



Palaeostress configuration of Pan-African orogeny: evidence from the Igarra schist belt, SW Nigeria

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Abstract

The stress configuration and tectonic analysis of the Pan – African orogeny is drawn from the Igarra schist belt, southwestern Nigeria. The analysis of conjugate shear fractures of the schist belt indicates that two distinct compressive events (NE – SW and E – W) occurred in this Pan – African mobile zone. The palaeostress systems reveal a clockwise rotation of compressional axis from D_1 (NE – SW) to D_2 (E – W) during the propagation of the schist belt. The dominance of E – W compression related structures and the identification of E – W compressive stress in other Pan – African regions suggest that only the E – W compression probably had a strong regional effect during the Pan – African orogeny, other episodes of deformation most likely had a partially regional or local effect. The occurrence of structures related to the E – W compression in the younger rocks (granite and syenite) and the absence of structures related to the NE – SW compression in these rocks indicates that the E – W σ_1 is a younger episode of deformation (D_2) than the NE – SW σ_1 deformation (D_1) and probably lasted for a longer period. The dihedral angles (2Θ) of the conjugate shear fractures range from 35° to excess of 80° and this situation shows that the orogeny produced a combination of both brittle and ductile deformation.

Keywords: Igarra schist belt, Pan – African, Compressive stress, Conjugate shear fracture.

1. Introduction

The Nigerian sector of the Pan-African mobile belt is part of the 3000 Km long Trans-Saharan belt which formed in the Neoproterozoic (between 750 and 500 Ma) by a continental collision between the converging West African, Congo and East Saharan blocks (Ferre et al. 2002). It is surrounded by Adrar des Iforas (to the north), Saharan metacraton (to the east) and the Borborema Province (to the south). The Pan-African orogeny was interpreted as a tectono-thermal event, during which a number of mobile belts formed, surrounding older cratons (Fig 1). The Nigerian sector of the Pan-African orogenic belt contains poly-deformed high-grade metamorphic assemblages, exposing middle to lower crustal rocks, whose origin, the environment of formation and structural evolution are quite difficult to reconstruct. The protoliths of these assemblages consist of much older Mesoproterozoic to the Archaean continental crust that was strongly reworked during the Neoproterozoic (Kalsbeek et al. 2012, Ekwueme and Kroner 1997). There are over thirteen schist belts in Nigeria which were either formed or reworked by the Pan – African orogeny. This includes the prolific Igarra schist belt, southwestern Nigeria which is outstanding because of its level of exposure, structural variance and number of rock types within the belt.

These schist belts contain good evidence of the geometry of the principal stresses (σ_1 , σ_2 and σ_3) that operated in the region during the orogeny. However, studies of the principal stresses from the available shreds of evidence are lacking in the literature. Most of the studies in this region used the geometry of structures to infer the episodes of deformation that was active during the Pan-African orogeny. Such studies are highly speculative because of the ambiguity in the development of structures during deformation. For instance, the geometry of a foliation in schist may be different from a foliation in marble even when both rocks were subjected to similar stresses in the same region. This is because different rocks will respond to the same level of stress in a different rheology thus the subsequent structure that will develop may have varying geometries even when they were developed by the same stress. Moreso, a rock that was deformed by coaxial deformation will produce a structural geometry different from that of a rock that was deformed by non-coaxial deformation. Both deformation patterns (coaxial and non-coaxial) can be activated by the same principal stresses in a region. These can easily mislead a researcher to think that structures with slightly different geometries belong to different phase of deformation. The determination of the geometries of the principal stresses (σ_1 , σ_2 and σ_3) and the episodes of deformation that was active in an orogeny requires a deterministic and time-consuming approach such as conjugate shear

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fracture studies, palaeostress inversion from fault slip data or even strain partitioning. This work used conjugate shear fractures from the Igarra schist belt southwestern Nigeria to determine the phase of

deformation, the geometry of the principal stresses and the nature of Pan-African deformation. The results herein were compared with the results gotten from other Pan-African mobile belts.

