Original Research Article

FRACTURE ORIENTATION SIGNIFICANCE IN THE STUDY OF Pb-Zn MINERALIZATION OF LOWER BENUE TROUGH, ABAKALIKI SE NIGERIA

ABSTRACT

The Lower Benue Trough, in South-eastern Nigeria, hosts several lead-zinc deposits. The mineralization is frequently hosted by Cretaceous black shales that appear to have undergone low grade metamorphism, and subordinate sandstones. Most parts of the deposits have been epigenetically formed, and occur as blocky shaped, discordant veins, fracture, and possibly open-space fillings, of hydrothermal origin. For this reason, structural evaluation constitutes an important criterion for the investigation of the mineralization. In particular, the orientation of fractures occurring at the Pb-Zn deposits can be useful in the differentiation of the relative ages of the mineral vein deposits. A total of one thousand, one hundred and forty-seven fractures around mineralized zones, at the study localities, were measured and analysed. Results indicate that the vein deposits are structurally controlled, have four main orientations, and most likely formed by crack-seal process. The most prominent fracture sets show NW-SE, NNE-SSW to N-S orientations, while the less prominent ones are displayed in the NE-SW and ESE-WNW directions. The NW-SE, NNE-SSW to N-S fracture sets is interpreted as 'ac' extension fractures from two different deformation episodes that affected the trough, while the NE-SW, ESE-WNW to E-W sets is the two 'bc' tensile fractures, respectively parallel to the axes of F_1 and F_2 folds which occur in the trough. Small variations of the NNE-SSW and ESE-WNW brought about the occurrences of N-S and E-W sets respectively. Indication are that the two deformation episodes affected the trough: the first episode produce the NE-SW (F_1) fold axes, while the second less intensity episode produce the ESE-WNW (F_2) folds. The most dominant mineral vein trends in the study area are the NW-SE and NNE-SSW to N-S orientations, in which mineral veins are loaded in the 'ac' extension fractures. The less dominant mineral vein trends are the NE-SW and ESE-WNW orientations, which are in the 'bc' tensile fractures. At the NW-SE trend, vein minerals mainly occur along 150-160^o from N, although it ranges from 135-175^o from N. Vein width up to 7.0m can be obtained from both the NW-SE and NNE-SSW directions. The Lower Cretaceous sediments appear to be characterized by the NW-SE (major) and NE-SW (minor) sets of veins, while the upper Cretaceous sequence is most likely characterized by the NNE-SSW (major) and ESE-WNW (minor) vein sets. The widest Pb-Zn vein in the study area is 11.5m wide, located in the Enyigba axes sub-area and trends in the NE-SW direction with evidence of slickensides which indicates faulting.

Keywords: Benue Trough, Lead-Zinc, Mineral Veins, Fracture, Hydrothermal

1. Introduction

The study area is the southern part of the Lower Benue Trough. Geopolitically, the area is located at Ebonyi state, SE Nigeria. It is bounded by longitude $07^{0}29^{I}59.98^{II}E - 08^{0}20^{I}59.98^{II}E$ and Latitude $05^{0}55^{I}59.98^{II}N - 06^{0}34^{I}59.98^{II}N$, with an entire map area of 5,533 km^2 (Fig. 1). The study area is endowed with vast Pb-Zn vein deposit. Mineralization is localized along NE-SW trending belt of Cretaceous sedimentary sequences of Albian Asu River Group sediments associated with saline water intrusions [40,41,59]. The sediment is about 500km thick [40,41]. Unfortunately, these deposits have not been adequately studied.

Pb-Zn deposits occur in the form of veins and veinlets within the host rock [23,40,41,54,63,64]. The mineralization occurs in almost the entire 800km length of the Benue Trough (Fig.2) with its primary reported occurrences by early and recent workers [23,24,55,60,64,66] at Enyigba axes and Ishiagu at the study area. It is interesting to note that the particular host rock of the mineralization and its relationship to the deposits appear to be lacking. Therefore, through detailed field mapping, this present study indicated other new locations of occurrences and the particular host rocks.

The study focuses on vein minerals which are of hydrothermal in origin. The formation of such hydrothermal mineral deposits is due to the interaction between various processes such as fluid flow, structural (for structural control and deformation), geothermal transport, mineral dissolution and its precipitation. Geological structure in various geological settings plays a very significant role in mineral deposit [87]. Therefore, structural processes represent one type of critical control on mineralization [87]. In view of this, early and recent investigators had reported only two orientations of the fractures that controls the mineralization of the study area. Some authors noted that it trends N-S or $N15^{0}W$ [24, 64]. One said that the mineralization occupies a NE-SW trending en-echelon fault [82]. While others agreed that the mineralized vein trends N-S and NW-SE [2, 47, 61]. Two generation of galena had been reported: the first one is generally recrystallized granular, sheared, striated and deformed, while the second one is well crystallized and appears in cubes and octahedra [62]. In addition, the mineralization is said to be restricted to NW-SE and N-S fractures sets, while the more common NE-SW fractures are barren [25, 55]. The ore formed before the end of Turonian [23], but it is argued to be pre-Turonian in age [62]. Within the study area, there are many artisanal miners just like other locations in the world who ends up spending their money without achieving their aim as the result of their inability to understand the appropriate trends of the mineralization. This underscores the need for detailed mapping of all the exposed outcrop and structures using basic geology.

These exposed geologic structures are features which occur in rocks in the study area following a pattern that is usually associated with stresses, strain and the dominant environmental conditions of formation. However, the observed crustal structures in rocks are related to stress configuration, its amount and amount of strain that produced them. Therefore, structural analysis of the rocks in the study area will be used to determine the tectonic history that affected these rocks in the time past. Meanwhile, information from such analysis gives insight into the orientation of principal stresses $(\sigma_1, \sigma_2 and \sigma_3)$ which affected the rocks' framework in the time past, the associated dominant structures occurring within the study area and the one that controls the mineralization.

Through a detailed geological field mapping exercise of the study area, the associated lithologies, regional tectonic history, predominant crustal structures, and the structure that control the mineralization can be revealed. This is because it may lead to the determination of exploration targets strategies and the discovery of more ore bodies within the study area.

2. Geological Setting

The study area is a sedimentary environment overlying conformably on a non-fossiliferous intra-continental oldest sedimentary rocks deposits of probable Aptian age [82]. These rocks were accumulated within the southern Benue depression basins and river valleys. They were formed unconformably on the surface of the Basement Complex, consisting poorly sorted quarzitic or arkosic sandstones and are overlain by fossiliferous Albain shales, siltstones and micaceous sandstones [73, 75, 82].

Among the three major litho-petrological components that make up Nigeria geology is the basement Complex (Fig. 3ab). Nigeria seems almost equally divided between the Cretaceous to Quaternary sediments with volcanics and the crystalline basement rocks. This basement complex forms part of the Pan-African mobile belt which lies between the West African Craton to the West, Congo Craton to the Southeast and Taureq Shield to the North [10, 31, 46]. The basement is intruded by Mesozoic Younger Granites (calc-alkaline ring complexes) of the Jos Plateau and it is also unconformably overlain by younger and Cretaceous sediments [46]. Migmatite gneiss complex (MGC), Schist belts and the Older Granites suites are three lithologic groups commonly used to described Nigeria's Basement Complex. Migmatite gneiss complexes is the oldest rocks of the Basement Complex believed to be reworked older crust (probably Liberian in age), which in turn further reworked by later orogenies such as Eburnean (2000 + 200 Ma) and Pan African (600+150 Ma) with addition of granitoids and schist belts [31, 46]. During the Kibaran (1300-1100 Ma), sedimentation and deformation evidences with no magmatic event are reported [31, 32]. Kibaran was followed by Pan African event giving rise to migmatite, gneisses, older Granite, intrusive with other similar rock units. Middle to late Paleozoic age had no magmatic or sedimentation records [31, 46]. While Mesozoic age is marked by intrusion and uplift of Younger Granites (a series of alkaline, anorogenic, shallow sub-volcanic intrusive) which fall within a N-S narrow belt in Jos Plateau extending north ward into Niger Republic [31, 46]. Unconformable sedimentation to the basement began in the Lower Cretaceous, followed by rift initiation in early Jurassic. The formation and infilling of many basins flanking the basement highs began through marine transgression and regressions marked by transcontinental seas and epirogenic movement growths [34]. As a result of the marine incursion, sedimentation had Periodically continued throughout Tertiary and Quaternary [33].

