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An outcrop evidence for polycyclic orogenies in the basement complex of Southwestern Nigeria

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Abstract

In this work, the tectonic history of a classic outcrop of the Migmatized-Gneiss Complex of Southwestern Nigeria was systematically investigated. The aim of this research is to investigate how the polycyclic nature of the basement complex in Southwestern Nigeria is preserved at a local or outcrop scale. Detailed geological mapping of the outcrop was done using ‘bit-a-bit’ technique in four pre-defined quadrants. Structural measurements include a detailed inventory of fold geometry, attitudes of veins, joints, and boudins. The outcrop is characterized by alternating leucosomes and melanosomes, fractures, S-C fabric and microfolds. Three metamorphic events were interpreted in the outcrop M1, M2 and M3, which are linked to deformation D1 to D3. These events suggest that the outcrop evolved through a complex interplay of compression, extension, and late stage sinistral movement. Phase I extension is coincident with the emplacement of veins, which were later compressed into ptygmatic folds. These veins were intersected by joints associated with Phase II deformation. During the third episode of extension, quartzo-feldspathic veins were emplaced normal to the orientation of earlier joint sets. The N-S, NE-SW and NW-SE trends of the structures are consistent with the polycyclic fabric of the Nigerian basement complex. This work has shown that macroscopic structures in the study area present unique evidence for the regional polycyclic history of the bedrock in Southwestern Nigeria.

Keywords: Outcrop, Fabrics, Polycyclic, Nigerian, Basement

1. Introduction

The basement complex of Southwestern Nigeria is located in a triangular portion of the Nigerian basement, an extension of the Dahomeyide shield of the West African Craton (WAC; Figure 1). Rocks of the region include Migmatized-Gneiss Complex (MGC) that is characterized by a) grey foliated gneiss, b) ultramafic rocks and c) felsic component comprised of pegmatite, aplite and granitic rocks (Rahaman, 1981). The MGC in Southwestern Nigeria is affected by three major geotectonic events ranging from Early Proterozoic of 2000 Ma to Pan African events of ~600 Ma (Woakes et al., 1987; Ajibade & Fitches, 1988; Oyinloye, 2011). The rocks of the basement have been affected by medium pressure Barrovian metamorphism (Rahaman et al., 1983; Oyinloye, 2011).

The attitudes of tectonic structures in the Nigerian basement have been documented in terms of orientation and magma-induced veins and dykes such as quartz veins and pegmatites (Rahaman et al., 1983; Ajibade et al., 1987). Deformation of the Nigerian basement complex occurred in two phases, a ductile phase, which is responsible for the formation of planar structures (foliations) and a brittle phase resulting in jointing and fractures, many of which have been filled with quartzo-feldspathic veins, dolerite dykes, pegmatite and aplitic veins and dykes. The polycyclic nature of the basement complex is well-documented at regional scale. In outcrop, it is often difficult to distinguish the different events highlighted earlier as a consequence of the Pan African orogeny which has overprinted and reconfigured earlier orogenic imprints. Since macroscopic structures remain relevant to the study of regional structures and events (Sander, 1950; Wilson, 1951; Price & Cosgrove, 1990), this research is aimed at investigating the degree to which the polycyclic nature of the basement complex in Nigeria is preserved at local or outcrop scale.

In this work, we have systematically analyzed the history of a rock exposure, taking inventory of all available structural data and correlating their trends with regional structural imprints. We provide a simple and descriptive analysis of the structures with a view to elucidating their evolution. This paper starts with a brief discussion of the geological setting of the study area; the methods used in the study, especially the novel 'bit-a-bit' technique for modal mineral estimation and a discussion on how the structures evolved and their relationship with regional structural forms. The observations and discussions made in this work are based on a single outcrop. Hence, our result is not devoid of the problem of representativeness of observation.

