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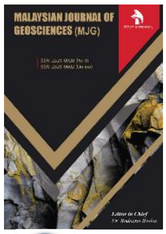

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RESEARCH ARTICLE

STRUCTURAL CHARACTERIZATION AND TECTONIC ANTIQUITY OF PRECAMBRIAN ROCKS OF KEFFI ENVIRONS, NORTH-CENTRAL NIGERIA

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ABSTRACT

A field-based geological mapping and geospatial approach were used to characterize the geological structures of the study area, intended at increasing the structural geological knowledge of the area. Geological mapping of Nigeria has been ongoing since 1964, with periodic updates that may overlook local geology due to the extensive area coverage. There is a need to promote local geologic mapping as a means of addressing this limitation. Four different rock types were identified; migmatitic gneiss, banded gneiss, mica schists and biotite granite as well as later igneous intrusive bodies. Results from petrographic analysis showcase an average mineralogical composition ranging from quartz (30%), orthoclase (23.27%), biotite (36.25%), and hornblende (5%) to other accessory minerals (5%). This research aimed at creating an updated structural geologic map of the study area, taking into account the sequence of deformational past of the area. Over 205 structural geological features, including faults and joints, were meticulously measured using geological tools. The utilization of structural geological software, such as Openstereo™ among others, facilitated statistical data visualization and evaluation. The results from rose diagrams and stereographic projections revealed a prevailing structural trend of NW-SE, N-S and NNE-SSW directions, with mean values of 310°±5, 010°±2, and 034°±2 respectively. Consequently, the direction perpendicular to the aforementioned trend (i.e., NE-SW) aligns with the paleo stress field responsible for the area's structural deformation.

KEYWORDS

Rose diagram, Paleo Stress, Deformation, Pan African Orogeny

1. INTRODUCTION

Structural geology is a pivotal branch of geology that delves into the deformation and arrangement of rocks in the Earth's crust. This study provides crucial insights into the processes shaping our planet, influencing scientific understanding and practical applications across various domains. The significance of structural geology extends from unravelling the Earth's tectonic history to addressing contemporary challenges in resource management and environmental protection (Twiss and Moores, 2007). By examining rock deformations, such as faults, folds, and shear zones, geologists can reconstruct the tectonic history of a region. This understanding is fundamental to the theory of plate tectonics, which explains the movement and interaction of the Earth's plates. Such insights are crucial for advancing our knowledge of Earth’s dynamic systems and contribute to our broader understanding of geological phenomena (Hawkesworth et al., 2016). Conducting structural geologic studies involves a systematic approach to analyzing and interpreting the deformation and arrangement of rock formations. This process is essential for understanding geological structures, tectonic activities, and the history of the Earth's crust. Geological mapping is a vital component of structural geologic studies, involving direct observation and measurement of geological features. Therefore, structural geologic studies aimed to elucidate the processes and forces responsible for shaping the Earth's lithosphere. This helps in explaining phenomena such as mountain building, earthquakes, and volcanic eruptions (Twiss and Moores, 2007).

The study area forms part of the North-central Basement Complex of Nigeria which comprises Archean to Proterozoic rocks, bearing the imprints of Pan-African (600Ma) orogenic events (Oversby, 1976). Several studies by geoscientific researches using numerous scientific approaches have been employed in the area, this include Hydrogeological studies by researchers, Geochemical analyses was conducted, and Mineralogical studies were also carried out by (Tanko and Dzigbodi-Adjimah, 2021; Steven et al., 2018; Goki, and Umbugadu, 2022; Anudu, et al., 2014; Kana et al., 2022; Aliyu, et al., 2018). However, few attempts were made to conduct structural geologic studies on a broader or regional scale, resulting in numerous features being overlooked. Therefore, there is a necessity to carry out a descriptive analysis of these structural features within the study area at a local scale, to highlight and represent these features, reconstruct their deformational history, putting into proper perspective the sequence of tectonic events that took place leading to the transformation of the area to its present form.