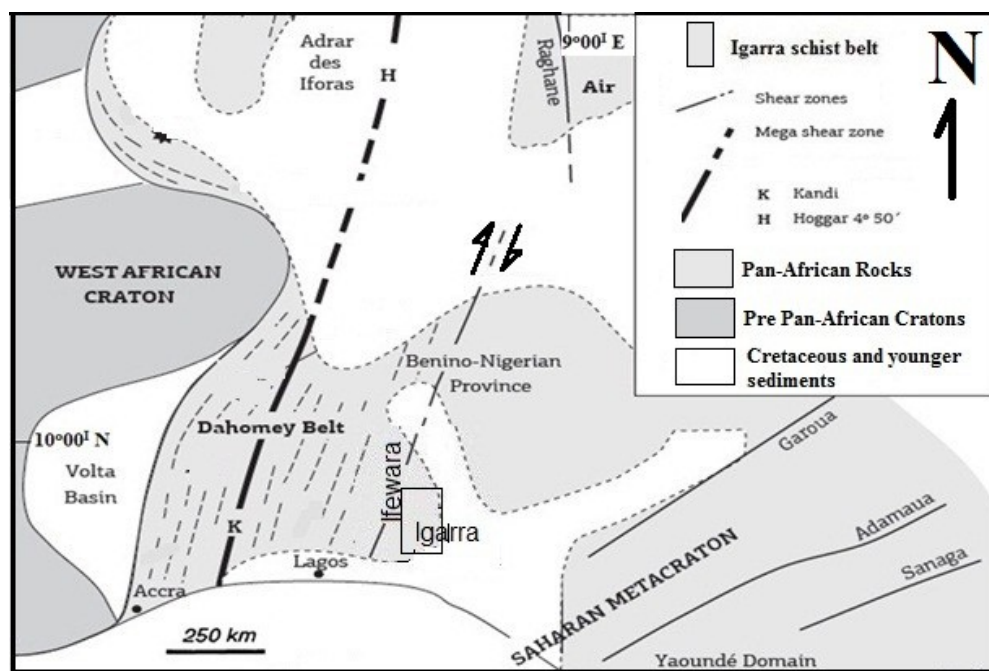


Fig. 1. Regional map showing the Nigerian section of the Pan-African orogeny and other associated regional structures. Redrawn from Cordiani, et al. (2014). The shear sense in the Ifewara shear zone is inserted from Ferre et al. (1995). The boxed area is the study area (Igarra schist belt).

2. Geologic and Structural setting of the Igarra schist belt

The southern Igarra schist belt contains a wide variety of rocks within a relatively small area. These rocks include metasediments such as schist, phyllite, quartzite, marbles, metaconglomerates, calc-gneiss and other rocks like granite-gneisses and porphyroblastic gneiss and all these rocks have been intruded by the Pan-African syn-tectonic granites as well as late stage dykes of syenite, lamprophyre and pegmatite (Fig 2). The rocks of the study area contain various structures such as joints, folds, faults, mineral lineations, foliations, mullions, strain markers and ductile shear zones (Fig 2). The Igarra area is 60% exposed in some parts (Egbuniwe and Ocan 2009) which made mapping of the rock and structure more efficient. The metasedimentary schists are by far the most extensive rocks in this region, they are composed of upper greenschist facies metapelite with interlayered quartzite, marbles and metaconglomerates (Ajibade, et al. 1987). The metasediments (schist, marbles, quartzite, metaconglomerates) occur as a supracrustal cover on the older migmatites (Hockey et al. 1986; Okeke and Meju 1985; Odeyemi 1988; Imeokpaira and Emofurieta 1991; Ajibade et al. 1987; Ekwere and Ekwueme 1991; Ocan

et al. 2003) and the pelitic schist sometimes forms continuous ridges overlain by narrow band of quartzite. The granite plutons in Igarra measures about 12km long and 2km to 5km wide covering an area of about 60km² (Fig 2). The massively jointed nature of the Older Granites in this region and their strong resistance to weathering tend to result in good topographic expression and a degree of out-cropping noticeably higher than the other major division of the basement complex. The large domed inselberg, rising abruptly from a widespread pediplain which is consistent with other parts of Nigeria (Hockey et al. 1986) is not also common in this area, however, it has been observed along Igarra - Somorika road (Oden and Udinmwun 2014a).

