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Mesoscopic Structural Analysis of the Schist Enclaves in Oban Massif, South-Eastern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author EAA wrote the first draft of the manuscript and analyzed the data. Author MIO designed the study. Author BEE checked the protocol of the study and managed the literature searches. Author EU appraised data quality. Author SUE checked the grammar and language. All authors read and approved the final manuscript.

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ABSTRACT

The schist enclaves in Oban massif, south-eastern Nigeria are deformed predominantly in a brittle manner and contain a superfluity of mesoscopic structural features such as joints, conjugate shear fractures, foliation planes and mineral veins. The analysis of these structural elements using standard structural techniques and statistical tools reveals the presence of only four major sets of fracture (N-S, NE-SW, E-W and NNW-SSE/NW-SE) with the NNW-SSE (150°-160° from the north) being the most prominent. Mesoscopic structural geometry in the schists unravelled the presence of pure and simple shear deformation with a somewhat dominant simple shear component. The increase in the dip of foliation planes from the western flank towards the east across some of the schist enclaves suggests the existence of a regional fold system which may have its axis trending in a N-S direction. This study provides foundation knowledge to mineral exploration, groundwater and quarrying activities in this area as they are usually structure controlled.

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1. INTRODUCTION

Mesoscopic structural analysis serves to elucidate the deformation characteristics that occurred in an area spatially and temporally. The formation of mesoscopic structures in rocks such as fractures, mineral veins, foliations, etc, is not a random process; rather these structures are associated with the laws of mechanics and prevailing environmental conditions. Consequently, the spatial distributions and styles of these structures in rocks are reflections of deformational episodes which occur over geological periods. Careful analysis of the mesoscopic structural profiles in an area is vitally important in understanding the structural control on mineralization in the area and can also serve as a guide in quarrying activities, solid mineral and groundwater exploration and exploitation in the region.

The occurrence of schist in Nigeria was initially believed to be restricted to the western part of the country. Schist belts of reasonable extent have been reported in the southwestern and northwestern parts of Nigeria. A good example is the Igara schist belt in southwestern Nigeria [1]. However, the presence of schists of various grades in Oban massif region of southeastern Nigeria has been reported by [2–7]. Although the schists within this basement complex are not as extensive as those in the western part of the country, they occur as enclaves with reasonable extent within the Oban basement complex. This study is concerned with the mesoscopic structural profile of the schist enclaves of Oban massif. The schist enclaves occurring in this basement area are mainly in the western part, however, the occurrence of some schists is also reported in the southeastern part of this study area, like in the Kwa falls area. These enclaves of schist were deformed dominantly in a brittle manner resulting in the prevalence of fractures in the region [5].

In the study area, joints, conjugate shear fractures, foliations and mineral veins are all in interesting orientations. Joints and foliations lend credence to the E-W trending maximum compression (σ_1) and a N-S direction of least compression (σ_3) determined by [6–9]. The structural geometry in these enclaves unravelled the presence of pure and simple shear deformation with a somewhat dominant simple shear component. Analysis of joints reveals the presence of four trends (N-S, NE-SW, E-W and NNW-SSE/NW-SE), with the NNW-SSE being the most prominent. These and other mesoscopic structural elements will be discussed in detail in the context of this paper.

2. REGIONAL GEOLOGIC SETTING

2.1 Oban Massif

Nigeria is sitting on the hub of the Pan – African mobile belt lying between the West African craton to the west and the Congo craton to the east and stretches from Hoggar to Brazil (Fig. 1).

This area was affected by the Pan African orogeny about 600+ 150Ma ago. The Nigerian basement complex is believed to have undergone polyphase deformation during the Precambrian [10–13]. During this period (Precambrian), the Nigerian basement was reworked at least four times [14]. These deformational episodes were the Liberian (approximately 2,700my), the Eburnean (approximately 2,000my), the Kibaran (approximately 1,100my) and the Pan-African (600 ± 150) [15]. As a result of these deformations, complex structures displaying varying spatial orientations are expected from this basement. The Pan African which was the most pervasive and most recent of these events, resulted in emplacement of large volumes of granitoids and resetting of mineral ages in virtually all rock types in the basement [11].

The Precambrian crystalline basement complex of Oban massif, South-eastern Nigeria, covers about 10,000 km^2 aerial extents and is regionally a western extension of the Adamawa plateau in to Cross River state. It is bounded by the Ikom-manfe embayment and Obudu massif at its northern flank and is partially overlain by Cretaceous to Tertiary sediments of the Calabar Flank in the southern part (Fig. 2).

This basement has an interesting geology which includes metamorphic rock units such as schists, gneisses, phyllites and amphibolites. These metamorphic rocks are intruded by granites, diorites, granodiorites, tonalites, pegmatites, monzonites, dolerites and charnockites (Ekwueme, 1990).

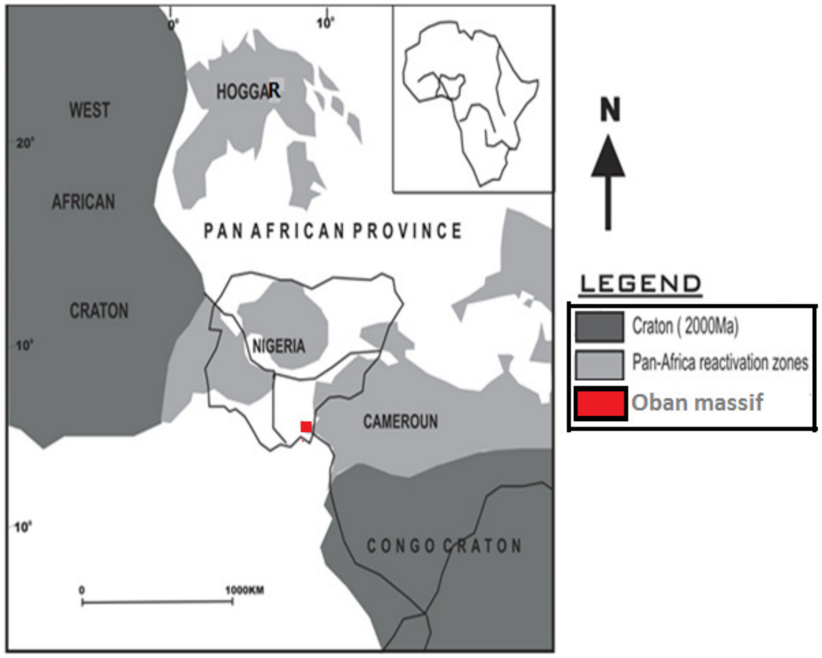

Fig. 1. Map showing Pan-African province of basement complex. Adapted after [16]

