Earth Science Research; Vol. 12, No. 1; 2023
ISSN 1927-0542 E-ISSN 1927-0550
Published by Canadian Center of Science and Education

Analysis of Joints Patterns in Albian to Santonian Strata on the Eastern Flank of the Abakaliki Anticlinorium: Implications on Paleostress Conditions and Fluid Flow Properties in an Unconventional Petroleum System

Ikenna Anthony Okonkwo[1] & Ogbonnaya James Igwe[2]

[1] Department of Geology, University of Nigeria, Nsukka, Nigeria

[2] Department of Geology, University of Nigeria, Nigeria

Correspondence: Ikenna Anthony Okonkwo, Department of Geology, University of Nigeria, Nsukka, Nigeria. Tel: 234-703-655-2097. E-mail: Ikenna.okonkwo@unn.edu.ng

Received: June 8, 2023 Accepted: June 23, 2022 Online Published: June 28, 2022

doi:10.5539/esr.v12n1p31 URL: https://doi.org/10.5539/esr.v12n1p31

Abstract

An analysis of joint patterns were carried out on multiple exposures in Albian to Turonian strata belonging to the Abakaliki Formation (Asu River Group) and the Eze-Aku Formation (Eze-Aku Group) on the eastern flank of the Abakaliki Anticlinorium of the Southern Benue Trough. The analysis was carried out using FracPaQ a MATLAB based toolbox for quantification of fracture patterns. The tool was used to calculate fracture density, and intensity of the traces; to quantify scaling distributions, and to determine dilation tendencies, slip tendencies, and to quantify connectivity, and fluid flow directions. Analysis show the presence of two major joint systems: 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°), 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. Fracture patterns show intensity and density ranging from 11.2395- 53.3443 m^{-1} and 85.2747- 629.5928 m^{-2} respectively. Joints in the NE-SW show high dilation and low slip tendencies given a NW-SE directed maximum principal horizontal stress σ_H stress field. The units of the Abakaliki Formation show better connectivity and lower permeability anisotropy as both fracture systems are well developed in those units. These joints, having formed in the period leading up to the Santonian inversion would have been ideal conduits for migration and flow of hydrocarbon and mineral fluids. 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 Albian- Turonian strata 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.

Keywords: Joints, Albian, Santonian, FracPaQ

1. Introduction

Fractures, planar to sub-planar structures where a body of rock has lost cohesion, are the result of stress exceeding the strength of the rock material in which they form. Extensional fractures planes propagate in an orthogonal direction to the least principal stress (Arlegui & Simón, 2001; Engelder, 1987; Pollard & Aydin, 1988). When several joints (the most common type of extensional fractures) show preferred orientation and distribution on a regional scale, they can be used to determine the orientation of the regional tectonic stress field (Engelder & Delteil, 2004; Engelder & Geiser, 1980; Peacock et al., 2018). In clastic - and especially fine-grained - successions in rapidly subsiding basins joint initiation may be by hydraulic processes as a result of fluid overpressure (Cosgrove, 1995, 2001; Engelder & Oertel, 1985; Osborne & Swarbrick, 1997). Basin analysis studies have, therefore, used data obtained from regional joint sets to understand the subsurface stress conditions at play in the history and evolution of sedimentary basin.

The Benue Trough is a conglomerate of wrench-related pull-apart basins (Benkhelil, 1989; Benkhelil et al., 1989; Binks & Fairhead, 1992; Fairhead et al., 2013; Fairhead & Binks, 1991; M. Guiraud, 1993). Thick deposits of Albian - Coniacian predominantly marine successions have accumulated in the southern part of the basin where rapid subsidence and a worldwide eustatic sea-level high stand played an important part (Kogbe, 1989; Nwajide, 2013; Ojoh, 1992; Petters, 1978). Previous studies of the evolution of the Benue Trough have placed emphasis 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 (Benkhelil, 1989; M. Guiraud, 1993; R. Guiraud & Bosworth, 1997). The intensely fractured nature of the Cenomanian-Coniacian shales in the basin is related to this tectonic development (Igwe & Okonkwo, 2016; Okonkwo et al., 2016).

The Nigeria Government has always understood the need for a solid mineral and energy resource base as a foundation for accelerated industrialization and national development. To this end, it has made the discovery and development of new and diverse mineral and energy resources a priority for the next decade. There is, as a result, renewed interest in the hydrocarbon potential of the inland sedimentary basins of Nigeria as the Federal Government seeks to add to the current 37 billion barrels of proven reserves. The Benue Trough is of particular interest as it has established source and reservoir units. The possibility of exploiting unconventional shale oil by creating artificial hydraulic fracturing (fracking) or by exploiting natural hydraulic fractures has made the thick organic-rich marine shales of the Southern Benue Trough a veritable prospect for hydrocarbon exploration. These fractures are also known conduits for mineralizing fluids which form Lead, Zinc, and Baryte deposits. Understanding the fractures in the Southern Benue is a vital step in the process of taking advantage of the potential of these units.

This paper presents an analysis of patterns of intensely fractured shales in parts of the Southern Benue Trough. A Matlab™ based software tool was used to analyse joint patterns in rock units. Parameters like density and intensity are determined. The orientation distribution of the pattern and the scaling of the lengths were used to quantify the effect on rock permeability and strength.

2. Geologic Setting

2.1 Tectonic Setting

The study area lies within the southern part of the Benue Trough, a NE-SW trending continental megastructure stretching 1000Km from southern to north-eastern Nigeria. The Benue Trough is a collection of sub-basins separated by axial basement highs. These structures are controlled by predominantly transcurrent motions along major basement shear zones of Pan-African age (Benkhelil, 1989; Benkhelil et al., 1989). These shear zones were reactivated in the Early Cretaceous Period during a period of extensive rifting and basin development on the African Plate preceding the opening of the Equatorial Atlantic Ocean (Fairhead & Binks, 1991; R. Guiraud et al., 1992). These shear zones were also the predecessors of major equatorial Atlantic transform faults: the Chain and Charcot Fracture Zones which currently extend (beneath the Niger Delta) into the trough axis (Basile et al., 2005; Benkhelil et al., 1995; Ofoegbu & Mohan, 1990). The Benue Trough is divided into Northern, Central and Southern geographical segments with distinct but related stratigraphic and structural elements. 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)**.