The granites average about 500m above sea level and trend in the N-S/NNW-SSE directions and they contain white to pink coloured, feldspar phenocrysts and xenoliths of schist, calc-gneiss, metaconglomerate and quartzites (Egbuniwe and Ocan 2009; Odeyemi 1976) which are preferentially oriented in the N-S to NW-SE directions (Oden and Udinmwun 2013). The unmetamorphosed composite syenite dyke measuring 6km by 0.7 km (Fig 2) and cutting obliquely across the metasediments, is emplaced in perhaps the last events to

affect the geology of this area (Odeyemi 1976). The stress configuration of this area reveals the tectonic evolution of the structural features in the rocks and shows at least two different phase of deformation in this region. The granite gneisses are prominent in the

northern part of the study area and they are foliated and contain basically pegmatite veins (Fig 2). These veins are emplaced in fractures or along foliation planes however in some cases, they do not occur as veins.

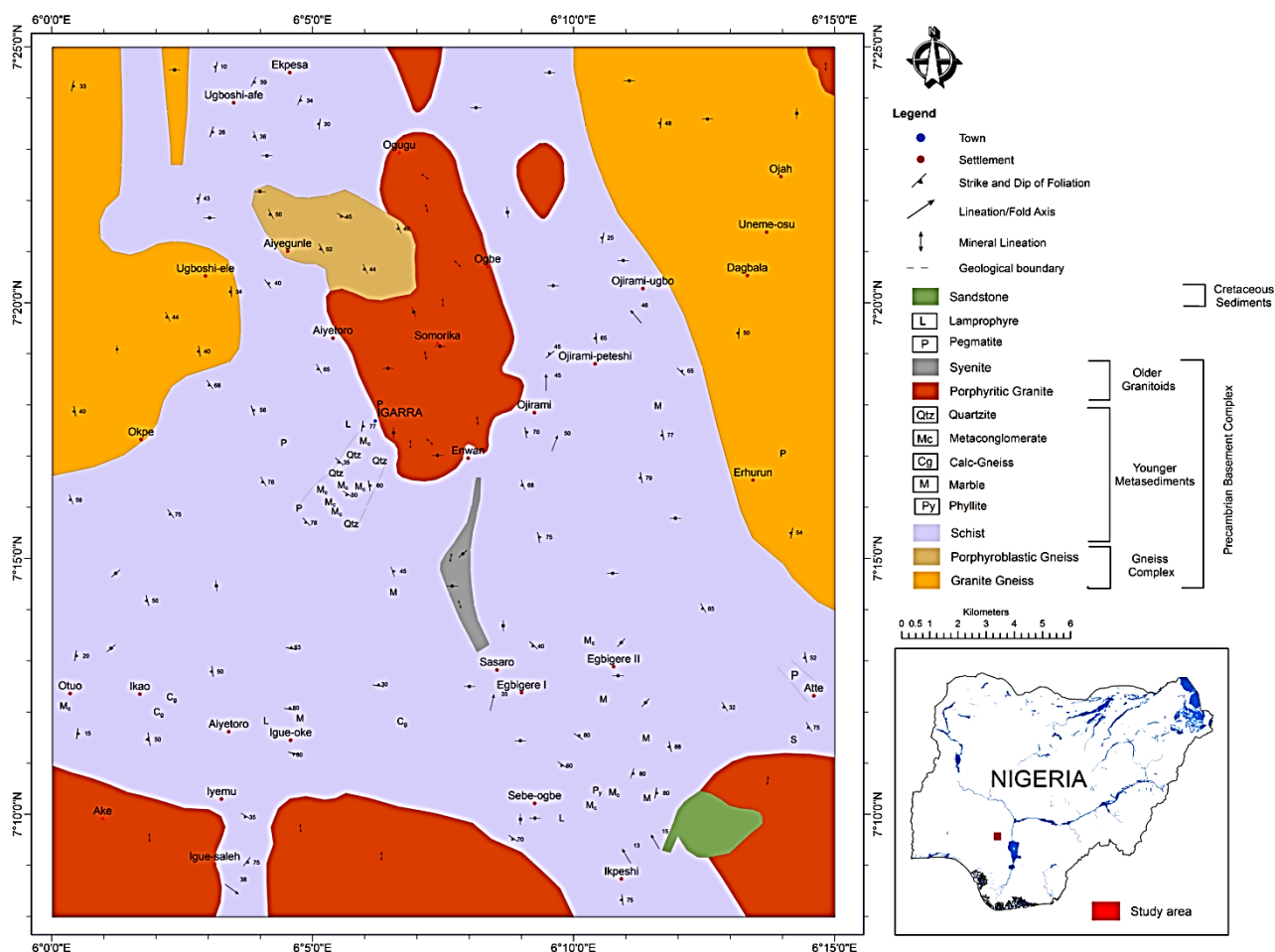


Fig 2. Geologic and Structural map of the study area.

