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Analysis of Joint Distributions in the Cenomanian-Turonian Shales of the Southern Benue Trough: Implications on Basin Paleostresses and Tectonics

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Abstract

Statistical analysis of the orientation distribution was carried out on joints in Cenomanian-Turonian shales of the Southern Benue Trough, Nigeria to determine preferred orientation directions which serve as proxies to determining the directions of the regional stress field in the basin. Joint orientation data were collected from eleven locations and were analysed using equal area lower hemisphere stereonets and rose diagrams. Two major fracture systems were observed: A Major Cross-Fold Joint (CF-J) system -orthogonal to the regional fold axes- consisting of the CF-J_1 set trending NW/SE (315±5°), the CF-J_2 oriented in the NNW/SSE (340±5°) and the roughly N-S (±5°) trending less prominent CF-j_3 set; and a subordinate Longitudinal Joint System (L-J) -subparallel to the fold axes- consisting of a NE-SW L-j_1 set, an ENE-WSW (60°±5°) L-j_2 set, and an E-W trending L-j_3 set. Mean Vector Azimuth values range from 315.1°±5.2° (due NW) and 343.6° ± 01.9° (NNW). Circular variance values range from 0.353 to as low as 0.0007 showing a strong preferred orientation of the fractures evidenced also by high concentration parameter (k) values. The Cross-Fold System precedes the folding episode in the Santonian period and is likely a result of overpressure conditions due to disequilibrium compaction in the Turonian shale units in an initial compressive regional tectonic stress field. The Longitudinal System formed later and is related to the outer-arc flexure of the folded units taking advantage of the nascent cleavage structures in the folded shale units. Fracture development point to a period of contractional tectonics and basin inversion initiated in the Coniacian and reaching its peak in the Santonian.

Keywords: *Joints; Benue Trough; Cenomanian; Turonian; Paleostress.*

1. Introduction

Fractures, planar to sub-planar structures where a body of rock has lost cohesion, are the result of stresses (local or remote) exceeding the strength of the rock material in which they form. Extensional fractures, especially joints, have been established as proxies for determining the state of stress affecting the rock body at the time of initiation and propagation [1–3]. When joints form with uniform orientation and distribution on a regional scale, they can be used to determine the regional tectonic stress field and to better understand the tectonic evolution of sedimentary basins [4–6]. In clastic - and especially fine-grained - successions in rapidly subsiding basins their initiation may be as a result of fluid overpressure and are therefore hydraulic [7–10]. Basin analysis studies have, therefore, frequently made use of data obtained from the orientation distribution of regional joint sets in rock units within a basin to understand basin palaeo- and neo- stress fields.

The Benue Trough is a collection of wrench-related pull-apart basins related to transcurrent movement along deep-seated oceanic transform faults [11–16]. The southern part of the basin accumulated thick deposits of marine shale successions from the late Cenomanian to the end of the Coniacian in a period marked by rapid basin subsidence and a worldwide eustatic sea-level high stand [17–20]. Current understanding of the structure and evolution of the Benue Trough has focused on regional-scale features revealed by remote sensing and geophysics coupled with extensive field data [21–25]. Studies of the evolution of the basin have focused on the timing of major tectonic events, the most important being the Santonian basin inversion which affected the southern part of the Benue Trough leading to the folding of Albian to Coniacian sediments [11,16,26]. The intensely fractured nature of the Cenomanian-Turonian shales in the basin is related to this tectonic development [27-28]. This paper presents an analysis of intensely fractured shales in parts of the Southern Benue Trough, showing the major orientation distributions, relation to the major regional structures as well as speculation on their genesis as well as their paleostress and paleopressure implications.

2. Geologic setting

2.1. Tectonic setting

The study area lies within the southern part of the Benue Trough, a NE-SW trending elongate basin stretching 1000km from southern to north-eastern Nigeria (Fig.1). The Benue Trough is a collection of pull-apart basins separated by axial basement highs which formed as a result of transcurrent movement along reactivated major Pan-African shear zones [11-12]. These transcurrent movements were part of plate motions of the African plate during the late Jurassic and early Cretaceous rifting and opening of the Equatorial Atlantic Basin [15,29]. The Precambrian shear zones were the predecessors of major equatorial Atlantic transform faults: the Chain and Charcot Fracture Zones which extended into the trough axis [30–32]. The Benue Trough is divided into Northern, Central and Southern geographical segments with differing but related stratigraphic and structural features within each segment. The Southern Benue Trough contains more than 5km thick Aptian to Maastrichtian sediments intruded by volcanics from magmatic episodes that last from the Cretaceous into the Neogene (Fig. 1).