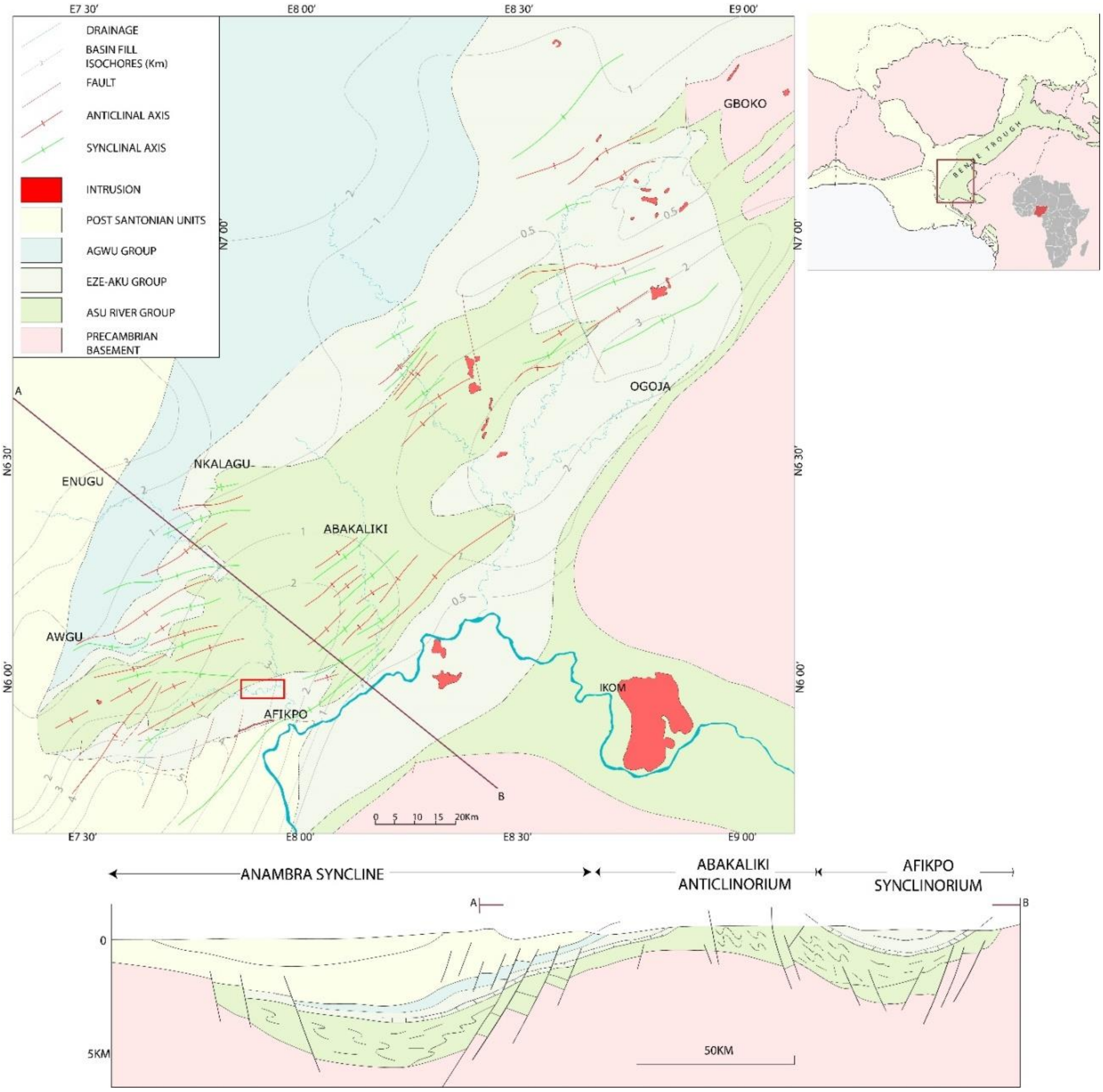

Figure 1. Structural Map and Cross-section of the Southern Benue Trough showing basin-fill thickness isochores revealed by Geophysics

The study area is a part of the Afikpo Synclinorium on the eastern flank of the Abakaliki Anticlinorium: 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 unconformably 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 (Nwajide, 2013; Nwajide & Reijers, 1996; Obi & Okogbue, 2004; Princeton Dim et al., 2020).

2.2 Stratigraphy

The Southern Benue Trough predominantly consists of clastic shallow marine deposits within a basin morphology consisting of a major northeast-southwest trough flanked by broad eastern and western shelves (Murat, 1972; Ojoh, 1992). The summarized stratigraphy for various portions of the basin is shown in Figure 2.