3. Materials and Methods

This study involves the detailed mapping of rocks and structures with a particular interest in the conjugate shear fractures. The field mapping was carried out in three phases between June 2012 and August 2013 and a data confirmation reconnaissance mapping was done in December 2014. Detailed mapping of the Igarra schist belt was done on a topographic map with a scale of 1:25,000 covering an area of over 850 Km². The map was subdivided into 12 grids with the northern 9 grids covering an area of about 85.5 Km² each and the lower 3 grids covering an area of about 34.2 Km². The attitude of structures particularly conjugate shear fractures was measured using standard structural techniques and presented using stereographic projection and rose diagram. The conjugate shear fractures were used to

analyse the stress configuration that was active in this region and this also gave the condition of deformation. The analysis of stress configuration involves the use of co-genetically developed conjugate shear fracture set projected as planes on a stereonet (a Lambert equal area stereonet for this work). The acute bisectrix of this pair defines the direction of the maximum compressive stress (σ_1) direction (Belayneh and Cosgrove 2010) and the intersection between the two planes marks the position of the intermediate principal stress (σ_2) (Fig 3). The σ_2 position is then rotated to the horizontal line and the maximum (σ_1) and minimum (σ_3) principal stresses lie in a plane which is 90⁰ from the σ_2 position. The angle between the two planes 90⁰ from σ_2 is the dihedral angle (2 Θ) and half of the dihedral angle (2 Θ) marks the position of σ_1 then σ_3 position is obtained by counting 90⁰ from the σ_1 position (Fig 3).

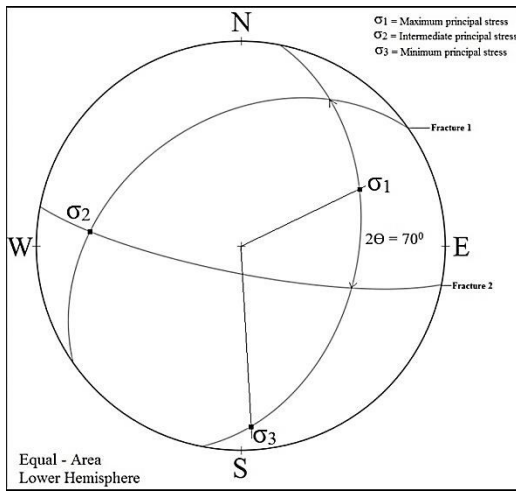


Fig 3. An analytical technique for determining the plunge magnitude and plunge direction of σ_1 , σ_2 , and σ_3 as well as the dihedral angle (2Θ).

4. Results

Stress configuration i.e. the determination of the plunge magnitude and plunge direction of the maximum (σ_1), intermediate (σ_2) and minimum (σ_3) principal stresses that were active during a deformation episode can be done using conjugate shear fractures. Conjugate shear

fractures may or may not show shear displacement and they are co-genetically developed in conjugate sets with a dihedral angle (2Θ) $>45^\circ$ (Singhal and Gupta 2010). Shear fractures tend to form at an acute angle to the greatest stress and parallel to the intermediate stress. (Hubbert and Willis 1957). Two sets of fractures that are thought to represent complementary shear set whether locally or regionally are referred to as conjugate sets (Hills 1972). The dihedral angle (2Θ) is the acute angle between the conjugate shear fractures and the acute bisectrix of the angle between the pair is parallel to the direction of the active maximum principal stress (σ_1) and normal to the trends of local folds (Shainin 1950; Wilson 1982). Suppe (1985) stated that conjugate joints systematically maintain an acute dihedral angle (2Θ) of about 5° to 60° between each other however a dihedral angle (2Θ) approximately equal to 60° (~ 60) is indicative of a brittle deformation which took place at shallow depth while a dihedral angle (2Θ) approximately equal to 90° (~ 90) shows a ductile deformation which took place at great depth (Singhal and Gupta 2010). Shear joints form at any angle to the principal stress direction other than 90° (Hobbs, et al. 1976). Actual shear fractures make an angle of less than 45° ($<45^\circ$) with the maximum principal stress (σ_1) axis (Billings 1972).

