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JOINT STUDIES IN THE WESTERN PART OF IKOM-MAMFE BASIN, LOWER BENUE TROUGH, NIGERIA

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ABSTRACT

The Ikom-Mamfe basin, also called the Mamfe embayment, is a bifurcation of the Benue trough in southeastern Nigeria and southwestern Cameroun. The basin is about 130km long, 60km wide basin and is filled with about 4km thick sedimentary rocks. Deformational events led to gentle folding of rocks in the basin and emplacement of magmatic rocks. Systematic and detailed field studies were carried out in eight (8) locations within the study area, in which the orientations of 1437 joints and 102 veins were acquired. Two sets of orthogonal joints observed in the study exhibited symmetry with respect to the directions of the fold axes and were dominated by high-angle dips averaging about 80°. This implies a syntectonic origin of these structures also during their propagation, the maximum principal stress directions (σ_1) were orientated in two different directions NW- SE and NNE-SSW for D_I and D_2 respectively. The relative strength of deformation during D_I was greater than D_2 and it was also unfolded that the 'ac' extension joints trending NW- SE and NNE-SSW hosted relatively thicker veins in both D_I and D_2. These joints served as better conduits for mineralizing fluids and also most suitable directions for future prospecting.

KEYWORDS: Benue Trough, Deformation, Ikom-Mamfe, Jointing, Syntectonics.

INTRODUCTION

Rock jointing

A joint is described as a fracture of tectonic origin that cuts through a rock but does not show any observable displacement on one side of the fracture parallel to the surface of the joint, with two surfaces moving predominantly away from each other (Ramsay and Huber, 1987; Aydin, 1988, 2000; Billings, 2008). This brittle structure had been long studied and numerous theories had been used to account for their origin, occurrence and characteristics. They are the most ubiquitous, the most confusing features of crustal rocks and vary greatly in appearance, dimension and arrangement. They occur in rocks of different geologic and tectonic environments (Price, 1966; Moseley, 1968; Hobbs et al., 1976).

Joints in rocks could be Mode I fractures (Figure 1a, d) when the relative displacement of the fracture wall is normal to the fracture plane; these are dilatational joints or extension joints with the fracture plane normal to the least principal stress, σ_3 and parallel to the maximum principal stress, σ_1 (Jaeger and Cook, 1976; Twiss and Moores, 1992; Davis and Reynolds, 1996). In the same vein, the joint could be Mode II (Figure 1b,) shear fracture with a shear displacement of the fracture walls that is invisible at the scale of observation, or as Mode III (Figure 1c, f) or the hybrid fracture (McClay, 2007). Although these structures frequently occur in virtually all types of rocks, the analytical difficulties they pose are mainly due to a number of basic characteristics of these structures. Therefore, there exists numerous field evidences demonstrating that joints may develop at practically all stages in rock history. For this reason,

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joint systems have been widely used in the determination of paleostress and contemporary stress directions (Dyer, 1988; Olsen and Pollard, 1989; Hancock, 1991; Bai et al, 2002; Igwe and Okonkwo, 2016; Adewumi et al., 2017 and Hasssan et al., 2021), in the delineation of possible metallogenic provinces as joints serve as conduits for fluid movements (Moore and Jackson, 1977, Offodile, 1979; Dominique et al., 2017, Cardona et al., 2021 and Patrick et al., 2021).