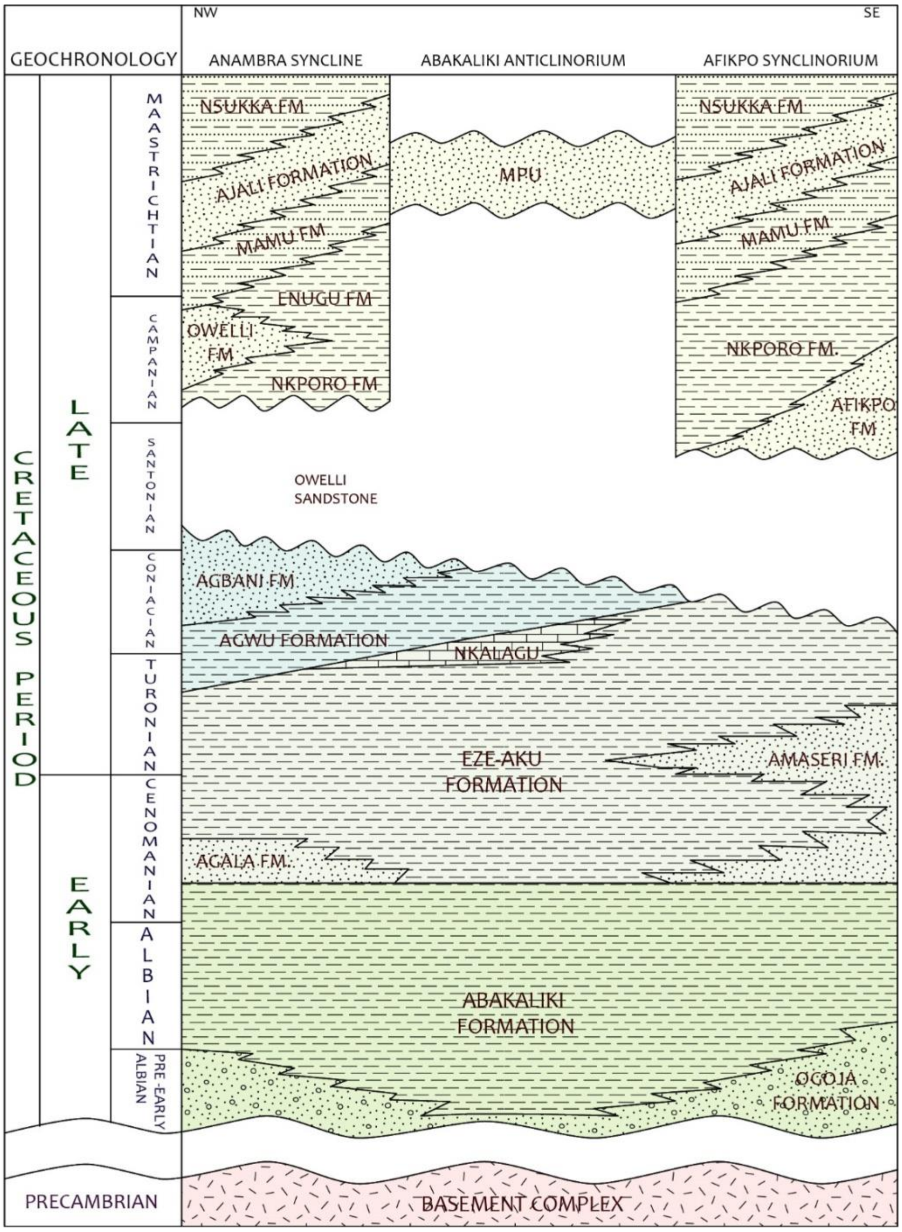

Figure 2. Stratigraphic Summary of the Southern Benue Basin Fill and the Anambra Basin (after Ojoh (1992), Nwajide (2013))

Continental alluvial fanglomerates sit on the Precambrian basement and are exposed at Ogoja (the Ogoja Formation) on the flanks of the Benue Trough. These synrift units, deposited from late Jurassic till the Aptian, form the basal units of the Southern Benue Trough (Nwajide, 2013; Tijani et al., 1996).

The units belonging to the Asu River Group were laid down during the first marine transgression into the basin. North of the study area, the Asu River Group is represented by shales, siltstones, and fine-grained sandstone interbeds with extensive soft-sediment deformation belonging to the Abakaliki Formation. The Late Cenomanian - Turonian Eze-Aku Group is the major stratigraphic unit in the study area. It consists of well-bedded fissile dark grey shales and marls with imprints of the *Innoceramus sp,* and rare bioclastic limestone occurrences belonging to the Eze-Aku Shale Formation, and highly indurated, bioturbated and subtidal to tidal storm dominated sequences Amaseri Sandstone Formation. The units of the Amaseri Formation forms asymmetrical ridges between the Eze-Aku shales (Banerjee, 1980; Nwajide, 2013) (**Fig. 3**). These Eze-Aku Group was laid down during a period of maximum subsidence of the Benue Trough and a period of a worldwide eustatic high stand.

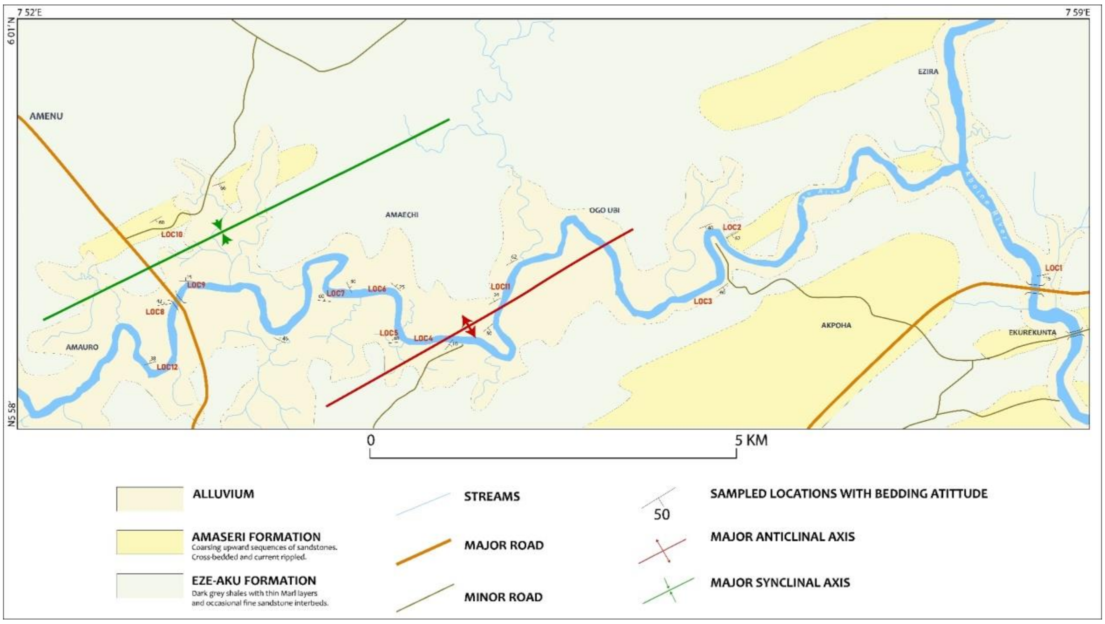

Figure 3. Geologic Map of the Study Area.

The Santonian Stage was one of basin inversion and folding accompanied by magmatism in the Benue Trough. It led to a shift in depositon from the now emergent Southern Benue Trough to its south-eastern and western flank (Benkhelil, 1986; Hossain, 1981; Obiora & Umeji, 2005). In the study area, the pre-Santonian units are a part folded synclinorium structure plunging towards the south where it is unconformably overlain by Campanian to Maastrichtian paralic to marine units of the Afikpo and Nkporo Formations, the Ajali, Mamu, and Nsukka Formations (Dim et al., 2018; Nwajide & Reijers, 1996; Obi & Okogbue, 2004; Oboh-Ikuenobe et al., 2005).

3. Methodology

Fracture pattern analysis was carried out using FracPaQ, a tool developed by Healy et al (2017). FracPaQ is a MATLAB™ based open-source, cross-platform, freely available toolbox for the quantification of fracture patterns from two-dimensional images. The application is available at the GitHub (http://davehealyaberdeen.github.io/FracPaQ/) or MathWorks FileExchange repository and is run on MATLAB™.