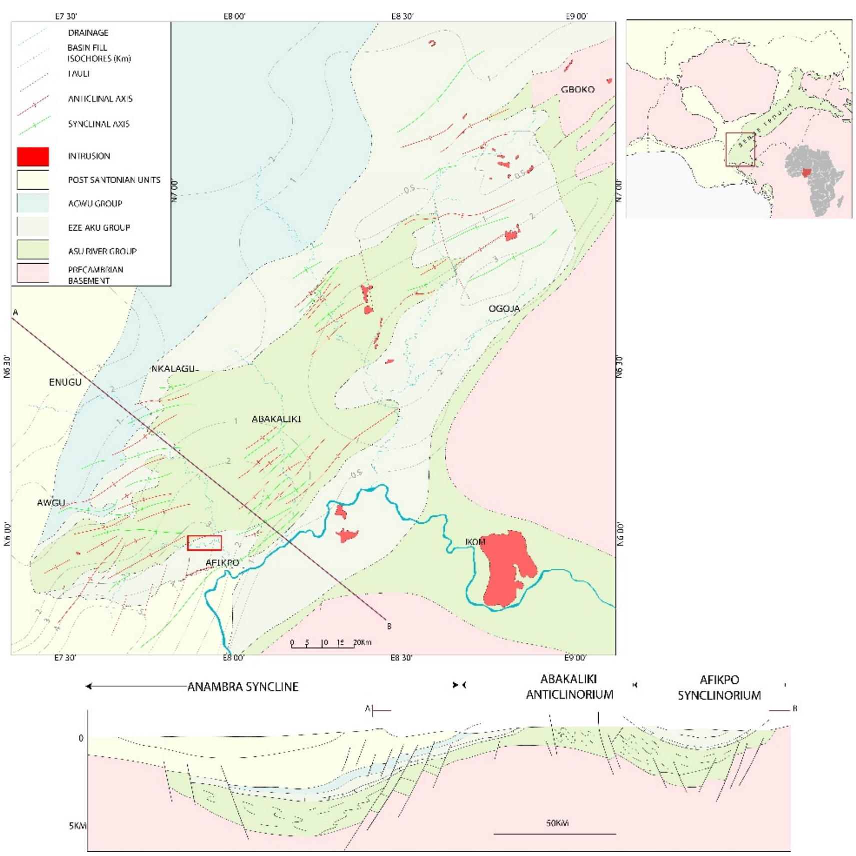


Figure 1. Structural Map and Cross-section of the Southern Benue Trough showing basin-fill thickness isochores revealed by Geophysics

The study area forms part of a synclinal structure – The Afikpo Synclinorium- on the eastern flank of the Abakaliki Anticlinorium which is the major structural unit in the Southern Benue trough (Fig. 1, Cross-section). This synclinal structure is formed by Albian to Turonian deposits which were folded in the Santonian. The synclinorium plunges to the south beneath Campanian and younger clastic sediments belonging to the Afikpo Sub-Basin: a part of the Anambra Basin which formed after the Santonian folding episode [18,33–35].

2.2. Stratigraphy

The stratigraphy of the Southern Benue Trough predominantly consists of clastic shallow marine deposits (Fig. 2) within a basin morphology consisting of a major northeast-southwest trough flanked by broad eastern and western shelves [19,36].

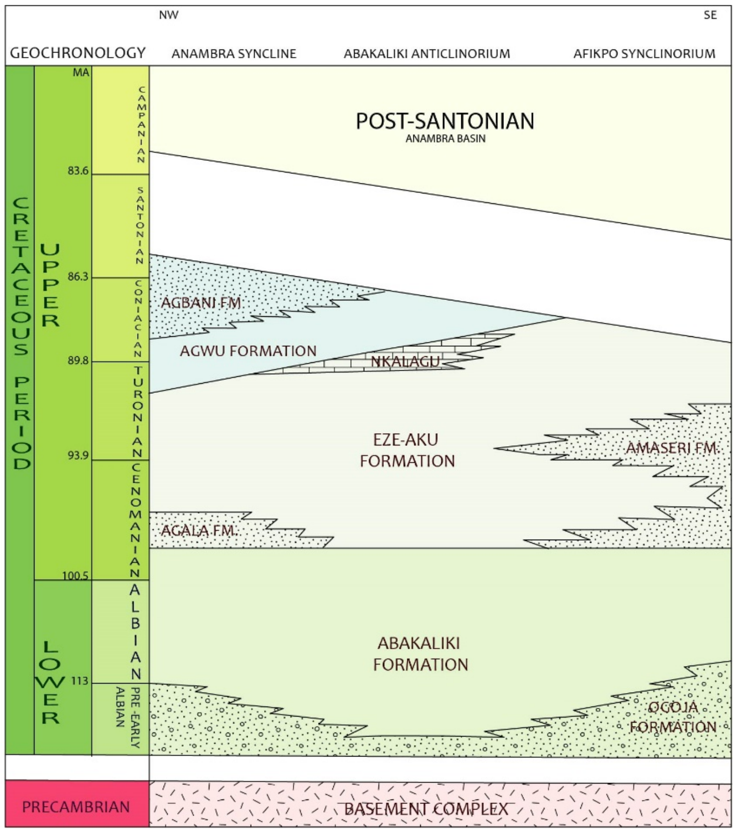


Figure 2. Stratigraphic Summary of the Southern Benue Basin Fill and the Anambra Basin (after [18-19])

Continental alluvial fanglomerates sit on the Precambrian basement and are exposed at Ogoja (the Ogoja Formation) on the flanks of the Benue Trough. They formed at the time of initial rifting and structuring the basin from as early as the late Jurassic till the Aptian [18,37] and are the basal units of the basin.

The first marine transgression in the Albian laid down deposits belonging to the Asu River Group. Just north of the study area, the Asu River Group is represented by shales, siltstones, and fine-grained sandstone interbeds showing extensive soft-sediment deformation and belonging to the Abakaliki Formation. The Eze-Aku Group is the major stratigraphic unit in the study area deposited between the Late Cenomanian and the Turonian. In the study area, the Eze-Aku Group consists of the Eze-Aku Shale Formation made up of well-bedded fissile dark grey shales and marls with imprints of the *Innoceramus sp,* and rare bioclastic limestone occurrences. The Amaseri Sandstone Formation, made up of highly indurated, bioturbated and subtidal to tidal storm dominated sequences, forms asymmetrical ridges between the Eze-Aku shales [18,38] (Fig. 3). These units formed during a period of maximum subsidence of the Benue Trough and a period of a worldwide eustatic high stand which led to a connection of the Atlantic to the Tethys Ocean through the Benue Trough.