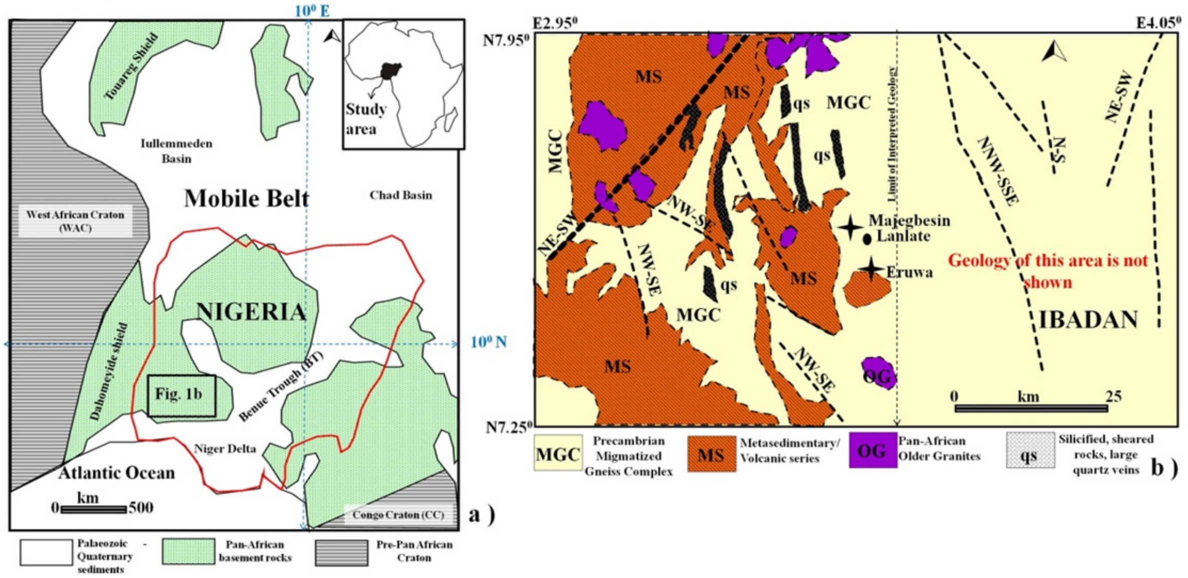

Figure 1. a) Regional geological map of Nigeria in the context of West African and Congo Craton (Modified after Woakes et al., 1987) b) Simplified geological map of the study area and environs. The major rock types include Precambrian Migmatized Gneiss complex, metasedimentary rocks of Archaean age and Pan African granitoids. Note: *The dashed line corresponds to the trend of major lineaments and faults* (Adapted from the Geological Map of Nigeria; Geology Survey Agency, 2006)

2. Method

The geological mapping of the outcrop was done by inventory, which involves dividing the outcrop into four principal quadrant/grids from NE clock wisely to NW. The modal mineral composition was estimated per grid, and the average calculated for the entire outcrop. A novel approach for estimating the mean mineral composition was introduced, which involves identifying the mineral types and their percentages in a small square in any part of the outcrop, and subsequently using the square as a template to quantify the mineral composition for the rest of the outcrop (Figure 2a). This method is called a 'bit-a-bit' technique for mineral identification. Furthermore, the average mineral composition in each of the quadrants was estimated (Table 1.2).

Tectonic structures such as veins, joints, foliations, boudinages and folds were systematically mapped through the grids. Parameters measured for the linear structures include strike and length. The axial plane and plunge of the folds were determined. Aspect ratio, AR of veins and boudinages was calculated as the fraction of their width to length. In addition, average perpendicular distance was estimated for veins and joints by calculating the mean of three orthogonal distance a, b, and c. The tip and intersection geometries of joints and other extensional structures were studied with a view to elucidating their mode of propagation and timing.

The important structural questions include a) whether the joints/veins are systematic or non-systematic, b) the number of joints /veins sets present, c) their cross-cutting relationship, d) the surface appearance of the joints/veins, e) spacing and density, f) relationship of the joints/veins to other geological structures and g) whether joints/veins are isolated or connected to a regional network (Omosanya et al., 2012 & 2013). The orientations of the structures were plotted on stereonets and rose diagrams in order to understand the relative trend of the major tectonic force(s) and how they connect with regional structural trends.

