



Fracture network characterization applied to mineralization in Lower Benue Trough, Nigeria

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Abstract

Structural characterization of fracture networks integrating field-based geological mapping and geometrical approaches was employed to improve the structural geological knowledge of the study area. A total of 156 fractures/joints were measured and analyzed using OPENSTEREO™ software. Rose diagrams, stereographic nets, and histograms produced display a general structural trend of NW-SE (i.e., with a mean direction of 324°, and an average dip amount of 78° NE). These fracture networks were analyzed geometrically using Matrix Laboratory (MATLAB™)-Fracture Pattern Quantification (FRACPAQ™) software, which provided some insights. Fracture networks were portrayed as maps and graphs with a sequence of branches depicting fracture tracks and intersection indicating their discontinuations and interactions. The results of the estimated intensity-density, slip-dilation tendency, and the fracture interactions (permeability) signify that due to the moderate proportion of X-Y nodes in the study area, it has rendered the area to be of moderate connectivity and prospect. Geological exploration programs for minerals, groundwater, and environmental pollution studies should, therefore, carefully focus on these major fractural trends (i.e., NW-SE and NNW-SSE), because both geologic and geometric analyses have unraveled the potential of these fracture networks as reservoir rocks.

Keywords Fracture networks · Stereographic net · Rose diagram · Geometric analysis

Introduction

Lead-zinc mineralization has drawn the attention of researchers in the study area. The first lead-zinc ore was produced in the mines in 1925, shortly before the Civil War, when systematic mining began (Farrington 1952). Between 1966 and 1970, mining activities were temporarily halted due to the Nigeria Civil War (Umeji 2000). Construction and automotive industries both use lead and zinc extensively (Mohr et al. 2018). They are predominantly used to produce lead-acid batteries with significant demand from the automotive sector and zinc is used for galvanizing steel for

construction industries. Hence, both have important applications within the global economy.

Within the study area, the presence of lead-zinc deposits within sedimentary basins has been linked to saline water intrusion, and mineral deposits have been observed to lie towards a narrow path or slender zone of about 30–50 km broad and extending approximately 560–600 km along the Benue Trough in Ebonyi, Benue, Nasarawa, Plateau, Bauchi, Taraba, and Adamawa states (Bamalli et al. 2011) (Fig. 1). Mineralization occurs as a result of hydrothermal and epigenetic processes that take place under mesothermal conditions (Olade and Ma 1976). The occurrence of the mineral deposit was limited to the Asu River Group of the Albian age, and the hydrothermal fluids (i.e., mineralized solutions) are related to recent volcanism of Santonian Age. Thus, fractures serve as permeable zones where minerals are localized.

Enyigba's lead-zinc lodes can be found throughout the district, including the Enyigba, Ameri, and Ameka communities (Onyeobi and Imeokparia 2014). Structural features, such as folds, faults, fractures, and other deformational structures (veins, sills, and stylolite) in the lithosphere, are known to control and affect the occurrence of economic

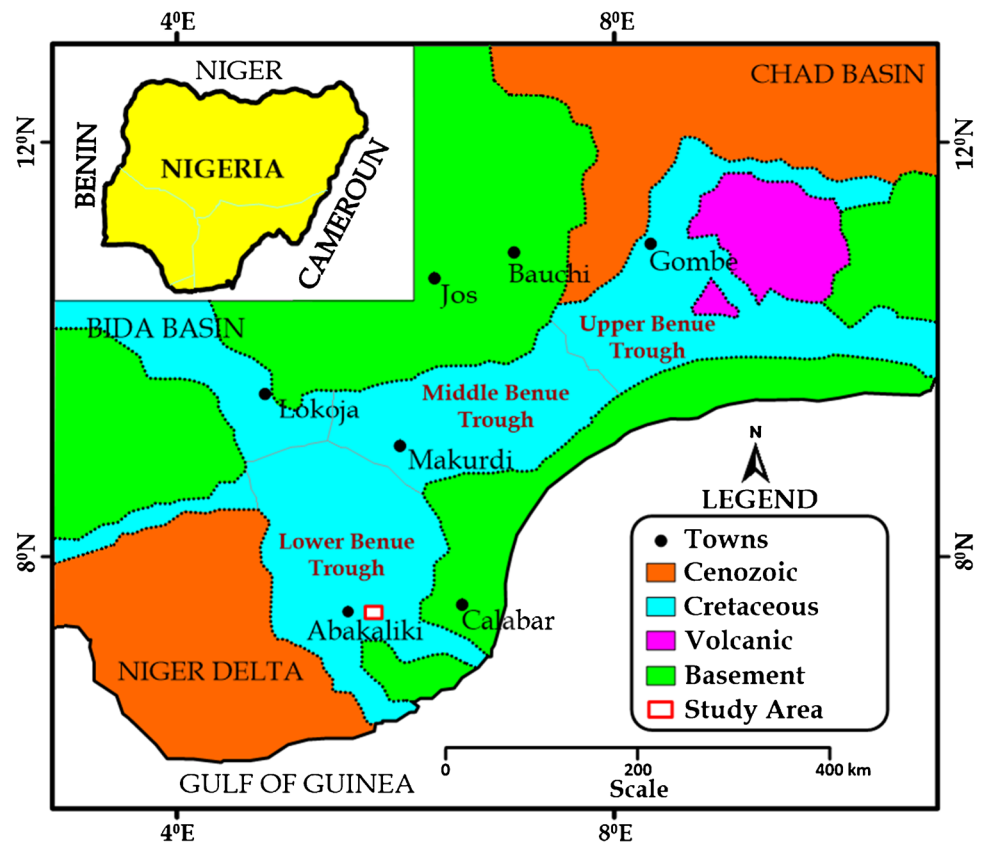
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Fig. 1 An outline of Nigeria's geology showing the Benue Trough. Insert is the study area (modified after Benkhelil 1989)



mineral deposits. Knowledge of these structural features is important in understanding the genesis of economic mineral deposits in a sedimentary basin and the information revealed by these structures in rocks is captivating and interesting which can also be useful to the society (Fossen 2016). An understanding of these features is also vital in determining the means of mapping, exploitation, and the possible environmental impact associated with exploitation.