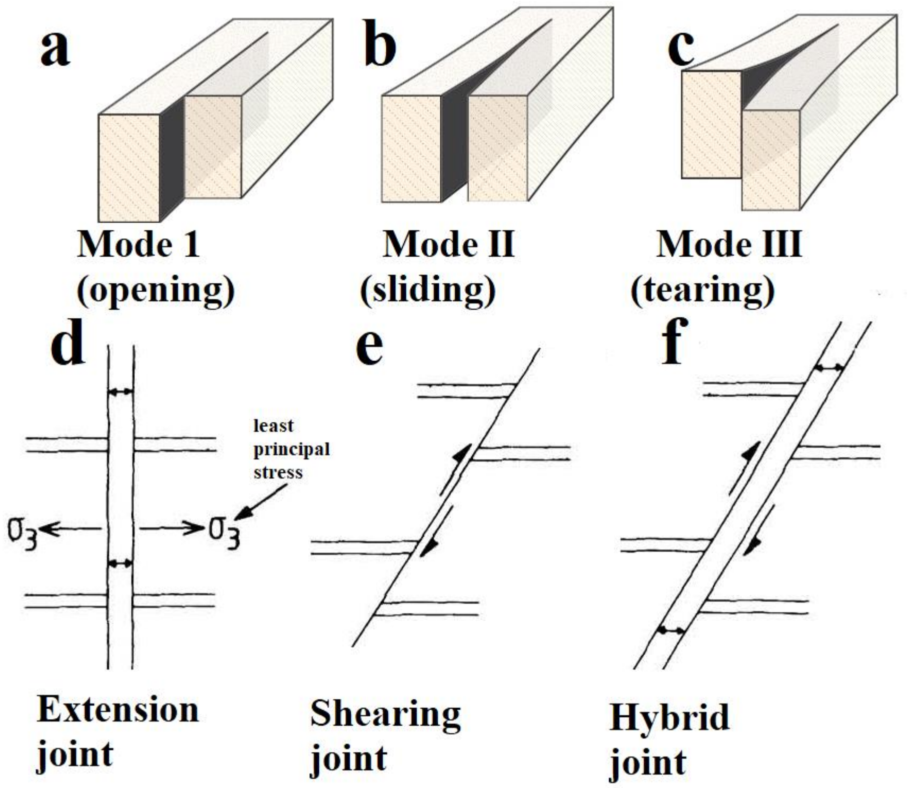


Figure 1: Fundamental modes of fracturing and the related joints (a) Mode I: tensile crack; (b) Mode II: shear-mode crack (c) Mode III: shear-mode crack; (d-f) (After Atkinson, 1987; McClay, 1987).

Jointing in folded rocks

Joint formation occurs in all stages during the propagation of a fold, thereby serving as clues to the folding mechanism which might be as a result of both local and regional fold-related stresses. Just like other types of deformation structures, both the barren and impregnated (veins) can be deformed by folding (Alsop et al., 2021; Jordi and Elena, 2022). The pattern of fracturing varies with various types of folding (Cosgrove and Ameen, 2000; Hanks et al., 2004). De Sitter (1964) observed the relationship between fractures or joints pattern and fold structure, which he considered complicated and thus skirted analysis. Two very important sets; the ‘ac’ and the ‘bc’ joints (Figure 2) had been identified by many researchers, and are defined based on the a-, b- and c- axes of the “tectonic cross” (Price, 1966; Stearns and Friedman, 1972; Hancock, 1985; Rawnsley et al., 1992; Rives et al., 1992; Bai et al., 2002) based on their positions in relation to direction of tectonic stress during compression. It is assumed that “a” is the direction of fold movement, “b” is parallel to the fold axis, and “c” is orthogonal to the ab plane. The set of joints which cut the fold at right angles to the fold axis and in the direction of tectonic stress is referred to as the ‘ac’-joints whereas the set which is perpendicular to the ‘ac’ set and parallel to the fold axis in the direction of stretching is known as the ‘bc’ joints (Melton, 1926; Hancock, 1985; Price and Cosgrove, 1990). The propagation of these joint sets are influenced by the orientation of the stress trajectories during the folding and are mainly extensional joints, the ‘ac’ fractures are favoured by mineralizing fluid as there are propagated parallel to the regional stress trajectory (Melton, 1926; Price, 1966; Oden et al, 2016). The hybrid and shear fractures may also be present. The ‘ac’ and ‘bc’ are regional fractures (Figure 2) formed respectively during the early and late stages of layer –parallel shortening (Melton, 1926; Stearns and Friedman, 1972; Fischer and Wilkerson, 2000; Bai et al., 2002; Hanks, 2004; Florez-Nino et al., 2005).

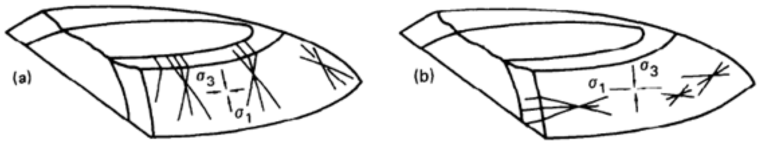


Figure 2: Fractures commonly associated with a fold (a) Early (‘ac’), (b) Late (‘bc’) (After Stearns and Friedman, 1972)

Information on the relation of joints to other structures provides insight into the tectonic conditions in which joints form and the timing of their propagation with respect to the formation of other structures in a region (Suppe, 1985; Ramsay & Huber, 1987; Ghosh, 1993; van der Pluijm and Marshack, 1997). The ‘bc’ joints according to Price (1966) are rarely mineralized or impregnated with dyke materials and form later than the ‘ac’ joints. This was also supported by Al-Kindi, 2020, who stated that the ‘bc’- fractures propagate at time the fold is undergoing tightening during compression.