1.1 The Study Area

Keffi is a town in Nasarawa State, central Nigeria. It's located at approximately 8°48′ 0.0″ to 8°56′ 0.0″ N latitude and 7°51′ 0.0″ to 7°58′ 0.0″ E longitude. Keffi covers an area of about 636 square kilometers, well-accessible, situated approximately 80 kilometers east of Abuja, Nigeria's capital, which facilitates easy connections by road. The town is linked to major highways, including the road, which connects it to other key cities (Akwanga, Nasarawa and some parts of Kaduna) in Nigeria. The area is a

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low-lying plain with few undulating areas, prominent among them being Maloney and Tudun Amama hills. The area is drained by the Antau River, rising from Gunduma Hill and flowing as far as Kogin Koto near Nasarawa LGA, proceeding into River Benue. Other rivers forming tributaries to the farmlands are dendritic drainage in nature. (Sufiyan et al., 2022). Keffi's climatic condition as reported by the Nigerian Meteorological Agency (NIMET), reflects a tropical climate typical of the region. Temperature ranging from 30°C to 35°C. The town has a distinct wet and dry season, with an average annual rainfall of about 1200 mm to 1500 mm and humidity levels are generally high during the rainy season and lower during the dry season (Sufiyan et al., 2022).

1.2 Geologic Setting

The area falls within the Basement Complex of Nigeria. Widely accepted to be Precambrian in age and is made up of the Migmatite-Gneiss Complex, the Schist Belt and the Older Granites (Obaje, 2009). The area features Precambrian rocks, among the oldest on Earth, dating back over 600 million years, precisely within the Migmatite-Gneiss Complex. These rocks primarily consist of migmatites, metamorphosed gneisses and schists, which formed under high-pressure and high-temperature conditions during the Proterozoic Eon as well as pegmatite quartzofeldsparthic veins (Obrike et al., 2011). Keffi area belongs to the Pan-African Granitoids unit of the North-Central Basement Complex (Wright, 1985). A polycyclic terrain that has responded to various tectonic events within the Pan African Orogeny (Obaje, 2009). The Pan African Orogeny comes with deformation, which imprint has been widely reported in the Precambrian rocks of Nigeria (Ajibade et al., 1987). Regional metamorphism was one of these events that accompanied the Pan-African deformation (Abaa, 1985). This has resulted in the formation of structures such as faulting and folding, jointing, veins, intrusions, foliations and mineral lineation. The main structural features in the area are the penetrative tectonic foliations trending mainly in the N-S, E-W, NE-SW and NW-SE directions (Olayinka, 1992). (Figure. 1)

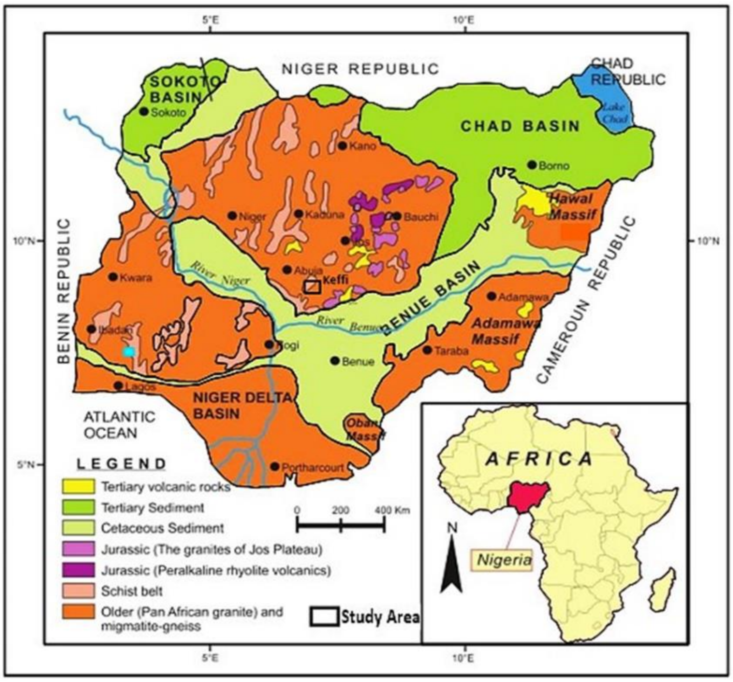

Figure 1: Geologic map of Nigeria. Insert is the study area. (Modified after Obaje, 2009)