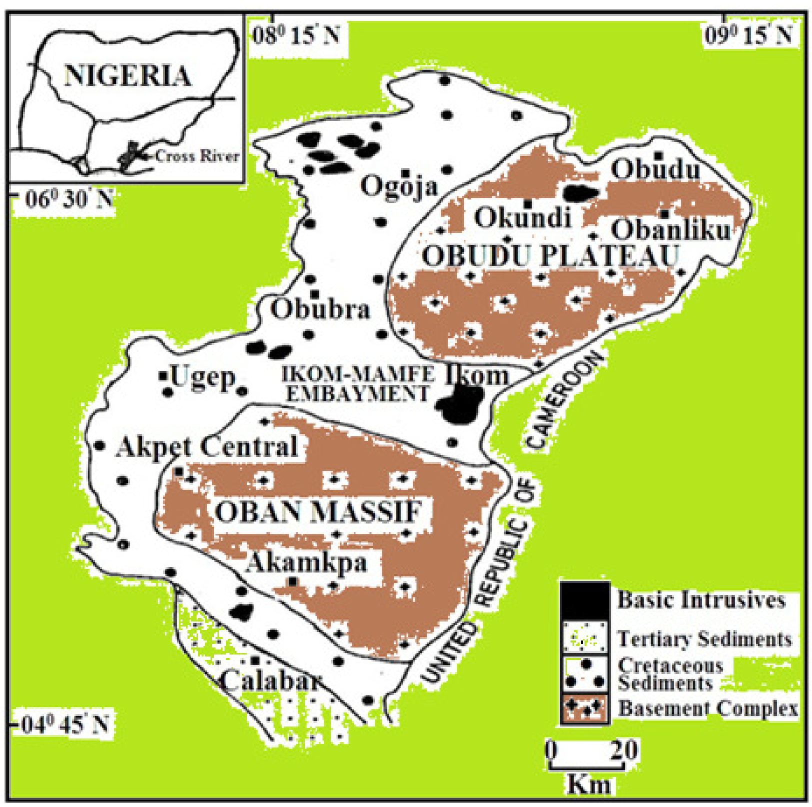

Fig. 2. Map of Cross River State showing the basement areas [17]

Structural features; foliations, joints, folds, fractures, lineations, mineral veins etc are reported by [3,5,16] in this area and are mostly associated with the Pan-African orogeny. A synthesis of the structural orientations of Pan-African orogeny origin, having in mind the stress configuration that operated at that time (Fig. 3) was proposed by [17]. Considering his findings from Uyanga-Akwa Ibami area (western Part of Oban massif) as well as those of [17–21] he identified five main axes by which stress was transmitted through the Pan-African tectonites during deformation. The E-W axis, approximately parallel to maximum compression, was that along which 'ac' extension fractures formed. E-W fractures have been observed near Ikot Ana at the western margin of Oban massif [17]. The N-S orientation is the pure shear direction; NE-SW and NW-SE axes are simple shear 1 and 2 directions respectively. The fifth axis of material deformation during this event was the vertical axis.

2.2 Schist Enclaves of Oban Massif

The schists of all grades are reported to exist within this basement complex. The schists are mostly garnet-mica schists as found in Akparavuni, Agoi Ibami and Ikot Ana, Quartz-mica schist in Calaro plantation and kyanite-silimanite schist in Kwa falls area [3,7].

Going from Ikot Ana in the west to the far flung Kwa falls in the east, there is a gain in biotite, sillimanite and kyanite and a loss of muscovite, garnet and chlorite [7]. The disappearance of low grade metamorphic minerals (muscovite, garnet and chlorite) and appearance of high grade minerals (biotite, sillimanite and kyanite) from west to east is a clear indication that the grade of metamorphism increases towards the east in the study area which result in high grade schist (kyanite-sillimanite schist) in Kwa falls [7].

The schist enclaves occurring in Oban massif are mainly in the western part, however, the occurrence of schists is also documented in the southeastern part of this study area, at Kwa falls area. Schists and Phyllites in Oban massif were deformed dominantly by brittle deformation resulting in the prevalence of fractures in the region [5,7]. [5,16,3] have showed that, the schists existing within Oban massif are characterized by structural elements which are tectonically induced and these tectonic stress-induced structural features in these schist enclaves can serve as good tools for determining the structural evolution of the Nigerian basement.

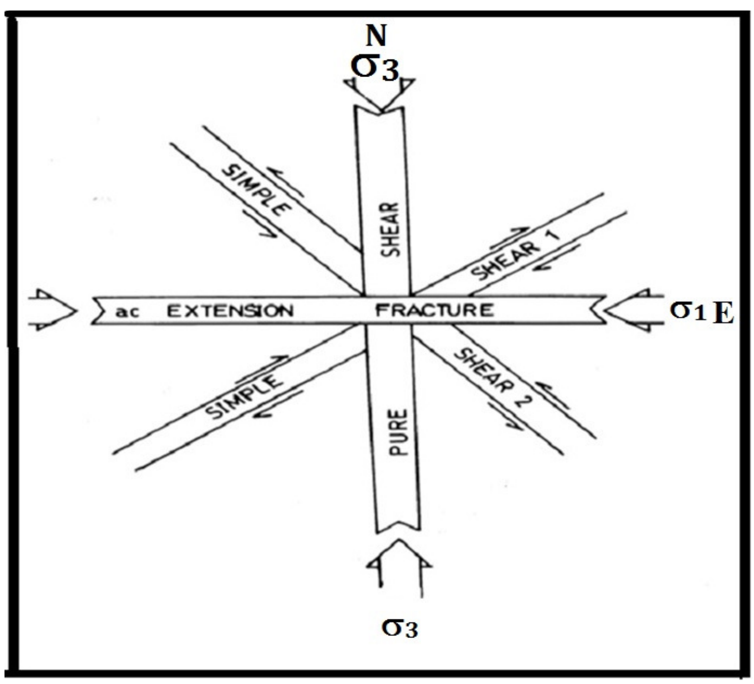

Fig. 3. The main tectonic axes of the Pan-African orogeny. (After [17])