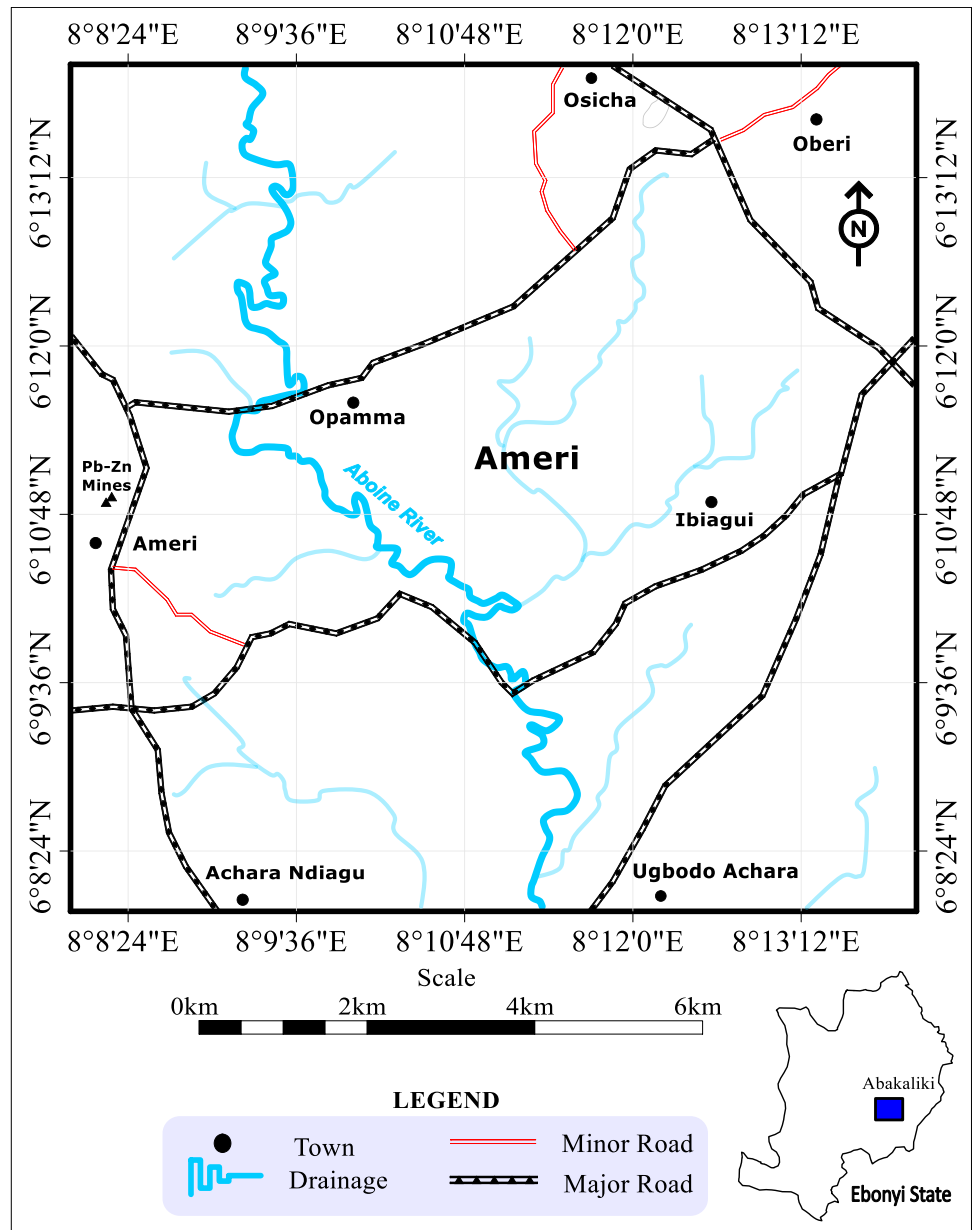
The relative displacement along a fracture plane is of extreme importance in understanding the geometry of deformed rocks produced by stress. Hence, the geometry of a fracture is known by its orientation, relative displacements, and distributions of interacting fractures. In general, structural geologic investigations begin with geological descriptions mainly based on direct observation. A series of such observations provide information about the types of structures present as well as information about the stratigraphy, rock types, and the thickness of the rock. As part of a geological description, fracture networks would be classified in terms of the kind of fractures present which include joints, faults, veins, and dikes. Therefore, a fracture network represents the spatial configurations of these fractures in which the location, orientation, and interactions among distinct fractures are mapped in two-dimension (2D) or three-dimension (3D) (Manda and Horsman 2015).

However, studies using different scientific approaches such as geophysical (Arinze et al. 2019), geotechnical (Igwe and Chukwu 2018), and geochemical (Obiora et al. 2016) have been employed. Some works have been carried out on descriptive analysis of structural discontinuities within the study area, but the role of fracture networks as conduit pipes or permeable zones to mineralized fluids has not been properly studied. Hence, the characterization of these fracture networks in the study area by means of its geometrical attribute would be prioritized.

The study area

Ameri district is located south of Abakaliki which lies within longitudes $8^{\circ} 08' 12''$ to $8^{\circ} 13' 24''$ east of Greenwich meridian and latitudes $6^{\circ} 08' 12''$ to $6^{\circ} 13' 24''$ north of the equator (Fig. 2). The study area was easily accessible, with many tarred and untarred routes. The major access roads include Abakaliki–Afikpo route and Ameri–Achara route. According to Bleach (2004), the study area is about 14.2km from Abakaliki town and located in Southeastern Nigeria. It lies within a tropical humid climate region of Nigeria, characterized by large trees and grass of various sizes. Shale of low erodibility potentials dominates the area, with undulating topography that exceeds 72 m in altitude (Igwe and Chukwu 2018).

Fig. 2 Map of the study area



The region experiences eight (8) months of the wet season, with 1200mm of mean annual rainfall, and four (4) months of the dry season, with an average annual temperature of 28°C (Mathias 2015). Mostly influenced by its geology, the area is drained primarily by the river Aboine with a dendritic drainage pattern (Fig. 2).

Regional geologic and structural setting

It is believed that Benue Trough’s origin can be traced back to tectonic activities that bring about the break-up of South American and African supercontinents at the end of Jurassic—the beginning of Cretaceous. Murat (1972) suggested

a mega tectonic framework for describing the geology of the Benue Trough, within which the study area lies. In general, Benue Trough is divided into three zones, Lower, Middle, and Upper Benue Trough, each of which corresponds to different geologic features (Maurin and Lancelot 1987; Benkhelil 1989; Rebelle 1990; Oha et al. 2017). There have been three major tectonic phases that control the stratigraphy of units in the basins, giving rise to successive depocenters (Anyiam and Onuoha 2014). Three cycles of basin deposition have been reported in the Lower Benue Trough: the marine Neocomian-Albian Asu River Group, the Turonian Eze-Aku Group, and the Coniacian-Santonian Awgu Group. Sediments of the Abakaliki Formation, which is a member of the Asu River Group, underlie the study area.

They consist of thick sequences of slightly deformed Cretaceous sedimentary rocks made up of essentially Albian shale with its subordinate of sandstone, siltstone, and mudstone (Fig. 1).