2. Material and Methods

Field mapping is a fundamental aspect of this study, involving systematic approaches to collecting and analyzing geological data in situ. Geological mapping is a core component of fieldwork in structural geology. It involves recording the locations, orientations, and characteristics of rock units and structural features. The study area was mapped and traverses were taken along streams, rivers, roadcuts and on top of hills in search of outcrops. Structural data (i.e., strike, dip and dip amount) were measured and documented using a compass clinometer. This will later help to deduce the orientation of the tectonic forces that produced some of the structural features observed. At each location, rock outcrops were carefully studied and plotted on the base map for later digitization using the Garmin Global Positioning System (GPS). Additionally, efforts were undertaken to understand petrogenesis and geochronology in explaining the sequence of events that affected the rocks in the area. At the end of these exercises' samples were taken with the aid of a sledgehammer for sample preparation and petrographic analysis. Over twenty (20) rock samples were sampled from the field of which four (4) representative rock samples were used to prepare thin sections at Ahmadu Tafawa Balawa University Bauchi (ATBU), Department of Geology, Petrography Laboratory. The processes involve cutting the rock into small rectangular pellets of 3mm, mounted on a glass slide using the resin Araldite. To create friction between the rock pellet and the glass, the mounted slide was lapped over a glass plate using medium-grain carborundum as an abrasive, resulting in a reduction in slide thickness to a desired thickness of 0.3mm. It has been demonstrated that rocks act as a transparent medium at this thickness, enabling light to pass through (Gribble, 2012). The focus was to observe and define the various structural geological features which can be used to characterize and reconstruct the deformational history of the area. 205 structural features (i.e., faults, joints. dikes and veins) were measured and recorded with numerous foliations, mineral lineation, fold and pinch and swells. The field-generated data (i.e., strike and dip and dip direction) were subjected to structural analysis to evaluate their spatial distribution, orientation and geometric attributes. OpenStereo™ and GoeRose™ software were used in producing rose plots, stereographic nets and histograms.

3. Results and Discussion

3.1 Petrographic Analysis

On the basis of megascopic to microscopic analysis carried out, results revealed that the rock types that underlain the area are predominantly metamorphic rocks which include; migmatitic gneiss, banded gneiss, schists and biotite granite with various igneous intrusions (Figure. 2). It's evident that the orogeny induced high-pressure & high-temperature conditions that resulted in the formation of various metamorphic rocks. (Klerkx, et al., 1994). Migmatite-gneiss form in high temperature and pressure conditions, though not as extreme as those required to form granulite. They often exhibit banded structures with alternating dark (melanosome) and light (leucosome) bands, reflects the degree of melting and deformation the rock has undergone (Abaa, 1985). The mineral modal comprises of quartz (30%), orthoclase (20%), biotite (40%), hornblende (5%) and other accessory minerals (5%) (Figure. 3a&b). The banded gneiss observed are characterized by their banded appearance and are formed from high-grade metamorphism of igneous rocks. Typically displays a banded or foliated texture, with alternating light and dark bands of felsic and mafic minerals respectively. Modal composition of quartz (40%), orthoclase (25%), biotite (30%), and other accessory minerals (5%) as the mineral assemblages, (Ekwueme and Ekwere, 1989) (Figure. 3a&b). The mica schists are relatively formed under moderate to high-grade metamorphic rocks characterized also by pronounced penetrative foliations, usually form from metamorphism of mudstones and shales under moderate to high temperature and pressure conditions, and found mostly in association with quartzite of possible sandstone origin, which comprises of quartz (20%), orthoclase (10%), biotite (50%), hornblende