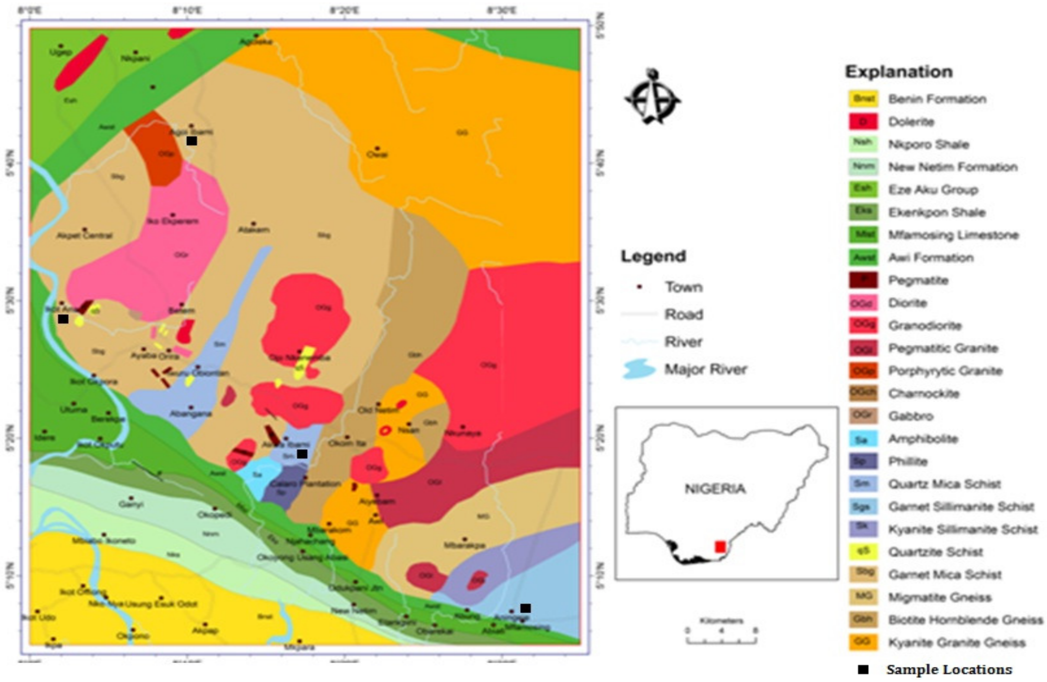

Fig. 4. Geologic map of parts of Cross River state showing the schist enclaves and other rock types
(Modified from [22])

3. MATERIALS AND METHODS

Fieldwork exercise was carried out in the study area. Schist outcrops in Akparavuni, Agoi Ibami, Calaro plantation, Ikot Ana (all in the western part of Oban massif) and Kwa falls in the southeastern part of Oban massif (Fig. 4) were carefully studied with particular interest in the structural features. The field data were acquired using the conventional methods of measuring the attitudes of geologic structures in rocks. A total of three hundred and ninety three (393) joints, one hundred and ninety five (195) conjugate shear fracture sets and four hundred and seventy five (475) foliation plane data were obtained from the study area. Other observed structures were pegmatite and quartz veins. The data acquired from the field were presented using rose and dip diagrams made with Grapher 7 and stereographic projections plotted with OpenStereo.

4. RESULTS

4.1 Joints in the Schist Enclaves

The study area contains a plethora of joints (Fig. 5a - d). The joints encountered in Akparavuni, Agoi Ibami, Calaro plantation and Ikot Ana consist of four sets, with the NNW-SSE (150°-160°) set being the most prominent. Joint sets trending N-S (0°-20° from N), NE-SW (30°-40° from N) and E-W (80°-100° from N) were also recorded in these locations (Fig. 6a – f), although in Ikot Ana, three of these trends are seen to be prominent (NNW-SSW, E-W and NW-SE), with E-W and NW-SE being the most frequently occurring (Fig. 6d). However, only two joint sets occur in Kwa falls (Fig. 6e) and the most frequent is the NW-SE (120°-130° from N) trend, while the minor set is trending NE-SW (40°-60° from N).

Fig. 5. Photographs showing joints in schist of the study area; (a) Joints in Agoi Ibami, (b) Joints in Calaro plantation, (c) Joints in Ikot Ana, (d) Joints in Kwa falls

