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DEFORMATION MECHANISMS, TIMING AND SHEAR SENSE ANALYSIS OF PART OF THE PRECAMBRIAN TERRAIN OF SOUTHWESTERN NIGERIA

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ABSTRACT

The study area is part of the polycyclic Precambrian Basement Complex of southwestern Nigeria, which comprises meta-sediments and granitoids of varying compositions. The area was primarily deformed into a large-scale sheeted structure, which was sequentially followed by developments of first and second phases of folding that interfered with each other. Brittle to semi-ductile shear deformations, initiated by an ESE-directed transport of the hanging wall of a major NE-SW trending low-angle normal fault culminated in the third phase of fold and development of widespread shear zones. Latter phases of deformation resulted in rotation of finite strain axis relative to the instantaneous strain during a non-coaxial progressive simple shear deformation. We posit that the dominant terminal mechanism of deformation in the area is the late-kinematic progressive heterogeneous simple shear during the late- to post-Pan African orogenesis.

Key words: Shear; deformation; tectonic; poikiloblast; rotation; isoclines.

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1. INTRODUCTION

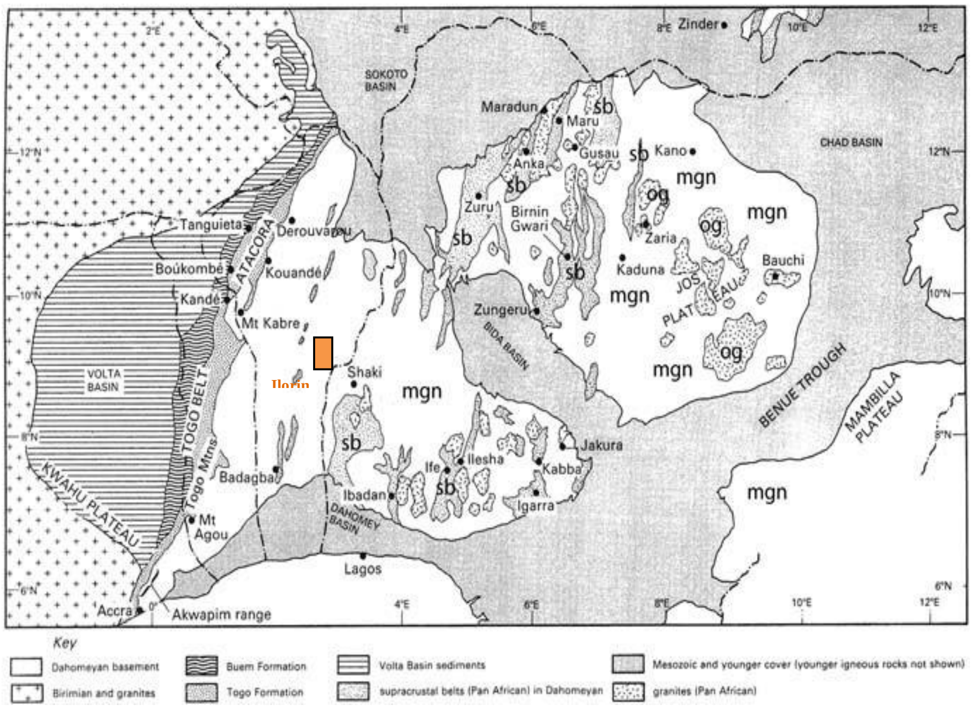
The study area, which forms part of the Neo-Proterozoic Basement Complex of Nigeria (Fig.1) lies between Longitudes 5^{o} 00′ – 5^{o} 07′N and Latitudes 8^{o} 30′ – 8^{o} 35′E. It constitutes the northern component of a 1200Km^2 (Fig.2) Precambrian terrain. This is a relatively less-studied area, unlike most parts of the Basement Complex of Nigeria, and has hitherto been mapped only by the correspondent author [1] and on which there are a few publications. The selected area of study, being an integral component of the north-south trending Trans-Saharan (Pan African) Belt, shares several geological and structural similarities with the Boborema Province of north-eastern Brazil [2, 3].

The Geology comprises gneiss, marble, quartzite, schist, granodiorite, granite, and pegmatite of varying compositions. Structural elements such as folds, faults and joints, including small-scale structures such as sigmoids, porphyroblasts, chicken beak structures, tension gashes, rootless intra-folial isoclines etc., were observed during the field mapping excercises. Such small-scale structures are preponderant in this terrain that has suffered polycyclic deformations from the Liberian (ca 2700Ma) to the waning ages of the Pan African (ca 600Ma), having witnessed a prolonged but intermittent periods of deformation and plutonism spanning about 1.7Ga [1]. A major domal structure that has been distorted by some component of rotation in the area, but with no report on the sense and degree of shear was also identified in the area [1]. About 100km northwest of the study area features which indicate significant level of shear deformation but with no references to the shear sense were reported [4, 5]. Widespread occurrences of NNE/SSW trending dip-slip faults, and shear zones are conspicuous evidences of intra-plate deformation in the study area. The sense of shear, which has not been reported, is an aspect of structural geology and also has implications for the evolution history of the area.

It is therefore the purpose of this paper to use the available information in the small-scale structures observed on the field and in thin-sections to determine the deformation mechanism, the timing, and the sense of shear, which occurred during the various events of multiple deformations that took place in the area. This is a new finding which has not been reported both in the study and adjacent areas of the Basement Complex of Nigeria. The result of this research is to lend credence, or otherwise, to some of the existing claims about the area; to assist in deducing the stratigraphic polarity of the area and also to serve as a guide for further research in the study area as well as in other areas of similar typologies.