(15%) and other accessory minerals (5%) (Figure. 3c&d). This composition indicates schists form in high-grade metamorphic rocks characterized by pronounced foliation (Ofoegbu, C. O. (1985). Biotite granite is a type of igneous rock belonging to granitic family. It's characterized by mineral assemblages; quartz (30%), Orthoclase (50%), biotite (15%) and other accessory minerals (5%). Therefore, the presence of biotite granite in the area, indicates that the regions have undergone significant magmatism (Abaa, 1985) (Figure. 3e&f). Table 1 shows the summary of mineralogical compositions of rock obtained from optical analysis.

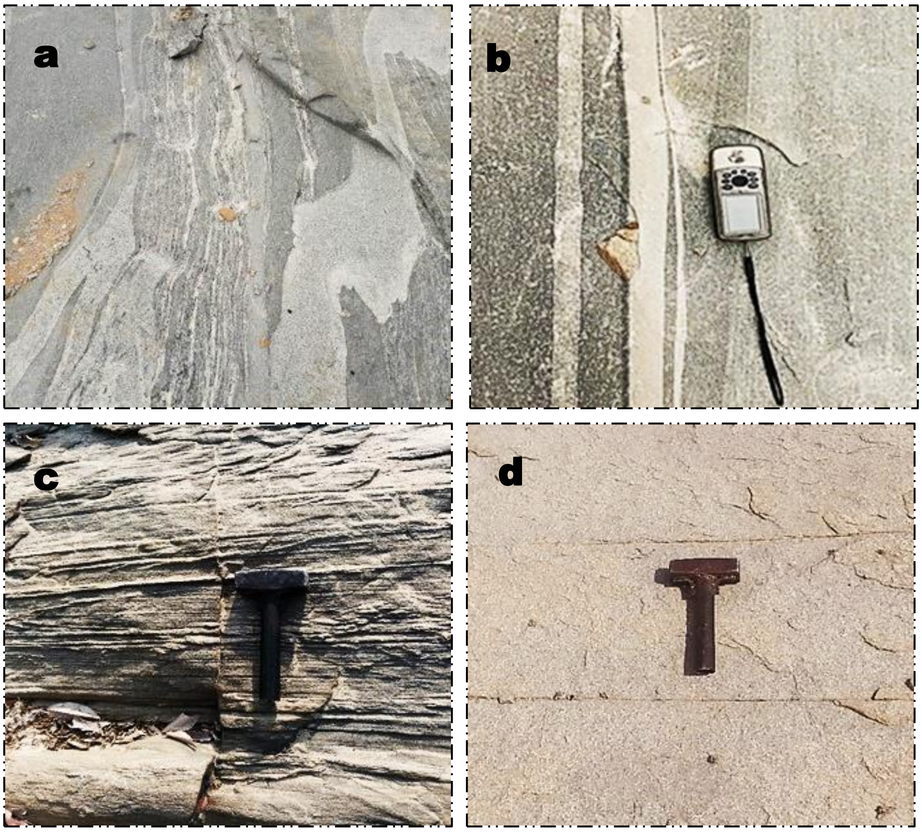

Figure 2(a-d): A field photograph of (a) Migmatite Gneiss (b) Banded Gneiss (c) Schists and (d) Biotite granite Scale= GPS:10cm