According to Hancock (1964) and Rixon et al. (1983), some joints are pre-folding brittle structures, others are younger than the fold containing them (post-folding joints), and others are syn-folding brittle structures.

A synfolding origin often is ascribed to joints that exhibit symmetry with respect to a fold axis (Stearns, 1968, Stearns and Friedman, 1972; Hancock, 1985; Cooper, 1992) and these fold symmetric fractures are mostly at high angles to bedding (Tavani et al., 2006) because the fold limb reaches a high angle with respect to σ_1 during compression. Statistical analysis of large high-angle fracture datasets (~60^o-90^o) frequently indicate the existence of a relationship between fractures attributes and structural position within folds (Srivastava and Engelder, 1990; Cooper, 1992) although there could be some important low angle sets (Mosley, 1968). For synfolding fracturing, there is a much higher population of joints in the crest region than the limbs of the folds, and the predominant fractures are usually normal with respect to the fold axes (Thorbjornsen and Dunne, 1997; Fischer and Wilkerson, 2000; Hanks, 2004; Florez-Nino et al., 2005; Bausa et al., 2009).

This paper is aimed at unraveling the orientation of joints system, distribution, relative density of joints and the most favorable directions of mineralization in the western flank of the Ikom-Mamfe Basin, southeastern Nigeria.

1.3. Geological setting

The Ikom-Mamfe Basin, also known as the Mamfe embayment (Figure 3), is an Early Cretaceous basin that cuts across the Lower Benue Trough in southeastern Nigeria and the southwestern axis of the Republic of Cameroon. The basin is sandwiched between the Obudu Plateau in the north and Oban massif in the south. According to Regnoult (1986) and Neba (1987), the Mamfe Basin has a width of about 20–40 km and a length of about 80km. It is considered as one of the sub-basins of the Lower Benue Trough or southern Benue Trough and is the smallest of the three sub-basins, the others being Abakaliki and Anambra Basins. The sedimentary deposits of the basin are over 4500 m thick, and were probably a major depocenter in the eastern Gulf of Guinea during the Early Cretaceous. (Petters et al. 1987; Fairhead et al. 1991; Heine, 2007)

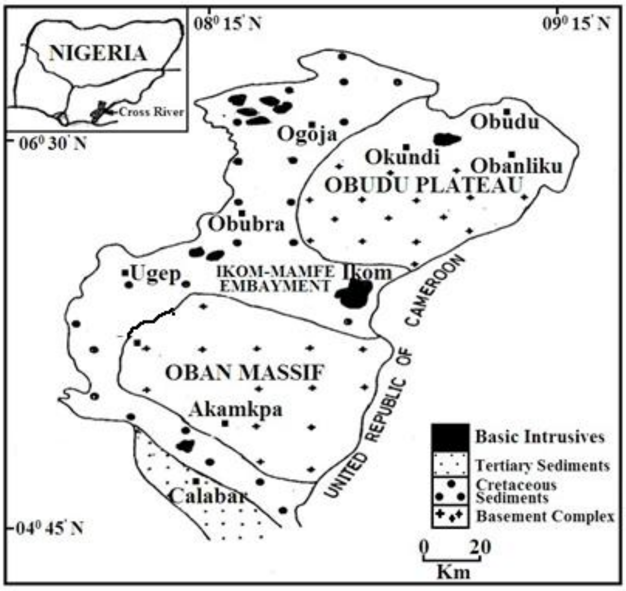


Figure 3: Simplified geological map of Nigeria showing the location of Mamfe Basin (modified after Abraham et al., 2014).

The origin of Mamfe Basin is linked to the formation of the Benue Trough. The Benue Trough is considered to be formed in response to the break-up of Gondwanaland (southern supercontinent) and the subsequent drifting apart of South American and African plates in the Late Jurassic to Early Cretaceous time. This break up is considered to be initiated by the West and Central African Rift System (WCARS) and the Northeast Brazilian rift system (NBRS) during the opening of the Atlantic Ocean (Nwachukwu, 1972; Olade, 1975; Benkhelil, 1989; Matos, 1992; Guiraud et al., 1992; Maluski et al., 1995; Basile et al., 2005; Bumby and Guiraud, 2005). The structural framework of the Lower Benue includes two main units: the Anambra Syncline and the Abakaliki Anticlinorium. The Anambra Syncline is a vast sedimentary basin trending N30^{o}E and mainly filled with Upper Cretaceous and Tertiary sediments while the Abakaliki Anticlinorium is composed of tightly folded Albian to Santonian sediments that are intruded by numerous igneous rocks. The folding in the Abakaliki Anticlinorium is attributed to a compressional episode of Santonian age (Simpson, 1954; Ofoegbu, 1985; Cratchley and Jones, 1965). However, Benkhelil (1989) attributed the fracturing and folding of the Cretaceous cover in Benue trough to a compressive phase in Late Maastrichtian.