2. METHODOLOGY

Geological field mapping was carried out on Scale 1:25,000 with emphasis on the attitudes of small-scale structures. Sampling was done using the methods of Paschier and Trouw [6]. The principal axes were pre-determined on the field in order to be able to determine appropriate directions of the sense of shear at outcrop level and in thin section. Thin-section preparation was done in the Geological Workshop of The Department of Geology and Mineral Sciences, University of Ilorin, Nigeria.



Study Area

Fig.1a. The West African domain of the Pan African Mobile Belt

3. RESULTS AND DISCUSSION

Brief Geology

Gneisses, quartzite, amphibolites, marble, schist, granodiorite, granite, and pegmatite of varying compositions are the rock types in the area. A co-eval structural relationship occurs between the gneisses, quartzite, amphibolites, marble and the schists while the granitoids are essentially intrusives which cut the fabrics of the pre-existing country rocks. These rocks have suffered varying degrees of thermo-tectonic alterations, including a large percentage of the granitoids, especially the syn-tectonic variants. Adedoyin [1] documented multiple deformation events, including three folding and four metamorphic events, besides the shearing and fracturing that post-dated most of the events. The outlines of fabrics of both brittle and ductile elements were used to construct the structural fabric map of the area (Fig.2). Syn-tectonic intrusives have cross-cutting contact relationships with the gneisses, quartzites amphibolites, marble, and schists but are weakly tectonised, unlike the post-tectonic types, which although also have cross-cutting contact relationships but still possess distinct igneous textures. All of these were recorded both during tectonic and non-tectonic periods. The detailed geology of the study area can be seen in Adedoyin et al [7], Adedoyin [1] and Adedoyin et al [8].

The study area is highly deformed and can therefore be treated as a terrain that has suffered multiple phases of deformation thus laying credence to the polycyclic deformations that have been identified in many parts of the Basement Complex of Nigeria [9, 10, 11, 12, 13, 14, 15,]. The polycyclic deformation of the area is reflected in polyphase folding and multiple metamorphic events which took place in the area [15, 16] and about 20km north of the area [17].

Adedoyin [1] identified at least four metamorphic phases; $M_{1,}$ $M_{2,}$ $M_{3,}$ and $M_{4.}$, which are preserved in hydrous phases of pelitic rocks, and also support the claim for multiple deformation in the study area. The various folding phases F_1, F_2 and $F_{3,}$ which were identified on the field, are also signatures of multiple deformations. So also, several sets of joints as well as various magnitudes of faults and shear zones were identified both in the tectonites and non-tectonites, especially quartzite, amphibolite, schist and leucocratic porphyritic granite. These also denote multiple deformations in the study area. Around the marble deposit in the eastern part of the study area and within the gneisses and schists, different folding phases were identified. Adedoyin [1] opined that shearing coupled with axis rotation took place in the area during one of the various deformation episodes. Axis rotation during deformation of the Basement Complex of Southwestern Nigeria has been reported [19]. The apparent rotation that took place became expedient because shear deformations always have components of rotation.