The study area located at the southern part of the Lower Benue Trough is part of the Benue depression that comprises Abakaliki Anticlinorium and Afikpo syncline to the east and Anambra Basin to the west (fig.3ab). Benue Trough is an inter-continental Cretaceous Basin of about 1000km in length stretching in NE-SW direction with 80-150 km width fault-bounded depression containing up to 6000m of deformed Cretaceous sedimentary and volcanic rocks which extends from Niger Delta and linking northward with Chad Basin through the Gongola rift [9, 26, 62]. Two important models of its origin are proposed. Many authors portrayed the trough as an elongate basin, installed as the failed arm of a trilate fracture system separating the Afro-Brazilian plates, during the break-up of the Gondwana supercontinent and the opening up of the southern Atlantic and Indian oceans [3,11,12,13,16,22,30,36,39,62,74]. Therefore, these failed arms of an RRR triple junction include Gulf of Guinea, South Atlantic and Benue Trough [22, 30, 36, 39, 62]. The trough evolution is also related to the effects of Equatorial Atlantic oceanic fractures zones transmitted along the Benue Trough through transcurrent movements along deep-seated faults extending along the trough during the early stages of separation of Africa and South America [7, 8, 86]. These faults are linked to Romanche, Chain and Charcot Fractures [6, 7] (Fig. 3a). Benue Trough is arbitrarily subdivided into Upper, Middle and Lower parts [45] (fig. 3b).

The Lower Benue (the Abakaliki-Benue basin) is first made up of Asu River Group (ARG) sediments. The ARG sediments was first described as lower Shales [4], roughly consist 2000-3000m of poorly bedded shales (Abakaliki Shales), sandstone, siltstone with sandstone occurrences, sandy limestone lenses and mudstone [1, 21, 23, 57, 58, 77, 78]. It was deposited during the first Cretaceous marine transgression in Nigeria, which occurred during the middle - lower Albian, leading to the deposition of the oldest marine sediment in Nigeria [74]. The sediment is a predominantly black carbonaceous shale with occasional intercalations of thin calcareous matter [43, 44, 63, 64, 65, 73, 74]. It constitutes the Albian Asu River Group and its lateral equivalents which are Awe Formation, Uomba Formation and Arufu limestone. There is an extensive weathering and bleaching of the sediment which is evident at Enyigba axis [64]. Following the transgression was a period of regression which led to the deposition of Odukpani Formation in Calabar flank resting unconformably on the Basement Complex during the Cenomanian [39, 53, 56]. The deposits consist of arkosic sandstones, a quartzose sandstone-limestone facies with a predominance of shale in the upper parts and are about 600 meters thick [72]. The marine regression was terminated by another marine transgression during the Turonian allowing sea water to enter into the interior of Benue Trough. This marine incursion led to the deposition of Eza-aku Group comprising Amasiri Sandstone Formation, Nkalagu Limestone and the base of Agwu shale. Eze-aku Group consists black calcareous and hard grey shale, limestone, sandstone and siltstone, with its lateral equivalent at Yolde and Pindiga Formations in the Upper Benue Trough [43, 74]. Coniacian-Santonian was a period of marine regression. Agwu Formation was fully deposited during the Coniacian times which are mainly shale, then sandstone and are about 800m thick [74, 75]. Santonian is a period of folding, faulting and magmatic activities at the Southern Benue Trough which affected only the Albian – Coniacian sediments [7, 72, 73]. The Coniacian-Santonian long period of regression was terminated by a short marine transgression followed by regression during the Campanian-Maastrichtian period. During the Campanian, Nkporo Formation of about 700-1200m thick were deposited with their lateral equivalents at Afikpo Sandstone, Owelli Sandstone, Otobi Sandstone and Enugu Formation constituting the basal beds of Anambra Basin [7, 73, 74]. At the Maastrichtian, sea gradually became shallower forming a paralic sequences depositing Mamu Formation with coal beds [77]. Mamu formation was overlain by Sandy sequence of Ajali Formation and then Nsukka Formation [43, 74]. General stratigraphic succession of Southern Benue Trough is presented in figure 4.

3. METHODOLOGY

The method of study is sub-divided into two parts. They include detailed field mapping of the host rocks and the structures with particular interest on the structures that control the mineralization and the behavior of the vein minerals with respect to other structures. The detailed field mapping was carried out in three phases between January 2017 with Members of the Nigerian Geological Survey Agency during their routine economic mineral update, then April to early June, 2017; and February to May, as well as December, 2018. Finally, a data confirmation mapping was done in March to May, 2019.The fieldwork was carried out where the Lower Cretaceous ARG sediments and mineralization are exposed- the open mine pits.

With the use of a base map (fig. 1), the detailed mapping of the study area was carried out in a scale of 1:50,000 having a coverage area of 5,533 km^2. Using the map, only areas of interest such as Izzi mineral axis (including Mkpuma-Ekwoku Ndieze, Izenyi Omenyi, Olua, Ndijoko and Ndikpa), Abakaliki mineral axis (including Mkpuma Akpatakpa and Echara Nuhu) Enyigba mineral axis (including Enyigba, Ameri and Ameka), Ohaozara mineral axis (including Agu-ogwu Uburu, Obiagu Umuobuna Uburu and Agu Amankalu Oshiri) and Ishiagu mineral axis at Ihetutu was mapped. At each location, the structures and geology of the location were systematically mapped and recorded. A geological map having structural features of the ARG sediments is presented (Fig. 5).

Producing and abandoned Pb-Zn mine sites within the area were mapped. The mapping instruments used for this study include the simple basic geological mapping instruments such as Global Positioning System (GPS), Silva compass/clinometer, measuring tape and a hammer. The attitude (strike and dip) of the structures (joints, faults and folds) that control the mineralization and the mineral vein were measured based on the standard structural techniques. The strikes and dips of the fractures (joints) were measured using Silver Ranger compass/clinometers. Its data was presented using rose diagram and stereographic projection. The mineral veins width was measured with the use of measuring tape and its data with the vein orientation was used to prepare a scatter plot of vein width versus orientation. A GPS device (Garmin 76) was used to determine the coordinate locations at data collection points.

4. RESULTS

4.1 Joints/fractures

The dips and orientations of 1112 joints/fractures were measured from both abandoned and producing mine sites across the study area and were presented using stereographic projections and rose diagrams. This indicates that the study area is heavily fractured/jointed. Most of the joints were measured from shale because shale occupies most of the study area. Joints are the most common secondary structures exposed on the present-day surfaces of rocks which though may seem featureless, that constitute a vital structural element both locally and regionally, which can elucidate the tectonic history of a region when properly studied [5, 20, 38].

The observed joints/fractures are usually straight, long distance parallel joints (Fig. 6a) on the surface, and in few instances are curved (Fig. 7a & 11f). The observed joints are also cross fractures (Fig. 6d) and in so many cases are conjugate fractures (Fig. 6c). But in all, the fractures have smooth planar surfaces (Fig. 6abc). The appearances of the fractures suggest that the study area is a tensional-extensional environment with prominent presence of shear fractures (Fig. 6c).

At all the locations visited, a series of well developed; steeply dipping joints were observed in the shale environment (Fig. 6a, b, c). In the sandstone zones, the area is also characterized by such steeply dipping joints with both joints having parallel mostly NW-SE trending joints (Fig. 7a, b, d). The joints generally can be followed through a long distance and are hardly seen to terminate against each other, except in few cases (Fig. 7c), where one is perpendicular to the other, forming a T-junction. In this case, when joints terminate against each another, the one terminating is younger [17]. Joints terminating against each other are more evident in sandstone (Fig. 7d, having joints labeled ‘y’ terminating against the one labeled ‘z’) than in shale, though they are present.

Figure 9a shows the composite rose diagram of the measured fracture orientations. The diagram indicates six main petals, having the most frequent occurring directions in the NW-SE (about 150-160^0 from N) directions, while the less prominent directions which are obvious ones are in the NNE-SSW, N-S, ESE-WNW, E-W and NE-SW directions.