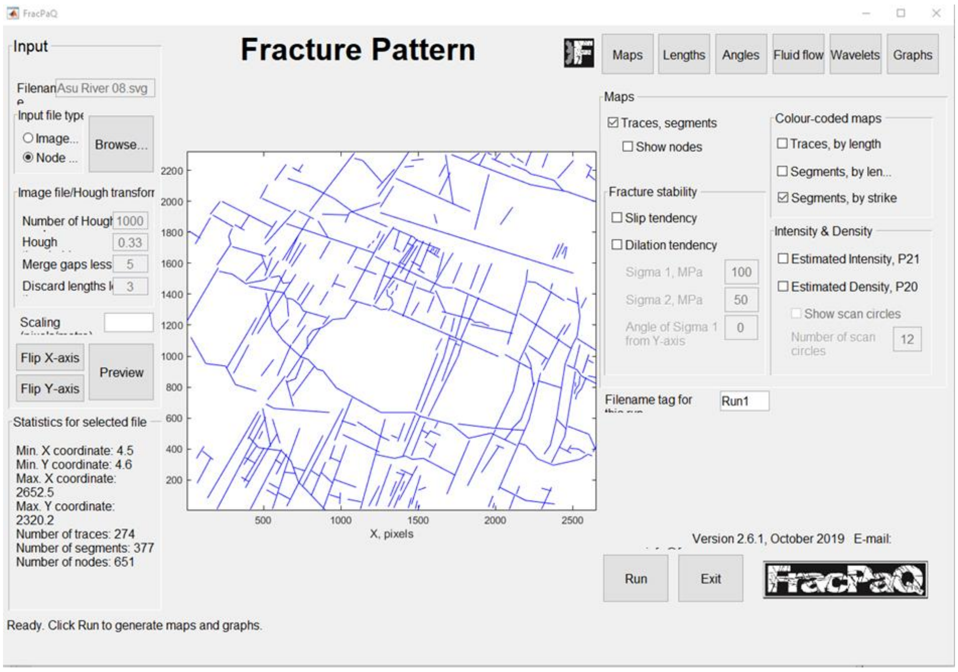

Figure 4.The FracPaQ user interface.

The input is either a 2 dimensional raster image (*.JPG/.JPEG or *.TIF/.TIFF image file) of fractures, or vector files of digitized fracture traces in Adobe Illustrator or Corel Draw (*.SVG file), or an ASCII tab-delimited text file of (x,y) coordinates that mark the nodes of each fracture trace (*.TXT file). The outputs from the toolbox include quantitative estimates for the attributes of individual fractures (e.g., their lengths and orientations) and the attributes of the whole pattern (e.g., intensity, density, connectivity, permeability) (**Fig. 4**).

FracPaQ uses the circular scan window method of Mauldon et al. (2001) to calculate an estimate of fracture intensity (m^{-1}) and density (m^{-2}). Estimated fracture intensity is *n/4r*, where n is the number of fractures intersecting the perimeter of a circle of radius r, and fracture density as $m/2\pi r^2$ where m is the number of fractures terminating within a circle of radius r.

Maximum Likelihood Estimators (MLE) Analysis estimators compare the scaling of the traces to expected distribution for Power Law, Log-Normal, and Exponential Distribution to understand scaling (Rizzo et al., 2017).

The Morris et al. (1996) method is used to calculate for the 2D stress field specified by σ^1, $\sigma^{2,}$ and θ (angle in degrees of σ1 from North = Y-axis). Measure of the tendency towards slip (T_s) and/or dilation (T_d) can be given based on the relationship of the fracture orientation to the 2D stress field. They are plotted as traces and rose diagrams coloured by T_s or T_d (Figure 18). Fractures that are closer to 45 ° of the maximum principal stress directions σ^1 (σ^H) are likely to be reactivated by slip. Fractures parallel to the σ^1 (σ^H) are likely to be dilated as a result of the compressive stress making them better conduits for fluid flow.

Sanderson and Nixon's (2015) scheme is used to characterize a fracture network in terms of its connectivity, by counting the number of nodes (|N|) of each type - |I|, |Y| and |X|. Where |N| = |I| + |Y| + |X|

Where:

The nodes |N| represent the tips and intersections of fractures

I-nodes at the isolated tips of fractures.

Y-nodes where one fracture meets or abuts against another: and

X-nodes where two fractures crosscut one another.

An I-Y-X connectivity map and a ternary plot of segment connectivity can be generated, showing the location of the relative proportions of isolated (I), splay or abutment (Y), and intersection (X) nodes in the fracture network. Better connected fractures plot at the bottom of the plot (Manzocchi, 2002).

Permeability ellipses show relative 2D permeability anisotropy in flow and gradient direction. The greater the ellipticity of the permeability tensor, the greater the anisotropy whether for flow or gradient.

4. Results

Field observations and measurements of orientation show that 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.