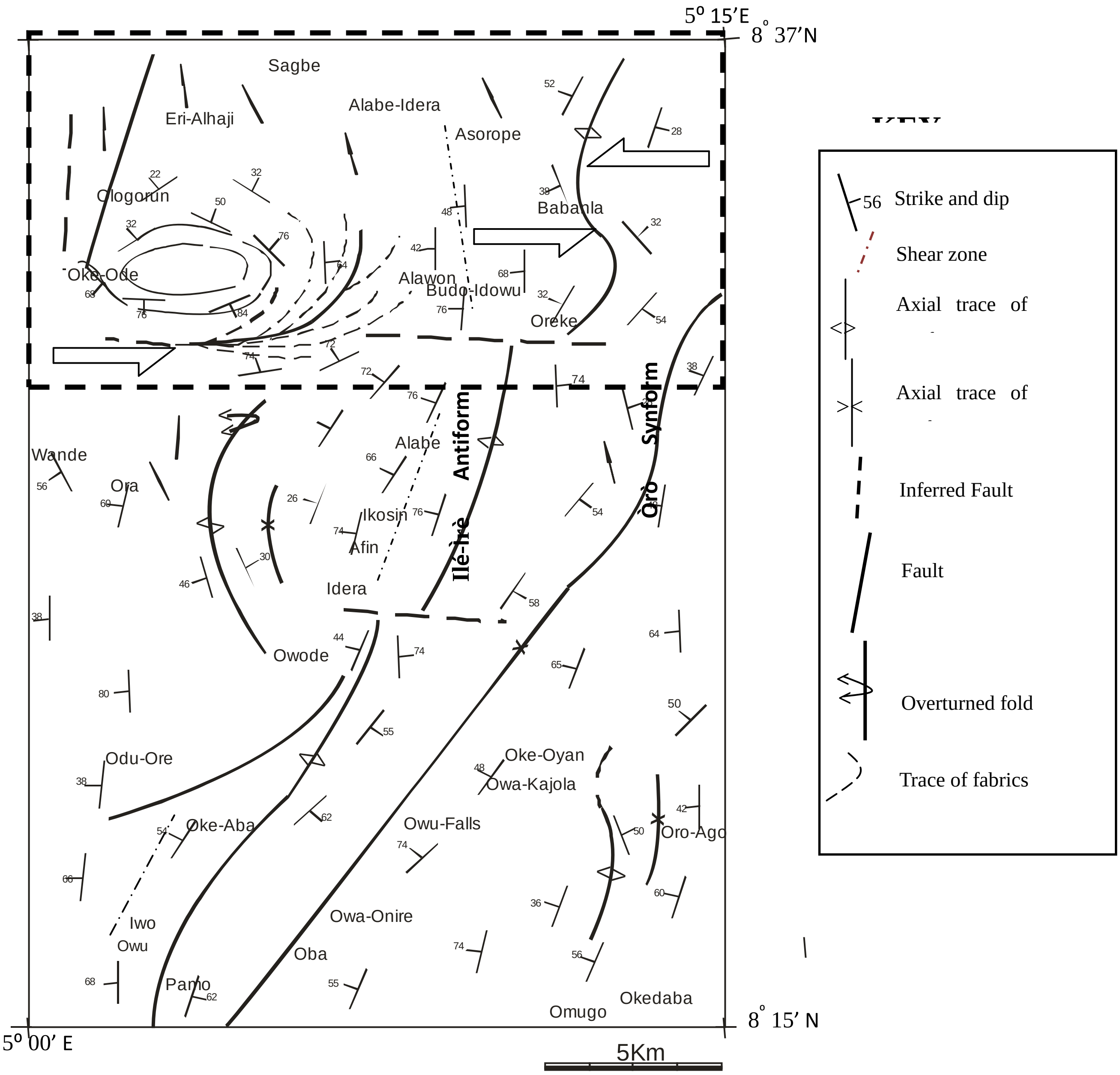


Fig.2. Outlines of Structural Fabrics in the study area (in dashed box); part of the area studied by Adedoyin [1]

On the quartzite ridges in the northwest, a large-scale isoclinal crenulation fold with two sets of lineation was identified by Late Dr H.P. Baer while on a reconnaissance mapping with the corresponding author (as an undergraduate project student) in 1985. The first set is generally N-S trending and plunges at between 20°- 25° northerly. It is likely to be the earlier set.

The other set of lineation is E-W trending, sometimes trending along WNW-ESE direction and seems to be the younger lineation set. This often plunges at a low angle of less than 20^{o} easterly. Boudinages defined by amphibolitic units as well as pinch-and-swell structures denoted by quartzo-feldspathic veins are common in the area, especially within the gneissic and schistose layers.

The different types of fold structures, which occur in the area, ranging from asymmetric, isoclinal, and recumbent as well as the interference patterns (Fig. 3) within the tectonites also suggest interferences between older and younger phases of folds. On the whole, the most dominant structural features in the area are the large scale dome, the shear zones and the faults. The dome has been described [1, 15] based on the quaquaversal nature of the dips of the strata. It has also been identified that the present orientation of the domal structure, which is sub-elongate in outline, is due to rotation during one of the phases of deformation. This present morphology was attributed to the tangential deformation during the late Pan-African time [1]. Affaton et al [20] are also of the opinion that tangential shear deformation occurred during the Pan-African time.

There are also major faults in the northwestern part of the study area. One of them was closely examined on the exposed scarp. It is a low-angle (ca 30^{o}) normal fault (Fig. 4) with an ESE (top-to-east) transport. On the fault scarp are striations and grooves which show evidences of perceptible dextral movement of about 5cm that connotes the lateral component of movement. Two other faults were identified northwest of the study area. The first, which strikes north-south, was inferred and coincides with the river course that was apparently flowing in a southeasterly direction but changed abruptly, when it hit the fault and now flows southerly. Several minor right-lateral (dextral) and left-lateral (sinistral) faults were identified at outcrop scales. To the east of the dome, a N-S trending ductile shear zone was identified. It cuts the psamitic, schistose and even granitic rocks. Within the shear zone, minor shear cleavages with sinuous attitudes (Fig. 5) were identified, especially in the tectonised leucocratic granite. Southeast of the dome, tension gashes which have been transposed occur in form of quartz boudins. They are actually tension gashes later filled by silica. The tension gashes occur as en echelon structures in shear zones cutting the boundary at angles of about 30^{0} or even more (Fig, 6). Brittle deformations result in initiation of array of veins and as fractures begin to grow under progressive deformation, tension gashes in form of sigmoids develops [19, 21, 22]. Post tectonic deformation usually alters the orientation of the structures as observed in the study area. Minor shear zones were also identified in many parts of the study area occurring in both the tectonites and non-tectonites.