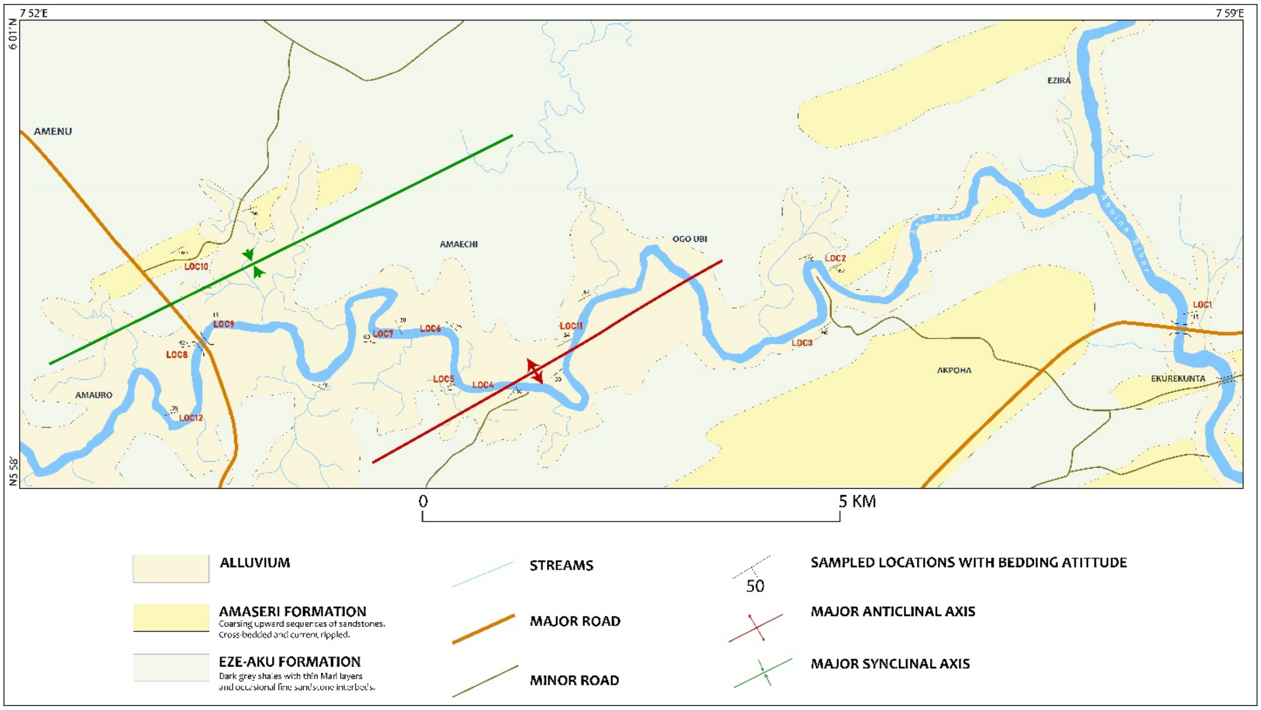


Figure 3. Geologic map of the study area showing fracture sampling locations

The Santonian Stage was one of basin inversion and folding accompanied by magmatism in the Benue Trough leading to a shift in depocentre from the now emergent southern Benue Trough to its southeastern and western flank [39–41]. In the study area, the pre-Santonian units are a part folded synclinorium structure plunging towards the south where it is covered by Campanian to Maastrichtian paralic to marine units of the Afikpo and Nkporo Formations; and the Ajali, Mamu and Nsukka Formations [33-34,42-43].

3. Fracture orientation analysis

3.1. Methodology

Fracture orientation data were collected from eleven locations, most of which are exposures along the Asu and Aboine Rivers. These highly seasonal rivers expose, beneath the alluvium, shale and minor marl, siltstone and sandstone units along their banks and on the river beds. Areal Sampling methods of largely limited exposures were applied [44-45]. Orientation data (strike, dip and dip direction) was measured using both the compass clinometer and digitally using the Field Move Clino™ mobile Application. Morphological data for individual fractures: surface ornamentation, infilling, intersection relationships were noted. Lower hemisphere stereographic projections and rose diagrams of joints and bedding were developed using both Stereonet 10™ and Open Stereo™.

A measure of the distribution of the orientation of the fractures can be described by computing relevant statistics [46]. Each fracture orientation is represented as a unit vector and its directional components in a coordinate system. The Mean Direction ($\bar{\theta}$) is the resultant of these vectors whose direction is given by:
$\bar{\theta} = \tan^{-1}(\sum_{i=1}^{n} \cos\theta_i / \sum_{i=1}^{n} \sin\theta_i)$; and the mean resultant magnitude or length of the resultant ($\bar{R}$) given by: $\bar{R} = \frac{\sqrt{\sum_{i=1}^{n} \cos\theta_i^{\,2} + \sum_{i=1}^{n} \sin\theta_i^{\,2}}}{n}$

This average length is also a measure of the dispersion of the fracture orientations about the mean with values approaching 1 indicating preferred orientation as opposed to 0 with the orientations more dispersed. Related to the mean resultant length is the circular variance, $S_o^2 = 1 - \bar{R}$, which is also a measure of the dispersion in orientation.

