Full Length Research Paper

Anisotropic fracture mapping at environs of Aiyegunle, Igarra expanse, Nigeria

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Abstract

Simulating of fracture anisotropy in Aiyegunle expanse of Igarra Southwestern Nigeria was done by geologic mapping of exposed outcrops and azimuthal resistivity survey (ARS) at three vertical electrical sounding (VES) stations. Rose diagrams, stereographic projections, and resistivity anisotropy polygons were used to delineate and integrate surface and subsurface structural trend. Dominant joints orientation is North-west-South-east (NW-SE) and North-South (N-S). The orientation of fracture in the subsurface is N-S with anisotropy prominent in the NW-SE direction. The coefficients of anisotropy ($\lambda$) at depth are less than 2.2, with the degree of fracturing opening and closing with depth. The diversity of fracture attitude implies they were products of different tectonic episodes corroborating evidence of multiphase deformation. The fracture directions suggest that surface structures are hard-linked and produced by similar tectonic event relative to subsurface fractures of Pre-Pan African orogenies.

Key words: Fractures, orientation, surface, subsurface, anisotropy.

INTRODUCTION

Fracture anisotropy is associated with electrical and hydraulic variation resulting from the preferred orientation of fracture sets (Slater et al., 2006). Fracture networks are important consideration for prediction of underground contaminants, groundwater and mineral exploration, and foundation investigations. Azimuthal resistivity survey is a technique used for determining the principal directions of electrical anisotropy and intensity; a change in apparent resistivity with azimuth is indicative of fracture anisotropy (Slater et al., 2006; Boadu et al., 2005; Skyernaa and Jorgensen, 1993).

The architecture of fractures is space and time related, the intensity of fracturing in an area can be observed on different scales, from megascopic (seismic section, satellite images, and aeromagnetic maps), macroscopic (joints, faults and veins in outcrop) to microscopic scale in thin sections (Omosanya et al., 2012 a,b).

Depth-related fractures observed in macroscopic scale are therefore, deep seated, hard-linked and apparently connected to regional tectonic events or trend. The Nigerian Schist belts represent the structural grains of the basement rocks (Rahaman, 1981; Olade and Elueze, 1979). The structural information of the entire basement rocks was derived or up-scaled from studies of the belts. The Igarra schist belt is characterized by a complex geological framework made of different structures and rocks.

The aims of this work include (a) identifying fracture
Local geological setting

Nigeria is located within the mobile belt that separates the West African Craton (WAC) from the Congo Craton (CC) (Black, 1980). The geology of the country is divided into equal proportion of crystalline and sedimentary rocks (Woakes et al., 1987). The Precambrian Basement Complex of Nigeria is polycyclic in nature (Ukaegbu, 2003; Ajibade and Fitches, 1988) as it has been affected by different orogenies accompanied by deformation and metamorphism. The most prominent of these being the Pan African/ Brasiziliano Orogeny which overprinted and obliterated earlier structures of the basement rocks (Van Breemen et al., 1997; Fitches et al., 1985).

The Precambrian basement rocks of Nigeria include the Migmatized gneissic complex (MGC) of Achaean to early Proterozoic age (Dada, 1999; Dada et al., 1993; Grant et al., 1972), N-S trending schist belts of Upper Proterozoic age (Rahaman, 1988) and the Older Granitoid of Pan African age (Fitches et al., 1985). The Migmatized Gneiss complexes are the most widespread and occupy about 60% of the total surface area of Nigeria (Rahaman and Ocan, 1978). The polycyclic Migmatized-Gneiss complexes are characterized by grey foliated biotite acid/biotite hornblende quartz feldspathic gneiss of tonalitic to granodioritic composition; Mafic to ultramafic component which outcrops as irregular boudinaged lenses or concordant sheet of amphibolites with minor amount of biotite-rich ultramafite; and Felsic component, a diverse group comprised of pegmatite, aplite quartz-oligoclase veins, fine-grained granite gneiss, and porphyritic granite (Rahaman, 1981).

The schist belts represent N-S trending synformal troughs infolded into the migmatite-gneiss complexes which are best developed in the western part of the country. The schist belts are largely sediment-dominated.
Figure 2. Integrated geological and structural map of the study area.

in contrast to other schist belts of South Africa and Australia. The most important lithologies are pellites, semi-pellites, banded iron formation and quartzite (Turner, 1983). This rock suite provides information on the structural pattern of the basement rocks. The contact between the migmatites and the metasediments are fault-bounded in most cases (Odeyemi et al., 1999) while the schists are presumably a fault-controlled rift like structure (Olade and Elueze, 1979). The metasedimentary succession in the Igarra formation consists of (a) Quartz biotite Schist (b) Mica Schist (c) Marble and Calc-Silicates and (d) Metaconglomerates. The presence of both calcareous rocks and conglomerates is peculiar to the Igarra Schist belts in Nigeria. These rock types together with quartzites occur as bands in the dominant biotite schists. The gneisses at the margin of the metasediments may be a highly metamorphosed basal part of the sequence.