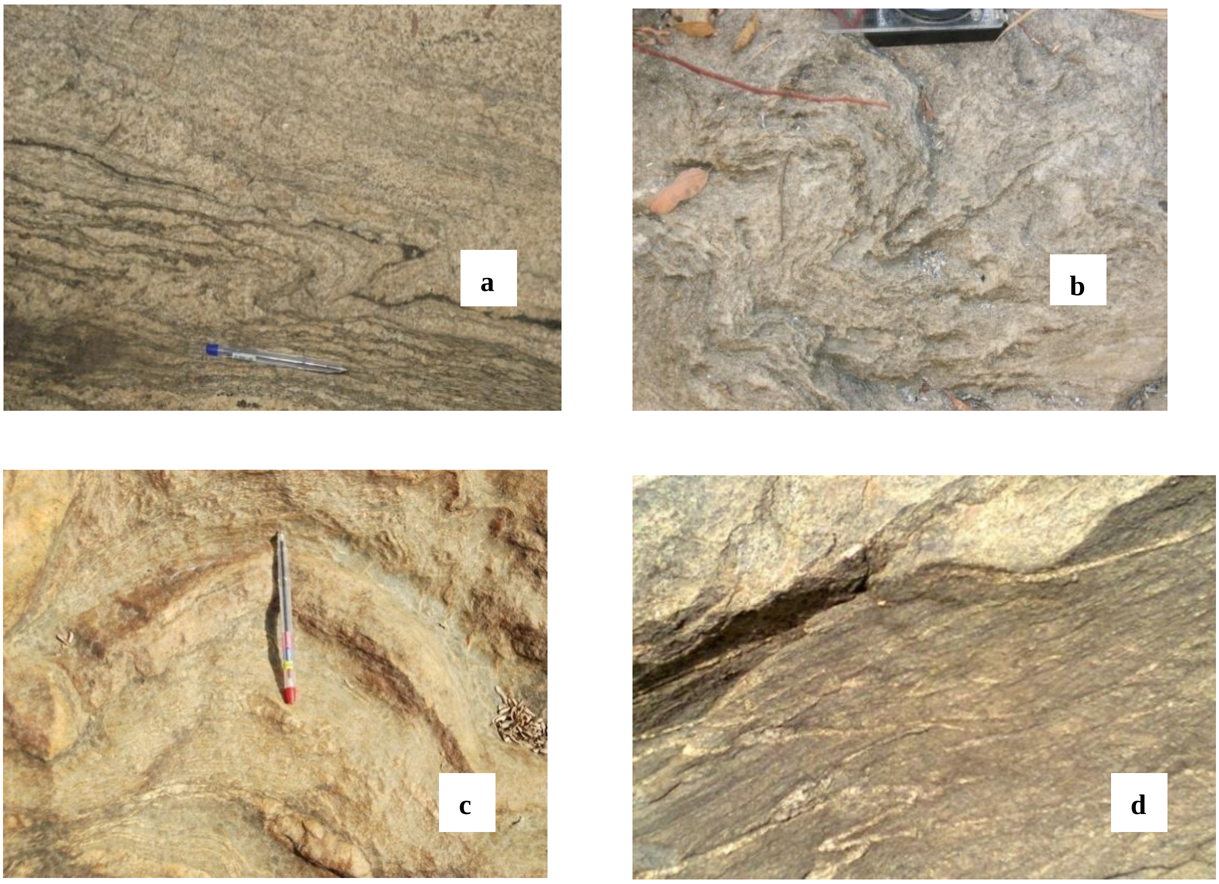


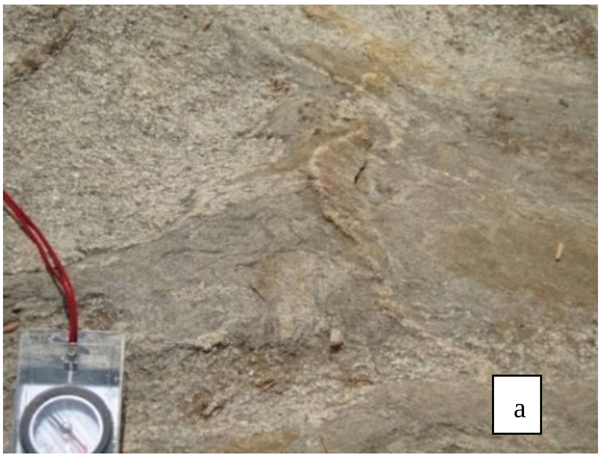
Fig.3. Different fold patterns in the area, (a) Recumbent fold in granitic gneiss (b) F_2 fold in marble (c) Open asymmetric fold in psamitic gneiss (d) Z- folds in quartz-biotite gneiss

Large scale shearing is exemplified by the major pinched-in synform, southeast of the dome. This kind of structure has been identified and treated as shear zones in Okene area, central Nigeria [14] and the study area [1]. This synform was determined on the basis of sharp deflection of strike directions in the area.

The axes of the synform and the minor sinuous shear cleavages in the major shear zone are in tandem with the outline of the minor F_3 fold axes that occur in the eastern part.

Deformation mechanisms

The mechanisms which are responsible for the various deformations were inferred from both the orientations and deformation mechanisms of the geological structures that pervade the area. The small-scale structures of different types and styles were used to determine the mechanism and, ultimately, the sense of shear.



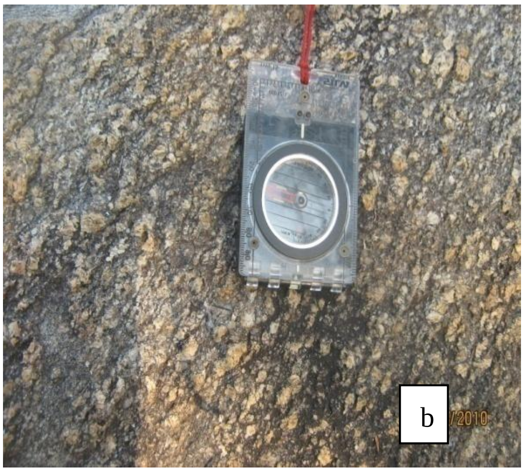
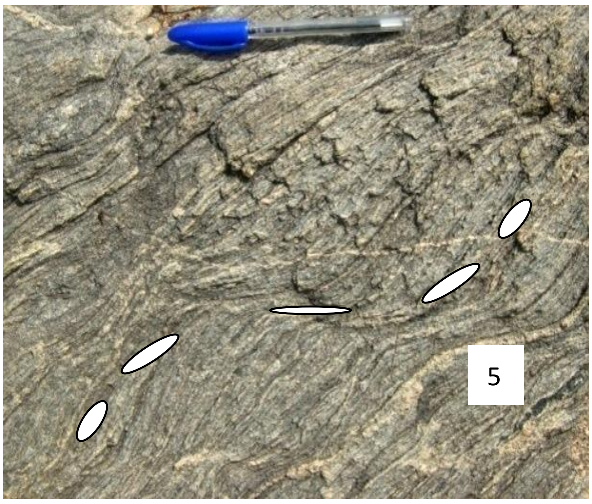