Within the trough, folds and fractures originating from Santonian tectonics dominate the structural composition (Leach et al. 2010; Oha et al. 2017). Numerous authors, among them Grant 1971, and Olade 1975, have studied the tectonics of the trough. Tectonic activity in Lower Benue, where the research area is situated, involved compression along an established NE-SW trend, leading to folding and uplifting of the Abakaliki area consisting of NW-SE and N-S fractures. These series of magmatic activities have led to the uplift and folding of the superimposing sedimentary rock units of the Asu River Group. As a result, the area is deformed showing numerous anticlines and synclines, where prominent among them is the NE-SW trending Abakaliki anticlinorium, within which Ameri is located. In addition, igneous intrusions led to intense fracturing of the Cretaceous rocks, as veins and veinlets were observed within the sediments (Arinze and Emedo 2021). Also, the area is identified by the following lithostratigraphic succession which includes the Albian sequence, Cenomanian-Coniacian, the Campanian-Maastrichtian, and Paleocene-Neogene (Ekwe-nye et al., 2016) (Table 1).

Local geology

Pb-Zn mineral deposits at the Ameri area were hosted by an undulating range of clay-rich shale outcrops. The shale is part of the Abakaliki Formation, a member of the Asu River Group. The shale is characterized as light to dark gray or brown, highly indurated, compacted, and sometimes baked with varying lengths of extensive joints and fractures (Fig. 3), with some portions showing laminated beds of extremely indurated siltstone. Intense weathering has converted the black shales which were bleached into pale gray, reddish to yellow at shallow depth because of subjection to intense weathering as well as iron oxide stains along the fractures. The mineralization consists of a series of fracture filling occurring in veins and veinlets that are mostly isolated. The Ameri lode trends NW-SE to N-S as vein filling which appears to be a continuous extension of Enyigba with lode housing more sphalerite than galena.

Methodology

Field geologic studies were conducted to analyze, investigate, and characterize exposed sediments of the Albian Asu River Group of the Abakaliki Formation. Data from Google Earth Pro™ were used to assist field studies. The focus was to observe and define the various structural features which

can be used to characterize geologic features, such as fractures, joints, and veins. A total of 156 fractures from three (3) locations were identified and studied within the study area. The field generated data (i.e., strike and dip and dip direction) was subjected to structural analysis to evaluate their specific orientation and geometric attributes. Fractural data were analyzed with the aid of open-source software (OpenStereo™) in producing rose plots, stereographic net, and histogram, whereas geometrical analysis was performed using a combination of Adobe Illustrator CC™ and MATLAB-FRACPAQ™ software (Healy et al. 2017) in producing different structural attributes such as fracture length and angles, intensity and density, slip and dilation tendencies, and fluid flow (Figs. 4 and 5).

Results and discussion

Descriptive analysis

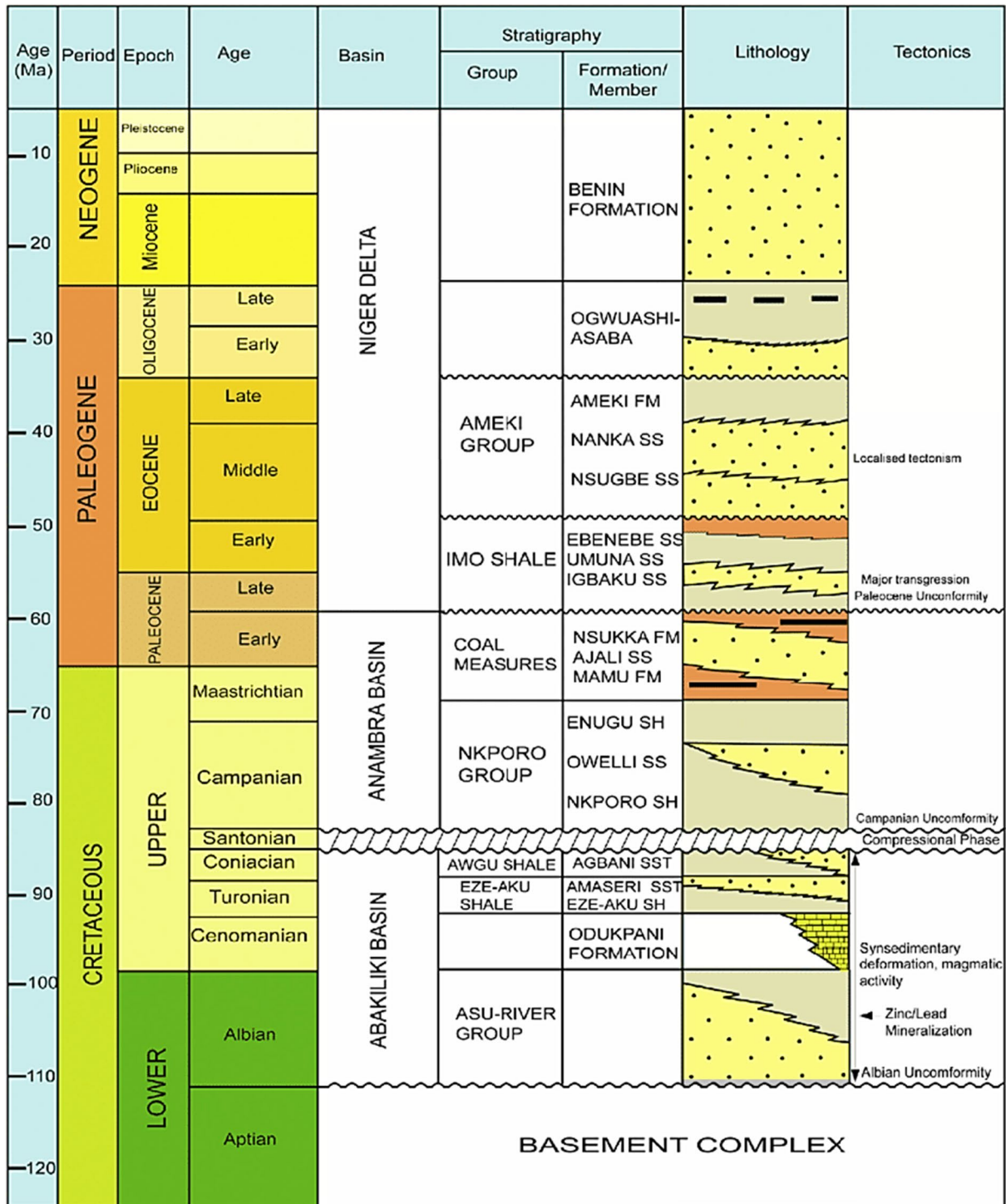
Studies have revealed that the lithological unit that underlies the area is primarily the shale of the Abakaliki Formation of the Asu River Group. Characterized as a dark indurated to fissile shale with a lens of marble concretions with depth, grayish brown, reddish yellow, weathered bleached shale was described at shallow depth due to weathering and oxidation. These were exposed because of the activities of artisan miners and were massive and intensely fractured (Fig. 6).