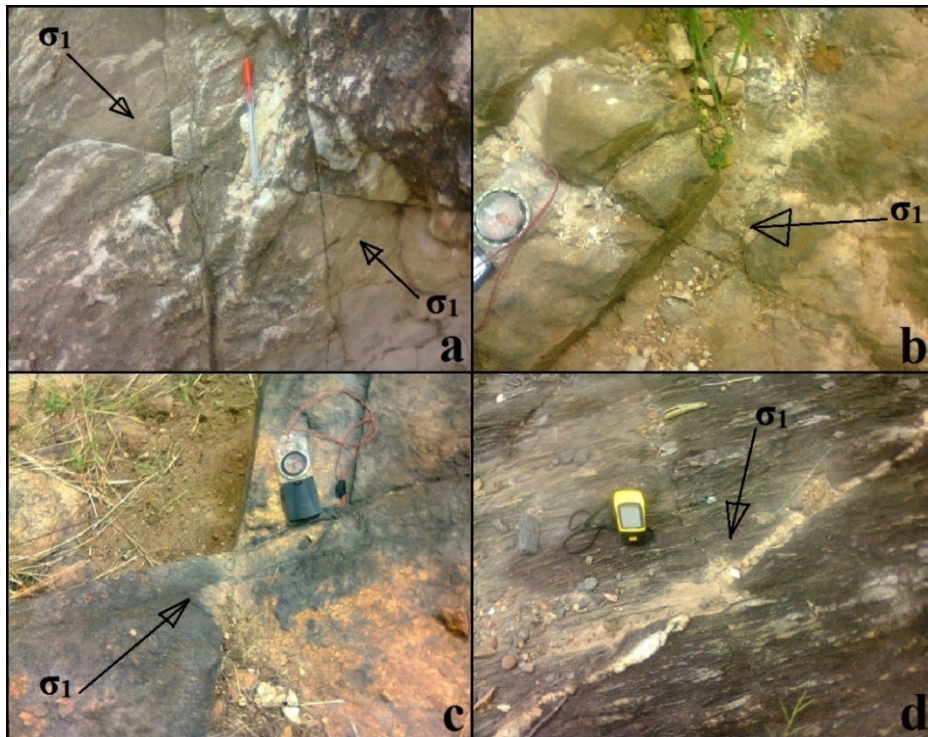


Fig 4. Co-genetic conjugate shear fractures (a) Conjugate shear fractures in quartzite (b) Conjugate shear fractures in marble (c) Conjugate shear fractures in granite gneiss (d) Conjugate shear fracture in schist with one of the fractures filled with quartz.

Conjugate shear fractures are not abundant in the study area, however, fifty-two (52) pairs were measured from granite gneiss, schist, marble and quartzite (Fig 4).

The plunge magnitude and direction of each of these positions (σ_1 , σ_2 , and σ_3) were determined and recorded for further interpretation. The stereographic projection of 52 conjugate fracture data points (Fig 5) shows two sets of σ_1 and σ_3 , the first set of the σ_1 plunge in the NE-SW direction (Fig 5a) while the second set plunge towards the E-W direction (Fig 5b). Complementarily, the first set of the σ_3 plunge in the NW-SE direction (Fig 5c) while the second set plunge in the N-S direction (Fig 5d). Comparing this result with strain analysis carried out by Udinmwun (2015) in this region, the NW – SE σ_3 direction is consistent with the λ_1 direction obtained from metamorphic spots in schist and clasts of metaconglomerates while the N – S σ_3 aligns with the λ_1 direction derived from the phenocrysts and xenoliths in granite and those obtained from the phenocrysts/xenoliths in granites. Strain analysis studies

using phenocrysts by Oden and Udinmwun (2013) and Udinmwun (2015) showed that only the E – W compression was active in the granites. However, this work shows that a NE – SW and E – W compression was active in the Schist.