In addition, Figure 9b shows the composite stereographic projections of poles to planes of the measured joints orientations from the mine sites which was contoured using RockWorks17 distribution counting method. The rose diagram analysis of the joints from Izzi mineral axis shows that the joints are majorly high angle joints with main petal directions of NW-SW, N-S and ESE-WNW trending joints with a minor NE-SW and E-W directions (Fig. 8c).

The same is not true of Abakaliki axis; the dominant high angle trending joints from the rose diagram are the NW-SE and NNE-SSW petals with the minor NE-SW and E-W trending joints (Fig. 8a). This is similar to Enyigba mineral axis joints rose diagram, which shows that the joints are also majorly high angle joints mainly trending in NW-SW and N-S directions with a minor NNE-SSW and NE-SW orientations (Fig. 8b). Uburu axis displays a strong NW-SE and

N-S trending joint sets, with a weak NE-SW sets and a very weak ESE – WNW and E-W joint sets (Fig. 8d). Ishiagu axis, like Uburu axis displays a strong NW-SE, N-S and NNE-SSW joint sets of high angle dips and a weak low angle NE-SW joint sets (Fig. 8e).

Conclusively, the study area joint configuration (Fig. 9) shows six petal sets of directions as noted earlier. They are the very strong, dominant major occurring NW-SE trending joint set, the strong N-S and NNE-SSW joint sets, the minor but weak and few occurring NE-SW set and the very few and so weak occurring E-W and ESE-WNW joint sets. The joints are usually high to medium angle with a mostly preferred direction of dip to SW.

The fracture petals configurations obtained in this mineralized zone of the study area is closely related to what had already been obtained and interpreted in the study of barite veins of the Benue Trough and Ikom-Mamfe basin, respectively [48, 50, 51]. Four petal directions of fractures which is an extension of Benue Trough has been noted [50], while six petals have been observed here, even though two sets may be too weak to compare with others. The NW-SE fractures of barite studies are 'ac' extension fractures perpendicular to the axes of (f_1) folds and the NE-SW fractures are 'bc' tensile fractures parallel to the first deformation fold axes (f_1) and to the axis of the trough [48]. These fractures were developed in the first episode of folding, both in the trough and Ikom-Mamfe basin [50].

The NNE-SSW and N-S fractures are interpreted as 'ac' extension fractures of the second deformation episode, while the ESE-WNW and E-W fractures were seen as the 'bc' tensile fractures of the second deformation episode parallel to the resultant fold axes (f_2). The N-S and E-W are very few and weak fractures probably belonging to the second deformation, which may have formed at the very late stage of the episode. As already noted, there are two sets of 'ac' extension fractures of different ages in the Trough: the NW-SE stronger set (by the reasons of their numbers, with high and medium dip angles) and NNE-SSW (a weak set) with the N-S (weaker set) [50]. The two sets are of Santonian and Maastrichtian deformation episodes respectively [50, 52]. Each 'ac' extension fracture set is orthogonal, or nearly so, to a fold axis of the same deformational episode [51].

4.2 Host Rocks

The host rocks of the study area's vein mineral deposits range from shale, siltstone to sandstones of the Lower Cretaceous Asu River group sediments. The shale host rocks are designated as Unit A and Unit B as observed from drilled core log of the area [23]. Part of the Unit A is made up of black, hard, compacted and indurated fractured shale, hosting the mineralization as observed in the field. While the other part is hard, compacted, whitish sandstone and siltstone, underlying the black shale. Their Unit B is the greyish brown to pinkish red shale, which is fissile, laminated and also fractured as observed in the field. This shale has been weathered and is leached. Siltstone and sandstone are found around Oshiri, Uburu and Ishiagu hosting the vein deposits. The sandstone in some places interbeds with shale. The sandstone is also highly fractured with both high and medium dip angles. The sandstone to siltstone makes up about 20 percent of the study area, while the shale occupies 80 percent. Both lithologies were observed in the field hosting the mineralization (Fig. 10). The persistence of barite veins of the Benue Trough into the basement complex below the Cretaceous cover is an indication not only of how deep the veins are, but more importantly, how thick-skinned the Cretaceous deformation was that produced the joints initially [48]. Such is the case of these Pb-Zn deposits.

4.3 Mineral Vein Analysis

As seen from table 2, a total of one hundred and eleven (111) vein minerals were measured in the study areas as at the middle of June, 2019. The mineral veins are 85 percent Pb-Zn veins (Fig. 11d & f) and 15 percent accessory vein minerals such as siderite, calcite, quartz and copper ores (Fig. 11b, c, e). They were measured across the southern part of the Lower Benue Trough. The vein minerals were emplaced in fracture planes of preferred orientations (Fig. 11b-e) and in a few cases, the bedding planes (fig. 12d). The mineral vein orientations as observed in the field are mainly controlled by the fractures (fig 11a-f), folds (Fig. 12b-c), faults (Fig. 12a) and the stress configurations during the deformation episodes.

In the field, two types of occurrences were seen. The concordant type of occurrence (Fig. 12d), which is very much less frequent (about 5 percent) and has so far been seen at Enyigba and Ishiagu mineral axes. It is hydrothermal in origin [48], ellipsoid in shape and is not multilayered, but frequently occurred along the bedding planes in the unit B of the sedimentary sequence. It is weathered and almost turned into iron ore. The discordant type of occurrence (Fig. 12b-d), is by far (about 95 percent) the more common vein occurrence in the study area, with a width range from 2cm to 11m. Some of the veins are found at Enyigba axis, with widths of 7-11m (including the widest veins) and Abakaliki axis with a width range of 2cm-7.6m. Veins of the northeastern and southwestern parts of the study area- Izzi axis and Ishiagu axis respectively, have strong NW-SE orientation, with a little or minor occurrence of NNE-SSW trend. Veins at the eastern part of the study area- Abakaliki and Enyigba axis-mainly align in the NW-SE and NNE-SSW directions, with a minor direction of NE-SW. The veins at the southeastern central part of the area, the Uburu axis-perfectly align in NW-SE and NNE-SSW orientations.

The trends of Pb-Zn veins in the southern part of the Lower Benue Trough are best illustrated by a rose diagram. Figure 13 shows the orientations of 111 Pb-Zn mineral veins in this part of the trough. 69.4% of the veins are orientated in NW-SE quadrants, orthogonal or nearly so, to the axis of the Benue Trough, with the most frequently occurring veins oriented between 140-150^{o} from N (Fig. 13d & 14d). 19.8% of all the measured veins are oriented in the NNE-SSW (N20^{o}E) corridor with the most frequently occurring veins between N1-15^{o}E (Fig. 13d & 14d) and 4.5% of N-S trend. The NNE-SSW and N-S is the second strong trend of the mineral veins of the trough. Figure 14d shows that NNE-SSW and NW-SE are the two main orientation of the mineral vein of this study area.

The NW-SE and NNE-SSW to N-S vein trends are definitely the very strong directions of preferred orientation of the mineral veins which incidentally are the same as in the Ikom-Mamfe basin. These two main vein orientations are the two 'ac' extension fracture directions. Veins in ESE-WNW and NE-SW orientations only make up 2.7% and 3.6%, respectively measured in the trough. These are vein minerals loaded in fractures parallel to the axes of the folds f_1 and f_2 and are less prominent than 'ac' mineral veins, as can be seen by their percentages and widths. They are the two 'bc' tensile fracture trends of the trough. Therefore, a few 'bc' tensile fractures in this part of the trough are mineralized, quite like the Ikom-Mamfe basin [50], but its extent cannot be compared to those of the 'ac' extension fractures, both in frequency and vein widths.

This indicates that the axis of the trough itself is not a favored vein orientation direction, contrary to what has been averred. This is shown by the few number of veins along the axis of the trough. In addition, it is important to note that out of the population of mineral veins in this part of the trough, the N-S to NNE-SSW orientation is far less than the NW-SE trend orthogonal to the axis of the trough and the former set obviously belong to another phase of deformation. Therefore, the Pb-Zn mineral veins of the Lower Benue Trough are tightly structurally controlled based on the vein orientations and widths.