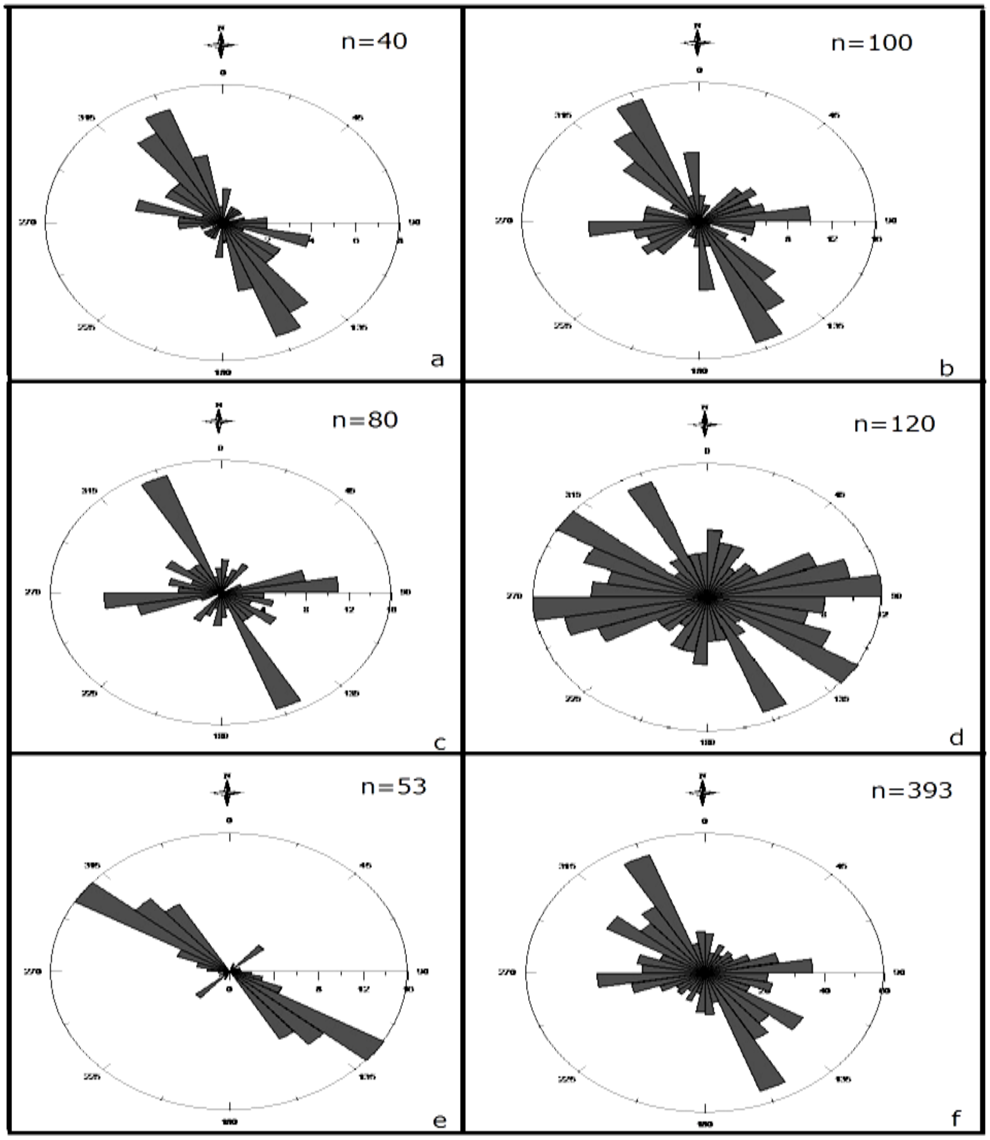

Fig. 6. Rose diagrams of joints in schists of the study area; (a) Joints in Akparavuni, (b) Joints in Agoi Ibami, (c) Joints in Calaro plantation, (d) Joints in Ikot Ana, (e) Joints in Kwa falls, (f) Combined joints in study area

On analysis, these joints fall into four trends or sets and the most prominent and consistent is the NNW-SSE, with a trend of 150°-160° from the north. Other joint sets are E-W, with a trend of 70°-90° from north, NW-SE trending 120°-130° from north, N-S which trends 0°-20° from north. Minor joints trending NE-SW (20°-40°) also occur within this study area (Fig. 6f). Fig. 7(a), (b), (c), (d), (e) and (f) are stereo-plots of the joints/fractures measured in the study area. The dip of joints in schists of this basement mostly range from 70°-90° (Fig. 8a - f).

4.2 Conjugate Shear Fractures

These structures (conjugate fractures) are syngenetic fractures of tectonic origin and were encountered in the study area (Fig. 9a-e). Conjugate shear fractures encountered in Akparavuni are basically trending in the NE-SW and NW-SE directions, however a few are trending in the NNW-SSE and E-W directions and this is consistent in the other four locations. The dip angles of these shear fractures in the various locations are characteristically low (Fig. 10) when compared to those of extension fractures discussed earlier. Dip values between 60° and 70° are the most frequent, although fracture planes displaying lower and higher dip angles (between 44 – 57° and 70 – 80° respectively) also exist within this area (Fig. 10a-f). The dip directions of a pair of these structures are usually in opposite directions. [23] have shown that the dihedral angle between these conjugate fracture planes is generally between 55° – 60°.

4.3 Foliation Analysis

The schist outcrops encountered within the study area are all found to occur along stream channels and they show very good foliation planes (Fig. 11a - e). The various locations visited within Oban massif display variable behaviour in terms of the strike and dip of foliation planes. Foliation planes encountered in Akparavuni area on analysis were found trending 20°-30° from the north (Fig. 12a) and their dips range from 60°-70° (Fig. 13a) in the SE direction.