The concentration parameter (k) is a measure of how the distribution of the fracture data follows the Von Mises Distribution of orientation data and is determined from tables based on calculated values of $\bar{R}$ (ref). A k value of 0 indicates that there is no preferred orientation while higher values of k point to the preferred orientation. These statistics were calculated using Stereonet.

3.2. Morphology

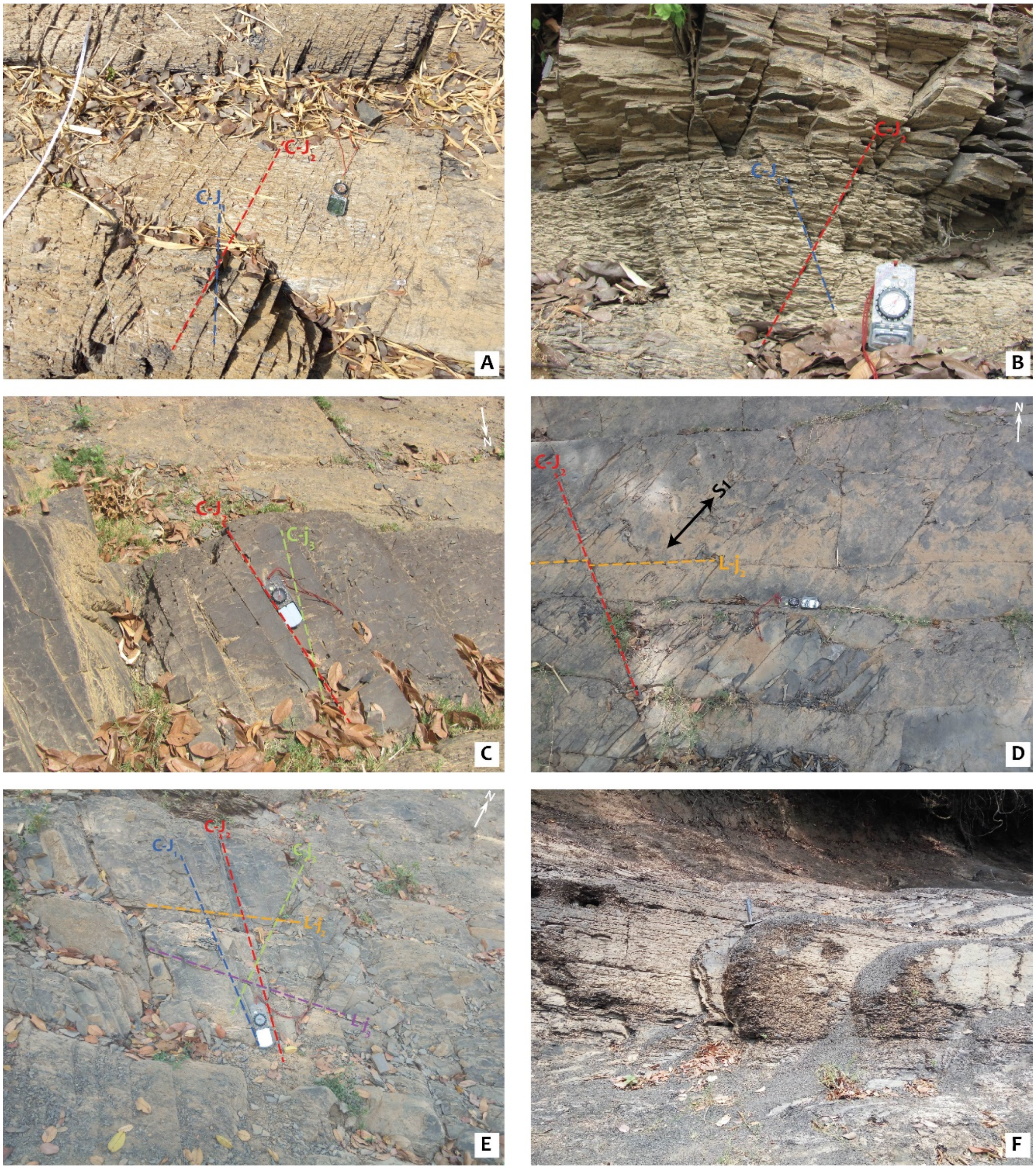


Figure 4. A. Shale units showing Major Cross-Fold System joint sets. B. Dip section of shales showing x-intersections of C-J1 and C-J2 sets. C. C-J1 and minor C-J3 sets D. Section showing Cross Fold System Joints intersected by Longitudinal System joints. Note that L-J2 terminates at C-J1. E. Section showing the major Cross-Fold and Longitudinal Systems and their field relationships. F. Joint surface exposures lacking ornamentation

The majority of the fractures in the study area are extensional joints. They are most developed in the shales where they show a close spacing of usually less than 30 cm and as low as 5cm (Fig. 4A&B). The spacing is much larger within the interbedded sandstones and marl units. The joints extend across the shale units but may sometimes terminate at bedding planes or concretion layers. The joint surfaces, where visible, do not show visible ornamentation (Fig. 4F) and on rare occasions may be filled with calcite mineralization.

3.3. Orientation distribution

Field observations, as well as measurements, were plotted on equal area stereonets and orientation rose diagrams. From their field characteristics, illustrated in the stereonet and rose diagram maps shown in Figure 5A and B, there is a preferred orientation of fracturing on a regional scale. More details analysis, taking into consideration age relationships observed in the field, point to two major joint systems in the study area:

- A major *Cross-Fold Joint (CF-J)* system consisting of two major sets, CF-J_1 and CF-J_2; and a minor joint set, CF-j_3 **(**Fig.4A, B, C&E). This system is orthogonal to the major fold axes in the study area.
- A subordinate orthogonal *Longitudinal Joint (L-J)* system consisting of 3 minor joints sets L-j_1, L-j_2, L-j_3 (Fig 4D&E). This system is roughly parallel to the major fold axes in the study area.