The most common vein structure profile of the barite vein of the Benue Trough is the vertical block structural type [48]. The Lead-Zinc veins of this study area are not an exception, for they have about 97% vertical block structural type (fig. 11c, d), except in few cases where the mineral deposits were seen along the bedding planes of the ARG sediment, forming a lenticular or ellipsoidal structural type (Fig. 12d). This simple structure in profile should make modeling of the vein minerals in the sub-surface a more accurate exercise, as it makes mining and beneficiation easier [48].

Figure 14 is the data of the 111 analyzed mineral vein widths, which shows that the vein widths of the study area vary from 1cm to 11.50m (with an exponential time stamp of $y^2 = 0.9993$), unlike what had earlier obtained in the barite vein studies of the Benue Trough. As seen in Figure 14b, the most frequently occurring vein widths, out of 111 measurements, are those between 1 cm to 1m, which make up 64.9% of the total measurements. Out of this 1cm to 1m, 11cm to 20cm (Fig 14a) is the highest occurring vein width. 22.5% is between 1-2m, 7.2% is between 2.1-3m, 2.7% is between 3.1-4m, 1.8% is between 7-8m and 0.9% ranges between 4-7m in intervals and 11.5m respectively. The 11.5m vein width has NE-SW trend at Enyigba, although there is evidence of faulting (Fig. 11e) by the presence of slickenlines. This indicates that the smaller veins (0-4m) are by far more frequently occurring than wide veins (5-11m). Barite veins of the Benue Trough have 6m width [48]. From figure 13d and 14d, the most frequently occurring trends of the veins deposit within the trough are in150-160^o (NW-SE) and NNE-SSW (0^0-20^o from N) trends. Looking at figure 14d, the most frequently occurring vein widths within the southern part of LBT ranges from 0-2m in the NW-SE and NNE-SSW orientations. These two orientations are the two 'ac' extension fracture directions of the Benue Trough which belong to the two deformation episodes of the Trough. During the first phase of deformation in the trough, maximum principal stress (σ_1) oriented in the NW-SE direction and formed NW-SE vein sets which is the first vein sets to form in the trough [48]. In the second phase of deformation, maximum principal stress (σ_1) oriented at NNE-SSW direction producing NNE-

SSW veins sets which were parallel to σ_1 at that time [48]. The NW-SE vein sets brecciated as a results of the new second deformational episodes stress configuration, hence the resulted joints were taken over by neomineralization fluids from the later deformational phase[48].

The dip angles of the mineral veins (fig. 9c, 13c & 14c), indicates high angle steeply dipping vein deposits existing within the trough. This is because, the most frequently occurring vein dips are between 80-90^o making up 57.7% of the total dip values and medium dips of 50 to 70^o which make up 31.5% of the total dips. Present also are dips of 32 to 48^o, making up 10.8%of the total. it is important to note that dip angles between 72 – 90^o make up 72% of the total dips (fig. 9c, 13c & 14c) and these comes mostly from NW-SE, and NNE-SSW 'ac' extension fractures. Also note that the vein dips above 60^0 are more common than less. The concentration of some of the dips of NE-SW and ESE-WNW at the high to medium range dips, indicates that they are really *'bc'* tensile fractures. The vein-filling mineral in this study area are not only lead ore (galena), zinc ore (sphalerite), but also includes siderite, quartz, pyrite, chalcopyrite, calcite, marcasite, etc. The later are altogether subsidiary mineralization.

In the upper and middle crustal rocks, veins are prevalent and can influence crack propagation due to their strength and stiffness, in contrast to their host rocks [83]. Vein-fracture interaction most common examples are crack-seal veins [69]. Therefore, in the presence of a reactive fluid, successive sets of parallel fractures are assumed to correspond to crack-seal patterns that are propagated by a subcritical crack formation mechanism; and such fractures represents a time-sequence record of an aseismic and anelastic process of rock deformation [71]. At the vein-host rock interfaces, crack seal veins are formed called antitaxial veins or when there is repeated fracturing with sealing localized inside the vein, syntaxial veins are formed [14, 15, 19, 70]. Only one persistent growth plane of a vein is a syntaxial vein growth [14, 70, 79, 81]. But when vein crystals grow inside the vein, while growing towards the wall rock, from a median line, having two persistent growth planes on the outer surface of the vein, antitaxial vein growth occurs [14, 35, 68, 85]. In the case of the vein minerals of the study area, they are mostly syntaxial vein (fig. 11b), because vein observed appears not to have median line with two persistent growth planes.

5. Discussion

The mineral vein patterns of the study area are tightly structurally controlled, just as found in other parts of the world. Example: The Alcudia Valley Pb-Zn deposit in the southern central part of the Iberian Peninsula, Eastern Sierra Morena Spain, are structurally controlled by WNW–ESE synclines and anticlines with reverse and normal faults hosting Zn–Pb–Cu mineralization along the fold axes [67]. The South Pennine Pb-Zn orefield of Central England is structurally controlled or localised by faults or fracture systems of Carboniferous (Dinantian) limestone host rocks [42]. The tungsten vein-type deposits in the "tungsten belt" Central Rwanda, hosted by quartz veins is structurally controlled by large secondary anticlinal folds, which contain numerous higher order folds [28]. The Broken Hill Pb-Zn-Ag Deposit of New South Wales, Australia is majorly structurally controlled by folds [84]. The gold mineralization in Elizabeth British Columbia, localized in NE trending, steeply NW dipping vein systems [76], etc.

The structures which control the geometry of the vein minerals have been analyzed in this study. The rocks which host the vein minerals are the black hard compacted shale covering 80% of the study area, while sandstone make up 20%. In this study, two units of the host rocks have been designated. Unit A is a hard-compacted shale and sandstone which is the main host of the mineralization, while Unit B is the weathered, bleached, pinkish gray to brownish shale which does not host mineralization.

Early and recent authors had reported on the trends of this mineralization. Some agreed the ore deposit trends N-S or N15^{0}W [24, 64]. While others reported N-S and NW-SE trend of the mineralization [55, 47, 61, 2]. It is noted that the more common NE-SW fractures are barren [55, 25]. But in this present study, six trends of this mineralization are obtained. This include the main prominent NW-SE, NNE-SSW and / N-S directions, while the less prominent ones are in the ESE-WNW, E-W and NE-SW directions. With these vein orientations, new locations of the occurrences of this mineralization can be obtained. Because the world is now tending towards green energy due to global climate change, Pb-Zn mineralization is now an important ore deposit, since lead is used in production of car batteries [29, 37], including electric cars.

It is quite evident in this study that fractures/joints including folds and faults controlled the orientations and geometry of the veins, as seen in other parts of the world. For example: Aplite and quartz deposit in Igarra schist belt of SW basement complex of Nigeria trends in N – S and NW – SE directions and moderately/steeply dipping in E – W and N – S direction [80], Broken Hill Pb-Zn-Ag Deposit of New South Wales, Australia, majorly controlled by fold [84], Tungsten Deposits in Central Rwanda controlled by anticlinal fold [28], etc. In comparison with what was obtained at Ikom-Mamfe basin, the NW-SE and NNE-SSW and / N-S are the two 'ac' extension fracture preferred orientation of the joints and mineral veins of the study area, while the NE-SW, ESE-WNW and / E-W orientations are the two 'bc' tensile fractures and veins [48, 49, 51]. The NW-SE joints & vein sets of the 'ac' extension fractures are perpendicular to the axis of the first deformation fold (f_1) axis, while the NE-SW fractures and veins are the 'bc' tensile fractures parallel to f_1 and to the axis of the trough [48, 50, 51]. The NNE-SSW and N-S joints & veins sets are interpreted as 'ac' extension fractures of the second deformation episode perpendicular to the fold (f_2) axis, while the ESE-WNW and E-W joints & veins sets are the 'bc' tensile fractures of the second deformation episode parallel to the resultant fold axes (f_2) [48, 50, 51]. The N-S and E-W are very few but so weak joints and vein sets of the second episode, which may have formed at the very late stage of the deformation. These joints and vein minerals were thought to have developed during the first episode of folding of Asu River Group sediments.