Orientation analysis

Results of rose diagram and stereographic projection show a major general trend of NW-SE and minor trends of N-S, with a mean direction of 324° and dip amount of 78°. Hence, this indicates that the NE-SW tensional principal stress direction is said to be responsible for the development of N-S and NW-SE fractures of extensional origin (Fig. 7). Similarly, Igwe and Okonkwo (2016) carried out research on paleostress distribution in Benue Trough which also reveals that the fractures within the study area are tensile or extensional fractures. There was a major NW-SE trend associated with the Orogeny Pan-African (less than 900 million years) (Oden et al. 2015). Compared to NE-SW trends, these trends have ages that correspond to the Santonian tectonic event.

Their origin is linked to a major magmatic episode that occurred along with the Cameroon volcanic ranges (Ugbor et al. 2021). This magmatic event is believed to be responsible for the intense fracturing of shale and subsequent mineralization of the fractures (Arinze and Emedo 2021). The pre-Pan-African Orogenic activities were characterized by minor brittle changes that resulted in the formation of fractures that correspond with the minor slight N-S fracture trend (Oha et al. 2017).

Table 1 Stratigraphic succession Lower Benue Trough and Niger Delta (modified after Ekwenye et al. 2015)



LEGEND



Fig. 3 The geologic map of the study area, inserts are rose plots showing the general trends of fracture networks (NW-SE)

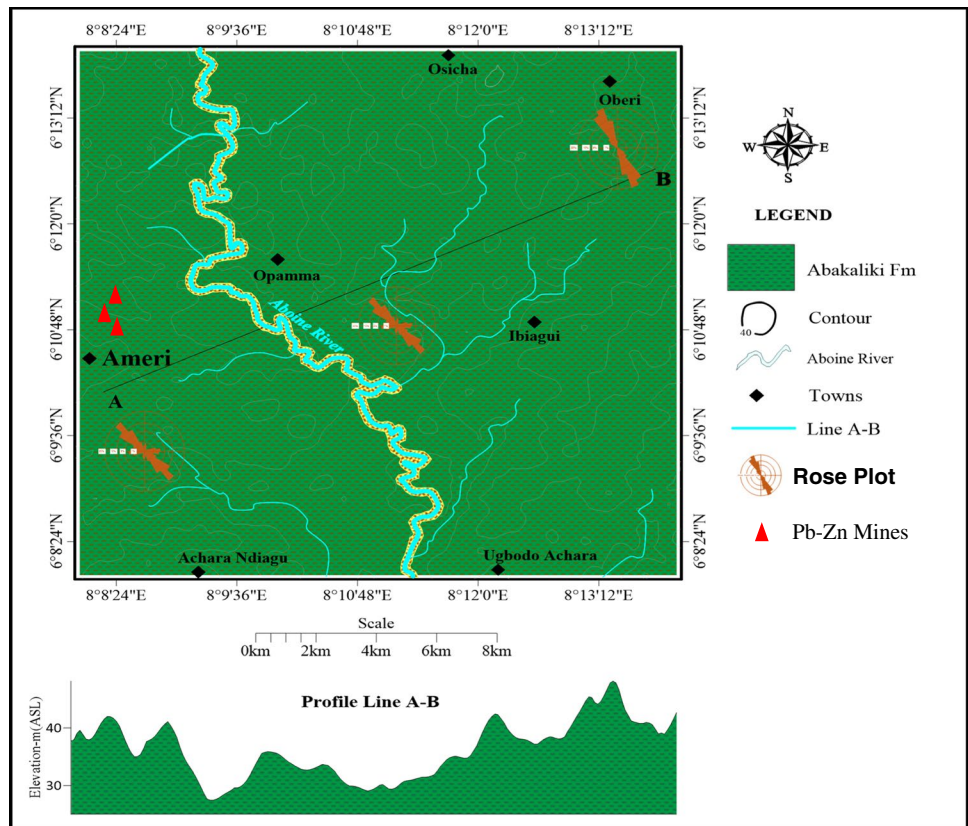
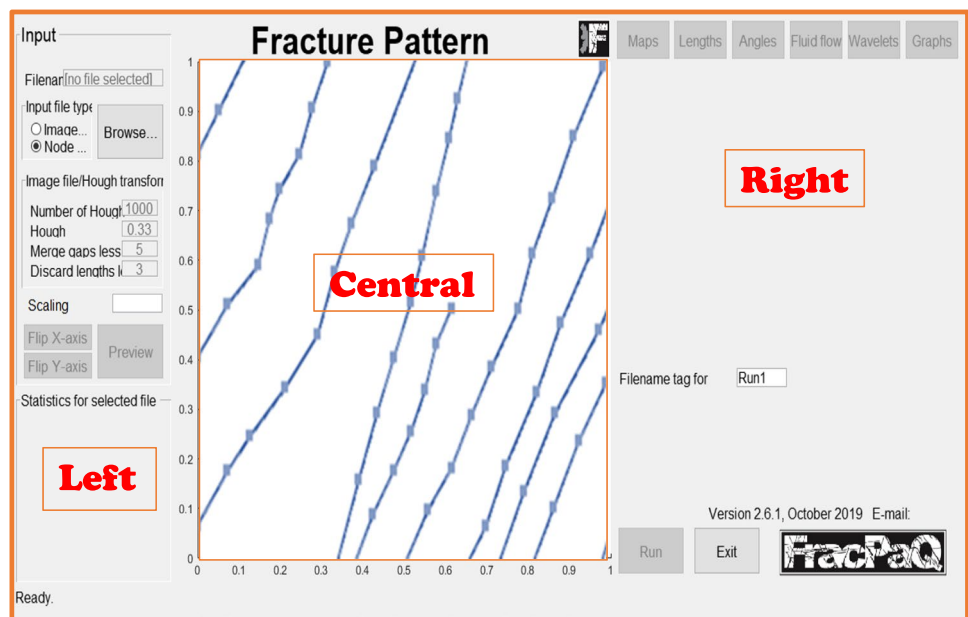


Fig. 4 A graphical user interface (GUI) of FRACPAQ. The input parameters are on the LEFT side of the interface, with the output options appearing on the RIGHT and in the CENTER, for previewing the input data as a fracture trace map



Geometric analysis

Fractures were analyzed based on their relative orientation, frequencies, angles, and abutting or cross relationships. However, a 2D fracture network with nodes and branches was considered, in which the nodes signify

fracture tips, and the branches signify the fracture intersection points (Sanderson and Nixon 2015). Hence, the interactions of fractures in terms of their geometries, i.e., fracture intensity and density, slip and dilation tendencies, and permeability or fluid flow, were characterized below.