Since the schist are definitely older than the granite from their contact relationships (Udinmwun 2015), thus the absence NE – SW compression imprint on the granites strongly suggests that the phase of deformation (NE – SW compression) has probably ceased before the granites were emplaced. Therefore the NE – SW compression is older (D_1) than the E – W compression (D_2) indicating a clockwise rotation of the maximum compression direction (Fig 6a and b). Nevertheless, studies by Odeyemi (1976), suggests that the E – W compression was the final phase of deformation activities in the Igarra area. The dihedral angle (2Θ) ranges basically from 60° - 80° , however, 2Θ values as low as 35° were recorded while 90° was also observed (Fig 7).

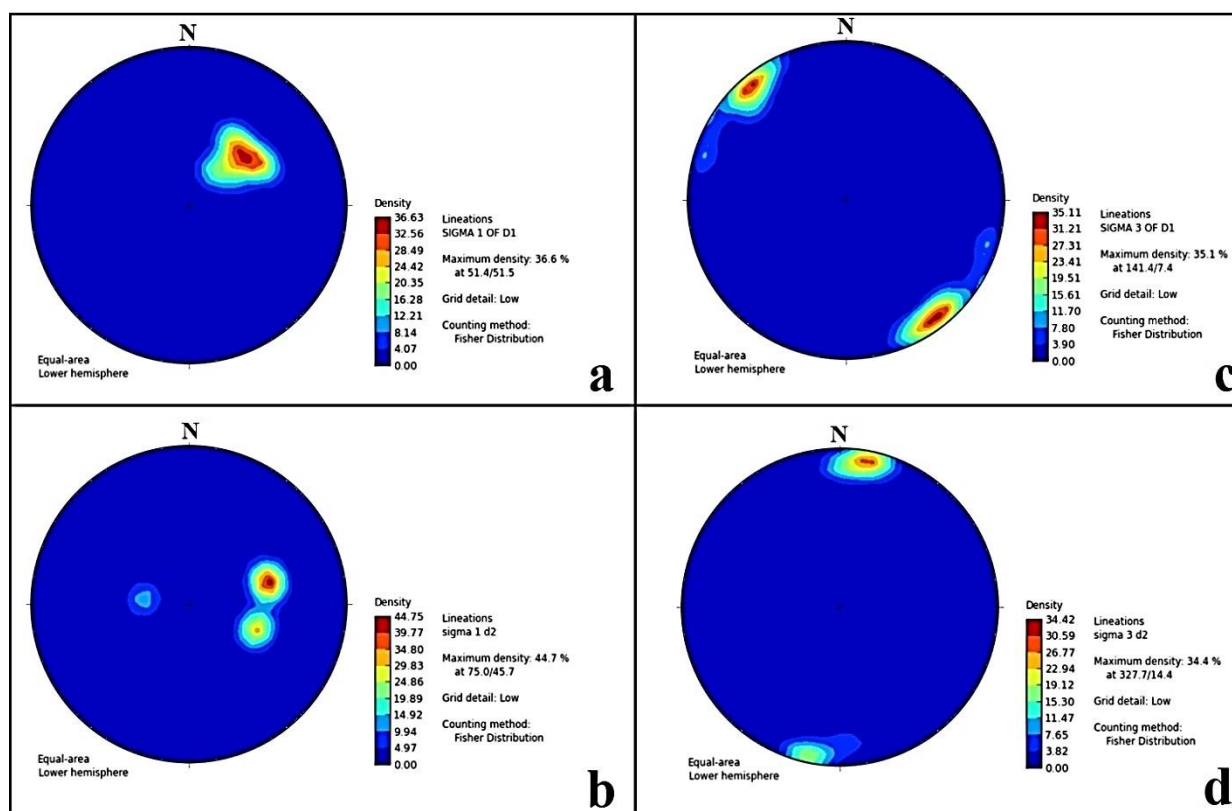


Fig 5. Stereographic projection of the principal stresses obtained from conjugate shear fractures. (a) Maximum principal stress (σ_1) of D_1 (b) Maximum principal stress (σ_1) of D_2 (c) Minimum principal stress (σ_3) of D_1 (d) Minimum principal stress (σ_3) of D_2