The two 'ac' extension fracture and vein sets are by far in the majority and are the most important trends, compared to other orientations. While the less important orientations occur in the 'bc' tensile fractures and bedding plane structures which are called 'mineral flats'[27] as well as shear fracture planes. But the widest vein (11.5m) observed at the field occur along the 'bc' tensile fractures of the first episode (NE-SW) contrary to what [25, 55] averred. It has a blocky shape with evidence of faulting around the vein deposit, (Fig. 11e). Along the NW-SE petals, mineralization occurs more especially between at 150-160^{o} SE, although it has a range of 135-175^{o} SE (Fig. 9d & 13d). This is because, 150-160^{o} fracture trends are more predominate occurring compare to other trends in the study area. Therefore, the favoured trends of mineralization within this study area is 150^{0}-160^{o} SE and 1^{0}- 20^{0} North.

Since the NW-SE fractures and veins sets are more predominant compare to NNE-SSW to N-S fracture and vein sets of the ‘ac’ extension fractures, and that of the NE-SW veins are more compared to ESE-WNW veins of the ‘bc’ tensile fracture sets, it could be inferred that the stress configuration that produced the NW-SE fracture and veins sets persisted much longer than and are different from that which produced the NNE-SSW fracture and veins sets [48] ,which is also the same with the ‘bc’ counterparts. This possibly occurred if fluid pressure remained the same during the post-sedimentary deformation in the trough [48]. This study reveals that NE-SW fracture sets are not more common as claimed by [25, 55]. Rather it is NW-SE fracture sets followed by NNE-SSW fracture sets are more common and are highest in population. These mineral veins loaded in the ‘ac’ extension fractures of the trough are parallel to σ_1 directions and are also perpendicular to the fold axis (f_1, f_2) formed with them [50, 51]. These ‘ac’ extension fractures and veins are parallel to the maximum principal stress (σ_1) which produced them and the direction in which such discontinuities can expand is that parallel to the minimum principal stress (σ_3) [20, 50]. Maximum principle (σ_1) was in the NW-SE during the first episode (Lower Cretaceous) and NNE-SSW, during the second episode (Upper Cretaceous), in the trough and both stress orientations produced folds. The first fold (f_1) axis is oriented in the NE-SW while the second episode (f_2) axis are in the ESE-WNW directions [50].

The preference for medium range to wider veins of the NW-SE and NNE-SSW orientations is quite consistent in the trough, irrespective of the host rock type and they are medium to high dip angle (Fig 13c & 14c). Such consistency in mineral vein geometry, which is also observed in the trough and Ikom-Mamfe basin, is now a safe diagnostic criterion to identify the ‘ac’ extension fractures, as well as the directions of maximum compression [48, 49, 50, 51].

The growth of these mineral deposits in the study area is seen to be enhanced by crack – seal process as noticed in Fig. 11a [69]. Mineralizing fluids, even though they invade all available discontinuities in a sedimentary formation, including bedding planes, can most successfully develop mineral veins, by the ‘crack-seal’ mechanism along ‘ac’ extension fractures [18, 50, 69, 70]. The evidence of crack – seal process was seen along the vein walls of the wall rock as small calcite and quartz minerals aligned parallel to the vein walls [50, 69, 70]. This study has successfully indicated the prominent orientations of the prospective mineral veins and this knowledge should guide those who are carrying out surface exploration and geophysical traverses for Pb-Zn mineral deposits in the study area.

The vein widths of the study area vary from 1cm to 11.50m. 1 - 6m width in the barite studies of the Benue Trough have been reported [48]. While 2 to 20m width of the Pb-Zn deposit have been documented [2] but was not obtained throughout the three years of gathering data for this study. The majority of the veins sampled in the first (NW-SE) and second (NNE-SSW) generation categories of veins are narrow in width, ranging from 0.2 to 2m (Fig. 11b, d). This is an indication that the hydrothermal fluids which these veins precipitated out were not highly pressurized and were probably deficient in essential solutes [48]. But there is a vein that is up to 11.5min width bigger than what was obtained at Barite veins of the Benue Trough with 6m width [48].

6. Conclusion

The southern part of the Lower Benue Trough is an important region of Pb-Zn mineral deposits, just like Pb-Zn mines in Red Dog Alaska, Missouri, Colorado, Idaho and Montana in U.S.A, Rampura Agucha mine in India and Mount Isa mine in Australia. The deposit correct orientations are now revealed in this study, for proper exploration and exploitation. Other important huge mineral deposits within the area include, limestone and salt brine fluids. The main host rocks are the hard-black compacted shales and sandstones.

Since geologic structure controls mineral deposits, e.g. gold mineralization in Elizabeth British Columbia, localized in NE trending, steeply NW dipping vein systems; aplite and quartz deposit in Igarra schist belt of SW basement complex of Nigeria trends in N – S and NW – SE directions and moderately/steeply dipping in E – W and N – S direction; Ikom – Mamfe basin and the Benue Trough of Nigeria barite mineralization emplaced mainly in extension fractures. The study area is emplaced in extensional-tensile fracture vein system. The deposits are controlled by faults, folds and joints. It has six orientations, including NW-SE, NNE-SSW and/ N-S main trends and NE-SW, ESE-WNW and E-W minor trends. With these trends, exploration targets are made easy, as new locations of occurrences can be found following these trends.

The similarity of attitudes of the fracture sets as well as the mineral veins sets indicates that the fractures were the main conduits for mineralizing fluids, where the vein deposits were formed through crack-seal process. The lead-zinc mineral veins are placed mainly in the two ‘ac’ extension fractures set (NW-SE, NNE-SSW or N-S) and rarely in the two ‘bc’ tensile fractures set (NE-SW, ESE-WNW or E-W). These two generations of ‘bc’ tensile fractures (NE-SW, E-W to ESE-WNW) in this study area indicate the presence of two independent folds axes (f_1, f_2) corresponding to two deformational episodes in the trough. The widest Pb-Zn vein in the area is 11.5m in width, which occurred in NE-SW orientation in Enyigba mineral axis of the study area. The first episode of deformation probably produced more vein deposits, with widths ranging from 0.2-7m. while the second episode, probably produced fewer veins in a N-S to NNE-SSW direction with a majority of the widths ranging from 0.1-3.5m.

REFERENCE

1. Adeigbe O. C. and Jimoh A. Y. (2014). Rare Earth Elements Fingerprints: Implication for provenance, tectonic and depositional Settings of Clastic Sediments of Lower Benue Trough, Southeastern Nigeria. *New York Sci Jour*., 7(2):11-26.

2. Akande, S. O, Mucke, A. and Umeji, A. C. (1990). Mineralogical, Textural and paragenetic Studies of the Lead-Zinc Copper Ores in the Lower Benue Trough and their genetic implications. *Journal Mun. Geol. 26, 127-165.*

3. Avbovbo, A. A., Ayoola, E.O., and Osahon, GA., (1986). Depositional and structural styles in the Chad Basin of northeastern Nigeria. Am. Assoc. Pet. Geo. Bull., 70(12): 1787- 1789.

4. Bain, A.D.N. (1924). The Nigeria Coalfield: Section1 Enugu Area. With Appendices by R.B. Newton and A.C. Seward, Geol. Survey of Nigeria bulletin. No. 6.

5. Belayneh, M and Cosgrove, J. W. (2010). Hybrid veins from the southern margin of the Bristol Channel Basin, UK. Journal of Structural Geology. 32, 192–201.

6. Benkhelil J., and Robineau, B. (1983). Le fossé de la Bénouéest-il un rift? Bulletin des Centres de Recherches. Exploration-Production Elf-Acquitaine 7, 315 – 321.

7. Benkhelil, J. (1982). Benue Trough and Benue chain. Geological Magazine 119, 155 – 168.

8. Benkhelil, J., and Guiraud, R. (1980). La Bénoué (Nigéria): une chaine intracontinentale de style atlasique. ComptesRendus de l´Academie des Sciences Paris (D) 290, 1517 – 1520.