Fig. 5 **a** A field photograph of fractures, being traced using Adobe Illustrator CC™ (scale= Pen:15cm). **b** A trace map, with segments colored by strike, with a north correction of -55° , -25° , applied. Inserts show equal area rose plots superimposed with a general trend of NW-SE (Nemec, 1988)

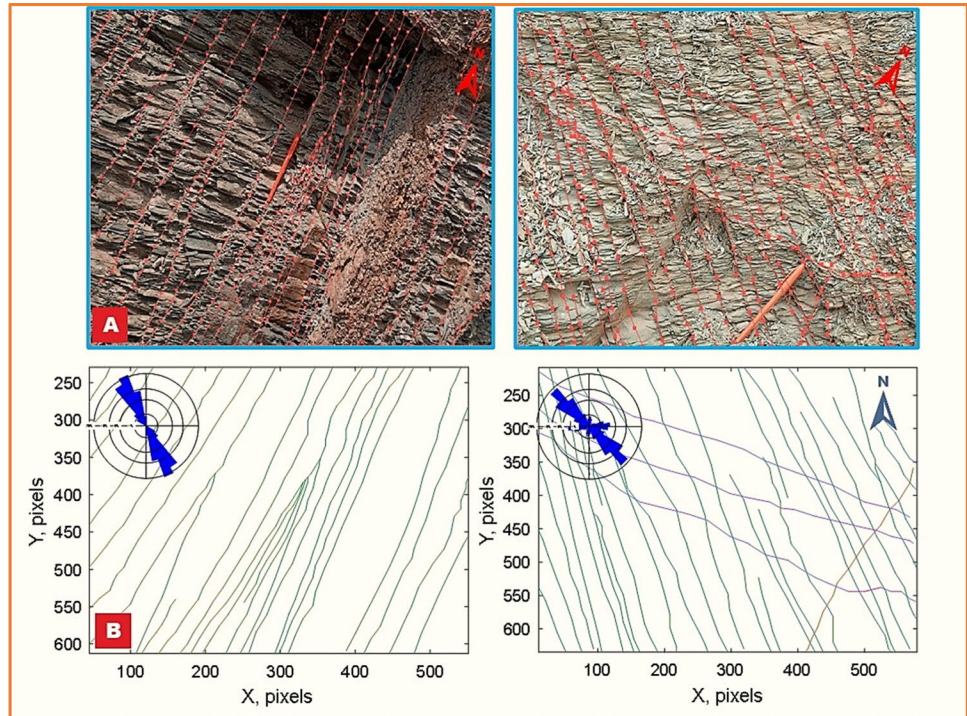
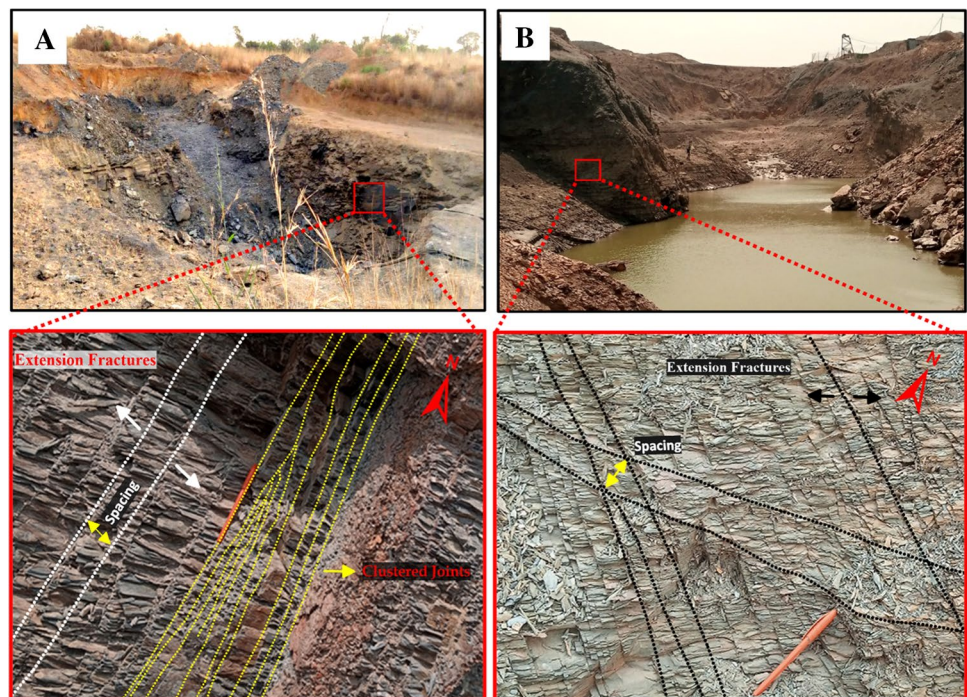


Fig. 6 **a** A photograph of two open mines with cropped images of their walls showing fractures. **b** A field photo illustrating clustered, elongated tensile fractures on shale (scale = Pen:15cm)

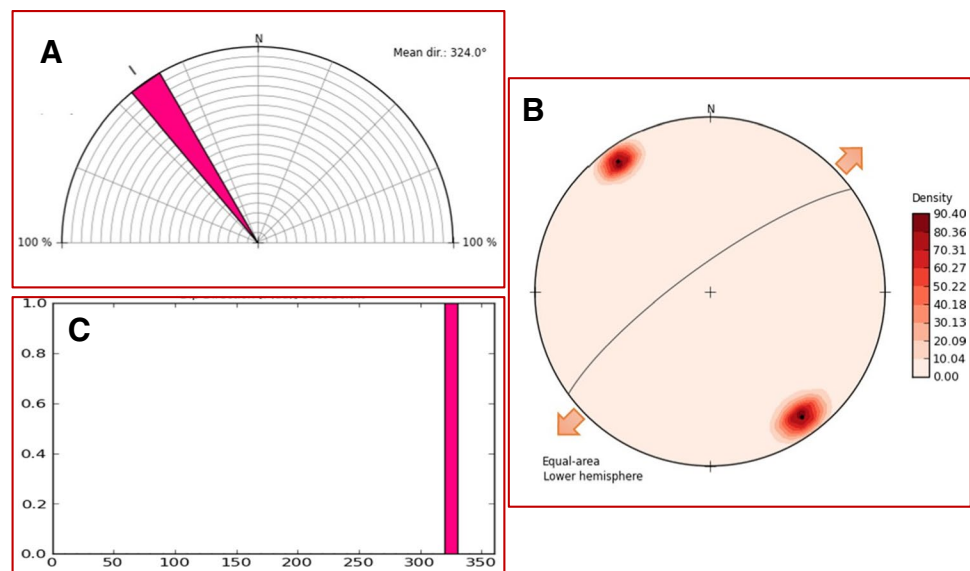


Intensity and density of fractures

Results of fracture intensity and density indicate low to moderate intensity-density, ranging from 0.05 to 0.1 and 0.002 to 0.005 respectively; this was accomplished with the aid of a circular window scan technique of Mauldon et al. (2001). This implies that the extent of occurrence of fractures and

joints within the study area is pretty much common and indicates that the Santonian tectonism that affected the study area was mild to moderate (which explains the higher occurrence of short-length fractures compared to longer fractures), therefore, suggest areas of moderate rating will tend to accommodate more fluids, i.e., mineralized fluids (Fig. 8).