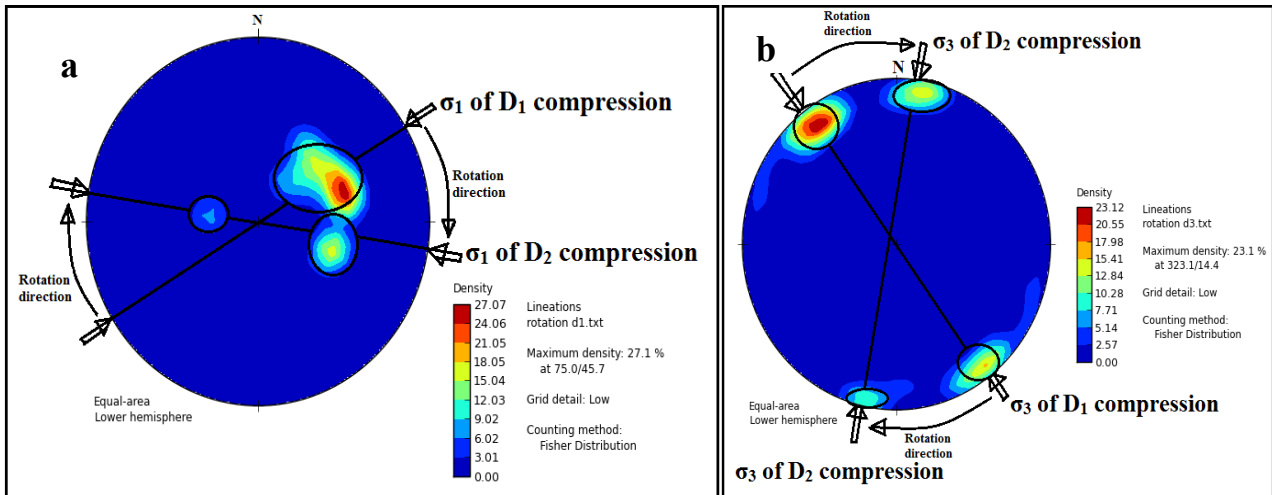


Fig 6 (a) Stereographic projection of the maximum compression axis showing the rotation direction. (b) Stereographic projection of the minimum compression axis showing the rotation direction

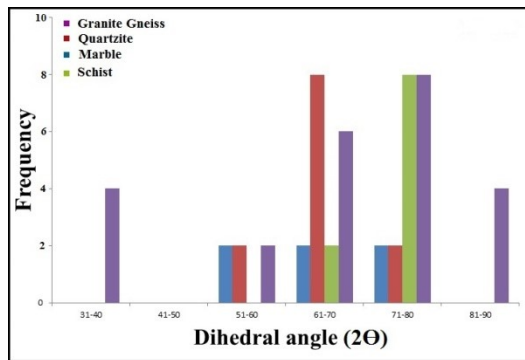


Fig 7. Histogram showing the frequency of occurrence of the dihedral angles (2Θ).

5. Discussion

The stress configuration of the Pan – African orogeny is presented in this work considering the evidence from the Igarra schist belt, southwestern Nigeria. The stress configuration in the study area tracked by conjugate shear fractures show that at least two deformation episodes affected this region with NE – SW and E – W σ_1 directions and a complementary NW – SW and N – S σ_3 directions respectively. Comparing this result with strain analysis carried out by Udinmwun (2015) in this region, the NW – SE σ_3 direction is consistent with the λ_1 direction obtained from metamorphic spots in schist and clasts of metaconglomerates while the N – S σ_3 aligns with the λ_1 direction derived from the phenocrysts and xenoliths in granite and those obtained from the phenocrysts/xenoliths in granites. Since the schist and metaconglomerate are older than the granite as the granites intruded the schist, it, therefore, means that the NE – SW compression (D_1) is older than the E – W compression (D_2) indicating a clockwise rotation of the maximum compression direction (Fig 6). This clockwise rotation for the Pan – African palaeostress has also been observed in the Dahomeyide Orogen of