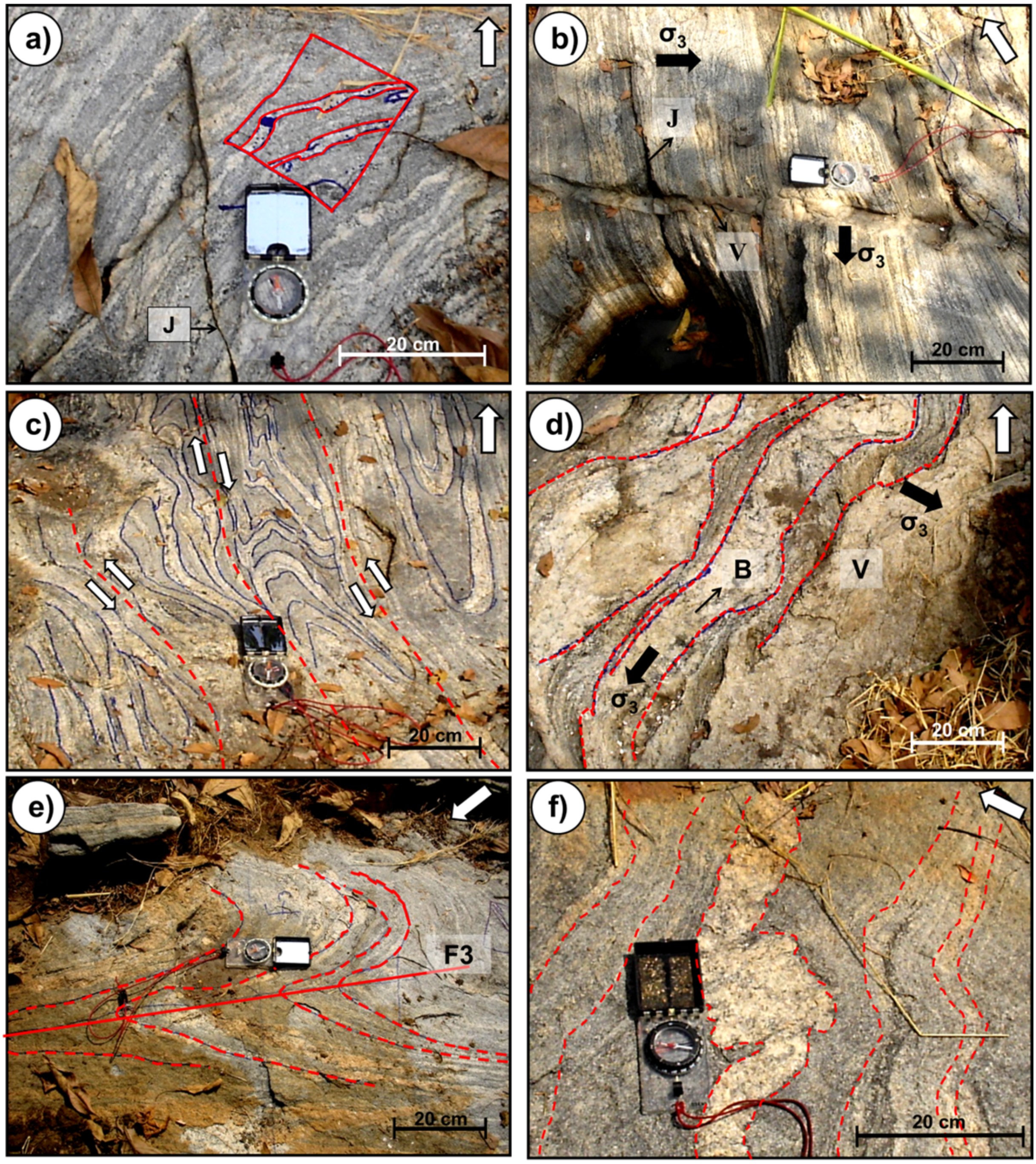

Figure 2. a) Estimating the modal percentage of minerals using a novel 'bit-a-bit' technique. The percentages of the minerals in the square were used to establish the overall mineral percentage in the entire outcrop. In situation where the square is not representative, newer and additional sets were drawn to estimate the percentage mineral composition. Mafic minerals include biotite and hornblende while quartz, alkali feldspar and plagioclase minerals are the main felsic mineral b) Example of intersection geometry between a joint and a vein in the study area c) S-C fabric suggestive of shearing folding was interpreted in the southern part of the outcrop d) Example of boudinage from the study area and outline of e) asymmetrical folds f) Ptygmatic fold. *Note: B-Boudin, J-Joint, V-Vein and F- Fold*

3. Results

3.1 Petrography

Minerals identified on the field include dark-coloured minerals (biotite and hornblende) and light coloured minerals (quartz and feldspars). The modal percentages of the minerals are shown in Table 1.1. Biotite is a flaky dark shiny mineral that is predominant at the southwestern part of the outcrop. The biotite was found in association with the hornblende, forming distinct mineral bands at the SW and SE part of the outcrop. In contrast, feldspars occur in higher proportion at the NW and SE part of the exposure (Table 1.2). Quartz is the dominant mineral in hand specimen with an estimated average of ~38% and in combination with the plagioclases they make up the principal minerals in the veins (Table 2).

Banding in the outcrop presumably resulted from the segregation of the mafic and felsic minerals; the outcrop is grey and bears characteristic features related to the Migmatized Gneiss Complex (MGC), thus, described as grey gneiss in accordance with the description of Rahaman (1981). Furthermore, banding in the outcrop is predominant in the western part of the outcrop. The rock exposure as a palaeosome of banded biotite-hornblende gneiss is intruded by younger veins i.e., metasome of quartzo-feldspathic composition.

In the next section, the dimensions, orientations and characteristics of the interpreted tectonic structures are presented.

3.2 Geometry and Orientation of Structures

Foliations

The foliation planes are continuous and comprised of fine bands of dark- and light-coloured minerals (Figures 2a, 2b and 5). Foliation planes are moderately expressed especially on the eastern part of the outcrop with major trends in the NNE-SSW and minor trend of NNW-SSE and NW-SE directions (Figure 3a and 3c). The dominant direction of dip is NW and E suggests the presence of a regional fold with a NE-SW oriented axial plane (Figure 4).