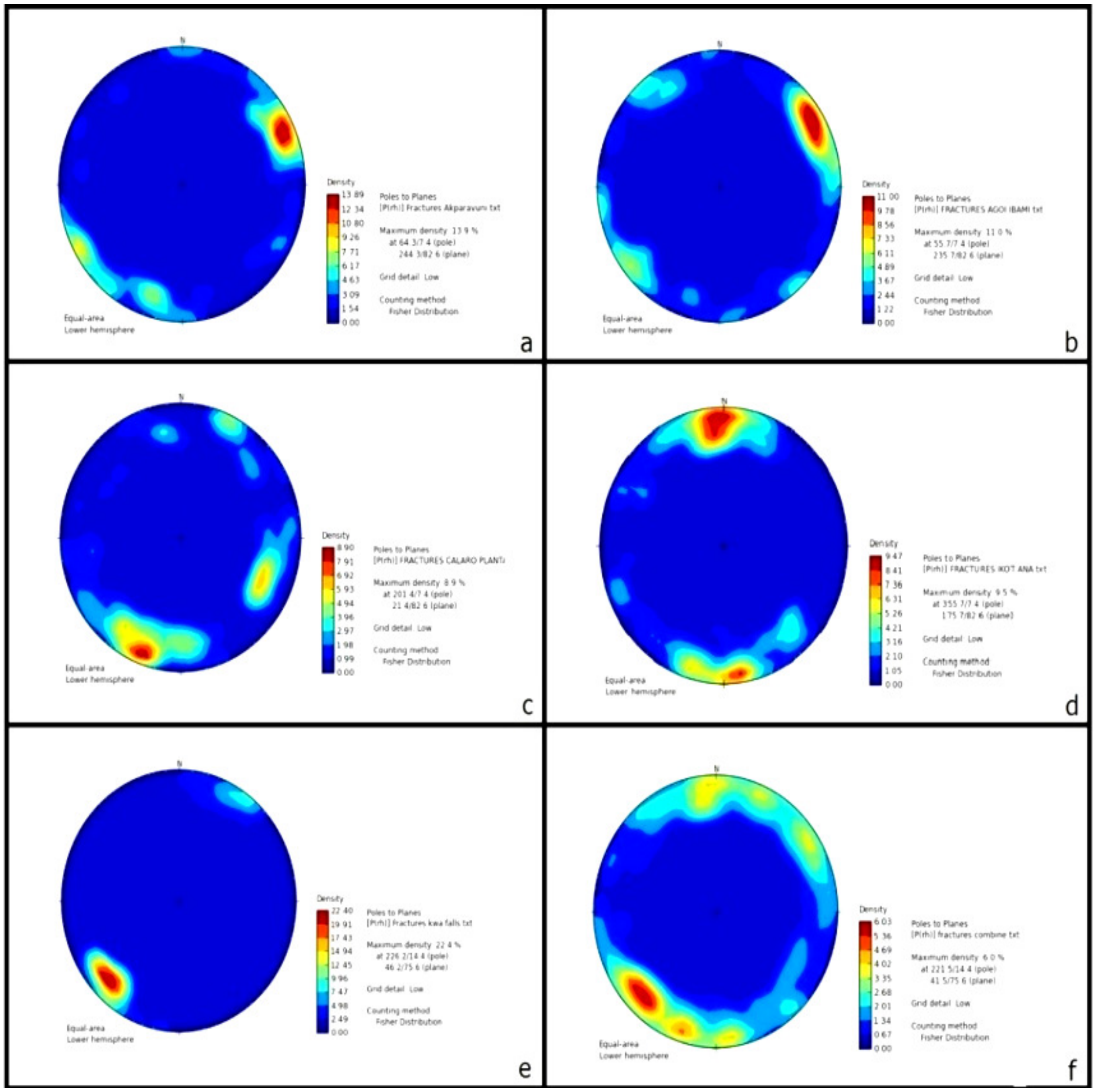

Fig. 7. Stereo-plots of joints in schists of the study area; (a) Joints in Akparavuni, (b) Joints in Agoi Ibami, (b) Joints in Calaro plantation, (c) Joints in Ikot Ana, (d) Joints in Kwa falls, (f) Combined joints in study area

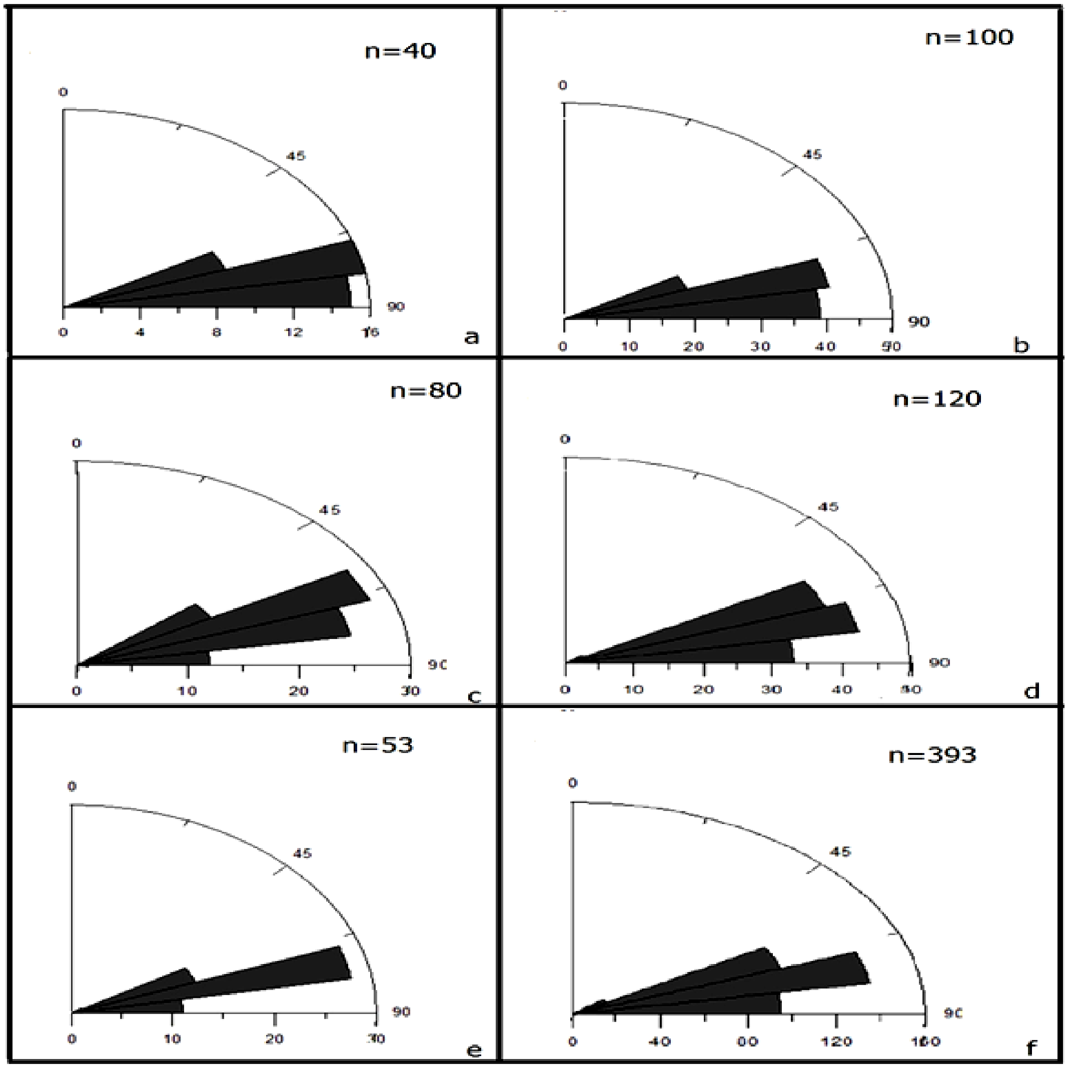

Fig. 8. Dip diagrams of joints in schists of the study area; (a) Dip of joints in Akparavuni, (b) Dip of joints in Agoi Ibami, (c) Dip of joints in Calaro plantation, (d) Dip of joints in Ikot Ana, (e) Dip of joints in Kwa falls, (f) Combined dip of joints in study area

The foliations existing in Agoi Ibami schist outcrop strike mainly in the NNE-SSW direction, mostly between 10°-30° from the north (Fig. 12b), their dips range from 15°- 60° in the SE direction like those of Akparavuni. It was observed that this variation in angles of dip of foliation planes within the schist enclave of Agoi Ibami is such that there is a gradual increase of this angle from the western part of the outcrop towards the eastern flank. Fig. 13b shows the variation in angle of dip of foliation planes in this area; the dip angles between 15°- 20° were recorded at the western part, angles between 30°- 40° were obtained as one moved towards the east and this increases to 40°- 60° at the eastern flank of this schist enclave. The foliation planes in Ikot Ana also offer a similar behavior of increasing angle of dip towards the east like those observed in Agoi Ibami, however, they display three different trends with the N-S (170°- 180° from the north) being the prominent direction, while minor trends are the NE-SW direction and E-W direction (Fig. 12d). This results in different dip directions of the foliation planes in this area. Although the general dip direction is towards the NE, dip directions of SSE and E were also recorded. Contrary to the dips of foliation planes in other locations within the study area, the foliation planes in the schist enclaves of Calaro plantation and Kwa falls are characterized by high dip angles ranging from 80°-90°, (Fig. 13c and e), although a few planes have angles between 70°-80° in Calaro plantation. These planes are strike NNE-SSW (20°-30° from the north), with dip direction of NW for Calaro plantation and NE-SW (40°-50° from the north) with dip direction of SE for Kwa falls. From figure 11, and bearing in mind the orientations of the paleostresses in this area; E-W trending σ_1 (maximum compression) and a N-S direction of least compression or σ_3 determined by [6–9,16], foliations in Akparavuni, Agoi Ibami, Calaro plantation and Kwa falls are in simple shear orientations while those of Ikot Ana are exhibiting more of pure shear orientation. The departure of foliations in Ikot Ana may be due to a change in the deformation mechanisms which favours pure shearing as against the prevalence of simple shear mechanisms in other locations.