Fig.4.(a) Sub-sinuous trace of normal fault (facing NNE) (b) Exposed portion along the fault (facing west). Note the elongated crystals of quartz and feldspar on the surface. About 5cm of lateral component of the displacement was identified on the fault scarp

The fault-bounded asymmetric dome which has been sheared and rotated occurs in the northwestern part of the area. Occurrence of sheared asymmetric refolded folds and small-scale extensional features in the area signify more than one generation of folding and deformation phases. Measurements on the minor folds such as axis, plunge and inter-limb angles showed that the F_1, F_2 and F_3 folds differ in terms of axial orientations.

Later, during the E-W Pan-African tangential shear that affected the area and its neighbourhood [5, 23], the dome was re-oriented thereby elongating it in the direction of the shear. This led to the apparent tangential disposition of the fabrics in and around the dome, to the regional N-S Pan-African axis as well as the developments of parasitic minor F_3 folds.



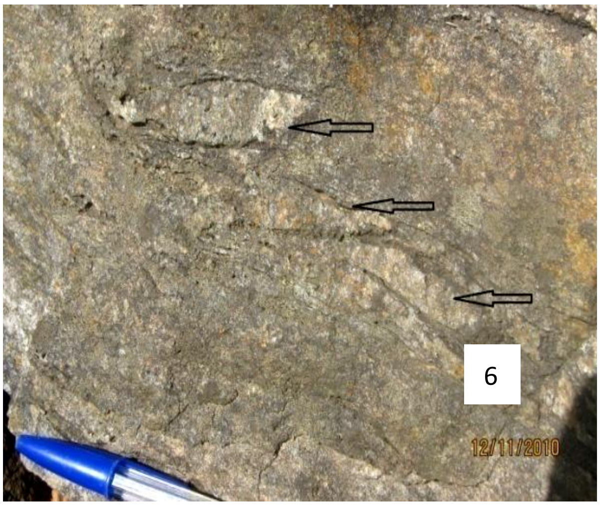


Fig.5. Sigmoidal shear zone in quatz-biotite schist, (left). The annotation depicts both the sense of shear and the relative amount of strain distribut. Fig. 6: Healed Tension gashes in micaceous quartzite (right)

The east-west shear deformation was also responsible for the sinuous attitudes of the fabrics in the eastern part around the major F_2 fold axes. The signature of the E-W deformation was earlier noted in shear fabrics within the shear zone and, later, in the sigmoidal outline of the major F_2 fold axis (see Fig.2). The same phenomenon caused it to be re-deformed into an F_3 fold. This was observed both at outcrop scales (Fig. 7) and on the structural map (see the sinuous attitude of the axis of the F_2 fold in Figure 2).

Within the shear zone, the fabrics exhibit dextral sense of shear and dip at low angles. However, two foliation phases, that is S_1 and S_2, were identified. The major normal fault, west of the dome, dips at about 30^o easterly. Grooves and slicken side striations, which occur on the scarp surface of the fault, are elongated in the ESE direction of movement.

Holt et al [24] are of the opinion that the Basement Complex of Nigeria was largely deformed under a progressive heterogeneous simple shear. We are of the opinion that progressive simple shear has been a dominant mechanism of deformation in this area. Interference between the first two phases of folding culminated in the domal structure under a non-coaxial progressive deformation, which took place under progressive simple shear, accompanied by rotation of finite strain axes, relative to the finite strain. Deformation by progressive heterogeneous simple shear is also considered to have resulted in the overprinting foliation transposition which is common in the study area. This occurred because the initial S_1 foliation was deformed by flattening and subsequent development of asymmetric folds. The S_1 was then deformed progressively along S_2 shear surfaces by transposition while the relics of fold hinges of the F_1 folds are then preserved in the transposed folia. In the study area, intra-folial folds and rootless intra-folial folds are well preserved (Fig. 8). Rotation of overprinting garnet crystals in pelitic quartz-sillimanite-biotite schists (Fig. 9) is also an evidence of deformation by simple shear. Fracture initiation and growth, coupled with the development of sigmoidal tension gashes are also products of progressive deformation. The over-all deformation mechanism in the area has been ascribed to heterogeneous progressive simple shear [1]. Establishment of top to the east motion on both flanks of the dome indicates that the whole area was re-activated under a large-scale intra-continental shear deformation.

Timing

The timing of the shear and the re-orientation of the dome was either late (syn-) or post-Pan-African. In addition, elongate leucocratic porphyritic granite emplaced within the fault have been constrained to the post- tectonic times [1] using Agrawal method [25]. Further still, the trace of the fault cuts the Pan-African fabrics in the tectonites, implying that the faulting post- dated such fabrics. All the millimetric- and diametric-scale structures indicate a late- to post- Pan African time in origin.