Folds

Folds in the study area are asymmetrical with their axial trace verging in the NE and NW direction (Table 1.2, Figure 2e and 2f). The inferred interlimb angle shows that the folds are open folds with angles of 112°, 122°, 100° and 108° for fold F1 to F4 respectively. The highest amplitude is interpreted in fold F3 with the least value of 38 cm estimated in F2. Plunge of axial traces is highest in F4 and F2 (22° and 20°) and lowest in both F1 and F3 with values of 04° (Table 1.2). Other fold types include shear folds shown by S-C fabrics and ptygmatic folds (Figures 2c and 2f).

Veins

Veins are composed of pegmatite and granitic minerals (quartz and feldspars). Pegmatite veins in the study area are dominantly oriented along the NNW-SSE direction (Figure 3e). The longest vein measures ~350 cm along strike, with the shortest mapped in the NW sub grid (Figure 4a). However, no vein was found in the SE grid. The estimated aspect ratio (width/length) ranged from 0.186 to 0.068 (Table 2). This implied that the veins have length greater than their width. Two (2) quartzo feldspathic veins were found in the outcrop, V1 measured ~70 cm along strike (N54°W) and V2 measured ~510 cm (N66^{0}W). The aspect ratios of these veins are 0.069 and 0.002 respectively (Table 1). The dominant trend is WNW-ESE (Figure 3e). In addition, the two veins cross-cut some of the joints mapped in the NE sub-grid (Figure 2b).

Joints

The joints appeared curved, straight and chaotic in map view (Figure 5). Joints were not found in the 4th sub grid (NW). The longest and shortest joints were mapped in the SW and SE sub grid (Figure 6). The average perpendicular distances between the joints are unequal, thus the joints do not occur in sets and are non-systematic (Figure 5). The dominant orientation for the joints is NE-SW, with NW-SE as minor trend (Figure 3f). Tip geometry includes T junctions and Y- geometry (Figure 5).

Boudinage

A foliation boudinage categorized as s-slip type (*cf.* Goscombe et al., 2004) was found at the boundary of the NE and SE sub-grids (Figure 2d). The boudinage was formed by extension of the longest pegmatite vein. The estimated aspect ratio is ~0.248, with length of ~145 cm along strike of N14°E.