Ikom-Mamfe Basin had been subjected to brittle and ductile deformation as earlier observed by Wilson (1928). Studies by Offodile (1976) and Oden et al. (2016) revealed that the Ikom-Mamfe Basin was deformed by two series of compression stresses in the Cenomanian age (first episode, D_I) and during the Santonian age (second episode, D_2). These compressional stresses resulted in the recorded folding activities. The fold axes were established to be directed in the NW-SE during D_I and NNE-SSW during D_2 (Offodile, 1976). These deformations lead to pervasive fracturing, Pb-Zn and barite mineralization (Farrington, 1952, Nwachukwu, 1972, Oden et al., 2015) and extensive emplacement of numerous mafic to intermediate intrusions and calc-alkaline lavas and tuffs which included basalt, dolerite, microdiorite and gabbro in the region (Murat 1972; Hossain, 1981; Benkhelil, 1989).

MATERIAL AND METHODS

Field studies were carried out in the western part of Ikom-Mamfe Basin (Figure 4), aimed at mapping existing fractures in the basic rocks. The relationship between various rock types and joint development were also observed. The orientations of exposed joints and veins, and the widths of veins in various locations were carefully measured.

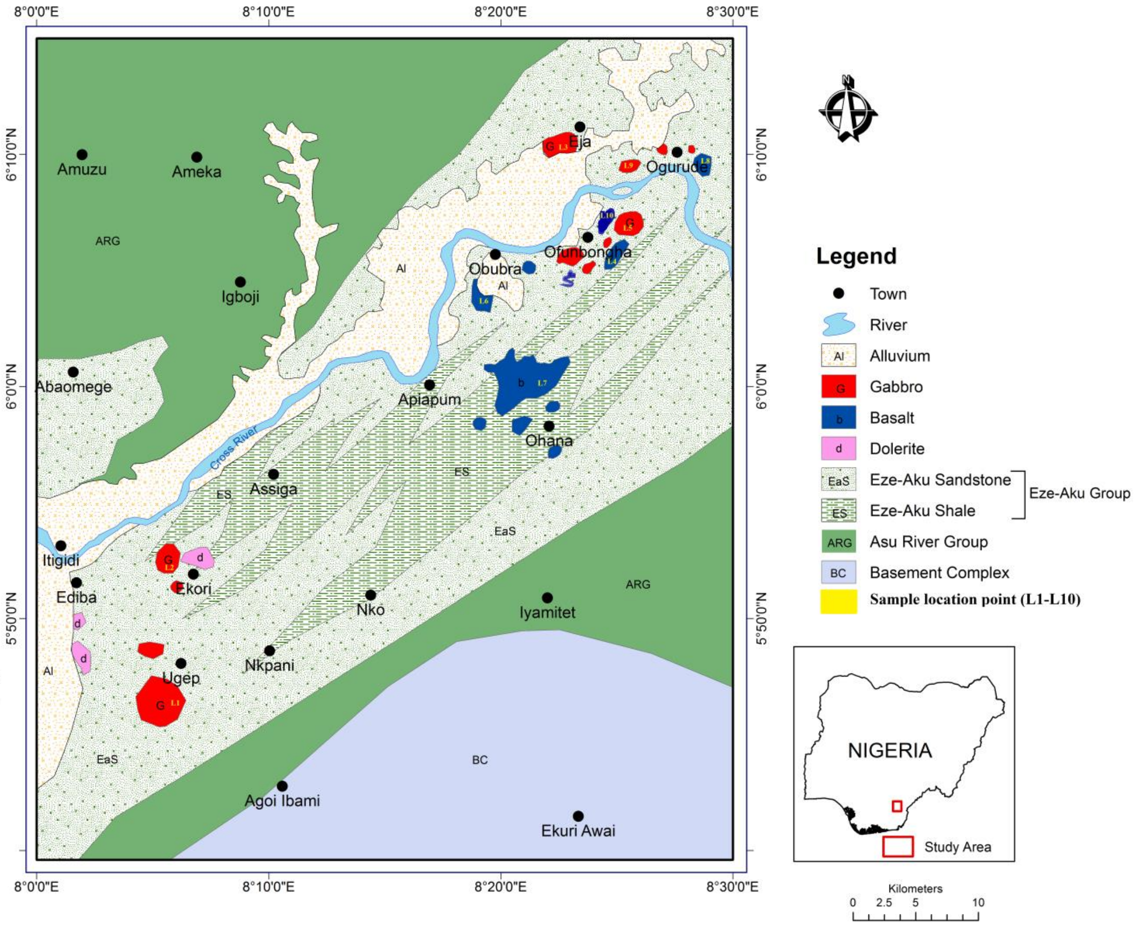


Figure 4: Geological map of the study area showing locations of Cretaceous intrusive and sampling points