Fig. 7 **a** A half-circle rose plot showing the mean fractural trend of the study area (NW-SE, with a mean direction of 324°). **b** A stereographic projection of the fracture's pattern, portraying the NE-SW tensional stress direction that was responsible for NW-SE tensile fractures. **c** Histogram also portraying the frequency distribution of fractural data



Slip and dilation tendencies of fractures

Based on the maximal horizontal principal stress (σ_1) and the minimum horizontal principal stress (σ_2), shear and normal stresses are determined onto the fractures, thereby determining the probability of fracture slip and dilation. σ_1 and σ_2 have a value of 100 MPa and 50 MPa in both the fractures examined at an angle of 55° to 25° respectively (Fig. 9). This reveals that NW-SE trending fracture planes have low to moderate tendencies (i.e., slip 0.2 to 0.6 and dilation 0.2 to 0.5). The result of the slip tendency shows that the fractures have a moderate fracture slip potential implying that shear slip is expected at hydraulic fracture pressures, thereby making them likely to hold mineralizing fluid. However, the slip tendencies of these fractures will be higher when the induced stress field causes the stress applied to the fracture planes to exceed the friction resistance of sliding (Morris et al. 1996). Analysis of the dilation tendency also shows that the study area is moderately stressed with a dilation value of 0.2 to 0.5. This was used to assess the fracture contribution to secondary porosity and permeability. Results indicate the chance of the fractures to dilate and enhance mineralizing fluid flow which agrees with the results of slip tendency. The understanding of this analysis was achieved using the Morris et al. (1996) and Ferril et al. (1999) schemes by calculating the 2D equivalent of both tendencies operating on a linear fracture segment with the aid of two major stresses and their pathways. The ideal location of ore deposits will be areas that have several fractures in proximity that have a high probability of being potentially active in response to the injection of mineralizing fluids (Fig. 9).

Permeability of fractures

The interconnectivity of the analysis of the fracture shows the dominance of the X and I type of nodes (i.e.,

abutting, or cross-cutting and isolated fractures respectively) (Fig. 10a and b). The Y-type nodes rarely occur within the study area as shown in Fig. 11a and b respectively. Peacock et al. (2018) showed that cross-cutting relation occurs when a later fracture cuts another to form an X node. Isolated interactions (I node) follow where the fractures are not connected to one another, which means there is no interactions. Branching relations (Y node) usually develop by split of a propagating fracture, where two of the branches normally form at a low angle of $<30^\circ$ to one another.

The ratio of the Y-, X-, and I-type nodes is shown as 0.30:0.20:0.50 and 0.11:0.65:0.24 respectively, which implies that only a few fractures crosscut each other suggesting that the fractures are neither intersected nor isolated or moderately interconnected. Hence, the probability of fractures being permeable is rated as mild. The success of characterizing these of fracture networks in terms of their permeability was accomplished using the concept of Sanderson and Nixon (2018) by counting the number of nodes of each fracture type (i.e., Y:X:I nodes). Consequently, the Santonian deformative stress that affected the study area is presumed to have been moderately intense resulting in mild fracture interactions, meaning that not all the fractures are mineralized. There is a probability that a significant number of delineated fractures and veins within the study area will be barren (Figs. 10 and 11).

Summary

In response to tectonic stresses and high fluid pressure, rocks tend to break or fracture, which result from strains that are caused by stress concentrations. This occurs in various scales ranging from microscopic to continental.