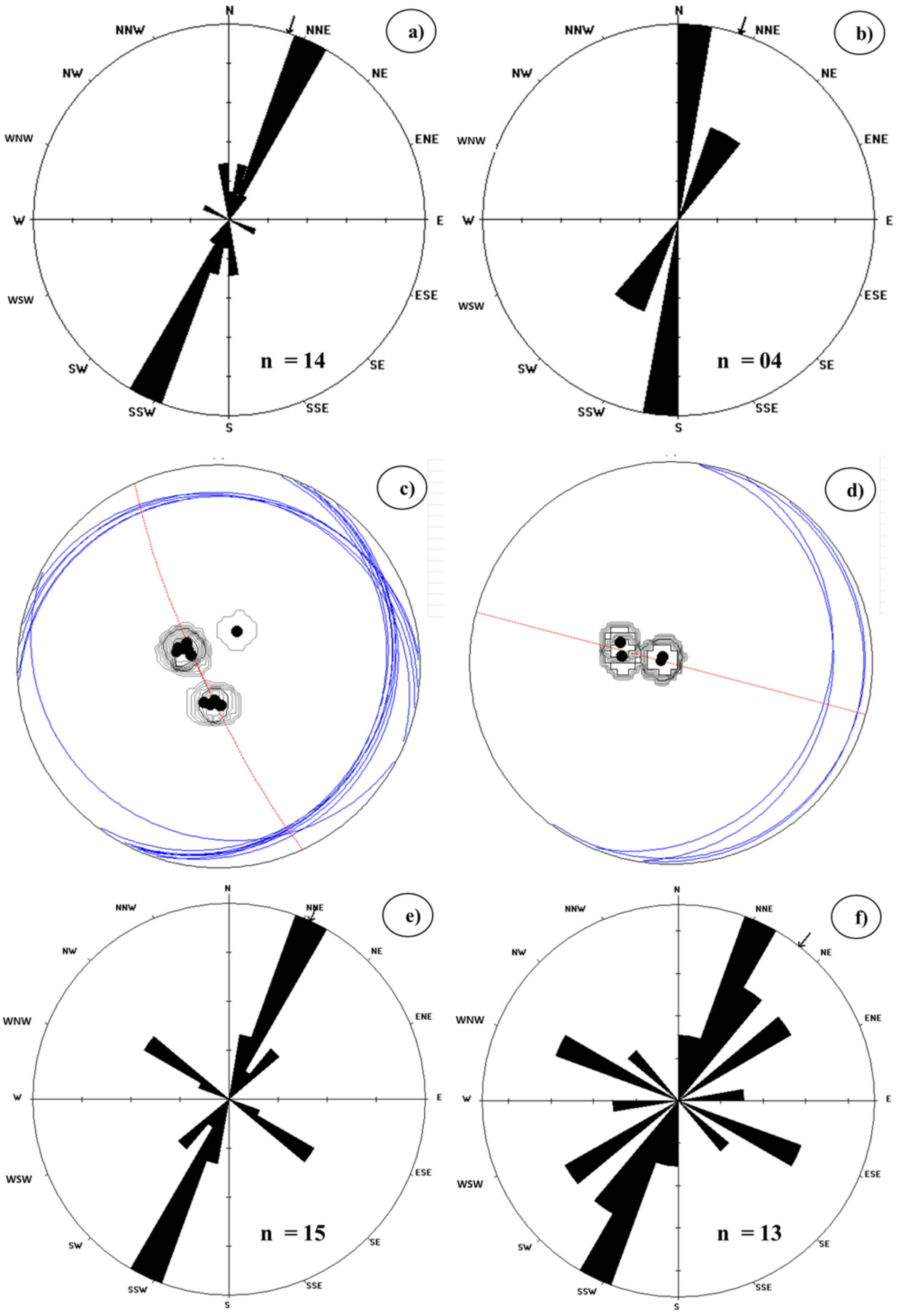

Figure 3. a) and b) Rose diagrams for orientation of foliation planes and axial planes of folds c) and d) Stereographic projection for attitude of foliation planes and plunge of axial planes of folds. The poles of the planes are plotted as filled-black circles while the red dotted lines represent the mean best-fit line for the great circles e) and f) Rose diagrams for orientation of veins and joints in the study area. *N.B: Arrows on the rose diagrams indicate the mean orientation of structures as discussed in the text*

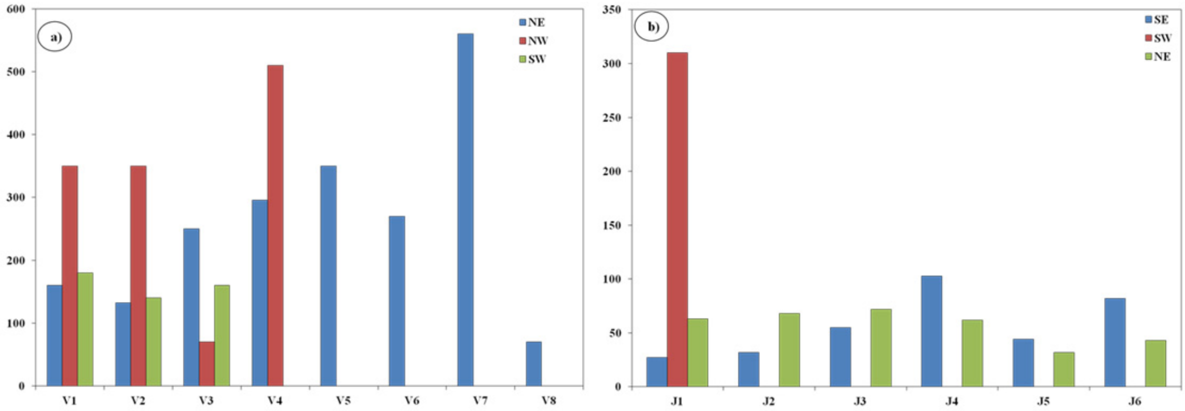

Figure 4. Histogram showing the length of veins and joints in the study area, the length was measured in centimetre.