The older granites correspond to the last rock types of the basement; these rocks represent a diverse and lasting magmatic cycle (750-450Ma) associated with the Pan African orogeny (Woakes et al., 1987). The older granite rocks constitute about 40 to 50% of the basement complex outcrop. They vary in composition from tonalite through granodiorites to granite; syenite granodiorite composition is the most common. The location of the study area is shown in Figure 1, the area is characterised by undulating topography which accounts for the sub-dendrite like drainage pattern. Climatic condition of the area is typical tropical rain forest of southern Nigeria characterised by alternation of wet and dry seasons.

METHODOLOGY

The method for this research was divided into surface fracture mapping and subsurface geophysical investigations. A reconnaissance survey was done by traversing along footpaths with the aid of a base map, compass clinometers and global positioning system (GPS). The GPS was used to update the base map to reflect the positions of modern infrastructures. During the course of
structural field mapping, attention was paid to the topography and vegetations at each location to provide hint on the geology (cf. Barnes, 1981; Ekwueme, 2004). Strike and dip of structural features such as joints, faults, and veins were measured on exposed outcrops. The respective positions of these data were adequately linked onto the base map. Furthermore, the attitudes of the structures were plotted on rose diagrams and stereographic projections in order to understand the trend of the major tectonic force(s) in the region. Fresh unweathered representative rock samples were collected and prepared for detailed petrographic examination of the rocks in the laboratory.

For the subsurface geological study, Azimuthal resistivity sounding/ survey using Schlumberger electrode configuration (ARS-VES) was employed at three sites in the study area namely; Ako mixed Grammar School, that is, Akograms (7°20’20”, N and 6°05’1” E), Uneme Nkhuam Primary School (7°20’542”1 N and 6°04’960”1 E) and Ayiegnu community secondary school (7°20’896”1 N and 6°04’804”1 E). Azimuthal resistivity measurements were performed by rotating the electrode array from 0°, 45°, 90° and 135° corresponding to the E-W, NE-SW, N-S, and NW -SE direction around a central fixed point at the AKOGRAMS ARS-VES station. In contrast, the electrode configuration was rotated at an increment of 0°, 60° and 120° corresponding to the E-W, NE-SW, and NW -SE direction for the other two ARS-VES stations due to accessibility and restriction by cultural features. The survey traverse was 100 m for AKOGRAMS and 50 m for the other two stations. The measured resistance R from the field were converted to apparent resistivity (μ) using the geometric factor for Schlumberger array. Consequently, the resistivity values for the different AB/2 spacing(s) were plotted on a polar diagram along the selected directions. The directional magnitude of the resistivity anomalies obtained from the anisotropy plots provided information on the subsurface fracture trend and variations with azimuth.

The anisotropy polygon was plotted with increasing AB/2; by contouring lines of equal resistivity value along azimuths of AB/2 separations. Anisotropy at values of AB/2 < 12 m were neglected as the resistivity anisotropy is often associated with surface irregularities at such depth (Omosanya et al., 2012b). Electrode spacing was converted to depth by the product of AB/2 and 0.6. For an isotropic homogeneous formation, the resistivity anisotropy polygon will assume a circular shape. Any deviation from a circle to an ellipse is indicative of anisotropic nature of the Formation (Malik et al., 1983, Skjerjerna and Jorgensen, 1993). The direction of the longest axis of the polygon corresponds to the strike (orientation) of the structures and the ratio of the long to short axis is an indication of the presence of fractures in an area if high, and otherwise if low (Skjerjerna and Jorgensen, 1993). The direction of electrical anisotropy is parallel to the direction of maximum apparent resistivity in the anisotropic polygon (Habberjam, 1972).