A total of 102 veins and 1437 joint orientations were obtained from eight (8) locations covering areas like Ugep, Ekori, Eja, Ofunbongha 4, Obubra, Ohana, Ogurude and Ofunbongha 2 with at least attitudes of 30 joints acquired from each location. The data were analyzed using SPSS package and Grapher 14 software.

RESULTS

Structural data were gathered from fractures which were prominent on the magmatic rocks in eight (8) locations within the study area (Figure 4). The fractures were composed of the mode I extensional fractures being the major structural element measurable in the study area (Figure 5). These fractures basically show no element of shearing and lack surface structures or markings such as fractographic structures like hackle marks, plumose structures or arrest lines, but rather exposed joints surfaces which were generally smooth.

Figure 5: Joints and vein occurrences in the study area

The lengths of joints were predominantly short, planar and die out within a short distance. The trends of joints in the study area are shown in Figure 6. The distribution of petals depicting dominant joint trends in the locations are Location 1(a): N40^{O}W, N40^{O}E, N15^{O}E and N80^{O}W; Location 2(b): N50^{O}W, N40^{O}E, N 20^{O}E and N80^{O}W; Location 3(c): N50^{O}W, N40^{O}E, N20^{O}E and N75^{O}W; Location 4(d): (phaneritic rock), N60^{O}W while N60^{O}W, N40^{O}E for the aphanitic rock (4e); 5(f): N50^{O}W, N50^{O}E, N20^{O}E and N80^{O}W; Location 6(g) :N50^{O}W, N15^{O}E; Location 7 (h): (phaneritic rock) N50^{O}W, N40^{O}E, N20^{O}E, for the aphanitic (7i)) N50^{O}W, N50^{O}E, N20^{O}E and N80^{O}W; Location 8 (j)): N50^{O}W, N40^{O}E and N20^{O}E. The joints were consistent in occurrence and at least two pairs of joint orientations were observed from the stereoplot.