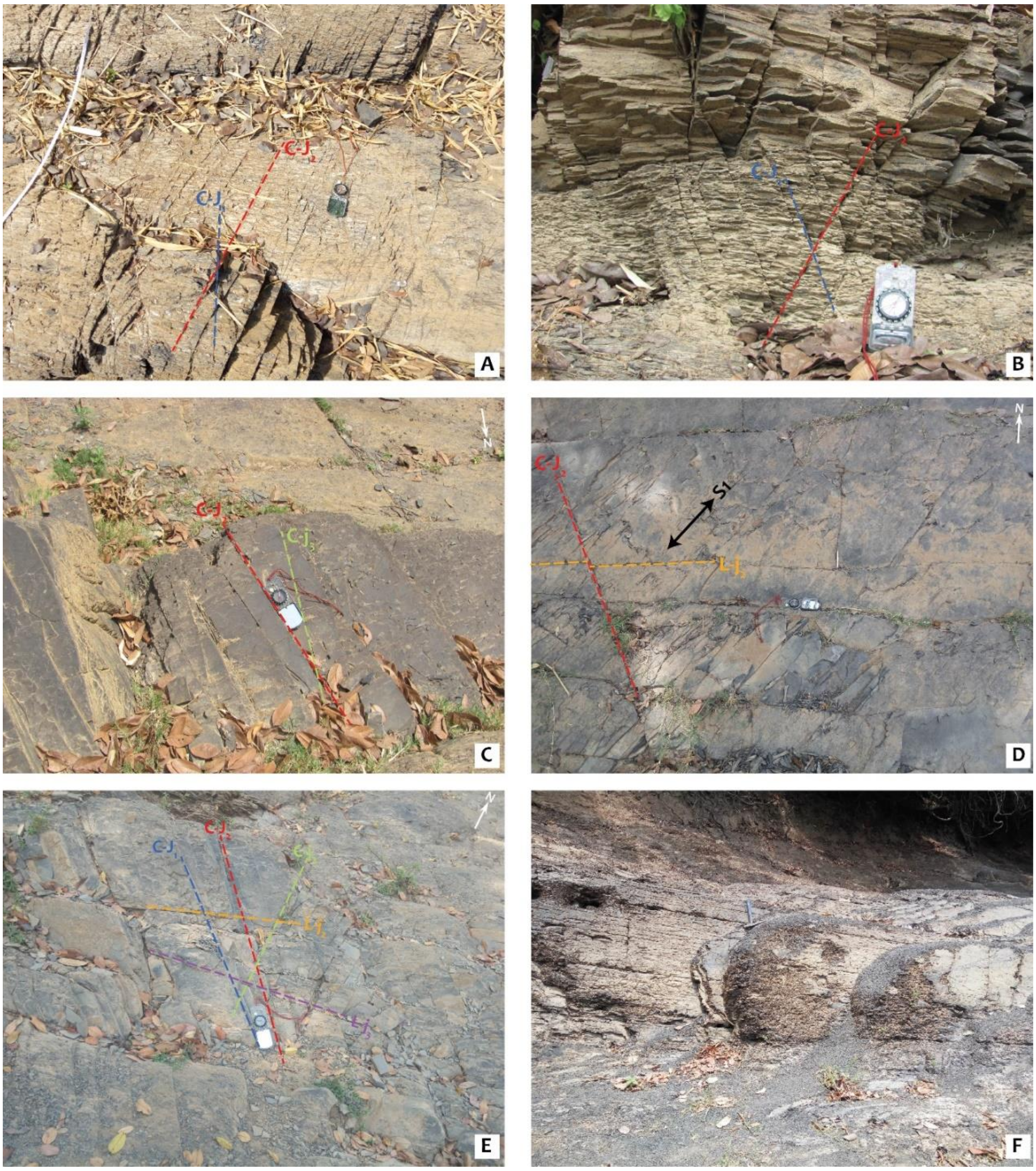

Figure 1. A. Shale units showing Major Cross-Fold System joint sets. B. Dip section of shales showing x-intersections of C-J1 and C-J2 sets. C. C-J1 and minor C-J3 sets D. Section showing Cross Fold System Joints intersected by Longitudinal System joints. Note that L-J2 terminates at C-J1. E. Section showing the major Cross-Fold and Longitudinal Systems and their field relationships. F. Joint surface exposures lacking ornamentation

There are 2 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.5A, 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 5D&E)**. This system is roughly parallel to the major fold axes in the study area.

Pattern analysis was carried out from exposures taken at nine (9) different locations (Figure 31). Joints traces were digitized and saved as *.SVG format before input into FracPaQ. Scaling factors and north correction were applied to make the images representative. The results of the analysis are shown in Figure 6 and Figure 7 and summarized in Table 1.

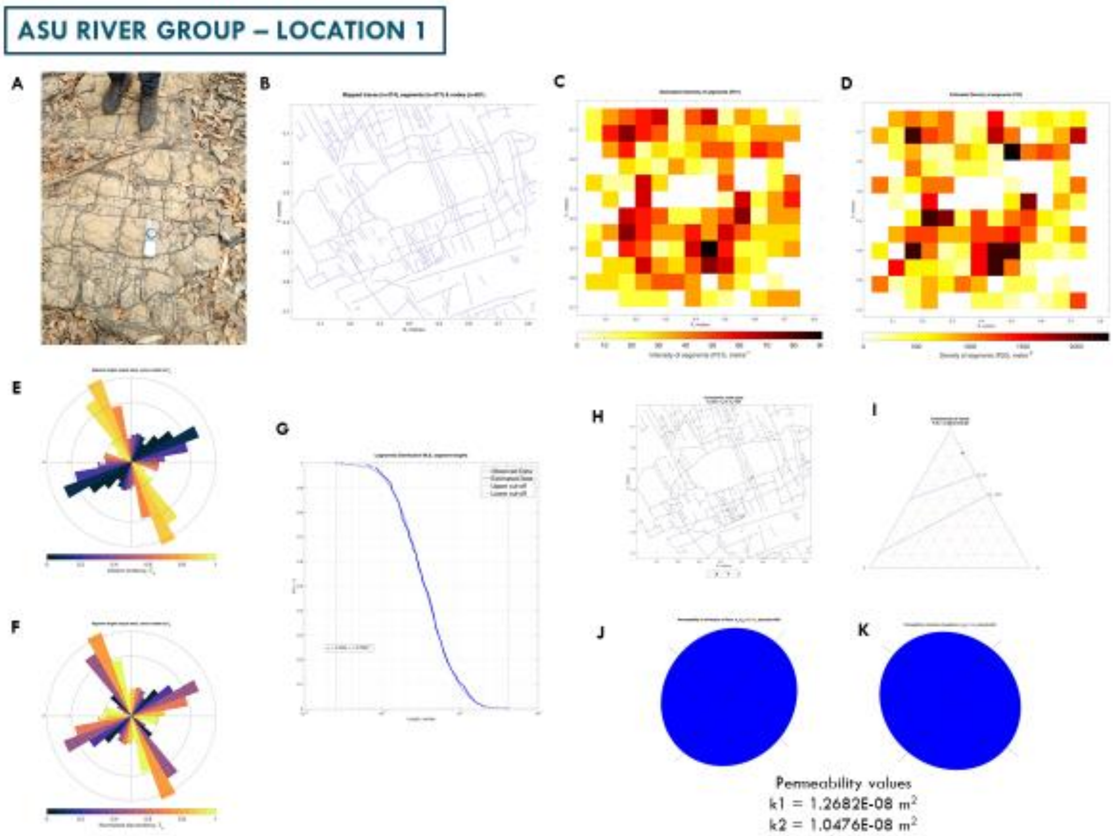

Figure 6. Summarized results for Asu River Group

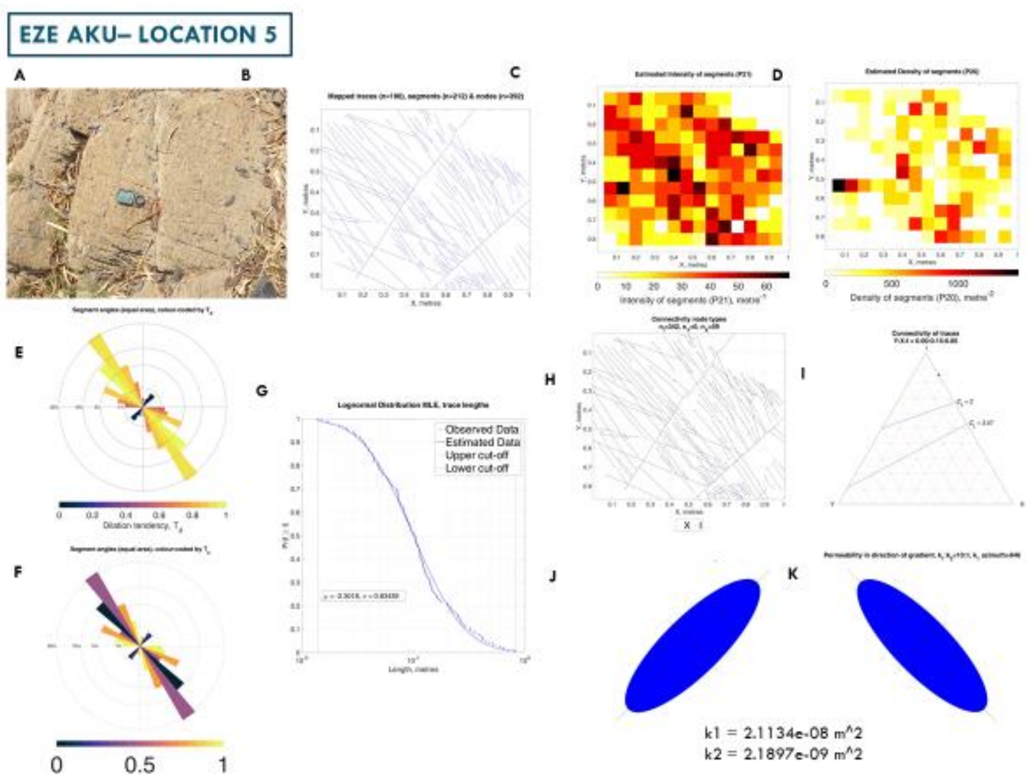

Figure 7. Summarized results for Eze-Aku Group

ISSN 1927-0542 E-ISSN 1927-0550
Published by Canadian Center of Science and Education