RESULTS

Surface rock types and fracture pattern

Rock types identified during the mapping exercise include Quartz Biotite Schist, Mica Schists, Gneisses and Metaconglomerates (Figure 2). The Schists are dark coloured and fine grained with narrow, alternating dark and light grey bands. The darker bands are dominated by biotite in contrast to the lighter band comprised of quartz minerals. Other schist types include the biotite- muscovite Schist. Marbles in the study area are calcic and dolomitized. The calc-silicate rocks can be classified into three main lithological groups, (a) Strongly banded calc-
silicate gneisses (b) Calc-silicate schists and (c) Massive calc-silicate rocks. The calc-silicate gneisses form the dominant and most widespread of the calc-silicate rocks. Marbles form numerous lenses and bands of variable dimensions intercalated with the calc-silicate rocks, which structurally overlie the quartz-biotite schist. The metaconglomerates are dark coloured conglomerates found in three principal zones, upper, middle and lower zones. These rocks had undergone various deformations with the adjacent migmatites-gneiss-quartzite complex. This is evidenced by migmatization, granitization and emplacement of Pan African granite plutons which marks the last of the Precambrian activities that affected the Igarra area (Anifowose et al., 2008).

Detailed petrography study was carried out on four representative rock samples to ascertain textural and mineralogical characteristics of the rock (Figure 3); the modal percentages of mineral in each slide were plotted on the histogram (Figure 3e-h). The mineral identified include quartz, biotite, muscovite, plagioclase, microcline and other opaque minerals. The dominant minerals in thin section are quartz, plagioclase and biotite. The observed mineral conforms to the result obtained from the initial geological mapping shown in Figure 2. Structural features identified from thin section include schistosity associated with sample 3 (Figure 3c).

The orientation of joints measured from the outcrop shows that joints found in the Schist and Gneisses are dominantly oriented in NW-SE with minor directions of N-S and ENE-WSW (Figure 4f). Joints in the porphyritic granite are trending N-S to NE-SW (Figure 4g) and the Veins are in the NW-SE direction. The metamorphic event, M1 identified in the thin section corroborates the foliation observed in the gneisses. These foliations are oriented in the N-S to NW-SE direction (Figure 5a). The direction of dip for foliation planes are dominantly NW-SE. Stereographic projection revealed that schistosity in the Schist dips SE, NE, and SW with minor inclination in the N-S direction. However, foliations in the Gneisses are inclined in all direction (Figure 5b).

Subsurface fractures

The results of the Azimuthal resistivity sounding (ARS) are presented in Tables 1, 2 and 3. Coefficient of anisotropy was calculated from the square root of the ratio of maximum to minimum apparent resistivity at any AB/2 spacing (Equation 1). For a formation characterised by anisotropic fractures pattern, the apparent resistivity (pt) measured normal to its strike direction is greater than apparent resistivity (ps) measured along the strike direction, when Schlumberger configuration is used (Lane et al., 1995).

The strike direction for fractures at ARS-VES Station 1 are oriented E-W at depth of 15 m (AB/2=25 m) and N-S at 7.2 m (AB/2=12 m) respectively (Figure 6a). Fracture
Figure 3. Photomicrograph of porphyritic granite showing phaneritic texture in which the mineral grains are angular and coarse. b) Biotite Gneiss with irregular crystalline bands and poorly defined schistosity. c) Mica Schist showing monocrystalline quartz grains unit with extinction and traces of muscovite flakes. d) Microgranular texture in Mica Schist. (Mag. X40). e- f) Histograms for corresponding modal mineral percentages.

orientation at ARS-VES Station 2 and 3 is N-S at depth of 7.2 m (AB/2=12 m) and 30 m (AB/2=50 m) respectively (Figure 6b and c) and NW-SE at depth 30 m (AB/2=50 m) at Station 3 (Figure 6b). The computed coefficient of anisotropy varies from 1.0861 to 2.9949, 6.3055 to 22.8736 and 8.573 to 21.609 for the three stations. The degree of fracturing at Aiyegunle closes with depth and then open up at 15 m (λ=1.054) and start to close up again at 24 m (λ=1.117) (Table 1, Figure 6d). Similar fracture dynamics was observed at Uneme-Nekua, the fracturing is constant with depth and closes at 15 m depth (λ=1.11) and later open up at 25 m (λ=1.12) (Table 2, Figure 6e). However, at Akograms, the degree of fracturing is initially constant with depth and later closes
Figure 4. Rose diagrams for different structures around Aiyegunle a) Mineral Lineation. b) Strike of Quartzofeldparthic vein. c) Joints in Mica-schist. d) Strike of foliation planes. e) Strike of axial planes of fold. f) Joints in Gneiss and g) Joints in Porphyritic Granite.

up at 24 m ($\lambda=1.86$) to re-open at 48 m ($\lambda=2.99$) and finally closing up at depth of 60 m ($\lambda=1.46$) (Table 3, Figure 6f).