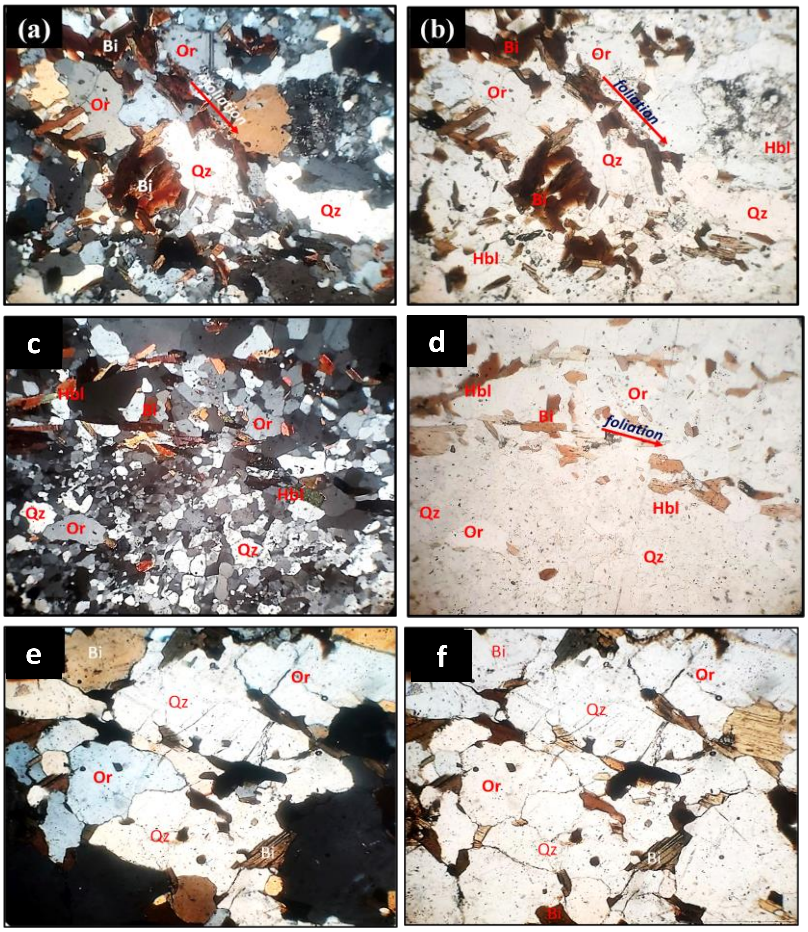

Figure 3(a-f): Photomicrograph of (a&b) migmatitic gneiss - banded gneiss, (c&d) mica schists, and (e&f) biotite granite under; Cross Polarize Light (XPL) and Plane Polarize Light (PPL) NB: Qz=Quartz, Bi=Biotite, Or=Ortoclase, Hbl=Hornblende, A=Accessory minerals (Magnification x30mm)

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Table 1: Average Mineral Modal Composition

S/N	Sample	Quartz %	Orthoclase %	Biotite %	Hornblende %	Accessory %
1	Migmatite Gneiss	30	20	40	5	5
2	Banded gneiss	40	25	30	0	5
3	Schists	20	10	50	15	5
4	Biotite granite	30	40	25	0	5

