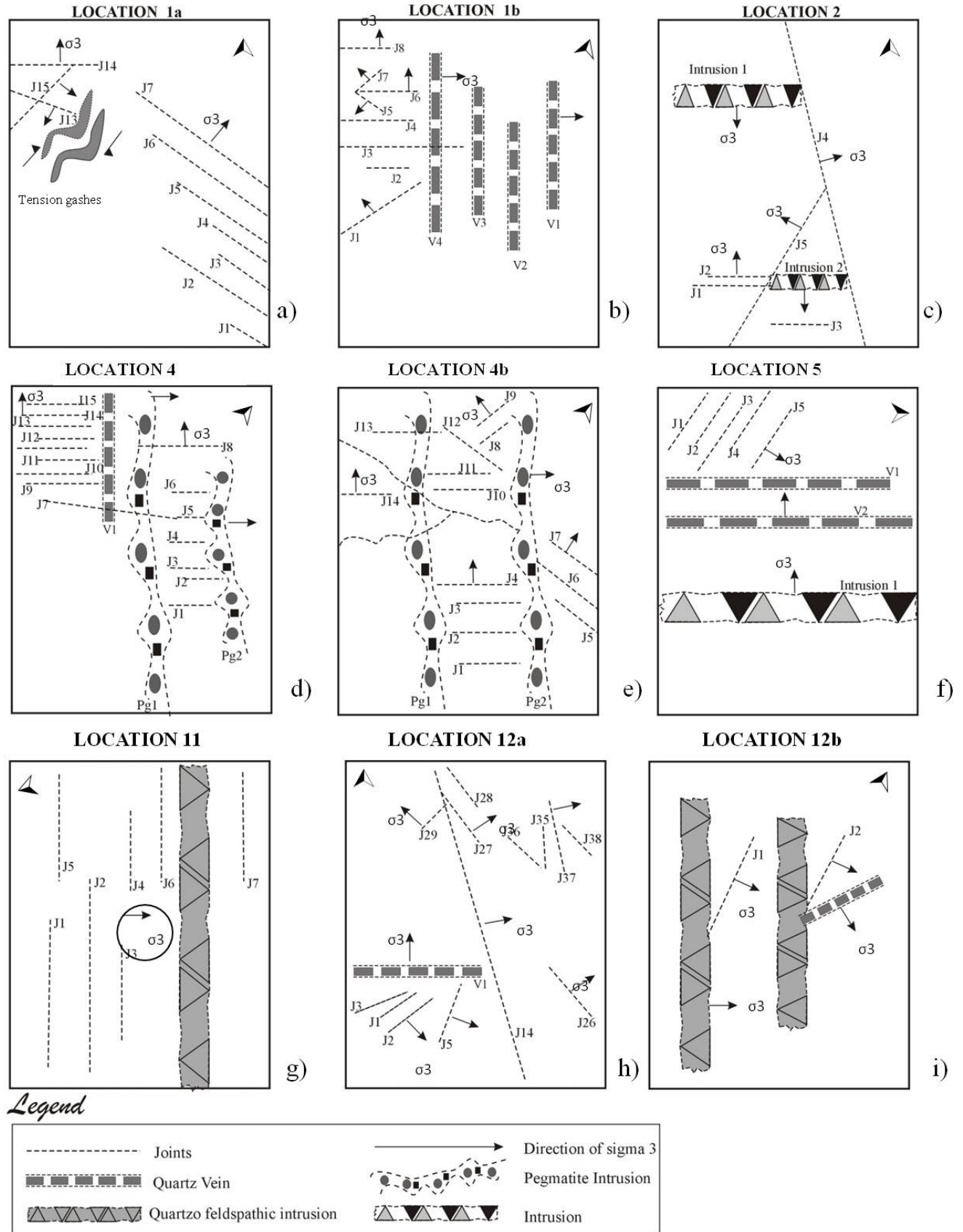
The absence of plumose marks or hackles on the joint surfaces does not exclude the joints as extensional fractures; it demonstrates how lithology controls the behaviour of the joints surfaces; plumose structures are prominent in sedimentary rock units and hard to map in crystalline rocks. Plumose structure is present on joints in a variety of rock types, but it is most clearly displayed in rocks of uniform fine-grained texture (Twiss and Moores, 2007), and for this reason it was difficult to establish the timing of the conjugate.

The intersection geometry of the joints is an important tool for unraveling the deformational history of structural forms. Evidence from the field mapping revealed that the intersection of the joints are not simple t-joints and cross

joints (Figure 9a and b); some of the joints intersect others by a gradual change in their direction of propagation creating bowl-shaped intersection with other joints (Figures 9c and d). This geometry is similar to drag sense common to normal fault, which often indicates their mode of propagation. For joints, the geometry may be related to (1) contemporaneous propagation of the intersecting joints; (2) possible reactivation and rotation of an older joint during a newer stress regimes; (3) deflection of the younger joint in response to boundary conditions of the older one; which is associated with perturbation of the stress of the younger joint by the older one (Dyer, 1983). All these factors point to reconfiguration of initial extension phases by recent activities.