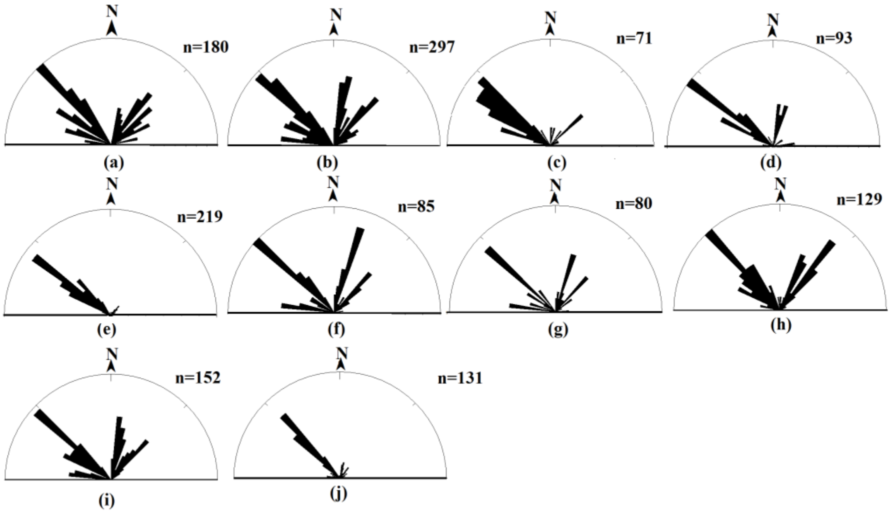
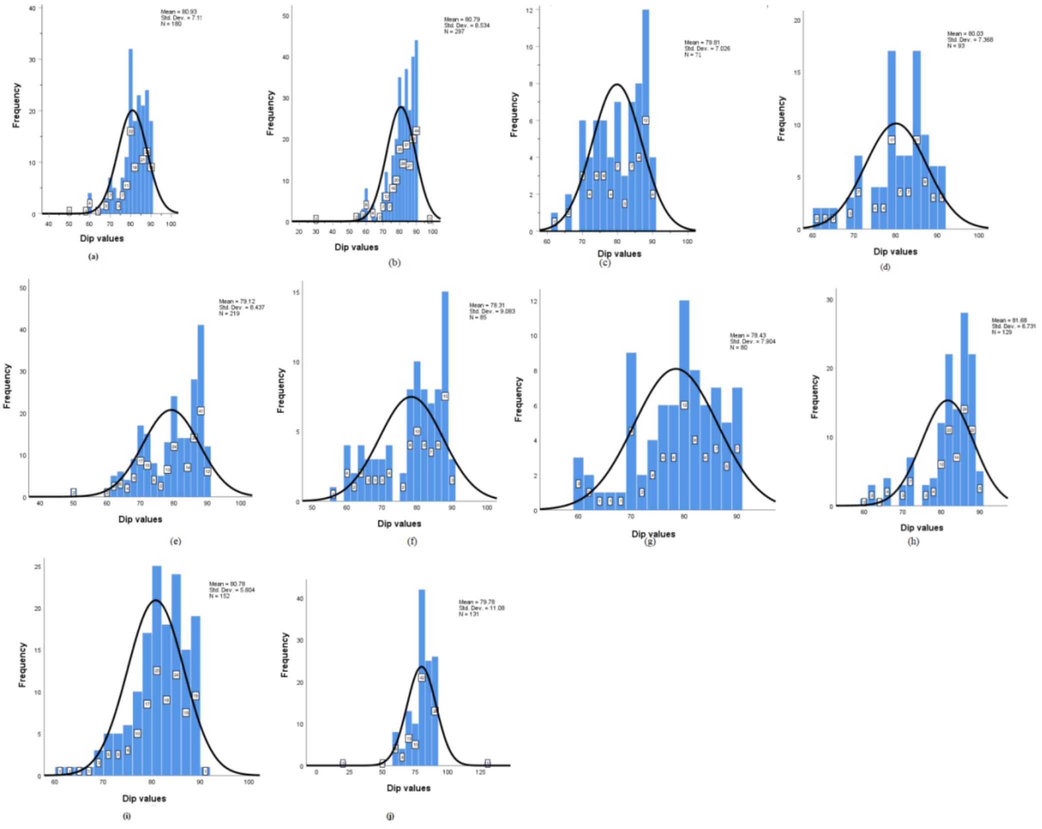


Figure 6: Fractures trend in the study area (a) Location 1; (b) Location 2; (c) Location 3; (d,e) Location 4; (f) Location 5; (g) Location 6; (h,i) Location 7 and (j) Location 8 (Ofunbongha 2)

The first dominant and most prominent fracture set in virtually all locations under investigation were the NW-SE set defined at N40°W - N60°W (Figure 6). The second set of prominence is the NNE-SSW set. This set is defined at N10°E to N20°E. The third and fourth sets observed are the NE-SW and WNW-ESE sets, trending at N40°E-N50°E and N75°W-N80°W respectively. The third and fourth sets were the least in abundance as they were absent in some locations and also of lower frequency relative to the first and second set. The numerical value of the major fracture set is shown in Table 1. In each location, the ac fracture set was dominant.

Table 1: Distribution of ‘ac’ and ‘bc’ joints in the study area

		D_1			D_2				
S/N	**LOCATIONS**	**AC_I**	**BC_1**	**TOTAL**	**AC_2**	**BC_2**	**TOTAL**	**% D_1**	**%D_2**
1	Ugep	55	37	92	33	30	63	59	41
2	Ekori	87	51	138	79	50	129	52	48
3	Eja	33	8	41	20	12	32	56	44
4	Ofumbongha 4	138	21	158	40	10	43	78	22
5	Ofumbongha 4	41	5	46	23	18	41	53	47
6	Obubra	26	16	42	23	17	40	52	48
7	Ohana	23	19	42	20	17	37	53	47
8	Ogurude	43	32	75	49	12	71	51	49
9	Ogurude	41	25	66	26	18	44	79	21
10	Ofunbongha 2	71	12	83	12	19	41	67	23



The dip angles of joints were also measured and presented in Figure 7. The dips were mostly high angles and few were vertical.

Figure 7: Fracture trend in the study area (a) Location 1; (b) Location 2; (c) Location 3; (d,e) Location 4; (f) Location 5; (g) Location 6; (-h,i) Location 7) and (j) Location 8 (Ofunbongha 2)

Mineral veins, mostly extensional, were also emplaced within the basic rocks of the area. These structures were not exposed in some locations but were dominant in the phaneritic rocks which were majorly quartz veins with moderate to high dip angle, ranging from 50^o to vertical. The width of veins in the study area were of a few centimeters ranging from 1.1cm to about 8.7cm (Figure 8).