3.2 Structural Analysis

The spatial distribution and orientation of the structural features mapped, were judiciously analyzed and represented using geometrical methods of data visualization in form of rosette diagrams, histograms, and stereographic plots. Moreover, rosette diagrams and Stereographic plots were used to visualize and characterize the portion of the tectonic forces that affected rocks and also evaluate the extent of the deformation in the study area. Fault (Strike-slip faults) are commonly found in regions undergoing horizontal shearing, such as transform boundaries and intraplate shear zones, characterized where the dominant tectonic stress regimes are horizontal and perpendicular to the fault plane (Tanioka et al., 2004). The spatial orientation and distribution of the strike-slip faults analyzed in the area are shown in (Figure. 4aandb), insert presents a rose plot with a general trend of NW-SE direction, with a mean value of 315°±5, and a magnitude of displacement in the ranged of 10-40 cm, evident by the movement of various quartz veins and aplite dikes, portraying both dextral and sinistral strike-slip faults, seen on the migmatitic-gneiss and biotite granite rocks outcropping majorly around Maloney hills, Tudun Amama and Abzat Quarry site behind Nasarawa State University Keffi. Joints are fractures or cracks in a rock along which no visible displacement has occurred. Figure. 4c, insert shows a rose diagram of joints analyze in the area, displaying a prevailing NW-SE directional trend, with a mean value of 313°±4. Therefore, its believe that the area is affected by extensional forces acting along the NE-SW direction, that led to the formation of these tensile fractures in form of closed to open joints cutting across the initially formed quartz vein and aplite dikes. Aplite dikes are fine-grained, light-coloured igneous intrusions that provide significant insights into the magmatic and tectonic processes in a given region. Often found intruding through older rock formations and exhibiting distinct structural characteristics as a dike. These were mapped, and found elongated parallel to the general strike of the parenting rock, varying in width from 20 cm to 1000 cm. Results shown by rose and stereographic projection, display an average general trend of NNE-SSW direction, with a mean value of 025°±5 (Figure. 4d). Thus, the arrangement and aligning of theses dikes is an indication of the direction of the principal stress exerted during their formations. Veins are created from mineral-rich solutions forming mostly quartz, feldspars to pegmatitic veins as they move through fractures in the Earth's crust. The structure of quartz veins observed varies widely, ranging from simple single-phase veins to intricate networks of intersecting veins, with widths ranging from 5 cm to 1000 cm wide. The development and dispersion of quartz veins are intricately tied to the tectonic activities impacting the vicinity. As shown in Figure. 4e, insert is a rose plots of quartz veins revealing duple orientations trending NE-SW (older vein) and NW-SE (younger vein) direction, with mean values of 027°±3 and 344°±1, respectively. Their relative age dating was achieve based on their morphological displays (cross-cutting relation) as indicated by magmatic activity. Foliation is a common structural feature in metamorphic rocks, characterized by the parallel alignment of mineral grains or structural elements. This texture results from the directional pressure and temperature conditions during metamorphism (Yardley, 1989). The foliation in the area signifies a gneissic banding type of foliation, which usually implies a high-grade metamorphic rock, where minerals segregate into alternating light and dark bands. Figure. 4f, shows the result from the rose plots of foliations, depicting a trend of NNE-SSW, with a mean value of 010°±1, similar to that of pinch and swell. This alignment has aided to unravelled the direction and magnitude of the paleo stress field as NE-SW trend, acting on the area during the tectonic or orogenic activities. Lineation is linear structural features observed in various geological contexts, often appearing as parallel arrangements of mineral grains, folds, or fractures within rocks. This occurs when elongated minerals, such as amphiboles or orthoclase align parallel to a particular direction due to metamorphic or tectonic forces. The orientation and distribution of lineation revealed by the rose diagram show an NNE-SSW directional trend, with a mean value of 023°±4. The linear arrangement of these features observed during the analysis often reflects the direction of major principal stresses (Figure. 4f), similar to that of pinch and swell. Researchers, postulate that in an area of intense deformation, mineral lineation in rocks typically aligns parallel to the direction of maximum stress during regional metamorphism (Simpson, and Schmid, 1983). Pinch and swell structures were also observed, they are distinctive geological formations observed in sedimentary and metamorphic rock sequences. These structures manifest as alternating zones of tighter and looser rock, often appearing as variations in rock thickness or deformation. In metamorphic rocks, pinch and swell structures are typically observed in layered or foliated rocks, where the original sedimentary or volcanic layering has been deformed during metamorphism (Allen and Allen, 2013). Analysis reveals that the alternating patterns of pinches and swells studied in migmatite-gneiss in the area, has a width ranging from 2 cm (Pinch) and 10 cm (swell) wide, striking NNE-SSW directions, with mean value of 009°±2 (Figure. 4f). This confirms with the numerous bearings of various features observed in the study area i.e., foliations, lineation and pinch and swells. The pronouncement of these structures features in the study area is tied to the tectonic forces acting on the region. Therefore, in an extensional tectonic setting accompanied by metamorphism, where the crust is being stretched, pinch and swell patterns can emerge, under favourable rheological conditions. Conclusively, we attest that all they structural features ranging from brittle to ductile deformations characterize in the area study are said to be imprints of metamorphism, magmatism and tectonic deformational episodes belonging to the pre-Pan - African to Pan - African orogenic events earlier reported by researchers (Abaa, 1985; Ajibade et al., 1987; Rahman, 1989; Olayinka, 1992; Obaje, 2009).