Furthermore, the architecture of the joints in Figure 9c and d revealed two dominant orientations for the joints, N-S and E-W. The intersection of joint E and D with B (Figure 9d) implies that E and D were single joints displaced by propagation of the thoroughgoing joint B which in turn was truncated on joint A. This structural style implies that the N-S sets were formed at different





**Figure 10.** Outcrop sketch map depicting the intersection and inter-structure relationship, the inferred direction of  $\sigma_3$  is shown in white circles for joints and filled circles for other structures.



times though oriented in the same direction. In addition, the drag at the intersection of G with F could not really provide information on their timing.

Consequently, conjugate geometry implies shear sense of propagation and formation of the joints in a compressive stress field. In contrast to conjugate normal fault that is ideally formed at the same time; conjugate joints traditionally evolve through propagation of a joint at a dihedral angle of  $<90^\circ$  with a pre-existing joint. In such a setting, resolving the history of the unassociated tensile joints is complicated by lack of intersection with the conjugate joints as evidenced in Location 2. The older tensile joints are often rotated and re-oriented in response to the newer compressive stress field.

### Correlation with regional structural trend

The E-W collision of the WAC and westward moving plate created N-S to NE-SW trending structures parallel to the edge of the WAC (Black et al., 1979; Champenois et al., 1987; Oluyide, 1988; Egesi and Ukaegbu, 2010). The regional effect of these movements is reflected as highly deformed series of multidirectional orientations found in folds, lineaments and faults in the entire Nigerian basement complex and Northern Cameroun (Mc-Curry, 1976; Rahaman, 1976; Onyeagocha, 1984; Toteu et al., 1990).

The N-S and NE-SW structures are presumably associated with the Pan African orogeny, while pre-Pan African structures are oriented differently to these directions in the basement (Onyeagocha and Ekwueme, 1982; Toteu et al., 1990). The Pan African orogeny reconfigured earlier structures in the basement rock of Nigeria (Mc-Curry, 1976; Rahaman, 1976). The N-S trend persistent with some of the intrusions and foliations implies that they are also Pan African orogenic structures. Thus, veins and the intrusions oriented NW-SE are likely pre-Pan African structures. The joints are essentially Pan African structures except for the E-W joints that are oblique with the Pan African trend. Furthermore, these joints type may be associated with earlier deformational phases. The Pan African orogenies as a multiphase events imply that these structures are interconnected in time and space.

### Conclusion

The diverse orientation of the structures recorded on the stereo nets and rose diagram shows that the tectonic structures of the study area were the product of heterogeneous stress field. The stress fields were dominant and responsible for the deformation observed in the outcrop at present time; some of them have been overprinted by succeeding orogenies.

In the study area, the N-S and NE-SW oriented joint and intrusions are linked to the Pan African orogeny and

were produced by E-W and NW-SE oriented  $\sigma_3$ . Earlier extension structures such as E-W joints and NW-SE veins were products of  $\sigma_3$  oriented in the N-S and NE-SW directions antithetic to the main Pan African trend. In addition, the N-S foliation, NNW-SSE veins and conjugate joints sets have trend consistent with Pan African (Egesi and Ukaegbu, 2010; Goki et al., 2011). The multiple orientations of  $\sigma_3$  through the history of the rocks give credence to the polycyclic nature of the basement rock in the study area.

### ACKNOWLEDGEMENTS

We appreciate the assistance of the department of Earth Sciences, Olabisi Onabanjo University, Fashola Gbotemi, Jamiu Makinde, Lawal Muhedeen, Odunsi Gabriel, Falana Louis and Ogunleye Dolapo during the mapping exercise. Also, we appreciate Rod Holcombe Australia, the provider of Georient software for academic and non commercial use in Cardiff University, United Kingdom.