Table 1. Summary of joint quantification parameters obtain from FracPaQ

		Fm	Trace	Segments	M.Azimuth	MLE % Trace			MLE % Segment			Intensity	Density	Permeability			
	LOC					Log	Exp	PL	Log	Exp	PL			k1	k2	k1 Azimuth	k1/k2
1	Okposi	AR	274	377	155.30	98.12	10.76	0	99.12	0	0	30.2502	629.5928	1.27E-08	1.05E-08	39.56	1.21
2	Akpoha	EZ	526	672	34.22	92.48	2.88	0	93.56	0.04	0	19.6588	260.9479	1.22E-08	2.08E-09	138.26	5.87
3	Amenu	EZ	127	153	60.28	76.84	55.52	2.12	82.84	13.24	0	15.1236	125.5511	1.16E-08	4.68E-09	105.00	2.48
4	Ogo-Obi #1	EZ	259	309	91.59	98.92	10.44	0	99.72	51.68	0	11.2395	85.2747	8.70E-09	1.52E-09	101.44	5.71
5	Ogo-Obi #2	EZ	180	212	138.89	97.68	30.64	0	98	37.2	0	29.503	242.8582	2.11E-08	2.19E-09	45.63	9.65
6	Ogo-Obi #3	EZ	148	150	139.56	99.64	77.4	0	99.64	85.16	0	12.2109	72.5005	4.89E-09	2.92E-09	21.36	1.67
7	Amauro	EZ	102	109	112.36	95.2	93.24	17.92	86.2	79.72	33.88	19.1138	175.7596	1.49E-08	2.98E-09	225.34	4.99
8	Ameni	AR	85	180	42.10	98.84	21.16	0	99.56	20.32	0	21.8055	402.6837	1.56E-08	5.67E-09	108.20	2.74
9	Ameri	AR	33	355	35.44	97.44	16.56	54.4	81.52	0	0	53.3443	2107.728	3.54E-09	2.20E-08	167.25	0.16

Analysis of the joint patterns shows intensity and density values ranging from 11.2395- 53.3443 m^{-1} and 85.2747- 629.5928 m^{-2} respectively. The Abakaliki Formation units have a lower joint density and intensity on average than the Eze-Aku Formation units. This is due to the greater spacing of the fractures related to a difference in rock type (fine-grained sandstone - siltstone) compared to Eze-Aku Formation (shale). Both Units have poor fracture connectivity plotting in the top half of the ternary diagram. Units of the Abakaliki Formation have better connectivity than the Eze-Aku Formation as they have 2 very well-developed joint sets intersecting at right angles to each other (The CF-J and L-J joint sets).

Joints in the Eze-Aku Formation are therefore expected to have lower secondary permeability and greater permeability anisotropy. This is shown by the shapes of the permeability ellipses.

The NE-SW joint sets have very high dilation tendencies and low slip tendencies in the given σ_H direction. this means that the joints were unlikely to be reactivated via shear given the paleostress field. High dilation tendencies especially for fractures of the earlier CF-J set of joints would have been dilated by the Santonian compressive event and could have aided the movement of mineralizing fluids and the migration of generated hydrocarbons.

5. Discussion

Orientation data from the joint found in the Albian to Santonian strata of the Southern Benue Trough can be used to model the trajectory of the regional maximum horizontal stress field acting in the basin within that period. It should run roughly parallel to the orientation of the major joint sets. A σ_H-trajectory map made based on the mean orientation of the Cross Fold Joint System (CF-J) shows a stress field that deflects slightly northwards from the southern part to the northern part of the study area (**Fig 8**). The σ_H direction is consistent with a paleostress field that leads to folding with axes in the NE-SW direction observed in the Abakaliki Anticlinorium.

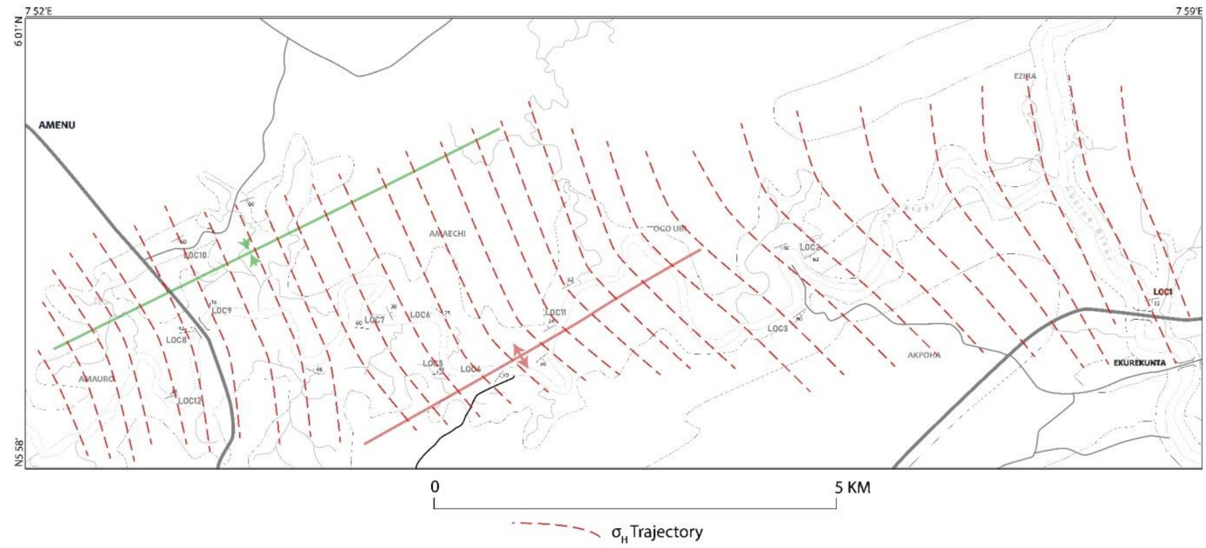

Figure 8. Geologic Outline Map of the study area showing estimated σ_H trajectories determined from mean joint orientations

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 (1997) 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, the evidence points to the presence of overpressure due to disequilibrium compaction in the presence of a compressive regional tectonic stress field. Their pervasiveness in the finer-grained (shales and siltstone) units as well as their morphology are evidence to the joints in the study area being hydraulic. According to Ojoh ((1992) the Southern Benue Trough accumulated up to 3600m of sediment from the Albian to the Santonian with a period of very rapid subsidence beginning from the late Cenomanian, peaking in the Turonian and continuing into the Coniacian. This represents the late rift and thermal sag period in the evolution of the Basin. Burial of mostly fine-grained clastics (shales, siltstones, and fine-grained sandstones) under such rapid conditions lead to subsurface conditions of overpressure conducive for the initiation of natural hydraulic fractures. The overpressure conditions coupled with possible basin instability especially around still active faults lead to fluidization and extensive soft-sediment deformation seen in the Abakaliki Formation.