The CF-J_1 set trends NW/SE (315±5°) and the CF-J_2 set is oriented in the NNW/SSE (340±5°) direction. Both sets are well developed and the most prominent in the field showing x-intersections (Fig. 4B). There isn't an obvious age relationship between both sets as they mostly cut across each other or terminate on each other randomly. The CF-J2 set seems to begin to predominate towards the north of the study suggesting clockwise rotation of this major joint system from south to north of the study area. The dip of these fractures varies depending on their relationship to bedding dip with the lowest dip values occurring when the joints strike in the same direction of steeply dipping bedding (Fig.6F). The minor CF-j_3 is not as prominent as the major set and has a roughly N-S (±5°) orientation.

The Longitudinal Joint System's sets are the NE-SW L-j_1 set, the most prominent ENE-WSW (60°±5°) L-j_2 set, and the E-W L-j_3 set (Fig 4D&E**)**. These sets are subparallel to fold axes with deflections similar to local deflections in fold axes.

The Mean Vector Azimuth calculated in the outcrops in the study area reflects this predominance of CF-J_1 and CF-J_2; with values that range from 315.1°±5.2° (due NW) and 343.6° ± 01.9° (NNW). Circular variance values are quite low, ranging from 0.353 to as low as 0.0007 showing a strong preferred orientation of the fractures. High k values show an orientation distribution typical of joints sets that show a preferred orientation. These statistics are summarized in Table 1.

Table 1. Summary of orientation distribution statistical analyses carried out on the joints in the study area

LOC	Rock type	Number sampled	Mean vector	Mean vector length	Circular variance	k
LOC1	SHALE	376	335.9° ± 01.9°	0.8178	0.1822	3.002
LOC2	SHALE	109	315.1° ± 05.2°	0.6465	0.3535	1.6913
LOC3	SHALE	27	316.1° ± 00.5°	0.9993	0.0007	500
LOC4	SHALE	99	320.5° ± 03.1°	0.8605	0.1395	3.9107
LOC5	SHALE	64	327.0° ± 02.9°	0.9261	0.0739	6.5394
LOC6	SHALE	108	336.1° ± 02.4°	0.9133	0.0867	5.8522
LOC7	SHALE	177	334.0° ± 02.4°	0.8597	0.1403	3.6804
LOC8	SHALE	286	328.2° ± 01.5°	0.912	0.088	5.8522
LOC9	SHALE	378	329.7° ± 01.8°	0.8364	0.1636	3.3011
LOC10	SAND/SILT/ SHALE	103	337.2° ± 01.4°	0.978	0.022	16.927
LOC11	SHALE	228	333.5° ± 02.6°	0.7939	0.2061	2.7538
LOC12	SHALE	77	343.6° ± 01.9°	0.9611	0.0389	12.766

3.4. Relationship to folding and cleavage structures

The units in the study area have been folded into anticlinal and synclinal structures with general NE-SW trending axes. These major axes are part of the regional scale folding of the pre-Santonian units in the basin. Folding is cylindrical and may have taken advantage of the mobility of the weak shale layers in the area during the folding process. Attitude measurements and observed field relationships show that the mean fracture orientations to be roughly orthogonal to fold axes (Fig. 5A). Where suitably oriented the fractures are seen to have propagated perpendicular to the bedding and, where they are suitably oriented relative to the bedding, have been rotated from their initially vertical orientation by the folded beds (Fig 6F). This relationship between the folded bedding and the joints suggest that fracture initiation and propagation (Especially for the Cross-Fold Joint system) occurred before the folding of the layers.

There is also localized centimetre to decimetre scale soft-sediment fold structures in the form of slumps and micro folds and sand intrusions (Fig 6A&B). These are especially found in the sandstone interbeds. Associated with this folding is a weak cleavage found mostly in the shales (Fig 6C, D & E). The cleavage is parallel to the fold axes and where it is well-developed forms pencil fragmentation with the associated bedding and fracture planes (Fig 6D). Some of the joints of the Longitudinal system may have taken advantage of the weak cleavage planes.