9. Binks, R.M. and Fairhead, J.D., (1992). A plate tectonic setting for Mesozoic rifts of West and Central Africa. In: P.A. Ziegler (Editor), Geodynamics of Rifting, Volume II. Case History Studies on Rifts: North and South America and Africa. *Tectonophysics,* 213: 141-151.

10. Black, R. (1980). Precambrian of West Africa. Episodes 4:3–8.

11. Burke, K., Dessauvagie F.T., and Whiteman, A. J. (1971). Opening of the Gulf of Guinea and Geological History of the Benue depression and Niger Delta. *Natur. Phys. Sci., 233, 51-55.*

12. Burke, K.C. (1976). The Chad Basin: an active intra-continental basin. Tectonophysics, 36: 197-206.

13. Carter, J. D., Barber, W., Tait, E.A and Jones, G. P. (1963). The geology of parts of the Adamawa, Bauchi and Bornu provinces in northeastern Nigeria. Geol. Surv. Niger. Bull., 30: 53-61.

14. Cox, S. F. (1987). Antitaxial crack-seal vein microstructures and their relationship to displacement paths. *Journal of Structural Geology* 9, 779-787.

15. Cox, S. F. (1991). Geometry and internal structures of mesothermal vein systems: implications for hydrodynamics and ore genesis during deformation. In: *Structural geology in mining and exploration. Extended abstracts* 25. Univ. Western Australia, 47-53.

16. Cratchley, E. R., Louis, P., and Ajakaiye, D. E. (1984). Geophysical and geological evidence for the Benue-Chad Basin Cretaceous rift valley system and its tectonic implications. J. Afr. Earth Sci., 2(2): 141-150.

17. Davis, G. H and Reynolds, S. J. (1996). Structural Geology of Rocks and Regions. John Wiley and sons. 371p.

18. Davison, I. (1995). Fault slip evolution determined from crack-seal veins in pull-apart and their implications for general slip models. *Journal of Structural Geology* 7, 1025-1034.

19. Durney D. W and Ramsay J. G. (1973)., in Gravity and Tectonics, Incremental strains measured by syntectonic crystal growths, eds DeJong K., Scholten R. (Wiley, New York), pp 67–96.

20. Engelder, T. and Geiser, P. (1980). On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian plateau, New York. J. Geophys. Res., 85(11), 6319-6341.

21. Eze, C. L., Mamah, L.I and Israel-Cookey C. (2004). Very low frequency electromagnetic (VLF-EM) response from a Lead Sulphide lode in the Abakaliki Lead/Zinc Field, Nigeria. *Int. Jour. of Applied Earth Obser. and Geoinf., Vol. 5, Issue 2, pp. 159-163.*

22. Fairhead, J. D. (1988). "Mesozoic Plate tectonic reconstruction of the Central South Atlantic Ocean: the role of the West and Central Africa Rift systems". *Tectonophysics, 155, 181-191.*

23. Farrington, J. L. (1952). A preliminary description of the Nigerian lead-zinc field. Econ. Geol. 47:583-608.

24. Fatoye F. B., and Gideon Y. B. (2013). Geology and mineral resources of the Lower Benue Trough, Nigeria. *Adv. Appl. Sci. Res., 4(6):21-28.*

25. Fatoye F. B., Ibitomi M. A. and Omada J. I. (2014). Lead-Zinc-Barytes mineralization in the Benue Trough, Nigeria: Their geology, occurrences and economic prospective. *Adv. Appl. Sci. Res., 5(2):86-92.*
26. Fitton, J. G. (1980). The Benue trough and Cameroon line - A Migrating rift Systemin West Africa. *Earth and Planetary Science Letters,* 51, 132-138.

27. Fyfe, W. S., Price, N. J and Thompson, A.B. (1978). Fluids in the Earth's Crust: Their Significance in Metamorphic, Tectonic and Chemical TransportProcesses. *Developments in Geochemistry 1, Elsevier Scientific Publishing Company Amsterdam - Oxford - New York, pp 383.*

28. Goldmann, S., Melcher, F., Hans-Eike,G., Stijn, D., De Clercq, F., and Muchez, P. (2013). Mineralogy and Trace Element Chemistry of Ferberite/Reinite from Tungsten Deposits in Central Rwanda. *Minerals, 3*, 121-144.

29. Gottesfeld, P., and Pokhrel, A. (2011). Review: Lead Exposure in Battery Manufacturing and Recycling in Developing Countries and Among Children in Nearby Communities. Journal of Occupational and Environmental Hygiene 8(9): 520-32.

30. Guiraud, R., and Maurin, J. E. (1992). Early Cretaceous rifts of Western and Central Africa: an overview. In: P.A Ziegler (Editor), Geodynamics of Rifting, Volume II. Case History Studies on Rifts: North and South America and Africa. Tectonophysics, 213: 153-168.

31. Haruna, I. V. (2017). Review of the Basement Geology and Mineral Belts of Nigeria. IOSR Journal of Applied Geology and Geophysics. Volume 5, Issue 1 Ver. I, PP 37-45.

32. Haruna, I. V., and Mamman, Y. D. (2005). A Brief Review of Some Metallogenetic Features of Uranium Mineralization in the Upper Benue Trough, N.E. Nigeria. *Technology and Development Journal, 9*, 1–8.

33. Haruna, I. V., Orazulike, D. M., Ofulume, A. B., and Mamman, Y. D, (2011b). Petrochemical and mineralogical constraints on the source and processes of uranium mineralization in the Granitoids of Zing-Monkin area, Adamawa Massif, N.E Nigeria. *Natural Resources Research, 20 (4),* 355-366.

34. Haruna, I. V., Valdon, Y. B., and Mamman, Y. D. (2011a). Uranium prospecting in an area around Mika, Adamawa Massif, N.E. Nigeria: A Research Note. A Research Note. *African Journal of Physical Sciences, 7 (3),*105-109.

35. Holland, M., and Urai, J. L. (2010). Evolution of anastomosing crack–seal vein networks in limestones: Insight from an exhumed high-pressure cell, Jabal Shams, Oman Mountains, J. Struct. Geol., 32(9), 1279–1290.

36. Hoque, M., and C. S. Nwajide. (1984). Tectono-sedimentary evolution of an elongate intracratonic basin (Aulacogen): The case of the Benue Trough of Nigeria. Nig. *Jour. Min. Geol., 21: 19-26.*

37. International Tin Association (2017). Lead-Acid Batteries impact on future tin use. Technical Report.

38. Koehn, D., Arnold, J and Passchier, C. W. (2005). Fracture and vein patterns as indicators of deformation histories: a numerical study. Geological Society of London, Special Publications, 243, 11–24.

39. Kogbe, C.A., (1989). The Cretaceous and Paleogene Sediments of Southern Nigeria. Geology of Nigeria 2nd Edition. Rock View (Nig) Ltd, pp. 325-334.

40. Mackay, R. A. (1950). “The lead-zinc veins in the Lower Cretaceous of Nigeria” *Proc. Int. Geol. Cong. XVIII Session pt. Vl. pp 217-220.*

41. McConnell, R. B. (1949). Notes on Lead-Zinc Deposits of Nigeria and Cretaceous Stratigraphy of Benue and Cross River Valley. *Geol. Surv. Nig. Report No. 408.*

42. Mostaghel, M. A. (1985). Sphalerite mineralogy and trace element geochemistry in the South Pennine Orefield. Proceedings of the Yorkshire Geological Society, Vol. 45, Part 3, Pp. 207-218.

43. Murat, R. C. (1972). Stratigraphic and Paleogeography of the Cretaceous and Lower Tertiary in Southern Nigeria. *Africa Geology, University of Ibadan press, 251-269.*

44. Nwachukwu S. O. (1972). The tectonic evolution of the Southern Portion of the Benue Trough, Nigeria. Geol. Mag. 109, pp 411-419.

45. Obaje, N.G., Weher H., Scheeder G., Abubakar M.B., and Jauro, A. (2004). Hydrocarbon prospectivity of Nigerian’s Inland Basin: From view Point of Organic Geochemistry and Organic petrology. *American Association of Petroleum Geologist (AAPG) Bulletin, 88(3): 325-353.*

46. Obaje. N. G. (2009). Geology and Mineral Resources of Nigeria. Springer Dordrecht Heidelberg London New York.

47. Obarezi J. E., and Nwosu J. I. (2013). Structural controls of Pb-Zn mineralization of Enyigba district, Abakaliki, Southeastern Nigeria. Journal of Geology and Mining Research, Vol. 5(11), pp. 250-261.