Fig. 9. Conjugate shear fractures in schists of the study area; (a) Akparavuni (b) Agoi Ibami (c) Calaro plantation (d) Ikot Ana (e) Kwa falls

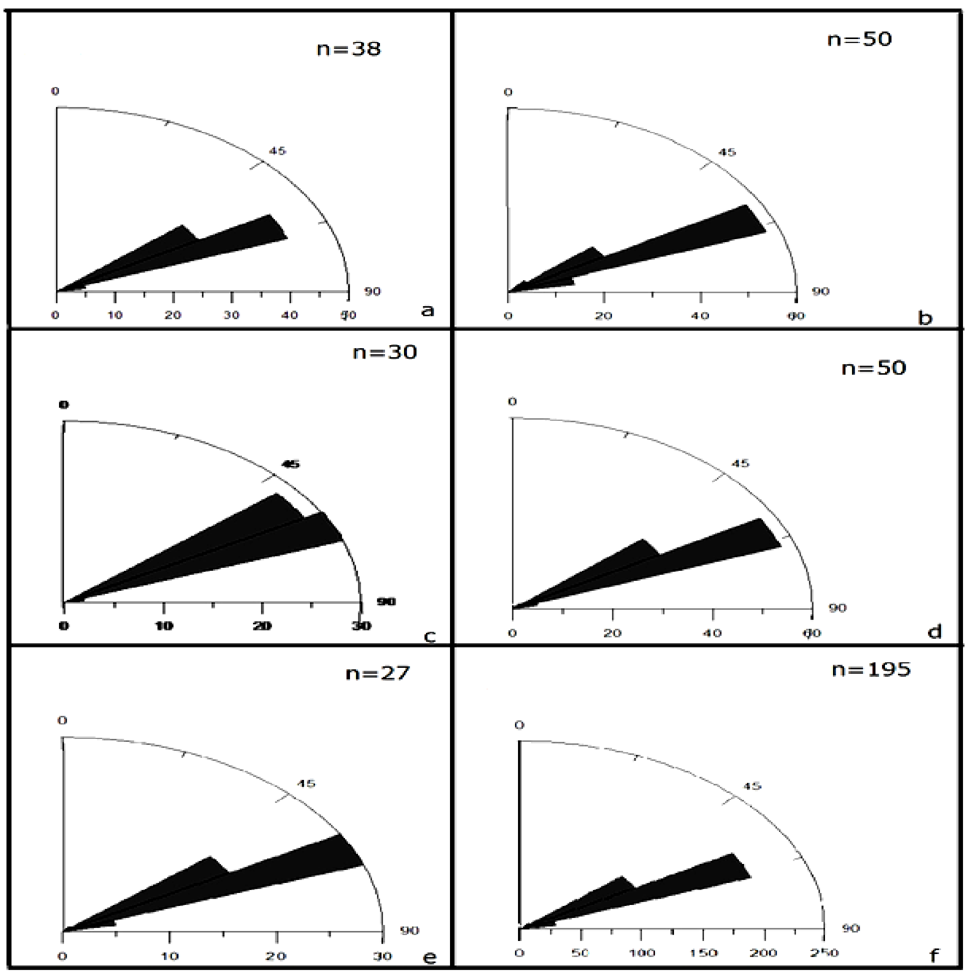

Fig. 10. Dip of conjugate shear fractures in schist of the study area; (a) Dip of conjugate fractures in Akparavuni, (b) Agoi Ibami. (c) Calaro plantation, (d) Ikot Ana, (e) Kwa falls, (f) Combined dip of conjugate shear fractures in study area

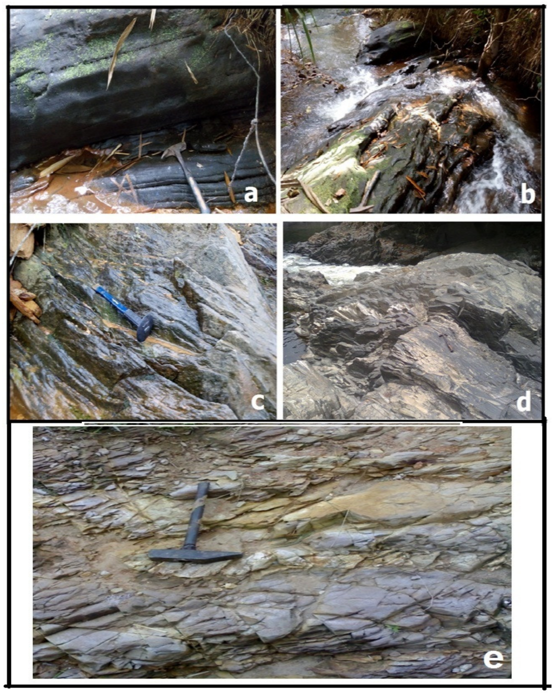

Fig. 11. Photographs showing foliation planes in schists of the study area; (a) Foliation in Akparavuni, (b) Foliation in Agoi Ibami, (c) Foliation in Calaro plantation, (d) Foliation in Kwa falls, (e) Foliation in Ikot Ana

Pegmatite and quartz veins of few centimeters in width are found to occur in the rocks taking advantage of some zones of weakness in the schists (Fig. 14a and b). This structure (pegmatite vein) was only recorded in Agoi Ibami and Kwa falls and none was recorded in the other three locations. In Agoi Ibami with low angle foliation (Fig. 13b), pegmatite veins are discordant and joint-controlled (Fig. 14a), while in Kwa falls where the foliation is upright (Fig. 13e), these veins are concordant and interfolial.