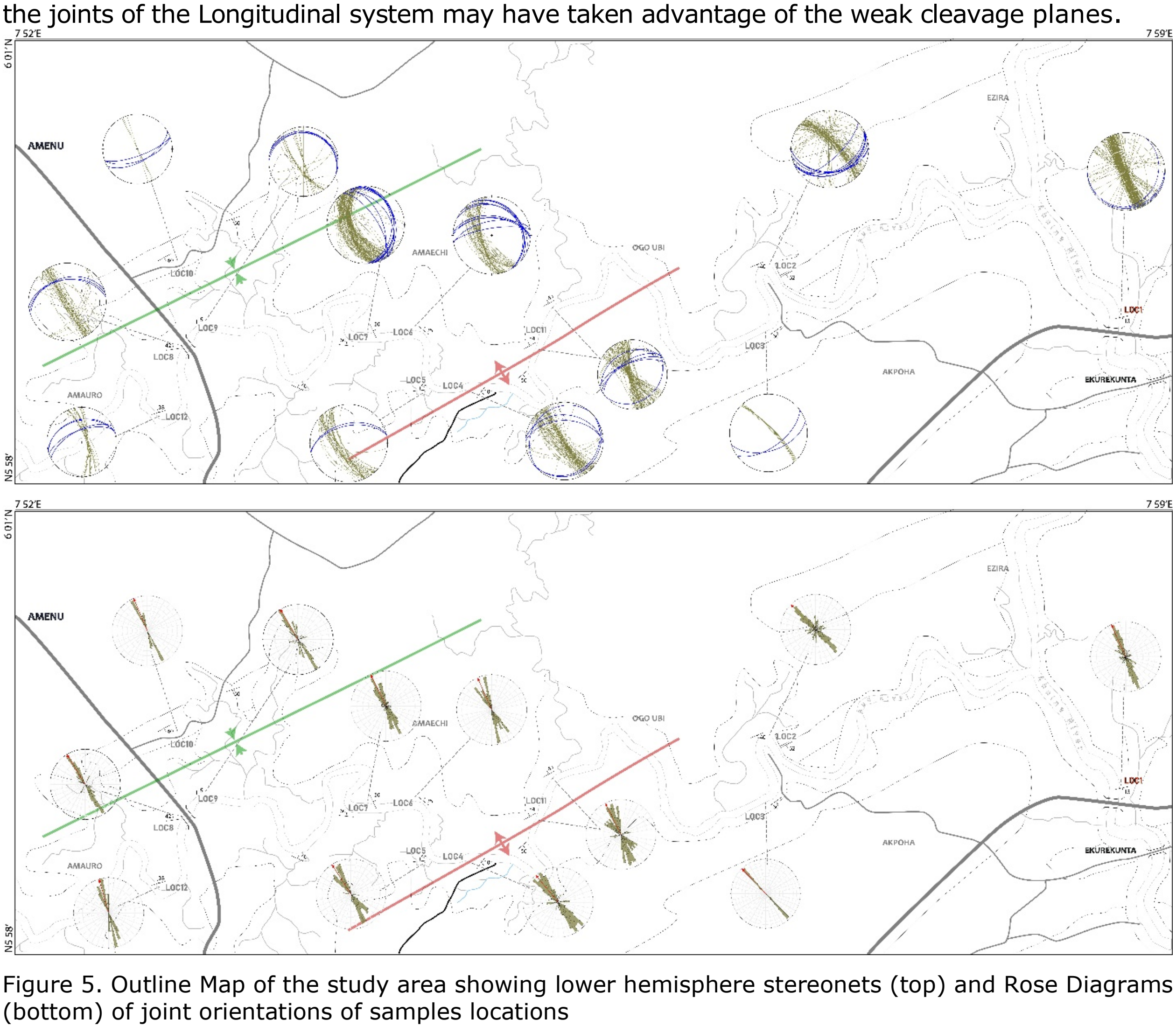


Figure 5. Outline Map of the study area showing lower hemisphere stereonets (top) and Rose Diagrams (bottom) of joint orientations of samples locations