Fig.7. Minor F_3 folds in garnet-sillimanite-biotite- schist (left). Fig. 8: Intra-folial folds in quartz-biotite schist (right)

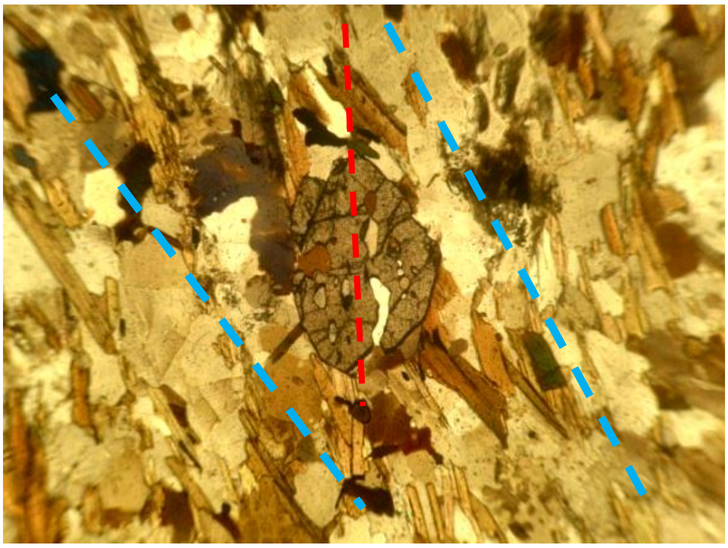


Fig.9. Overprinting garnet porphyroblasts. (a) Note the discordance of the long axis of the garnet crystal (dashed red line) to the fabric of the matrix (dominantly sillimanite, biotite and quartz) immediately surrounding the garnet (dashed blue lines)

Shear sense indicators

Major and minor structural features were used to deduce the sense of shear in the area. The most dominant indicator, albeit on regional scale is the E-W direction of the modified dome. This is observable on both the topographic map and the satellite imagery map of the area and portends a dextral sense of shear.

Minor structural features such as rotated blocks in fault zones (Fig. 10), isolated asymmetric objects, lozenge-shaped crystals, mantled porphyroclasts and sigmoids (Fig. 11) were used to deduce the shear sense. Minor rotated blocks show that rotations occasioned by lateral shear probably re-orientated certain fabrics by almost 90^0 rotations. Asymmetric boudins and included units) of amphibolitic units, dismembered quartzo-feldspathic units, quartz porphyroclasts, minor folds in gneisses and schists and the morphologic outlines of minor ductile shear zones (Fig. 12) are common in the area and were all used to deduce the sense of shear.

At microscopic level, identification of C-S fabrics and garnet porphyroblasts which contain internal fabrics (S*i*) were also criteria for determining shear sense direction of the area. This kind of texture is referred to as poikiloblastic; and garnet, being the poikiloblast, is one of the minerals used to determine the sense direction. Other minerals are cordierite, kyanite, feldspar and even biotite, but garnet is important because of its strength and rigidity. In the study area, there are occurrences of garnet poikloblasts, which appear to have been mechanically rotated relative to the matrix or vice versa. Porphyroblast rotation has been ascribed to simple shear deformation by many authors [1] and also to progressive growth [26]. Such phenomenon has been used to determine kinematic histories of basement terrains that suffered multiple deformations. They are indicative of syn-kinematic deformations especially when mica flakes wrap around the poikiloblasts as was observed in the study area (see Fig. 9). However, it was the matrix that rotated and not the garnet crystals and the sense of shear is essentially sinistral. The sense of shear in this case is sinistral as opposed to other indicators. This is very localized, occurring in within crude metamorphic aureoles that developed during magma emplacement. The amount of rotation was estimated from the poikiloblast-matrix association to be about 30^{o}. This estimation was possible because the initial orientations of the samples had been determined on the field. Based on the shear sense of the small-scale structures, we therefore posit that the whole area has witnessed large-scale right-lateral rotation with minor adjustments around major granitic bodies at later times.

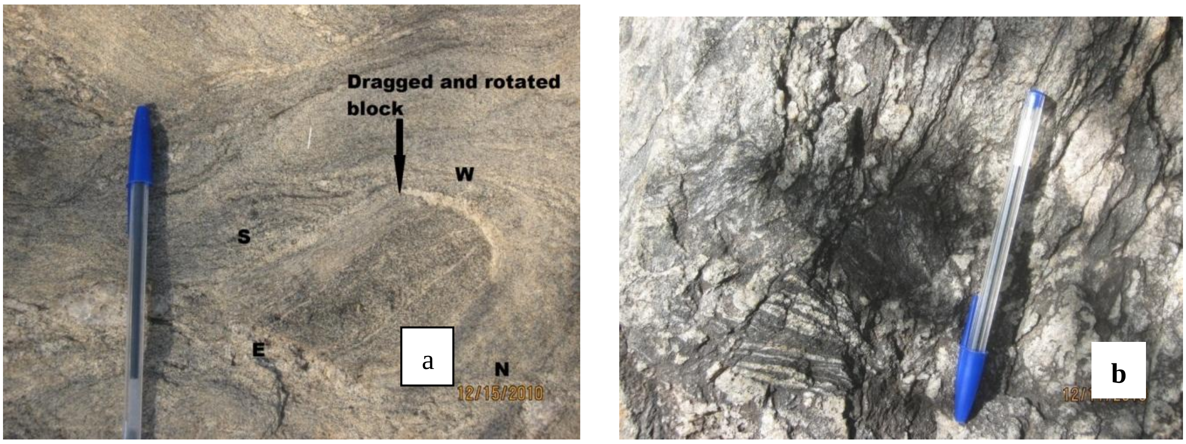


Fig.10. Rotated blocks in (a) fault zone, semi-pelitic schist. The rotated piece is rimmed by silica-rich material as a result of mechanical action and recrystalization. (b) shatter zone, psamitic gneiss. Note the discordance in fabric trends and lithologies