$$\lambda = \sqrt{\frac{\rho_f}{\rho_s}} \quad (1)$$

**DISCUSSION**

The rock types identified in the study area include older granites in the eastern part to mica-schist and biotite-gneiss westward (Figure 2). These rocks form part of the basement complex of Nigeria (Rahaman, 1988; Dada, 1989; Oyawoye, 1972); they are mainly metamorphosed semi-pelitic assemblage of syntectonic to late tectonic origin that intruded into both the migmatite gneiss complex and the schist belts. Structurally, the mica-schist and biotite-gneiss are folded and highly fractured. The textural and structural heterogeneity of the metasedimentary rocks of Aiyegunle area provides evidence for polyphase deformation and metamorphism. Foliation with dip amount of 10 to 80° are in the N-S to the NW-SE (0-45) direction in the major structures while minor overprinted structures with dip of 50-80° are in ENE-WSW to E-W directions. Ductile deformation is indicated by foliations folded into anticlines and syncline, which thicken towards their hinge with plunge of 10 to 42°. Mineral lineation (quartz and Quartzofeldparthic vein), foliation trend and joint orientation indicate linear features (Tables 1 to 3).

Surface structures in the rock exposures of the Aiyegunle are oriented NW-SE, N-S, NE-SW and ENE-WSW direction presumably formed by NE-SW, E-W, NW-SE and NNW-SSE oriented forces. The sub surface structures are oriented in N-S, NW-SE, and E-W direction. Thus, the NW-SE and N-S oriented structures
are deep seated and connected at depth. The ARS revealed significant anisotropy at 15 to 25 m depth with orientation of E-W, NE-SW, N-S, and NW-SE at AKOKO-EDO, UNEME-NEKHUA and AIYEGUNLE respectively. Coefficient of anisotropy shows that the degree of fracturing at the three stations are generally closing and opening with depth. The numerous orientations of fractures suggest differently oriented tectonic forces through the evolution of the structures. In addition, it implies that the different fractures were produced at different time.

Regionally, the collision of the West African craton and westward moving plate created N-S to NE-SW trending structures parallel to the edge of the West African craton (Black et al., 1979; Champenois et al., 1987; Oluyide, 1988; Egesi and Ukaegbu, 2010). These E-W movements is regionally replicated as highly deformed series of multidirectional orientations common in folds, lineaments and faults in the whole of the Nigerian basement complex and northern Cameroun (McCurry, 1976; Rahaman, 1976; Onyeagocha, 1984; Toteu et al., 1990). The N-S and NE-SW structures are presumably associated with the Pan African orogeny while pre-Pan African structures are oriented differently to these directions in the basement (Onyeagocha and Ekwumee, 1982; Toteu et al., 1990). Nevertheless, the Pan African orogeny as a later and presumably the last tectonic events in the basement reconfigured and obliterated earlier structures (McCurry, 1976; Rahaman, 1976).

Consequently, the N-S fracture orientations in the study area are thought to be Pan African fabric which wiped out some of the older structures trends. The NW-SE trend is persistent with pre Pan African structural trends and consequently accounts for the connections established for this trend in the surface and subsurface data. Regardless of the N-S orientation of the Nigerian schist belts, the NW-SE trend in the study area may be a localised orientation. This further compounds the understanding of the structural trends in the schists belts. Results from this study indicates that the schists belts of the Igarra area may not be Proterozoic in age but connected to earlier Pan African events in order to
conform with the regional N-S orientation of the belts and metallogeny.

**Conclusion**

Azimuthal resistivity surveys and geologic field mapping conducted at Aiyegunle area was aimed at characterizing fractures in the study area. Structural parameters obtained from the field measurements included fracture attitude, coefficient of anisotropy, mean resistivity of subsurface layers. These parameters are useful in making preliminary inference on the degree of fracturing and permeability of the rock mass.

Fracture trends are produced by dominant E-W to NE-SW tectonic forces and therefore the joints are exten-
Table 3. Apparent resistivity values measured at Aiyegunle community secondary school (ARS-VES 3).

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Figure 6. Anisotropy Polygon for a) ARS-VES 1 (AKOGRAMS), b) ARS-VES 2 (UNEME NEKUA) and c) ARS-VES 3 (AIYEGUNLE). d- f) Plot of coefficient of anisotropy wth depth.
sional structures. Overlap between fractures oriented at shallow subsurface reveal by electrical resistivity anisotropy polygon plot and that of fracture orientation on the surface rock exposures in the study area; suggest that fractures are penetrative and hard-linked. Thus, the fractures at both levels are produced by similar tectonic events.

REFERENCES