48. Oden, M. I. (2012). Barite veins in the Benue Trough: Field characteristics, the quality Issue and some tectonic implications. Environment and Natural Resources Research, 2(2), 21–31.

49. Oden, M. I. and Udinmwen, E. (2014a). Fracture characterization, mineral vein evolution and the tectonic pattern of Igarra syn- tectonic granite, southwestern Nigeria. British Journal of Applied Science and Technology. 4(17), 2417–2429.

50. Oden, M. I., Egeh, E. U and Amah, E. A. (2015). The Ikom –Mamfe basin Nigeria: A study of fracture and mineral vein lineament trends and Cretaceous deformations. Journal of African Earth Sciences. 101; 35–41.

51. Oden, M. I., Umagu, C. I and Udinmwen, E. (2016). The use of jointing to infer deformation episodes and relative ages of minor Cretaceous intrusive in the western part of Ikom –Mamfe basin, southeastern Nigeria. Journal of African Earth Sciences 121, 316-329.

52. Offodile, M. E. (1976). The geology of the Middle Benue, Nigeria. Publications from the Paleontological Inst. Of Univ. Uppsala, Spec. Pub., V4, 166p.

53. Ofogbu, C. O. (1985). A review of the geology of the Benue Trough of Nigeria. *Jour. Afric. Earth Sci. 3, 283-29.*

54. Ogwuma, S.D.N. (1974). Geology and mineralogy of Ameka lode in Abakaliki Lead-Zinc area. *Unpub. B.Sc thesis, University of Ibadan, 37pp.*

55. Oha, I. A., Onuoha, K. M., & Dada, S. S. (2017). Contrasting styles of lead-zinc-barium mineralization in the Lower Benue Trough, Southeastern Nigeria. Earth Sciences Research Journal, 21(1). 7 – 16.

56. Ojoh, K. A. (1992). Southern Part of the Benue Trough, Nigeria Cretaceous Stratigraphy, Basin Palaeo-oceanogphy and Geodynamic Evolution in the Equatorial domain of The South Atlantic, N.A.P.E., Bulletin, vol.2.

57. Okezie, C. N. (1957). "A preliminary report on the igneous rocks of Abakaliki town and environs and their relation to Lead-Zinc mineralization", *G. N. S., Rpt., No 1349 (unpublished).*

58. Okezie, C. N. (1965). The Abakaliki Pyroclastics. Rept Geol. Surv. Nigeria (*unpublished.*

59. Okoro, A. U., Igwe, E.O. and Nwajide, C.S. (2016). Sedimentary and petrofacies analyses of the Amasiri Sandstone, southern Benue Trough, Nigeria: Implications for depositional environment and tectonic provenance. Journal of African Earth Sciences, 123, 258-271.

60. Olade M. A and Morton R.D (1980). Temperatures of ore formation and origin of the ishiagu Lead-Zinc Deposit, Southern Benue Trough, Nigeria. *Jour. Min. Geol. 17(2): 119-127.*

61. Olade, M. A and Morton, R. D. (1985). origin of lead-zinc mineralization in the Southern Benue Trough, Nigeria – Fluid inclusion and trace elements studies. *Mineralium Deposita 20, 76 – 80*

62. Olade, M. A. (1975). Evolution of Nigeria's Benue Trough (Aualcogen): A tectonic model. *Geol. Mag. 112, 575-578.*

63. Olade, M. A. (1976). On the genesis of Lead-Zinc deposit in Nigeria's Benue Rift (Aualcogen): A re-interpretation. *Jour. of Ming. Geol. 13, 20-27*.

64. Orajaka, S. (1965). The Geology of Enyeba, Ameri and Ameka Lead-Zinc lodes, Abakaliki Division, Eastern Nigeria – A reconnaissance. *Jour. of Ming. Geol. Vol. 3, pp 49-51.*

65. Orajaka, S. (1972). Salt water Resources of East Central State of Nigeria. *Jour. of Ming. Geol. 3: 49-51.*

66. Orazulike, D.M. (1994). The mineralogy and Texture of Lead-Zinc-Copper Ores of Enyigba lode, Abakaliki, Enugu State, Nigeria. *Journal of Mining and Geology, Vol. 30. No.1, pp.25-32.*

67. Palero-Fernaˊndez, F. J and Martıˊn-Izard, A. (2005). Trace element contents in galena and sphalerite from ore deposits of the Alcudia Valley mineral field (Eastern Sierra Morena, Spain). Journal of Geochemical Exploration 86 (2005) 1 – 25.

68. Petit, J.-P., Wibberley, C.A.J., & Ruiz, G. (1999). 'Crack-seal', slip: a new fault valve mechanism? *Journal of Structural Geology* 21, 1199-1207.

69. Ramsay, J. G. (1980). The crack–seal mechanism of rock deformation, Nature, 284(5752), 135–139.

70. Ramsay, J. G., and M. I. Huber (1983). The Techniques of Modern Structural Geology Vol. 1: Strain Analysis, Academic Press, New York.

71. Renard F, Andréani M, Anne-Marie B., and Labaume, P. (2005). Crack-seal patterns: records of uncorrelated stress release variations in crustal rocks. D. GAPAIS; J. P. BRUN; P. R. COBBOLD; Eds. Deformation mechanisms, rheology and tectonics: from mineral to the Lithosphere. Geological Society of London Publication, pp.81-95, Special Publication 243. Hal-00105219.

72. Reyment, R. A. (1960). Studies on Nigerian Upper Cretaceous and Lower Tertiary Ostracoda Part 1: Senonian and Maastrichtian Ostracoda. Stoch. Contr. Geol. V. 7, 232P.

73. Reyment, R.A. (1965b). The Cretaceous Ammonoidea of Southern Nigeria and Cameroons. *Bull. Geol. Surv. Nig. No 25.*

74. Reyment, R.A. (1965a). Aspect of Geology of Nigeria. Ibadan, University press P. 30.

75. Short, K. C. and Stauble, A. J. (1967). Outline of Geology of Niger Delta. *Bull. Am. Assoc. petrol. Geol. 5, 761-40.*

76. Siddorn, J and Lee, C. (2005). Structural geology of the Elizabeth gold project, British Columbia. SRK Consulting, SRK 2CJ003.002.

77. Tattam, C. A. (1950). "General Aspect of the Nigeria Lead-Zinc Field", *Ret. To A. T.M.N. Ltd., pp 1-10 (unpublished).*

78. Thompson, A. B. (1997). Flow and focusing of metamorphic fluids. *In: Jamtveit, B. & Yardley, B.W.D. (eds.), Fluid flow and transport in rocks, Chapman & Hall, London*.297-314.

79. Toriumi, M. and Hara, E. (1995). Crack geometries and deformation by the crack-seal mechanism in the Sambagawa metamorphic belt. *Tectonophysics* 245, 249-261.

80. Udinmwen, E., Oden, M. I., Ayuba, R, and Asinya, A. E. (2016). Structural Control on Mineral Vein Geometry in the Igarra Schist Belt, Southwestern Nigeria. Journal of Earth and Atmospheric Sciences Vol. 1, No. 1, pp. 10-21.

81. Urai, J. L., and Williams, P. F. (1991). Kinematics of crystal growth in syntectonic fibrous veins, J. Struct. Geol., 13, 823–836.

82. Uzuakpunwa, A. B. (1974). The Abakaliki Pyroclastics, Eastern Nigeria: new age and tectonic implications. *Geol. Mag. Vol. 111, pp 761-769.*

83. Virgo, S., Abe, S., and Urai, J. L. (2014). The evolution of crack seal vein and fracture networks in an evolving stress field: Insights from Discrete Element Models of fracture sealing, J. Geophys. Res. Solid Earth, 119, 8708–8727.

84. Webster. A. E. (2004). The Structural Evolution of the Broken Hill Pb-Zn-Ag Deposit, New South Wales, Australia. MSc Thesis, University of Tasmania.