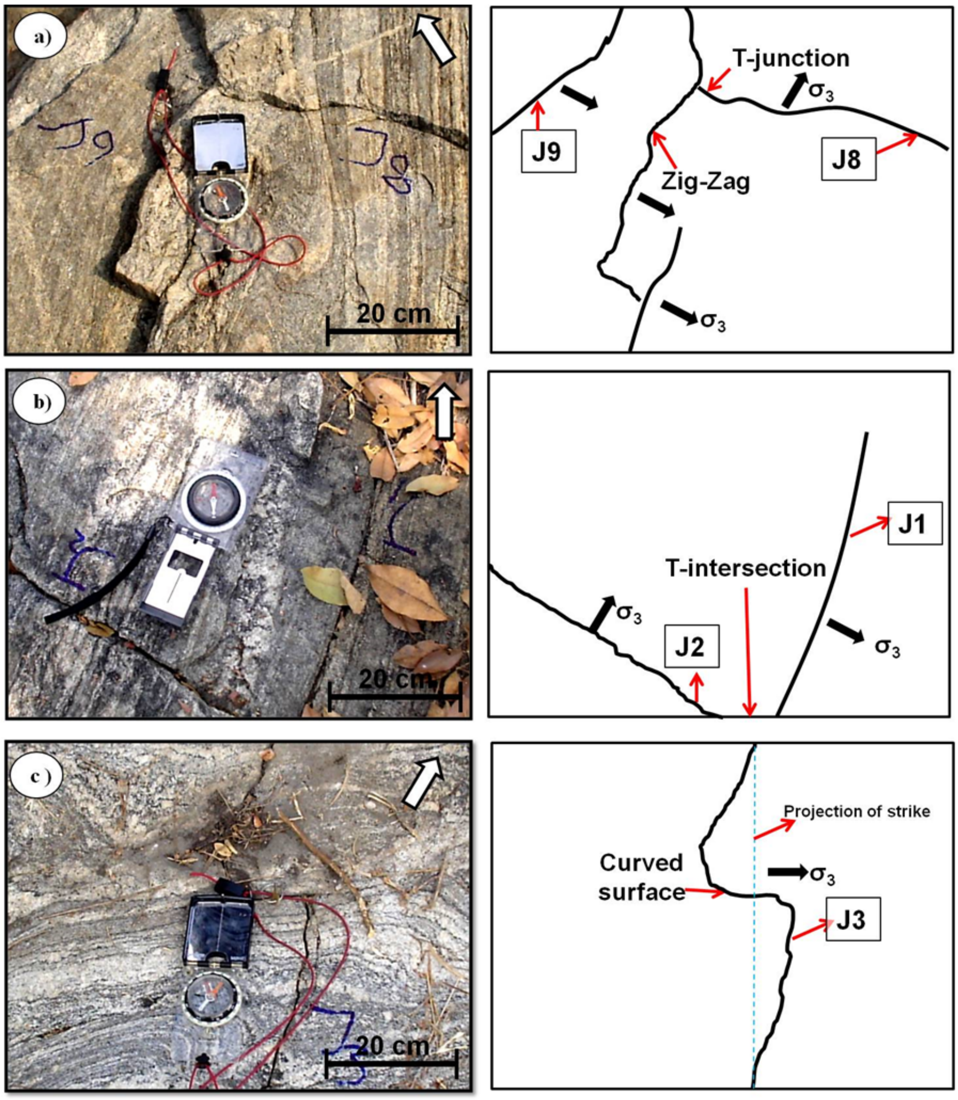

Figure 5. Joint surface and intersection geometries include a) T-junction b) T-Intersection and c) Curved surfaces

Table 1. Modal percentage of minerals, attitude of folds, and aspect ratio of intrusions

1.1 : Estimated Modal percentage of Minerals

Minerals	NE	NW	SE	SW	Av Mineral %
Quartz	40	40	35	20	**33.75**
Biotite	25	20	25	40	**27.5**
Feldspar	15	20	15	20	**17.5**
Hornblende	10	10	15	15	**12.5**
Others	10	10	10	5	**8.75**
Sum	100	100	100	100	**100**

1.2: Attitude of fold interpreted in the outcrop

	Vergence	Inter. Angle	Symmetry	Axial Plane	Plunge	Amplitude
F1	NE	112	A	216	04NW	41
F2	NW	122	A	188	20NW	38
F3	NW	100	A	188	04NW	55
F4	NW	108	A	202	22NW	43

A= Asymmetrical

Table 2. Aspect ratio of pegmatite and quartzo-feldspathic veins

	Length	**Width**	**Aspect Ratio**	**Mineralogy**
NE				
V1	160	12	0.075	Pegmatite
V2	132	16	0.121	Pegmatite
V3	250	17	0.068	Pegmatite
V4	296	20	**0.068**	Pegmatite
V5	350	30	0.086	Pegmatite
V6	270	50	0.185	Pegmatite
V7	560	40	0.071	Pegmatite
V8	70	4.8	0.069	Quartzofeldsphatic
NW				
V1	350	16	0.046	Pegmatite
V2	350	16	0.046	Pegmatite
V3	70	13	**0.186**	Pegmatite
V4	510	1	0.002	Quartzofeldsphatic
SW				
V1	180	23	0.128	Granitic
V2	140	10	0.071	Granitic
V3	160	12	0.075	Pegmatite

4. Discussion

4.1 Spatial and Temporal Evolution of Structural Forms

The oldest structural form interpreted in the outcrop is related to the metamorphic events here named, M1, which is observed as segregation of minerals into mafic and felsic bands. This event can be related to recrystallization of minerals during a regional metamorphic episode. The rock of the study area is presumably metamorphosed from a protolith of granitic rock composed largely of biotite and hornblende and the lack of schistocity suggests the outcrop is not derived from a sedimentary protolith. On the field, the metasomes are composed of quartz and feldspar minerals, representing simple pegmatites minerals, which were younger than the metamorphosed palaeosome. Hence, the outcrop is described as a Migmatized banded Gneiss. The foliation planes are attributed to M1 event which were later folded into asymmetrical folds by apparently E-W directed maximum stress, σ_1 (Figure 2e). Therefore, M1 is associated with S1 foliations and F1/D1 deformation linked with asymmetrical folding.