6. Conclusion

Analysis of joint patterns were carried out on multiple exposures in Albian to Turonian strata belonging eastern flank of the Abakaliki Anticlinorium of the Southern Benue Trough using FracPaQ a MATLAB based toolbox for quantification of fracture patterns. Fracture density, and intensity of the traces were determined. Scaling distributions, dilation tendencies, slip tendencies, connectivity, and fluid flow directions were quantified.

The joints in the study area belong to a major Cross-Fold Joint (CF-J) system -orthogonal to the regional fold axes and a subordinate Longitudinal Joint System (L-J) -subparallel to the fold axes. Intensity and density values ranging from 11.2395- 53.3443 m^{-1} and 85.2747- 629.5928 m^{-2} respectively were calculated from exposures from the Asu River and Eze-Aku Groups. Joints in the NE-SW show high dilation and low slip tendencies given a NW-SE directed maximum principal horizontal stress σ_H stress field. The units of the Abakaliki Formation show better connectivity and lower permeability anisotropy as both fracture systems are well developed in those units.

The joints were formed as a result of overpressured subsurface conditions in a regional stress field that led to the folding and inversion of basin units in the Santonian.

References

Arlegui, L., & Simón, J. L. (2001). Geometry and distribution of regional joint sets in a non-homogeneous stress field: Case study in the Ebro basin (Spain). *Journal of Structural Geology, 23*(2-3), 297-313. https://doi.org/10.1016/S0191-8141(00)00097-3

Banerjee, I. (1980). A subtidal bar model for the eze-aku sandstones, Nigeria. *Sedimentary Geology, 25*(4), 291-309. https://doi.org/10.1016/0037-0738(80)90066-4

Basile, C., Mascle, J., & Guiraud, R. (2005). Phanerozoic geological evolution of the Equatorial Atlantic domain. *Journal of African Earth Sciences, 43*(1-3), 275-282. https://doi.org/10.1016/j.jafrearsci.2005.07.011

Benkhelil, J. (1986). Structure and Geodynamic evolution of the Intracontinental Benue trough (Nigeria). *Elf Nig. Ltd., Nigeria. Bull. Centres Rech. Explor. Prod. Elf-Aquitaine (BCREDP), 12,* 29-128.

Benkhelil, J. (1989). The origin and evolution of the Cretaceous Benue Trough (Nigeria). *Journal of African Earth Sciences (and the Middle East), 8*(2-4), 251-282. https://doi.org/10.1016/S0899-5362(89)80028-4

Benkhelil, J., Guiraud, M., Ponsard, J. F., & Saugy, L. (1989). The Bornu-Benue Trough, the Niger Delta and its offshore: Tectono-sedimentary reconstruction during the Cretaceous and Tertiary from geophysical data and geology. In *Geology of Nigeria. 2nd edn. Rock view Ltd Jos, Nigeria*.

Benkhelil, J., Mascle, J., & Tricart, P. (1995). The Guinea continental margin: An example of a structurally complex transform margin. *Tectonophysics, 248*(1-2), 117-137. https://doi.org/10.1016/0040-1951(94)00246-6

Binks, R. M., & Fairhead, J. D. (1992). A plate tectonic setting for Mesozoic rifts of West and Central Africa. *Tectonophysics, 213*(1-2), 141-151. https://doi.org/10.1016/0040-1951(92)90255-5

Cosgrove, J. W. (1995). The expression of hydraulic fracturing in rocks and sediments. *Geological Society, London, Special Publications, 92*(1), 187-196. https://doi.org/10.1144/GSL.SP.1995.092.01.10

Cosgrove, J. W. (2001). Hydraulic fracturing during the formation and deformation of a basin: A factor in the dewatering of low-permeability sediments. *AAPG Bulletin, 85*(4), 737-748. https://doi.org/10.1306/8626C997-173B-11D7-8645000102C1865D

Dim, C. I., Onuoha, K. M., Anyiam, O. A., Okwara, I. C., Oha, I. A., … Ozumba, B. M. (2018). Analysis of Petroleum System for Exploration and Risk Reduction in the Southeastern Inland Basins of Nigeria. *Petroleum & Coal, 60*(2).

Engelder, T. (1987). *Joints and shear fractures in rock*. In Fracture Mechanics of Rock. Academic Press, London. pp. 27-69. https://doi.org/10.1016/B978-0-12-066266-1.50007-7

Engelder, T., & Delteil, J. (2004). The orientation distribution of single joint sets. *Geological Society, London, Special Publications, 231*(1), 285-297. https://doi.org/10.1144/GSL.SP.2004.231.01.17

Engelder, T., & Geiser, P. (1980). On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian Plateau, New York. *Journal of Geophysical Research, 85*(B11), 6319. https://doi.org/10.1029/JB085iB11p06319

Engelder, T., & Oertel, G. (1985). Correlation between abnormal pore pressure and tectonic jointing in the Devonian Catskill Delta. *Geology, 13*(12), 863-866. https://doi.org/10.1130/0091-7613(1985)13<863:CBAPPA>2.0.CO;2

Fairhead, J. D., & Binks, R. M. (1991). Differential opening of the Central and South Atlantic Oceans and the opening of the West African rift system. *Tectonophysics, 187*(1-3), 191-203. https://doi.org/10.1016/0040-1951(91)90419-S

Fairhead, J. D., Green, C. M., Masterton, S. M., & Guiraud, R. (2013). The role that plate tectonics, inferred stress changes and stratigraphic unconformities have on the evolution of the West and Central African Rift System and the Atlantic continental margins. *Tectonophysics, 594*, 118-127. https://doi.org/10.1016/j.tecto.2013.03.021

Guiraud, M. (1993). Late Jurassic rifting-early Cretaceous rifting and late Cretaceous transpressional inversion in the upper Benue basin (NE Nigeria). *Bulletin Des Centres de Recherches Exploration-Production Elf Aquitaine, 17*(2), 371-383.