southeast Ghana (Tairou et al. 2012) and in the western margin of South Africa (Viola et al. 2011). Although the polycyclic nature of the Pan – African orogeny is well known, the structural geometry of this region shows that the E – W compression was dominant during the deformation and from results of Pan – African palaeostress by different authors in different Pan – African regions (Table 1), we observe that all (100%) the regions in Africa shown in Table 1 experienced the E – W compression, 38% recorded the NE – SW compression, 30% identified the N – S and NW – SE compressions, 15% noticed the NNW – SSE compression and only 7% observed the occurrence of NNE – SSW, ESE – WNW, and ENE – WSW compressions. From this, we suggest that only the E – W compression had a widespread, lasting regional effect during the Pan – African orogeny, other compressional axes are probably associated with local or partially regional processes. Considering the structural geometry of the granites, the mineral lineation are mainly in the N – S direction (Oden and Udinmwun 2014a and 2014b), this is the σ_3 direction of the E – W compression and combining this result with strain analysis result from Udinmwun (2015), this direction is also the λ_1 direction thus it is clear that the E – W compression induced the mineral lineation in the granites. The strong presence of structures related to the E – W compression in the younger rocks (granite and syenites) and complete absence of structures related to the NE – SW compression suggests that the E – W compression is a younger deformation than the NE – SW compression thus we designated the E – W compression D_2 and the NE – SW compression D_1 . Evidence of D_2 occurs in most of the rocks in this region. The dihedral angle (2Θ) from stress configuration range basically from 60° – 80° however 2Θ values as low as 35° were recorded while 90° was also observed (Fig 7). This suggests that there was most likely a mixture of brittle and ductile deformation in this region.

Table 1. Compilation of observed maximum compressive stress (σ_1) direction for the Pan – African orogeny

S/N	Author/Year	Region	Rock Type	Method	Maximum Compressive Stress (σ_1)			
					D ₁	D ₂	D ₃	D ₄
1	Boullier et al. 1986	Adrar des Iforas (Mali)	Granitoids	Dyke swarms	-	ESE – WNW to E – W	NE – SW	E – W
2	Oden and Udinmwun. 2014b	Igarra Schist belt (Nigeria)	Granite	Fractures and Mineral vein lineaments	E – W	-	-	-
3	Naydenov et al. 2014	Hook Batholith (Central Zambia)	Multiple	Structural, geophysical and geochronological studies	E – W	N – S	-	-
4	Tairou et al. 2012	Southern Dahomeyide orogen (Ghana)	Granites, quartzites, dolomitic carbonates and granulites	Analysis of striated planes	NE – SW	E – W	NW – SE	NNW – SSE
5	This work	Igarra schist belt (Nigeria)	Schist, gneiss, marbles, and quartzites	Conjugate shear fractures	NE – SW	E – W	-	-
6	Delvaux et al. 2013	Lufilian Arc (DR Congo)	Multiple	Fault kinematics and palaeostress inversion	N – S	E – W	-	-
7	Oden 2012	Uwet area (Nigeria)	Granodiorite	Strain analysis	E – W	-	-	-
8	Ibrahim et al. 2015	Gabal Abu Houdied (Egypt)	Multiple	Palaeostress inversion using fault slip data	NNW – SSE to N – S	ENE – WSW	E – W	-
9	Liegeois et al, 1987	Adrar des Iforas (Mali)	Calc-Alkaline batholith	Conjugate shear fracture	-	E – W	NE – SW	-
10	Viola et al. 2011	Western margin of South Africa	Multiple	Remote sensing, conjugate shear fracture, and fault slip inversion	NW – SE	NNE – SSW	E – W	-
11	Frimmel 2000	Gariiep Belt (SW. Namibia and W. South Africa)	Multiple	-	E – W	NW – SE	NE – SW	-
12	Mbola Ndzana et al. 2014	Montalele region (Cameroon)	Multiple	-	-	-	E – W	N – S
13	Suliman 2000	Keraf shear zone (Sudan)	Multiple	Structural geometry and strain partitioning	NW – SE	NW – SE	N – S	E – W

6. Conclusion

Stress configuration shows that this region was subjected to at least two deformation episode with D₁ having a NE – SW maximum principal stress (σ_1) direction and D₂ with an E – W maximum principal stress (σ_1) direction showing a clockwise rotation of the

direction of maximum compression. The E – W compression have been identified in most Pan – African regions and as such it is most likely that only this compressional event had a full regional effect during the Pan – African orogeny. The strong dominance of D₂ related structures buttresses the regional nature of the E – W compression during the Pan – African orogeny.

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