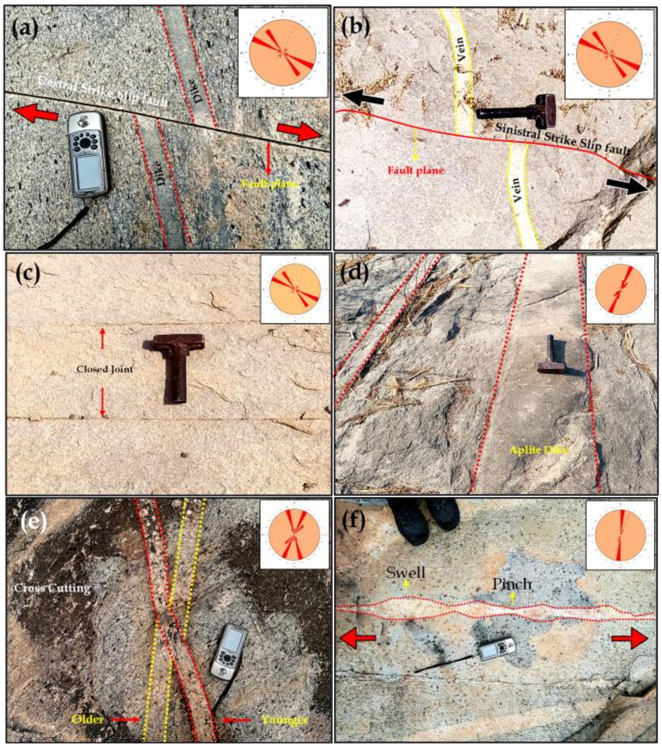

Figure 4(a-f): Structural photographs of (a) Dextral strike-slip fault (b) Sinistral strike-slip fault (c) Joints (d) Aplite dike (e) Quartz veins (f) Pinch & swell. Insert are rose plots showing their respective orientations Scale: Hammer=20cm & GPS=10cm

3.3 Local Tectonic Setting

The study area falls within the Northcentral Basement Complex region, earlier characterize by rocks of Precambrian age. Study has shown that the area is affected by series of tectonic activities, culminating in the current topography. These tectonic occurrences, termed "Pan-African Orogeny," bear testament to their widespread influence across African territories, dating back to approximately 600 million years ago. Hence, analysis carried out has unravelled the imprints of this orogenic activities in the following order of occurrence; regional metamorphism, Magmatism, and tectonic deformational episodes. Notably, the metamorphic effect was discernible when pre-existing Precambrian rocks, primarily of igneous origin, underwent intense heat and pressure, resulting in the formation of migmatitic gneiss and banded gneiss (see Figure. 5), leading to the emergence of rocks with distinct metamorphic characteristics, collectively referred to as Migmatite Gneiss Complexes (Obaje, 2009). Following this phase, a period of magmatic activity ensued, characterized by the eruption of magma of rhyolitic to granitic origin, intruding the previously formed metamorphic rocks in the form batholith, dikes and veins. Though, their spatial orientations display a prevailing trend in NW-SE and NE-SW direction as shown in Figure. 5. Subsequently, these phenomena were accompanied by tectonic deformations, giving rise to the formation of closed and open joints, as well as faults (strike-slip fault system). The identification of these features was facilitated by the displacement and offset across earlier formed aplite dike and quartz veins, portraying both dextral and sinistral strike-slip faults, with relative offsets of 4cm±2. Hence, it is deduced that the sequence of orogenic activities that impacted the studied area unequivocally aligns with the accounts provided by early researchers regarding the influence of Pan-African orogenic events on the Nigerian Basement Complex (Olayinka, 1985). (Figure. 5)