The dominant orientation of the vein is NE-SW suggestive of a NW-SE directed minimum stress (σ_3). Minor orientations of NNE-SSW and NW-SE implied that the veins were not produced solely by a single episode of extension. Hence, the dominant orientation may not necessarily coincide with the oldest episode of extension, but the most prominent period of extension. Furthermore, the relative timing of the vein could not be established as they lack intersection geometry. However, the pegmatite and granitic veins were compressed into ptygmatic folding folds which provide evidence for a second phase of contraction within the outcrop. These folded veins were later deformed by younger joints and fractures (e.g. Figure 2b and 2f). Consequently, the intersection geometry of the joints signifies propagation towards existing structural forms. The zig-zag and curved surfaces recorded in some of the joints is an indication to temporal shift in the position of the tectonic forces producing them (Blatt & Roberts, 1996). The only justification for such expression is that the propagation of the joints is not a thoroughgoing event, but it involved boundary restriction by pre-existing structural forms, e.g. pegmatite/granitic veins and foliation planes.

Furthermore, the T-intersection, T-junction and curved surfaces of the joints provided evidence for the polycyclic evolution of the joints with respect to temporal variation in the orientation of minimum stress, $\sigma3$ (Omosanya et al., 2013). Hence, the intersection geometry of the joints implies that they were produced by multiple phases of extension. Again, the dominant orientation of NE-SW may not be the oldest phase of extension associated with jointing or fracturing of the outcrop. In fact, joints are unreliable palaeostress indicator and should be used with caution (*cf.* Dyer, 1983). In terms of cross-cutting relationship, the joint exhibits two distinct characters with the veins: a) pegmatite veins that are cross-cut by joints and b) joints that are cross-cut by quartzo-feldspathic veins. Therefore, we propose that the outcrop witnessed three main phases of extension: a) Phase I associated with pegmatite and granitic veins with the dominant orientation of NNE-SSW presumably produced by ENE-WSW oriented $\sigma3$ b) Phase II extension associated with joints originating from principal ENE-WSW directed $\sigma3$ and c) Phase III extension connected with the quartzo-feldspathic veins that are dominantly oriented in a NW-SE direction suggestive of NE-SW oriented $\sigma3$.

The S-C fabrics interpreted in the SW quadrant are associated with shearing and micro-folding (Figure 2c). S-C fabrics are evidence for tectonically produced fabric during multiple episodes of deformation (Price & Cosgrove, 1990). Hence, these fabrics suggest localised/restricted shearing at the SW part of the outcrop relative to the other quadrants. The sense of lateral movement is interpreted to be sinistral (Figure 2c). Furthermore, the lateral movement is supposedly restricted by NNE-SSW veins which divides the outcrop into almost two equal halves and are also limited to the boundaries of the joints. These are supporting evidence that the S-C fabrics are younger than the other interpreted structural forms. Of concern is the timing of the boudinage shown in Figure 2d. The boudinage is oriented parallel to one of the pegmatite veins and shows no obvious connection with the joints, it is difficult to ascertain whether it pre- or post-dates these latter structures. However, based on the type and orientation of the boudinage, we surmise that the boudinage was formed either during Phase II extension or in opposition to the sinistral shear movement. In addition, there is an apparent alteration of the $\sigma3$ stress field. For example, in Figure 2d initial orientation of $\sigma3$ for the vein becomes orthogonal for the subsequent formation of the boudinage. Therefore, the original direction of $\sigma3$ becomes the new orientation for $\sigma1$.

Earlier in this section we have shown that the outcrop recorded a prominent metamorphic event M1. These pervasive foliation and associated folding are interpreted as evidence for regional metamorphism. Hence, M1 was produced during a regional metamorphic event. During Phase I and II extensions, the opening created by fracturing were subsequently filled by pegmatite minerals. We propose that contact metamorphism was recorded adjacent to the intrusions. Therefore, we define an additional metamorphic event, M2, which is corroborated by Phase I and II extensions, respectively. We conclude that sinistral movement evidenced by the S-C fabric is linked to a final dynamic metamorphism, M3.