### REFERENCES

- Ajibade AC, Woakes M, Rahaman MA (1987). Proterozoic crustal development in Pan-African regime of Nigeria: In A. Croner (ed.) *Proterozoic Lithospheric Evolution Geodynamics* 17:259-231.
- Anderson EM (1936). The Dynamics of the formation of Cone-Sheets, Ring-Dykes, Caldron-Substances. *Proceed. Royal Soc. Edinburgh* 56:128-157.
- Barnes JW, Lisle RW (2008). *Basic Geological Mapping*, fourth Edition, John Wiley and Sons Limited, United Kingdom. pp. 69-79.
- Black R, Ba H, Ball E, Bertrand JM, Boullier AM, Caby R, Davison I, Fabre J, Leblanc M, Wright LI (1979). *Outline of the Pan-African Geology of Adrar des Iforas (Republic of Mali)*, Band 68, Heft 2, seite pp. 543-564.
- Blatt HT, Robert J (1996). *Petrology: Igneous, Sedimentary, and Metamorphic*, 2nd ed., W. H. Freeman, ISBN 0-7167-2438-3. pp. 359-360.
- Burke KC, Freeth SJ, Grant NK (1976). The structure and sequence of geological. Events in the basement complex of Ibadan area Western Nigeria *Precamb. Res.* 3:537-545.
- Caby R (1989). Precambrian terranes of Benin-Nigeria and Northeast Brazil and the Late Proterozoic South Atlantic fit. *Geol. Soc. Am. Spec. Pap.* 230:145-158.
- Champenois M, Boullier AM, Sautter V, Wright LI, Barbey P (1987). Tectonometamorphic evolution of the gneissic Kidal assemblage related to the Pan - African thrust tectonics (Adrar des Iforas, Mali). *J. Afr. Earth Sci.* 6(1):19-27.
- Coelho S, Passchier C, Marques F (2006). Riedel-shear control on the development of pennant veins: Field example and analogue modeling. *J. Struct. Geol.* 28:1658-1669.
- Dada SS (1999). "Pb-Pb and Sm-Nd Isotope Study of Metaigneous Rocks of Kaduna Region: implications for Archaean Crustal Development in Northern Nigeria". *Global J. Pure Appl. Sci.* 6:7.
- Dada SS, Tubosun IA, Lancelot JR, Lar AU (1993). Late Achaeon U-Pb age for the reactivated basement of Northeastern Nigeria. *J. Afr. Earth Sci.* 16:405-412.
- De Swardt AMJ (1947). The Ife-Ilesa goldfield. (Interim report no. 2). *Geol. Surv. Niger. Annu. Rep.* pp. 14-19.
- Dyer JR (1983). *Jointing in sandstones, Arches National Park, Utah*. Unpublished PhD. Dissertation, Stanford University.
- Egesi N, Ukaegbu VU (2010). "Petrologic and Structural Characteristics of the Basement Units of Bansara Area, South-eastern Nigeria". *Pac. J. Sci. Technol.* 11(1):510-525.