5. DISCUSSION

This work investigated the mesoscopic structural profile of the schist enclaves of Oban massif basement complex. Fracturing of rocks is not a random process; it is often associated with the laws of mechanics and the prevailing environmental conditions [24]. Consequently, the spatial distributions of joints and fractures in rocks tend to occur in sets and in relation to the stress configuration that created them. Joints are one of the most frequently occurring structures in the schist enclaves of Oban massif, a good number of the shear fractures occur in conjugate pairs. Other mesoscopic structures such as foliation and its variation are also considered for discussion.

The analysis of joints in the study area reveals four trends (N-S, NE-SW, E-W and NNW-SSE/NW-SE) (Fig. 6). The E-W joints which are parallel or nearly so, to the maximum principal stress (σ_1) direction are the 'ac' extension fractures as these joints usually grow parallel to the direction of maximum compression and are also known as Mode 1 joints [25–29]. The N-S joints are the 'bc' tensile joints which are usually associated with the axes of folds and are perpendicular to the direction of maximum compression [29]. The nature of a majority of the dip angles (low to medium) of the NW-SE and NE-SW joints suggest that they are probably shear fractures which did not form any surface conjugate pairs. The Pan-African deformation involved a mixture of pure and simple shear (transpressional) distortions [17], the dominance of shear joints in the area is more likely an indication that the deformation here involves more of the simple shear component, favouring the NW-SE shear direction. The dominance of the NW-SE simple shear structures have been observed in the Pan-African regions in Nigeria [20,30]. In this study, the prevalence of joints and shear fractures is an indication that the schist enclaves of Oban massif were deformed dominantly by cataclastic flow mechanism and the difference in dip between the shear fractures (low dips) and extension fractures or joints (high dips) is a clear indication that the two were formed by different of distortion mechanisms even though they were formed in a single episode of deformation.

The foliations in the study area trend mainly in the N-S/NNE-SSW and NE-SW directions (Fig. 11a-e). In Ikot Ana (Fig. 11d), foliation planes trend mainly in the N-S direction with a minor trend in the NE-SW direction. This behaviour is different from those observed in the other locations (Akparavuni, Agoi Ibami, Calaro plantation and Kwa falls) which tend to favour the NNE-SSW and/or NE-SW directions. Foliations in rocks are usually expected to be parallel to σ_3 direction [31,32]. However, this is only true for a strictly pure shear deformation as other deformation mechanisms may produce foliations which depart from parallelism with σ_3 in a systematic way [33,34]. The σ_3 direction, in this region from stress configuration, is N-S, however, most of the foliations in the schist enclaves apart from Ikot Ana depart systematically from this direction. This probably implies the presence of a simple shear deformation which favours the development of foliation in the NNE –SSW and/or NE – SW directions. The dominance of foliations in the NE-SW to NNE-SSW appears to complement the dominance of fractures in the NW-SE to NNW-SSE. This relationship is necessary to transmit

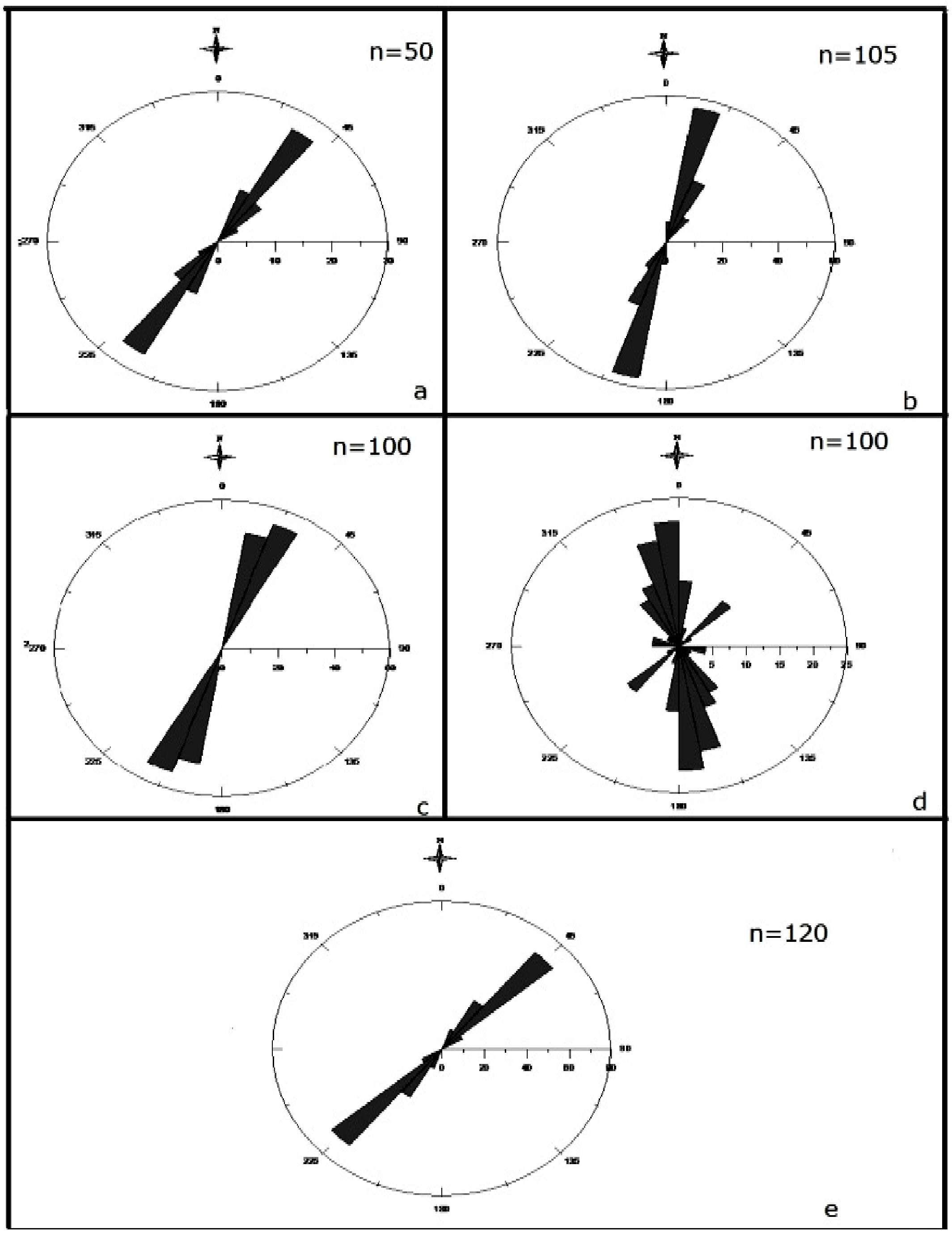

Fig. 12. Rose diagrams of strike of foliation planes in schists of the study area; (a) Foliation in Akparavuni, (b) Foliation in Agoi Ibami, (c) Foliation in Calaro plantation, (d) Foliation in Ikot Ana, (e) Foliation in Kwa falls