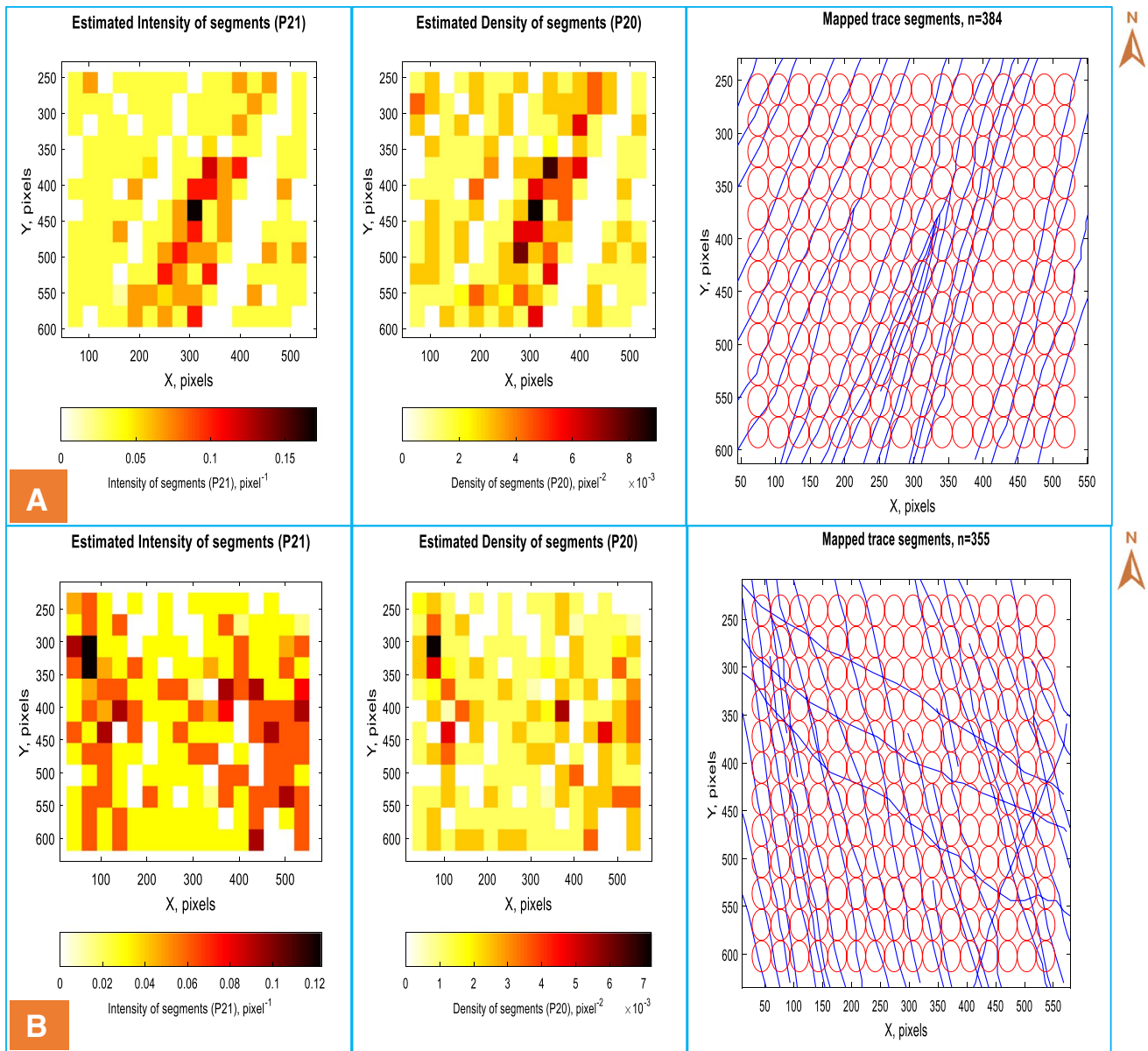


Fig. 8 a, b Both left side shows a map of estimated intensity (P21, m^{-1}). Center shows a map of estimated density (P20, m^{-2}). The right side shows the positions and sizes of the scan circles used in the assessments (Mauldon et al. 2001)

Consequently, because of their significance in mining, mining exploration, engineering, and hydrogeology, they act as conduits for fluid flow. An economical amount of petroleum, ore bodies, geothermal, and water supply reservoirs are found in fractured rocks.

The advantage of fractured reservoirs is that they are relatively permeable and rapidly recharged, making them essential and widely used class reservoirs. Therefore, studies from this research signify that these fracture networks are potential reservoirs because they occur in consistent directions (NW-SE) and are moderately connected over

hundreds of meters. The preferential orientation of major fractures may cause anisotropy in permeability, where the reservoirs being more permeable parallel to the dominant fracture orientation than in any other orientation. Hence, outcrop-scale mapping reveals the possible discharges of fluids (i.e., water, and mineralized solutions in veins), from NW-SE to N-S fractures, due to the intensity of their consistency in terms of their preferential orientation of the major fracture trend (324°) within the area studied.

Therefore, it is pertinent to say that future geophysical exploration for groundwater development, mineral, and

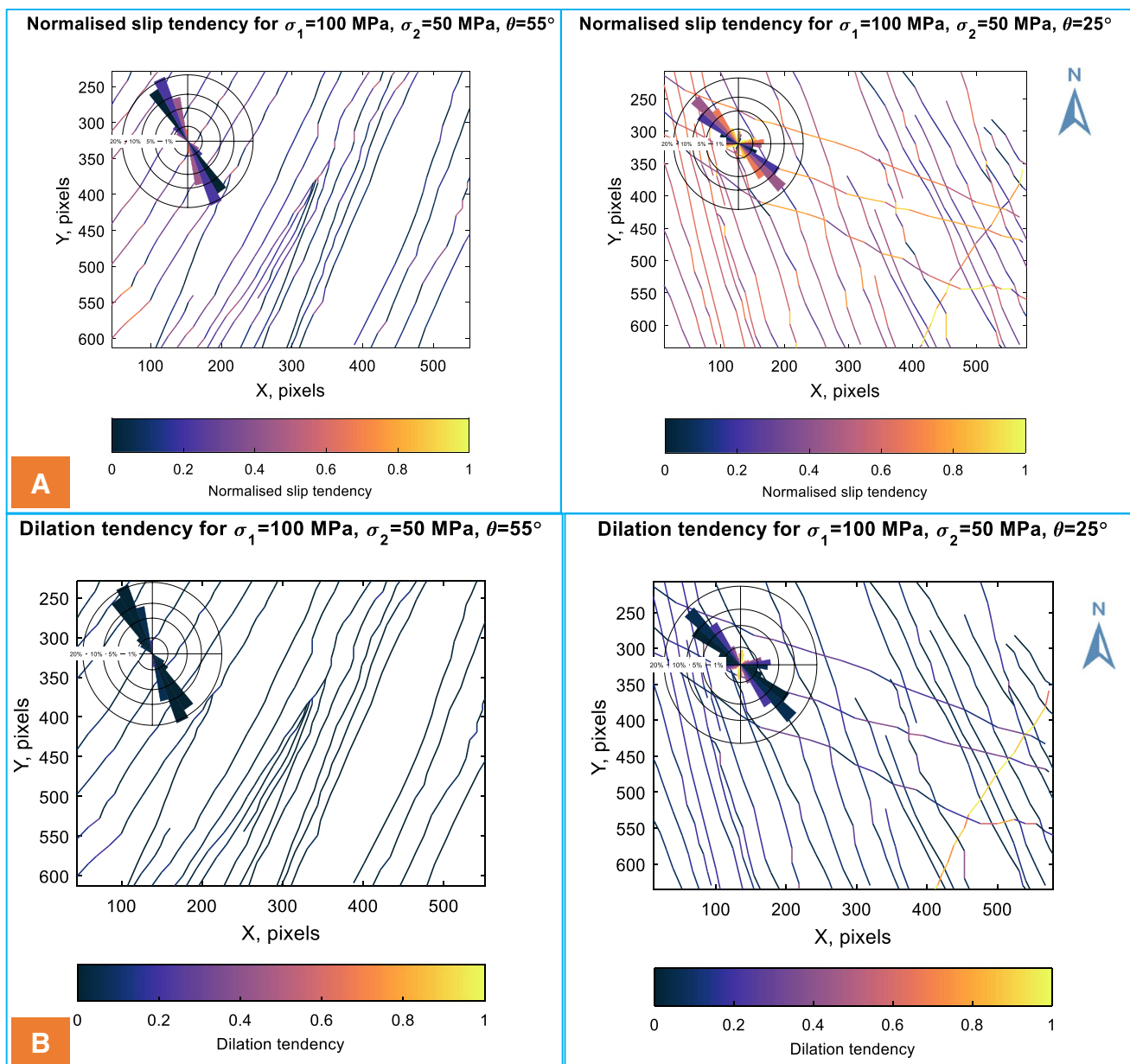


Fig. 9 a This shows segments colored by normalized slip tendency. Insert is an equal area rose plots of segment orientation color coded by normalized slip tendency (Morris et al. 1996). **b** This shows seg-

ments colored by dilation tendency. Insert is an equal area rose plot of fracture segment orientation color coded by dilation tendency (Ferrill et al. 1999)

pollution studies should carefully focus on these key fractural trends (i.e., NW-SE and N-S), because geologic and geometric analysis has unraveled the potential of these fracture networks as reservoirs with the possibilities of accommodating the occurrence of fluids such as water and mineralized solutions, in forms of fractured aquifers and mineralized veins respectively.