Guiraud, R., Binks, R. M., Fairhead, J. D., & Wilson, M. (1992). Chronology and geodynamic setting of Cretaceous-Cenozoic rifting in West and Central Africa. *Tectonophysics, 213*(1), 227-234. https://doi.org/10.1016/0040-1951(92)90260-D

Guiraud, R., & Bosworth, W. (1997). Senonian basin inversion and rejuvenation of rifting in Africa and Arabia:

Synthesis and implications to plate-scale tectonics. *Tectonophysics, 282*(1-4), 39-82. https://doi.org/10.1016/S0040-1951(97)00212-6

Healy, D., Rizzo, R. E., Cornwell, D. G., Farrell, N. J. C., Watkins, H., Timms, N. E., Gomez-Rivas, E., & Smith, M. (2017). FracPaQ: A MATLAB™ toolbox for the quantification of fracture patterns. *Journal of Structural Geology, 95*, 1-16. https://doi.org/10.1016/j.jsg.2016.12.003

Hossain, M. T. (1981). Geochemistry and petrology of the minor intrusives between Efut Eso and Nko in the Ugep area of Cross River State, Nigeria. *Journal of Mining and Geology, 18*(1), 42-51.

Igwe, O., & Okonkwo, I. A. (2016). Application of paleostress analysis for the identification of potential instability precursors within the Benue Trough Nigeria. *Geoenvironmental Disasters, 3*(1), 17. https://doi.org/10.1186/s40677-016-0051-z

Kogbe, C. A. (1989). *Paleogeographic history of Nigeria from Albian times*. In Geology of Nigeria. Elizabethan Publishers, Lagos. pp. 237-252.

Manzocchi, T. (2002). The connectivity of two-dimensional networks of spatially correlated fractures. *Water Resources Research, 38*(9), 1-1-1-20. https://doi.org/10.1029/2000WR000180

Mauldon, M., Dunne, W. M., & Rohrbaugh, M. B. (2001). Circular scanlines and circular windows: New tools for characterizing the geometry of fracture traces. *Journal of Structural Geology, 23*(2), 247-258. https://doi.org/10.1016/S0191-8141(00)00094-8

Morris, A., Ferrill, D. A., & Henderson, D. B. (1996). Slip-tendency analysis and fault reactivation. *Geology, 24*(3), 275-278. https://doi.org/10.1130/0091-7613(1996)024<0275:STAAFR>2.3.CO;2

Murat, R. C. (1972). *Stratigraphy and paleogeography of the Cretaceous and lower Tertiary in Southern Nigeria.* Proc. of the Conf. on African Geology Held at Ibadan, Nigeria. pp. 251-266.

Nwajide, C. S. (2013). *Geology of Nigeria's Sedimentary Basins*. CSS Press.

Nwajide, C. S., & Reijers, T. J. A. (1996). *Geology of the southern Anambra Basin.* In Selected chapters on Geology, SPDC, Warri. pp. 133-148.

Obi, G. C., & Okogbue, C. O. (2004). Sedimentary response to tectonism in the Campanian-Maastrichtian succession, Anambra Basin, Southeastern Nigeria. *Journal of African Earth Sciences, 38*(1), 99-108. https://doi.org/10.1016/j.jafrearsci.2003.05.001

Obiora, S. C., & Umeji, A. C. (2005). Petrography of some altered intrusive rocks from the Lower Benue Trough, Nigeria. *Journal of Mining and Geology, 41*(1), 1-9. https://doi.org/10.4314/jmg.v41i1.18824

Oboh-Ikuenobe, F. E., Obi, C. G., & Jaramillo, C. A. (2005). Lithofacies, palynofacies, and sequence stratigraphy of Palaeogene strata in Southeastern Nigeria. *Journal of African Earth Sciences, 41*(1-2), 79-101. https://doi.org/10.1016/j.jafrearsci.2005.02.002

Ofoegbu, C. O., & Mohan, N. L. (1990). Interpretation of aeromagnetic anomalies over part of Southeastern Nigeria using three-dimensional Hilbert transformation. *Pure and Applied Geophysics, 134*(1), 13-29. https://doi.org/10.1007/BF00878077

Ojoh, K. A. (1992). The southern part of the Benue Trough (Nigeria) Cretaceous stratigraphy, basin analysis, paleogeography, and geodynamic evolution in the equatorial domain of the South Atlantic. *NAPE Bull, 7*(2), 131-152.

Okonkwo, I. A., Onuoha, K. M., & Igwe, O. (2016). *Paleostress Analysis of the Upper Cretaceous Afikpo Synclinorium, South-Eastern Nigeria*. In Advances in Petroleum Geoscience Research in Nigeria. Utopia Publishers.

Osborne, M. J., & Swarbrick, R. E. (1997). Mechanisms for Generating Overpressure in Sedimentary Basins: A Reevaluation. *AAPG Bulletin, 81*(6), 1023-1041.

Peacock, D. C. P., Sanderson, D. J., & Rotevatn, A. (2018). Relationships between fractures. *Journal of Structural Geology, 106*, 41-53. https://doi.org/10.1016/j.jsg.2017.11.010

Petters, S. W. (1978). Mid-Cretaceous paleoenvironments and biostratigraphy of the Benue Trough, Nigeria. *Geological Society of America Bulletin, 89*(1), 151-154. https://doi.org/10.1130/0016-7606(1978)89<151:MPABOT>2.0.CO;2

Pollard, D. D., & Aydin, A. (1988). Progress in understanding jointing over the past century. *Geological Society of America Bulletin, 100*(8), 1181-1204.

https://doi.org/10.1130/0016-7606(1988)100<1181:PIUJOT>2.3.CO;2

Princeton Dim, C. I., Okonkwo, I. A., Anyiam, O. A., Okeugo, C. G., Maduewesi, C. O., Okeke, K. K., & Umeadi, I. M. (2020). Structural, Stratigraphic and Combination Traps on Outcropping Lithostratigraphic Units of the Anambra Basin, Southeast Nigeria. *Petroleum & Coal, 62*(1).

Rizzo, R. E., Healy, D., & De Siena, L. (2017). Benefits of maximum likelihood estimators for fracture attribute analysis: Implications for permeability and up-scaling. *Journal of Structural Geology, 95*, 17-31. https://doi.org/10.1016/j.jsg.2016.12.005

Sanderson, D. J., & Nixon, C. W. (2015). The use of topology in fracture network characterization. *Journal of Structural Geology, 72*, 55-66. https://doi.org/10.1016/j.jsg.2015.01.005

Tijani, M. N., Loehnert, E. P., & Uma, K. O. (1996). Origin of saline groundwaters in the Ogoja area, Lower Benue Trough, Nigeria. *Journal of African Earth Sciences, 23*(2), 237-252. https://doi.org/10.1016/S0899-5362(96)00065-6

Copyrights