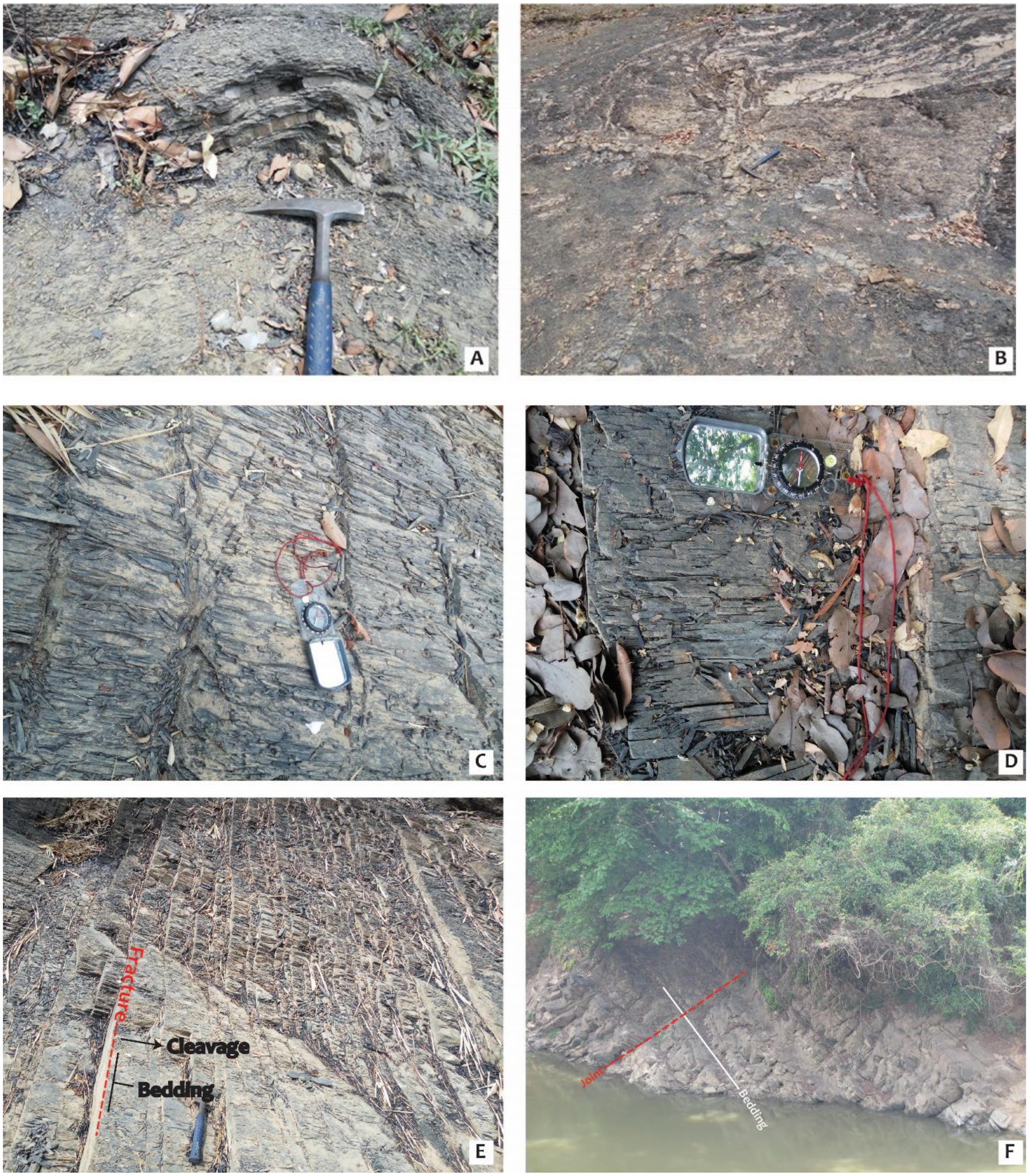
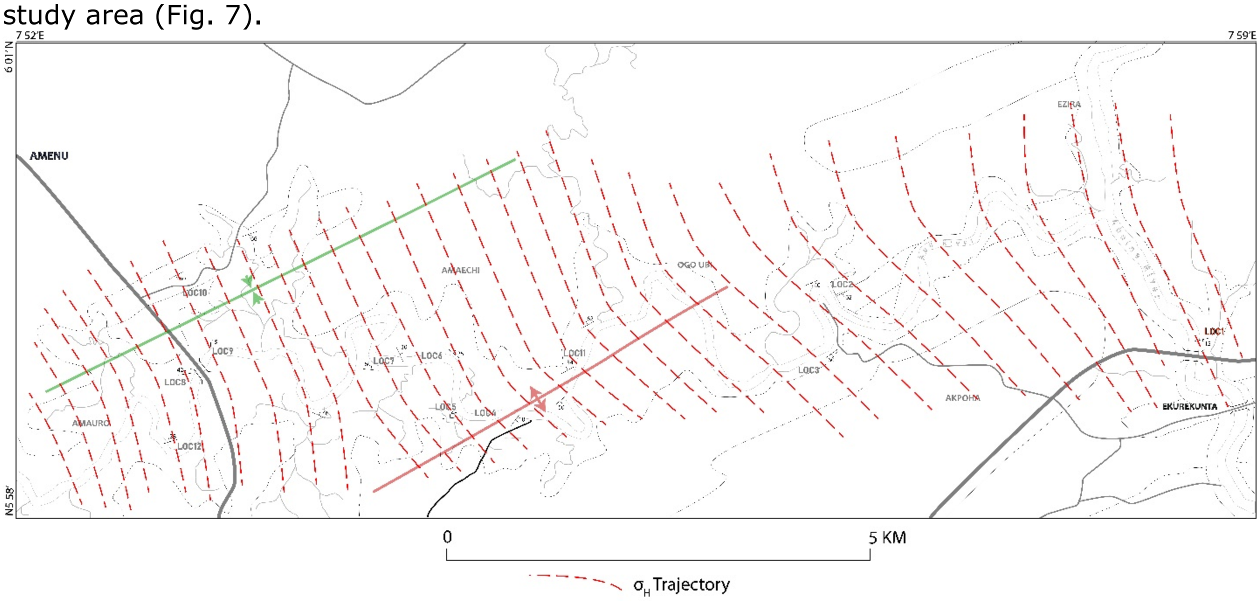


Figure 6. A. Micro folding in interbedded fine sandstone units withing the shales. B. Sandstone dykes cutting across shale beddingC. Weak cleavage (from right to left) in fractured shale. D. Cleavage and pencil fragmentation in shales. E. Relationshhip between Bedding, Cleavage and Joints in the shales in the study area. F. Relationship between Bedding and fracture showing rotation of fractures from vertical by folding.

4. Discussion

Joints are the classical opening or mode I fractures. They typically form perpendicular to the direction of least principal stress and can therefore serve as useful proxies in establishing the orientation of the regional stress field at the time of orientation. The regional stress field within a basin can be characterized by the relative magnitudes of the three principal stress axes and their orientation. Tectonic stress regimes are defined by which of these principal stresses are vertical (σ_v) and horizontal (σ_H and σ_h) according to Anderson's theory [47-48].

Joint orientation data can be used to model the trajectory of the maximum regional horizontal stress field which should be roughly parallel to the major joint orientations. It shows a stress field that deflects slightly northwards from the southern part to the northern part of the study area (Fig. 7).



Fracture initiation can be modelled based on the combination of the Navier-Coulomb failure criterion for shear fracturing and the Griffith failure criterion for extensional fracturing. States of stress with sufficiently large enough differential stresses (shown by the diameter of the Mohr circles) will lead to conditions outside the failure envelopes and the initiation of fractures. To form shear fractures the differential stress must be four times the tensile strength of the rock (4T) while for extensional fractures it must be two times more (2T) [8].

Fluid pressures act counter to compressive stresses leading to effective stresses that are low enough to cause hydraulic fracture initiation in otherwise compressive tectonic conditions. Osborne and Swarbrick [10] proposed several situations that could produce overpressure in sedimentary basins: Reduction in pore space due to compression either during burial (disequilibrium compaction) and/or tectonics stress; changes in fluid volume due to increase in temperature (aquathermal pressuring), diagenesis or the generation of hydrocarbon fluids; and fluid flow due to differences in fluid densities as a result in potentiometric head differences. In the Southern Benue Trough, evidence points to overpressure due to disequilibrium compaction in the presence of a regional tectonic compressive stress field.