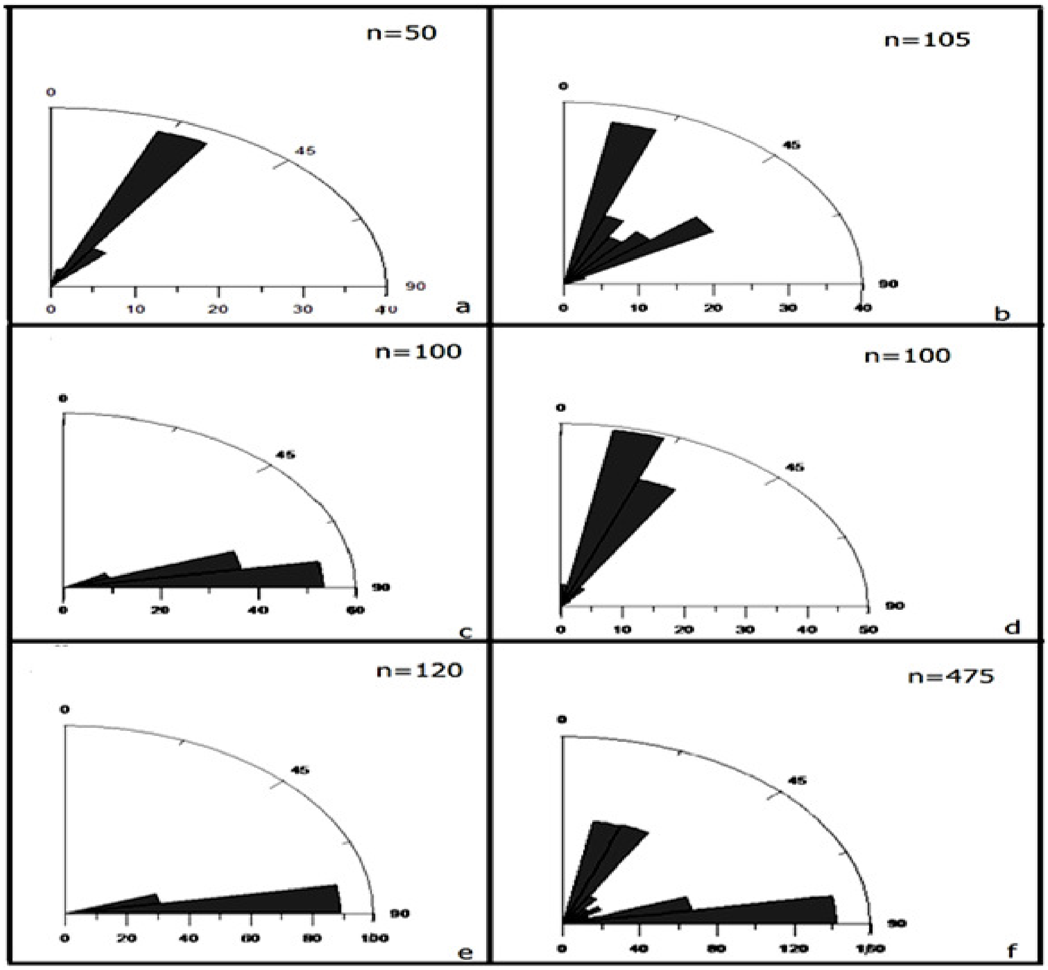

Fig. 13. Dip diagrams of foliation planes in schists of the study area; (a) Dip of foliations in Akparavuni, (b) Dip of foliations in Agoi Ibami, (c) Dip of foliations in Calaro plantation, (d) dip of foliations in Ikot Ana, (e) Dip of foliations in Kwa falls, (f) Combined dip of foliations in all schists

stress and deformation to the interior parts of the mobile belt. The dip angle of foliation in this area increases from west to east between Ikot Ana and Agoi Ibami, this situation is sometimes associated with regional folding whereby the foliation planes closer to the axis of the fold have a higher dip angle than those further away at the limbs. The fractures and foliations in the study area have shown the dominance of simple shearing nevertheless, in both cases, good evidence of pure shear deformation also exists. It is therefore safe to say that the deformation in the schist enclaves in Oban massif is a mixture of pure and simple shear as observed by [17] for Uwet granodiorite. Thus this has to be considered when inferring palaeostress conditions from structural geometry.

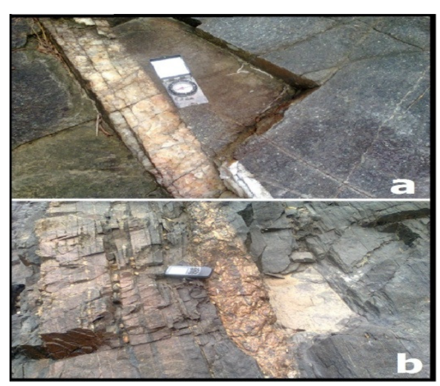

Fig. 14. Photographs showing pegmatite veins in schists of the study area; (a) Pegmatite vein in Agoi Ibami (b) Pegmatite vein in Kwa falls

6. CONCLUSION

The study of the schist enclaves of Oban massif, south-eastern Nigeria from the analysis of mesoscopic structural elements using standard structural techniques and statistical methods reveals only four major trends of fracture sets (N-S, NE-SW, E-W and NNW-SSE/NW-SE), with the NNW-SSE set, with a trend of 150°-160° from the north being the most prominent. The structural geometry in the schists unravelled the presence of pure and simple shear deformation with a somewhat dominant simple shear component. The increase in the dip of foliation planes from the western flank towards the east across the schist enclaves indicates the existence of a regional fold system which may have its axis trending in a N-S orientation. For exploration and quarrying activities in this area, the NNW-SSE (150°-160° from the North) trend of joints should be considered for optimal result and risk management. Foliation orientation and dominant shear fracture orientation in these schist enclaves probably complement each other, for optimum stress transmission into the interior parts of the Pan-African mobile belt.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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