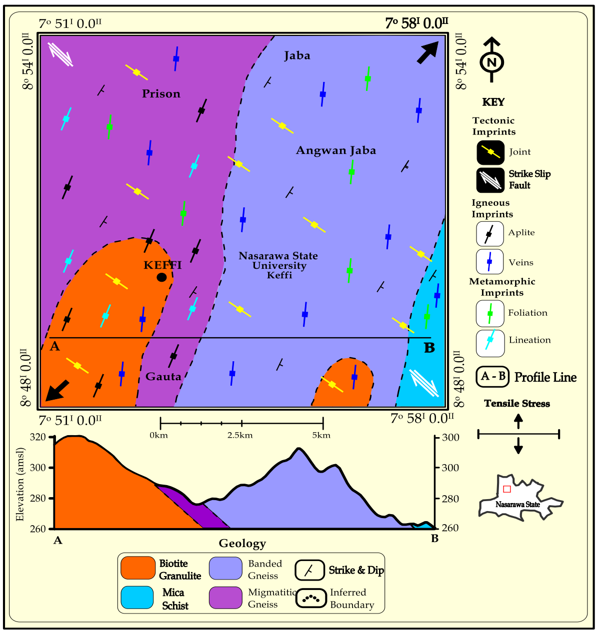

Figure 5: Structural Geologic map of the study area

3.4 Significance

The importance of structural geological studies in the exploration and exploitation of natural resources cannot be overstated. Such analyses play an essential role in resource exploration. Thus, an updated geological map has been created in light of the spatial characterization of structural features in the study area. This map has unveiled a sequence of deformational events, determined through the examination and descriptive analysis of the mapped structural features, petrographic and lithological features. Moreover, the geometric analysis applied to the structural discontinuities in the area has yielded significant findings regarding the challenges experienced in groundwater production within some districts. Encompassing areas around the Maloney, Tudun Amama and Prison area. These areas have encountered substantial obstacles despite numerous attempts at borehole drilling to considerable depths (Goki and Umbugadu, 2022). Analysis revealed that the district comprises high-grade metamorphic rock. Despite the prevalence of numerous fractures and joint distributions, it was believed that the permeability of most fractures and joints diminishes as temperature increases. This phenomenon is attributed to thermal expansion in rocks with increasing depth, resulting in reduced fracture aperture and a corresponding decline in permeability (Singhal and Gupta, 2010). Therefore, this has rendered a significant number of boreholes unproductive in the vicinity. Furthermore, the spatial orientations of quartz veins serve as crucial indicators for mineral exploration in the quest for ore bodies or pegmatitic veins as confirmed by (Tanko and Dzigbodi-Adjimah, 2021). Therefore, it is paramount to prioritize future exploration of groundwater prospects and ore bodies focusing on these prevailing trends. The analysis has illuminated the potential of these fractures as zones capable of accommodating fluids such as water and mineralized solutions, in the form of fractured aquifers and mineralized veins, respectively (Abdullahi et al., 2022).

4. Conclusion

A detailed field geological mapping of the Keffi area was carried out, with over 205 structural geological features mapped. Petrographic studies conducted on the four selected rock samples revealed distinct rock units comprising migmatitic gneiss, banded gneiss, and mica schists. Migmatitic gneiss and banded gneiss occupy 80% of the area, with intrusive bodies mainly known as veins and dikes. The statistical data of these structural features were systematically processed, and rosette plots and stereographic projections revealed a prevailing trend of NW-SE, NNE-SSW, and N-S directional attributes. This is a clear indication of NE-SW as the trend of maximum principal stress direction, as an extensional stress regime is presumed. Therefore, the analysis carried out in the study area has shown that the area was affected by a series of Pan-African orogenic events. Evidenced by the presence of metamorphism, magmatism, and deformation phases of rocks. Thus, it is recommended that, such analyses should be conducted in adjoining areas to provide a better understanding of the sequence of deformations occurring in the region as a whole.

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