During the Turonian to Coniacian period of rapid subsidence, overpressure conditions were created within the Eze-Aku shale units in the basin as a result of disequilibrium compaction. The onset of compressive tectonism from the late Coniacian and into the Santonian period may also have increased overpressure conditions to the point of initiation hydraulic fractures (Fig.8A). Low differential stress conditions (less than 2T) coupled with fluid overpressure led to the initiation of extensional natural hydraulic fractures belonging to the Cross-Fold Joint system in the shales with their mean orientations parallel to the maximum principal remote stress axis which was horizontal (σ_H) and oriented in a roughly NW-SE direction at the time (Fig. 8B). This direction is the direction of the regional compressive stress field affecting the basin during the period of basin inversion from the late Coniacian to the Santonian.

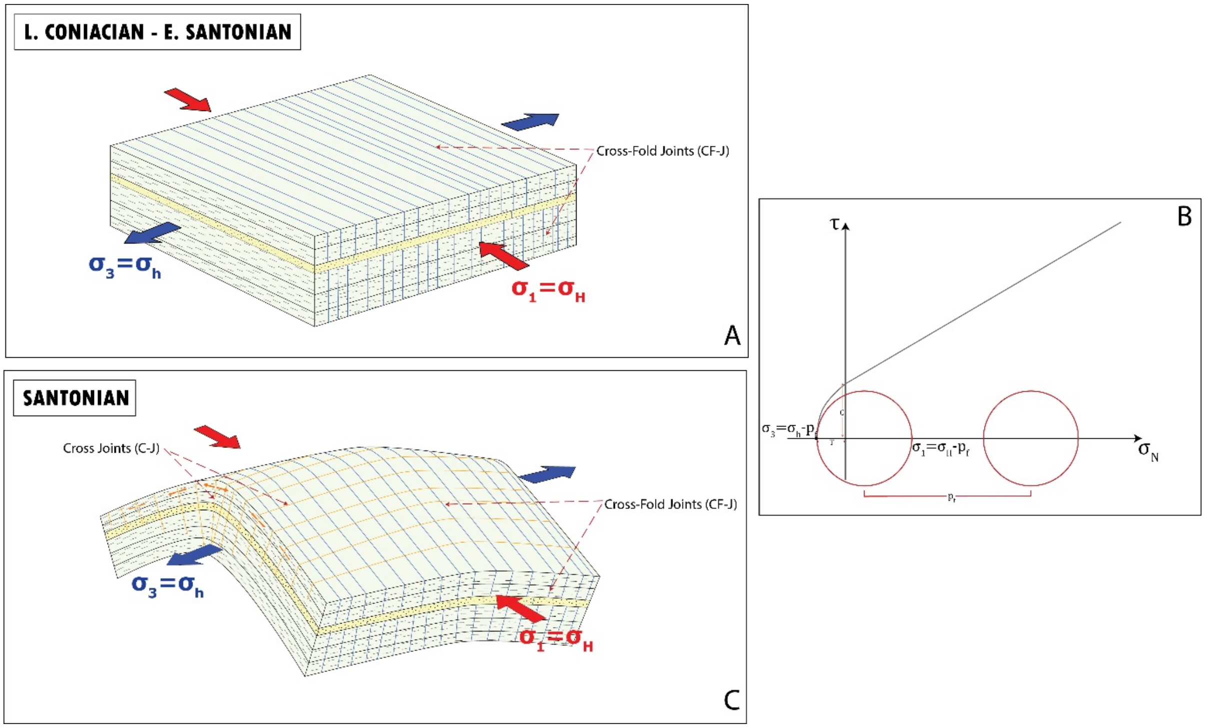


Figure 8. A. fracture initiation model showing Cross-Fold joints formed in the L.Coniacian-E.Santonian intial compression. B. Mohr Circle interpretation showing how elevated pore pressures lead to failure at low effective stresses. C. Santonian initiation model showing the formation of the Longitudinal Joint System

The spread of orientation (dip and strike) the main joint system points to a small difference between the horizontal principal stresses σ_H and σ_h [8]. The overpressure conditions also affected the thin sandstone interbeds leading to their fluidization and injection into some of the fractures as dykes, as well slumping and buckling.

Continued compression and increasing differential stresses during the main phase of the Santonian Inversion, led to the folding of shales with axes oriented in the NE-SW direction and the formation of a weak cleavage. This folding is related to the Longitudinal Joint system which is roughly orthogonal to the Cross-Fold Joint System and is parallel to the fold axes (Fig.8C). They may be the result of tensional effective stresses generated as a result of the outer arc folding of the layers taking advantage of the weakness of the cleavage planes.

5. Conclusion

Orientation distribution analysis on the joints in the shale units of the late Cenomanian to Turonian Eze-Aku Formation shows two systems: a major Cross-Fold and a minor Longitudinal Joint system. Their strong preferred orientation revealed by orientation distribution statistics point to the influence of regional remote stresses, specifically compressive, from the Coniacian to the Santonian Stage. Overpressure due to disequilibrium compaction and tectonic compression led to the initiation of fracturing in the shale units as well as fluidization and buckling in the interbedded sandstone units. Further compression during the Santonian basin inversion episode led to folding and the creation of a weak cleavage in addition to further fracturing.

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