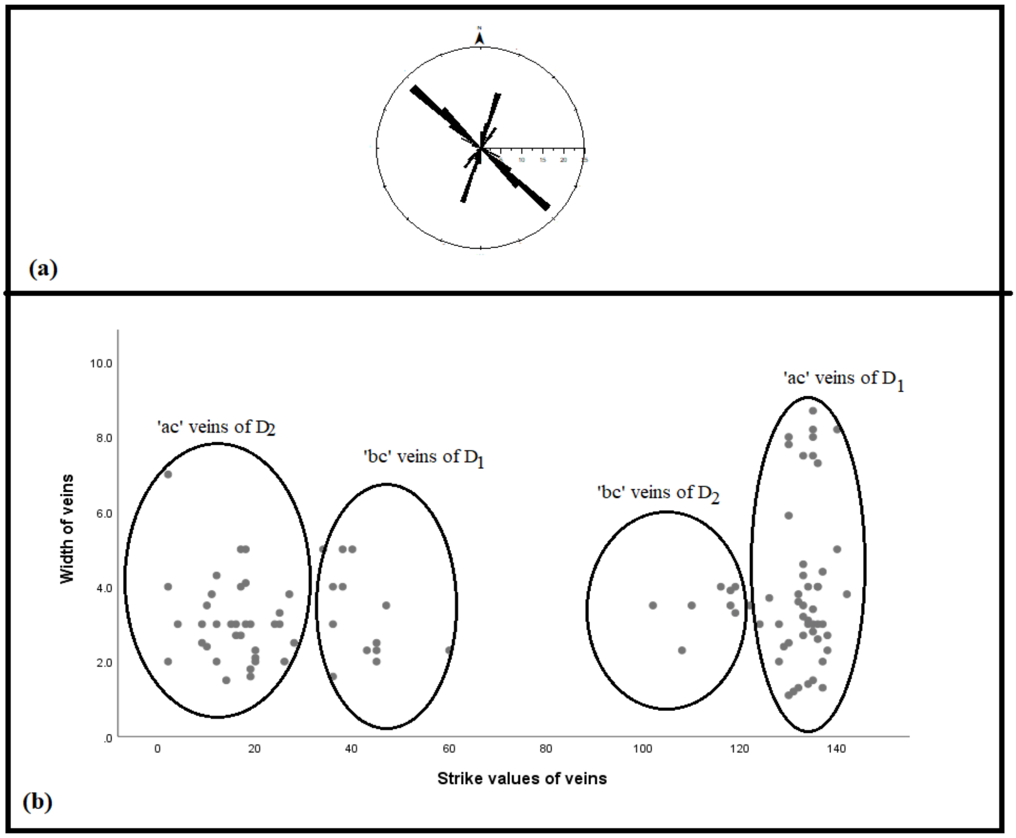


Figure 8: (a) Trend of veins (b) Distribution of vein width in the study area

DISCUSSION

From the study of fracture patterns, the stereoplots (Figure 6) show that NW-SE set was orthogonal to the NE-SW set; similarly, the NNE-SSW was also orthogonal to the WNW-ESE and they both represented two stages of Cretaceous deformation; D_I and D_2 (Olade,1975 and Oden et al., 2016). These fracture sets were symmetrical to the fold axes of two fold generations observed by (Furon, 1963; Offodile, 1976) with fold axes trending NE–SW and WNW-ESE implying that σ_1 was northwesterly during D_I and northeasterly during D_2. Fracture-fold relationship analysis shows that ‘ac_I’ and ‘bc_I’ (NW-SE and NE-SW) sets of D_1 exhibited a well-defined maxima at $N50^oW$ and $N40^oE$ respectively; whereas ‘ac_2’ and ‘bc_2’ (NNE-SSW and WNW-ESE) sets of D_2 were defined by the $N20^oE$ and $N40^oW$ (Figure 10). This systematic and symmetrical relationship of the joints to fold axes in the study area indicates that the joints and folds propagation were contemporaneously controlled by some regional stress fields operating at different times as was observed by (Melton, 1926; Price, 1959; Stearns, 1968; Stearns and Friedman, 1972; Hancock, 1985; Cooper, 1992; Pluijm and Marshak, 1997; Mehdi et al., 2019). This observed fracture pattern shows that the Cretaceous deformation did not occur in the same direction of σ_1, thus debunking earlier views by Nwachukwu (1972) who opined that those deformational episodes occurred in the same axial directions. Although local irregularities of the fold structure according to (Harris et al., 1960) may, to an extent, alter the trends and concentration of the dominant fracture sets, it was observed that a rhythmic spatial distribution, dominance and concentration of ‘ac’ and ‘bc’ fractures exist in each location (Figure 6 and Table 1). However, the ‘ac’ extensional fractures were the most ubiquitous fractures present and mappable in both D_I and D_2. These domineering occurrences of ‘ac’ joints were also recorded by (Price and Cosgrove, 1990; Thorbjornsen and Dunne, 1997; Fischer and Wilkerson, 2000; Bausa et al., 2009; Hanks, 2004 and Florez-Nino et al., 2005). It is evident that ‘bc’ set remains dormant and do not develop until significant shortening and tightening occur (Hills, 1972; Stearns and Friedman, 1972; al-Kindi; 2020), hence their numerical disadvantage in the study area. The ‘ac’ set constitutes more than 50% of joints in each location, with about 71% during D_1 and 61% during D_2 relative to the ‘bc’ with distribution frequency of 29% and 39% during D_I and D_2 respectively; since it is unusual for folds in hard rocks to lack at least the ‘ac’ joints (Hobbs et al., 1976) . This observation also provides an insight into the relative strength of the two deformation episodes. In essence, the compression in the earlier deformational episode D_I was stronger thus propagated more ‘ac’ fractures than the later episode D_2. Among the aphanitic rocks, the micro cryptocrystalline variety exhibits a higher fracture population in both D_I and D_2 than the phaneritic rock of same location (Locations 4 and 7). This observation also shows the difference in the time of emplacement of the two magmatic bodies in the study area (Oden et al., 2016) and also probably due to textural difference between the aphanitic and phaneritc rocks.