Shear sense analysis

The sense of transposition in the pelitic to semi-pelitic is right-lateral as deduced from the inherent structures. On the other hand, the whole area is amenable to treatment as a major shear zone or a shear bounded zone because of the several shear deformations that pervade the area. Pinched-in synforms, like the one that occurs around the dome, have been quantitatively determined to be amenable to interpretation as shear zones [13]. There are three types of shear related folds [27]. The study area can be classified into the pre-shear fold category because the fabrics within the shear zones cut those in the dome. They [27] also concluded that the asymmetry of a fold depends on the strain and rotation rates, so that pre-existing folds may even lose their original orientation and become completely transposed when certain strain limits are exceeded.

The average strike direction of the dome is E-W and this coincides with direction of the easterly transport of the bounding normal fault. Minor sheared, elongate, parasitic folds on the hanging wall signify that shear-induced rotation post-dated the F_2 phase. It is certain then that the original dome pre-dated the shearing. It is essentially understood that large scale folds and domes form in the lower crust as a result of flow. Shear deformation is a semi-ductile deformation which occurs deep in the crust [28]. Tangential shear occurred during the Pan-African orogeny [20]. The area may have thus been affected by such E-W tangential shear at a much deeper level in the crust.

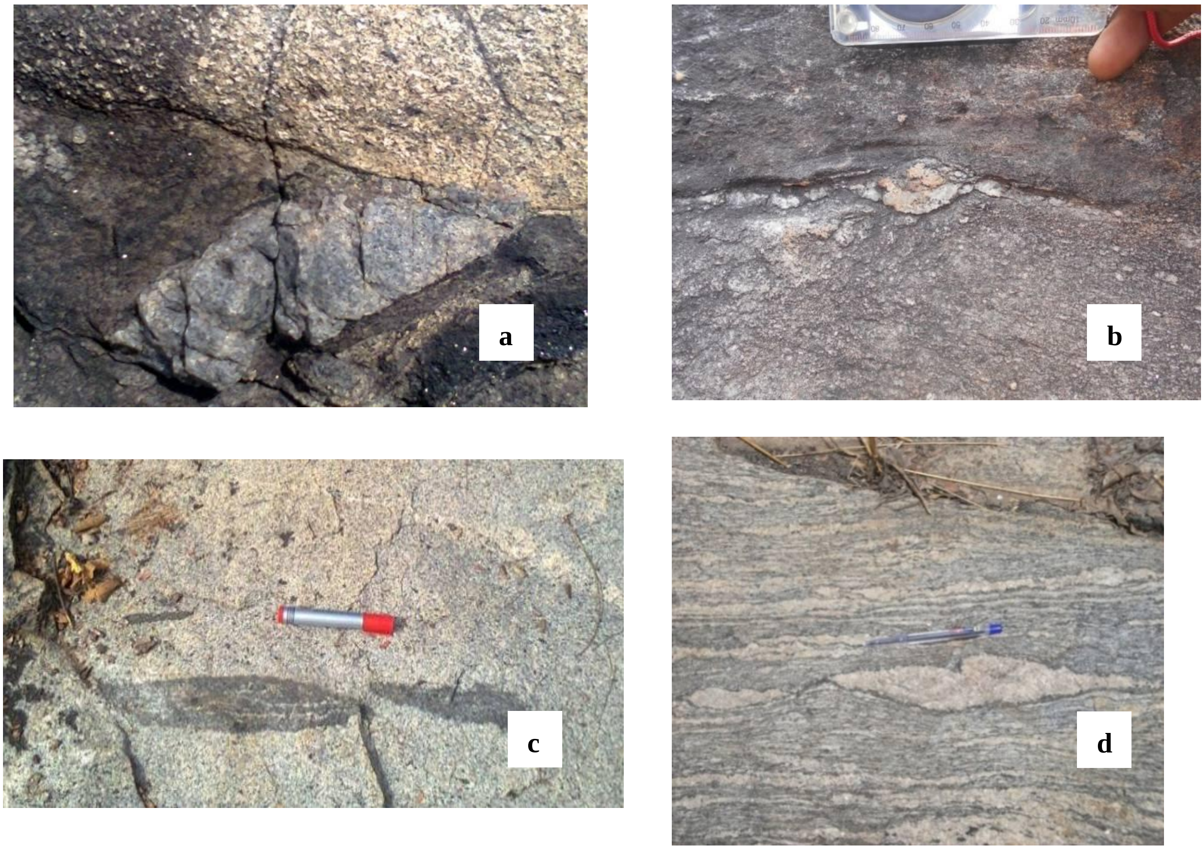


Fig.11. Isolated Asymmetric Objects: (a) Lozenge-shaped isolated quartz crystal in granitic gneiss (overlain by porphyritic granite). (b) Isolated feldspar porphyroclast indicating right-lateral shear by asymmetric recrystallized tails (c) isolated xenoliths of amphibole schists displaying right-lateral shear in weakly tectonised leucocratic granite (d) Boudinaged quartzo-feldspathic material deformed by right- lateral shear in migmatized gneiss

The fault developed towards the F_2 phase (during which period the dome was formed). Strike and dip measurements on the fault plane are approximately 020/30E.