4.2 Local structures as mimic of regional structural trends and orogenies

The basement rocks of southwestern Nigeria have been affected by multiple orogenies which make it polycyclic in nature. Polycyclic orogenies imply several phases of metamorphism, igneous activity, deformation and mountain-building. Four main orogenies affected the Nigerian basement rocks, Liberian of 2700 ± 200 Ma (Oversby, 1976), Eburnean of 2000 ± 200 Ma (Oversby, 1976), Kibaran of 1100 ± 2000 Ma (Ogezi, 1977; Ekwueme 1987), and Pan African of 600 ± 150Ma (Fitches et al. 1985; Van Breemen, et al. 1997). The Kibaran orogeny is contentious and poorly documented in Nigeria. Of utmost importance is the pervasive thermotectonic event of Pan African/Brasiliano orogeny (M^c Curry, 1976; Rahaman, 1976) which reconfigured and overprinted older Precambrian imprints. The E-W collision of the West African craton and westward moving plate created

N–S to NE-SW trending structures parallel with the edge of the West African craton (Black et al., 1979; Champenois et al., 1987; Oluyide 1988; Egesi & Ukaegbu, 2010). Hence, the Pan African orogeny is expressed as highly deformed series of multidirectional orientations found in the folds, lineaments and faults in the entire Nigerian Basement Complex and Northern Cameroun (M^{c}Curry, 1976; Rahaman, 1976; Onyeagocha 1984; Toteu et al., 1990). The dominant Pan African fabrics include N-S and NE-SW oriented structures as opposed to Achaean or pre-Pan African orogeny trends oriented differently to these directions in the basement (Onyeagocha & Ekwueme, 1982; Toteu et al., 1990).

Since smaller-scale structures are mimics of regional structures (Pumpelly et al., 1894; Wilson, 1951), larger-scale regional structures covering thousands of kilometres are often imitated by smaller-scale macro and micro structures found in outcrops and thin sections. In the study area, we identified M1, M2 and possibly M3 metamorphic events of Egbuniwe (1982) and Oyinloye (2011). The dispositions of the veins are consistent with deformation, D2 described by Oyinloye (2011) while the S-C fabric is possibly connected to the regional M3 event and D3 deformation. We suggest that the N-S and NE-SW oriented structures are presumably Pan African imprints while other differently oriented structures are precursory Precambrian fabric associated with Liberian, Eburnean and possibly Kibaran orogenies. However, the NE-SW foliations and compression are thought to be unrelated or completely obliterated by the Pan African orogeny.

It is noteworthy that the observations made in this work are based on an outcrop or 2D dimensional data. For future investigations, we propose further structural or three dimensional (3D) analysis of deformation in not only this outcrop but also in the surrounding exposures. In addition, petrographic description of mineral and grain fabrics will facilitate better understanding of the history especially the metamorphic phases and correlation to regional trends beyond the Southwestern basement complex farther into NW Nigeria and across the Pan African lines.

5. Conclusion

The rock of the study area is a banded hornblende-biotite gneiss that has been affected by different orogenies which are manifested as pervasive foliation and multiple structural forms. The NW-SE imprints are believed to be relics of pre-Pan African events while the N-S and NE-SW trends are seemingly associated with Pan-African orogeny. These structures are macroscopic indicators of the complex tectonic history witnessed by the basement rocks in Southwestern Nigeria. Thus, the outcrop provided a unique platform for studying the regional tectonic history of the study area. The evolutionary history of the outcrop is summarized as follows:

1. The first event is related to the emplacement of a granitic protolith suggested by the preponderance of alkali minerals in the palaeosome. The granitic protolith was later metamorphosed into strongly foliated gneiss. The regional metamorphism M1 event is evidenced by segregation of mineral into bands of light- and dark-colored minerals.
2. Other metamorphic episodes may be related to localized-contact and dynamic metamorphism signified by fracturing and emplacement of pegmatite and quartzo-feldspathic veins and finally by shearing and sinistral movement in the SW part of the outcrop, respectively. These are possibly M2 and M3 events of Egbuniwe (1982).
3. The compression of the rock by E-W and NW-SE oriented tectonic stresses produced folding of the foliations. The first folding event is F1 found in asymmetrical folds and F2 of ptygmatic folds. The contractions were followed by separate extension events described as Phase I and II extensions, respectively.
4. Phase I extension is coincident with the emplacement of pegmatite veins. Phase II extension resulted in joints that intersected the earlier veins while Phase III is associated with emplacement of quartzo-feldspathic veins. These latter veins are oriented normal to the orientation of the joints. The aspect ratio, AR of the veins is ≤ 0.186. The average perpendicular distances between the joints are unequal, thus the joints do not occur in sets and are non-systematic.
5. Shearing of the rock produced S-C fabrics in the SW part of the exposure and presumably s-slip boudinages in the NE.

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