Also, it was found that fractured aquifers (i.e., which are rock bodies that contain economically significant quantities of water), within the studied area, are prone to contamination owing to the rapid movement of contaminants through

fractures in the lack of confining layers. So rapid recharge along these fractures makes the area more vulnerable to contamination from an existing surface activity, such as illicit waste mining, mine-water disposal, heavy metals percolating from gangues, fertilization of fields, pesticide application, or spills. Also, direct links among the surface water bodies and groundwater through a major fracture also enhance the capability for water-borne pathogens entering the groundwater system, especially when there is excessive flow or when confining layers along riverbeds are compromised.

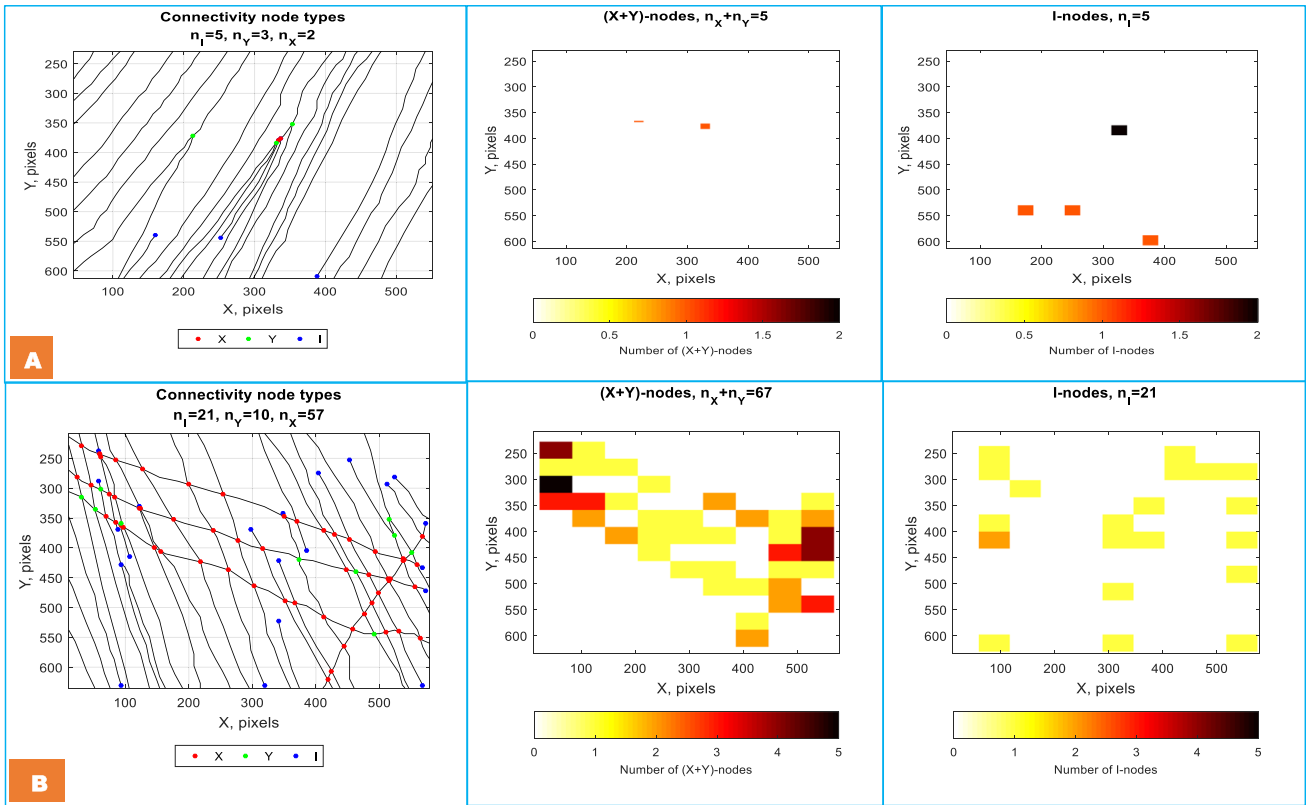
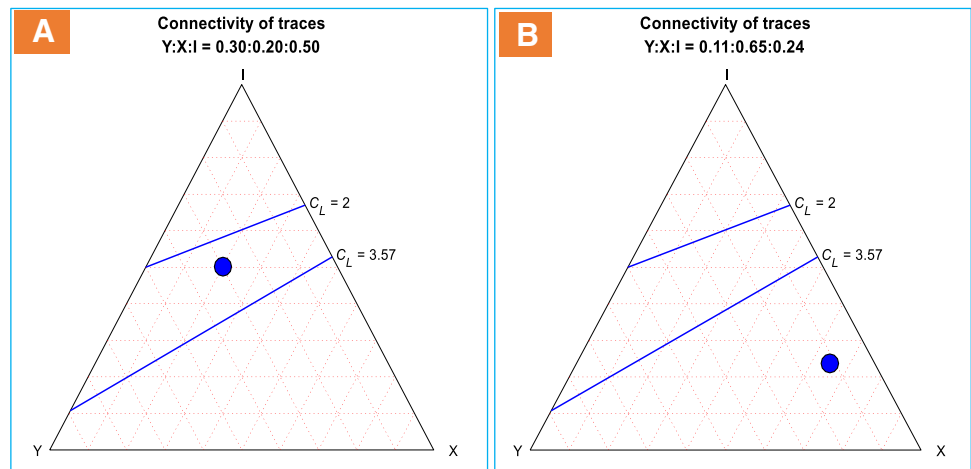


Fig. 10 a, b Both maps show the spatial distribution of different node types: X, Y, or I; a “heat map” of X+Y nodes is shown at the center, and a “heat map” of an I node at the right

Fig. 11 a, b A ternary plot of fracture connectivity outlines. With indicative values described by Sanderson and Nixon (2015), which depict two contour lines expressing connections per line (CL)



Conclusion

Field geological analysis of 156 fractures shows a general trend of NW-SE (a mean direction of 324° , with an average dip amount of 78° NE). The joints are said to be clustered and elongated throughout the shale. Fractured networks

were analyzed and classified as tensile or extension fracture type. Thus, the results of fracture intensity and density range from low to moderate, of slip and dilation tendency also range from poor to fair, and of fracture connectivity also range from low to moderate. To further characterize Albian deposits, extending the geometric analysis to other regions

(regional scale) containing older Albian deposits is recommended. It is recommended that geophysical explorations profiling should trend perpendicular to the general fractural bearing in order not to avoid missing the crucial targets.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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