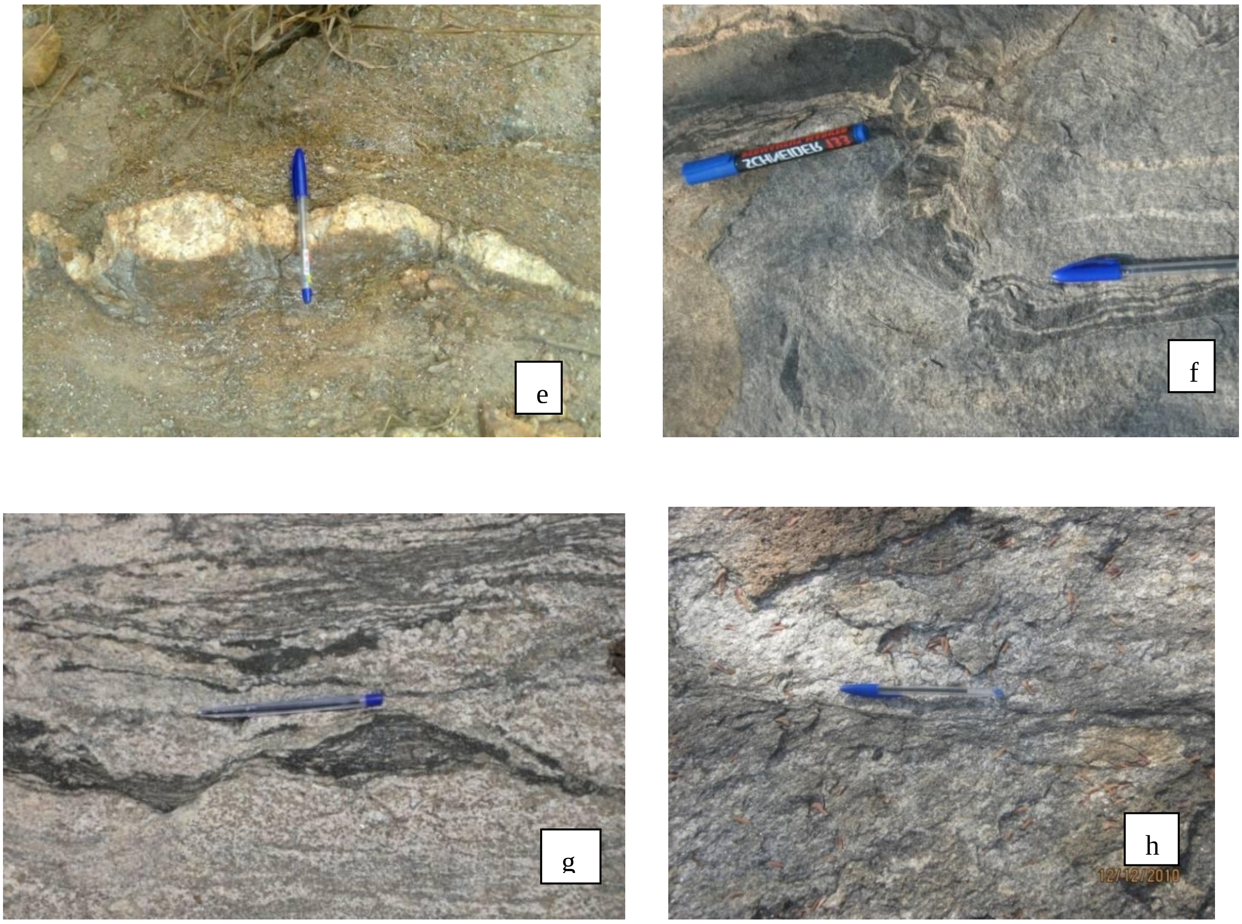


Fig.12. Asymmetric Objects (cont'd). (e) Shear band type asymmetric boudinage defined by a pegmatite layer in garnet-sillimanite-biotite- schist. This event is either post-Pan African or at the tail end of it because the pegmatite cross-cuts the fabrics of the F_2 folds in the pelitic schist and therefore connotes a possible F_3 fold in itself. (f) The folded amphibolitic layer shows that folding was followed by boudinage. This phenomenon depicts rotation from the shortening to the extension field. Terminally, therefore, the whole body was deformed by extension and this is a good shear sense indicator. (g) Asymmetric boudinaged amphibolitic vein in psamitic gneiss. (h) A narrow horizontal shear zone with dextral sense cutting late-tectonic coarse-grained Pan African granite

4. CONCLUSIONS

The mechanism, timing and sense of shear deformation of part of the Precambrian Basement Complex terrain, which hitherto have not been reported, were determined, using small-scale structures as indicators. Shear-induced rotations post-dated F_2 phase, in a terrain that has witnessed three folding episodes. The timing of the shearing also post-dated the peak of the Pan African tectonism, on the heel of the interferences between the F_1 and F_2 folds. This pre-dated the F_3 folds during a right-lateral axis rotation, under progressive simple shear. The whole area was ultimately reworked by late-kinematic non-coaxial heterogeneous simple shear, coupled with extension in the E-W direction, during a large-scale, deep-crustal, intra-continental shear deformation.

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