- Ekwueme BN (1987). Structural orientations and Precambrian deformational episodes of Uwet area, Oban Massif, S.E. Nigeria. *Prec. Res.* 34:269-289.
- Engelder LT, 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.* 85:6319-6341.
- Fitches WR, Ajibade AC, Egbuniwe IG, Holt RW, Wright JB (1985). Late Proterozoic schist belts and plutonism in N.W. Nigeria. *J. Geol. Soc. Lond.* 142:319-337.
- Goki NG, Amadi AN, Olasehinde PI, Dada SS, Ikpokonte EA, Adekeye JID (2011). Appraising the structural geology of Kakuri Sheet 144: Implications for the tectonic evolution of the basement complex. *J. Eng. Technol. Res.* 3(2):26-36.
- Goscombe BD, Passchierb CW, Handa M (2004). Boudinage classification: end-member boudin types and modified boudin structures. *J. Struct. Geol.* 26:739-763.
- Grant NK (1970). "Geochronology of the Precambrian basement rocks from Ibadan South-western Nigeria". *Earth Planetary Sci. Lett.* 10:29-38.
- Grant NK, Hickman M., Burkhotder FFt, Powell JL (1972). "Kibaran metamorphic belt in Pan-African domain of West Africa". *Nat. Phys. Sci.* 238:90-91.
- Griggs D, Handin J (1960). Observations on fracture and a hypothesis of earthquakes In: *Rock Deformation (A Symposium)* (edited by Griggs, D. & Handin, J.). *Mere. Geol. Soc. Am.* 79:347-364.
- Kehle RO (1964). The determination of tectonic stresses through analysis of hydraulic well fracturing. *J. Geophys. Res.* 69:259-273.
- Lisle RJ (2012). Shear zone deformation determined from sigmoidal tension gashes. *J. Struct. Geol.* In press, <http://dx.doi.org/10.1016/j.jsg.2012.08.002>.
- Lloyd GE, Ferguson CC (1981). Boudinage structure: some new interpretations based on elastic-plastic finite element simulations. *J. Struct. Geol.* 3:117-128.
- Mc-Curry P (1976). The Geology of the Precambrian to Lower Paleozoic Rocks of Northern Nigeria. A review, in *Geology of Nigeria*, Edited by C.A. Kogbe published by Elizabethan Co. Lagos. pp. 15-39.
- Muehlberger WR (1961). Conjugate joint sets of small dihedral angle. *J. Geol.* 69(2):211-219.
- Odeyemi I (1981). A review of the orogenic events in the Precambrian basement of Nigeria, West Africa. *Geologische Rundschau* 70(3):897-909.
- Ogezi AEO (1977). Geochemistry and geochronology of basement rocks North-western Nigeria. Unpub. Ph.D. Thesis, Leeds Univ. U.K.
- Oluyide PO (1988). "Structural Trends in the Nigerian Basement Complex". In: P.O. Oluyide. *Precambrian Geology of Nigeria*. *Geol. Surv. Nigeria*: Lagos, Nigeria. pp. 93-98.
- Omosanya KO, Ajibade OM, Akintola AI (2010). "Architecture of Joints at Ago-Sunmonu, South-western Nigeria". *Pacific J. Sci. Technol.* 11(2):625-635.
- Omosanya KO, Akinbodewa AE, Mosuro GO (2012). Integrated Mapping of Lineaments in Ago-Iwoye SE, SW Nigeria. *Int. J. Sci. Technol.* 1(2):68-79.
- Omosanya KO, Akinmosin A, Adio NA, Omosanya HO, Akinbodewa AE, Lawal MA (2011). A Simple 3D Visualisation of Joints In A Migmatized Gneiss, Ago-Iwoye NE, SW Nigeria. *Int. J. Emerg. Sci.* 1(3):418-432.
- Onyeagocha AC (1984). Petrology and Geological History of N.W. Akwanga in Northern Nigeria. *J. Afr. Earth Sci.* 2(2): 441-50.
- Onyeagocha AC, Ekwueme BN (1982). "The Pre-Pan-African Structural Features of North central Nigeria". *Niger. J. Min. Geol.* 19(2):74-77.
- Oversby VM (1976). Lead isotope study of aplites from the Precambrian rocks near Ibadan, South-western Nigeria. *Earth Planet. Sci. Lett.* 27:177-180.
- Oyawoye MO (1972). "The Basement Complex of Nigeria". *African Geology. Geology of Africa T.F.J. Dessauvague and A.J. Whiteman (eds.)*. University Ibadan: Ibadan, Nigeria. pp. 67-99.
- Oyinloye AO (2011). *Geology and Geotectonic Setting of the Basement Complex Rocks in South-western Nigeria: Implications on Provenance and Evolution*, Earth and Environmental Sciences, ISBN: 978-953-307-468-9, In Tech pp. 97-118.
- Pollard DD, Segall P (1980). Mechanisms of discontinuous faults. *J. Geophys. Res.* 85:4337-4350.
- Pollard DD, Segall P, Delaney PT (1982). Formation and interpretation of dilatant echelon cracks. *Bull. Geol. Soc. Am.* 93:1291-1303.
- Rahaman MA (1976). Review of the Basement Geology of South-western Nigeria. In: *Geology of Nigeria*, edited by C.A. Kogbe, Elizabethan Publ. Co., Lagos. pp. 41-58.
- Rahaman MA, Emofureta WO, Vachette M (1983). The potassic - grades of the Igbe area: Further evaluation of the polycyclic evolution of the Pan-African belt in South-western Nigeria. *Precambrian Res.* 22:75-92.
- Rahaman MA (1988). Recent advances in the study of the basement complex of Nigeria. In: P.O. Oluyide, W.C. Mbonu, A.E. Ogezi., I.G. Egbuniwe, A.C. Ajibade and A.C. Umeji (eds). *Precambrian Geology of Nigeria*. *Geol. Surv. Niger.* pp. 11-41.
- Ramsay JG (1967). *Folding and Fracturing of Rocks*. McGraw-Hill. New York. P. 568.
- Ramsay JG, Graham RH (1970). Strain variation in shear belts. *Can. J. Earth Sci.* 7:786-813.
- Swanson MT (1992). Late Acadian-Alleghenian transpressional deformation: Evidence from asymmetric boudinage in the Casco Bay area, coastal Maine. *J. Struct. Geol.* 14:323-341.
- Swanson MT (1999). Kinematic indicators for regional dextral shear along the Norumbega fault system in the Casco Bay area, coastal Maine. *Geol. Soc. Am. Spec. Pap.* 331:1-23.
- Toteu SF, Macaudiere J, Bertrand JM, Dautel D (1990). "Metamorphic Zircons from North Cameroon: Implications for the Pan-African Evolution of Central Africa". *Geol. Rundsch.* 79:777-788.
- Twiss RJ, Moores EM (2007). "Structural Geology" 2nd edition, Freeman and Company New York, P. 364.
- Van Breemen O, Pidgeon R, Bowden P (1997). Age and isotopic studies of Pan-African granites from North-central Nigeria. *Prec. Res.* 4:307-319.
- Vernon RH (2004). *A Practical Guide to Rock Microstructure*, Oxford University Press, Oxford. ISBN 0-521-89133-7.
- Woakes M, Ajibade CA, Rahaman MA (1987). Some metallogenic features of the Nigerian Basement. *J. Afr. Sci.* 5:655-664.