Additionally, there was a dominance of moderate to high dip angles of joints (Figure 7) with mean of about 80^{o}. Joints with moderate to high dip angles are usually associated with folded terrains (Moseley, 1968; Srivastava & Engelder, 1990; Cooper, 1992;Hanks et al., 2004 and Dong et al., 2014) and are interpreted to be syn-tectonic in contrast to lower angle joints mapped by Dong et al., (2014) interpreted to be prefolding. The attitudes of veins were mostly concentrated in the directions N30^{o}W-N50^{o}W and N2^{o}E-N20^{o}E which are mostly the ‘ac’ directions and were emplaced from the Lower to Upper Cretaceous according to Furon, 1963; Uzuakpunwa, 1974 and Oden et al., 2016. Veins with relatively thicker width (about 6.0 cm and above) were emplaced within the ‘ac’ joints of D_1 and D_2 and peaked in the directions N30W- N50W (Figures 8a and 8b). This shows that early-formed fractures serve as major conduits for mineralized fluids as they were bountifully impregnated during magmatism relative to the later form ‘bc’ fractures which were sparingly mineralized.

CONCLUSIONS

The Ikom-Mamfe Basin is a sub-basin that strides across south-eastern Nigeria and south-western Cameroon. This basin has been subjected to two episodes of compressional deformation, D_I and D_2 corresponding to Lower and Upper Cretaceous deformations respectively. These deformations produced two sets of folds with axes trending NE-SW and WNW-ESE. The deformational episodes were accompanied by magmatic activities and wide-scale brittle deformation. Structural studies show that the joints in the study area were mainly extensional joints that displayed a symmetric orientation with respect to the fold axes (‘ac’ and ‘bc’) which formed an orthogonal relationship in NW-SE, NNE-SSW, NE-SW and WNW-ESE directions. The implication was that D_I and D_2 occurred at different axes of σ_1 against earlier view. Again, the dominance in the frequency of ‘ac’ and ‘bc’ joints in the aphanitic rocks shows the ease of these rocks to brittle deformation as were observed from locations where they coexist with phaneritic rocks; also the relative strength of deformation was more intense during D_1 as evident by higher joint frequency during D_1 than during D_2 in virtually all the locations.

In the entire study area in both D_1 and D_2 the distributions of ‘ac’ joints were more prominent than the ‘bc’ joints and exhibited a relatively higher frequency distribution; this in combination with the high dips of joints of ~80^{o} indicates that the joints were due to compression activities. The size of quartz veins vary in both set of fractures; however, the ‘ac’ joint sets accommodated larger width veins relative to the ‘bc’ joint sets in both D_1 and D_2. It is therefore, conspicuous from the study that the proliferations of syntectonic joints in the study area were due to two tectonic events which differ in intensity and were generally formed due to the folding episodes of the regimes, and also ‘ac’ fractures in both episodes were better suited for minerals prospecting because they served as host to larger sized veins.

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