85. Williams, P. F. & Urai, J. L. (1989). Curved vein fibres: an alternative explanation. *Tectonophysics* 158, 311-333.

86. Wilson, R. C. L., and Williams, C.A. (1979). Oceanic transform structures and the development of Atlantic continental margin sedimentary basins - A review. J. Geol. Soc. Lond. 138, 311-320.

87. Zhang, Y., Schaubs, P. M., Zhao, C., Ord, A., Hobbs, B. E and Barnicoat, A. (2008). Fault-related dilation, permeability enhancement, fluid flow and mineral precipitation patterns: numerical models. In: C. A. Wibberley, W. Kurz, J. Imber, R. E. Holdsworth, C. Collettini (Eds.) The Internal Structure of Fault Zones: Implications for Mechanical and Fluid-Flow Properties, Geological Society, London, Special Publications, 299, 239–255.

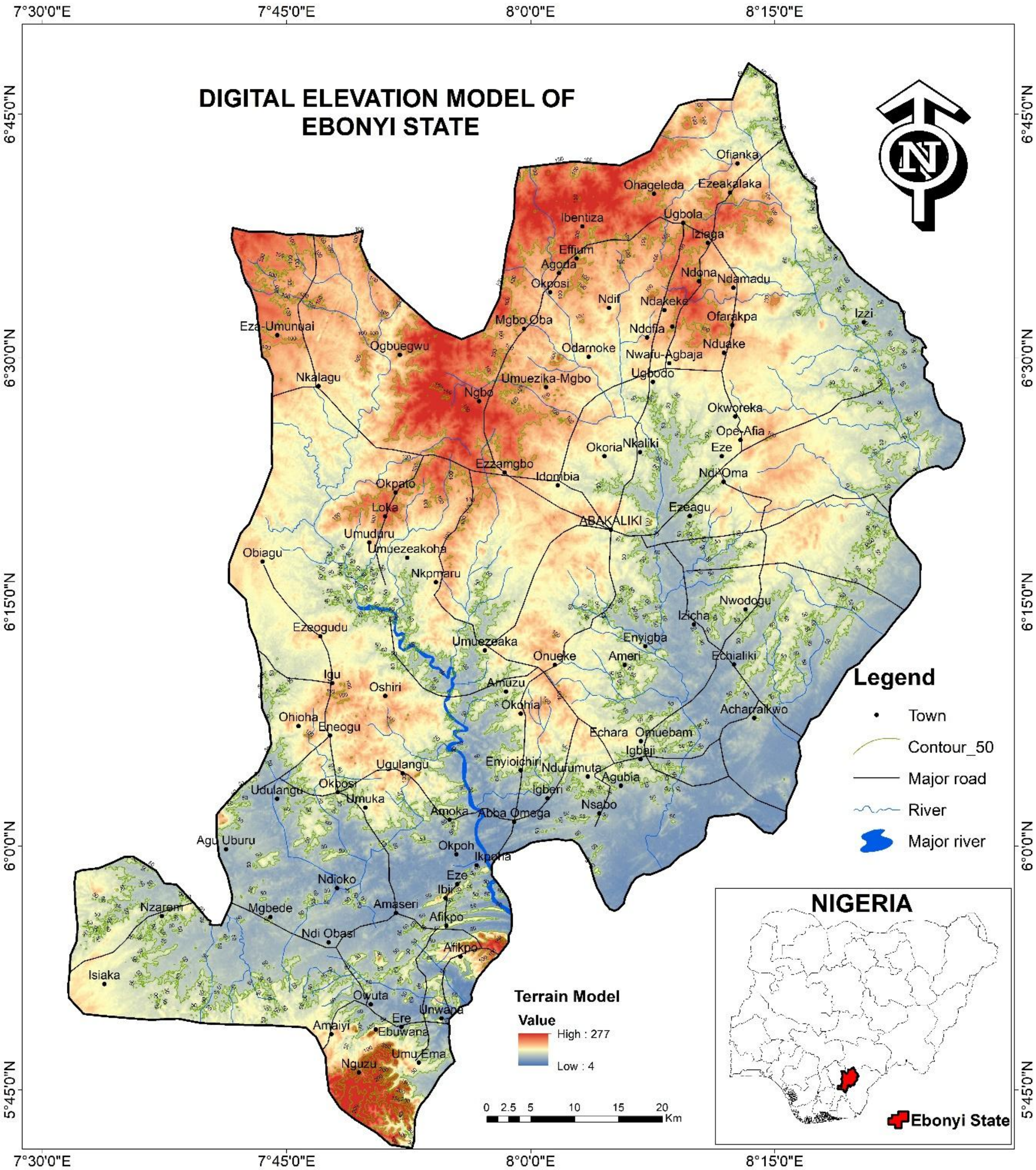


Figure 1: Topographic Map of the Study Area

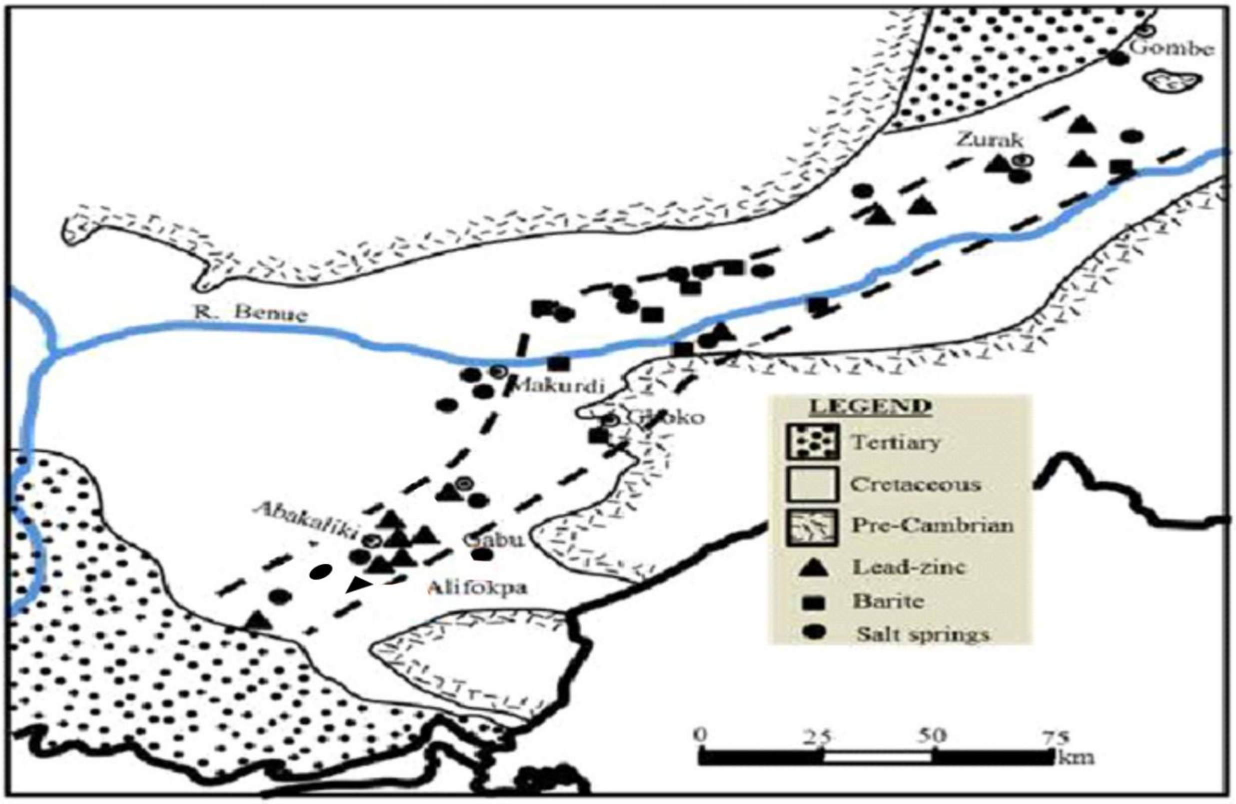


Figure 2: Distribution of lead-zinc-barite and salt mineralization along the Benue Trough, Nigeria (after Oden, 2012).

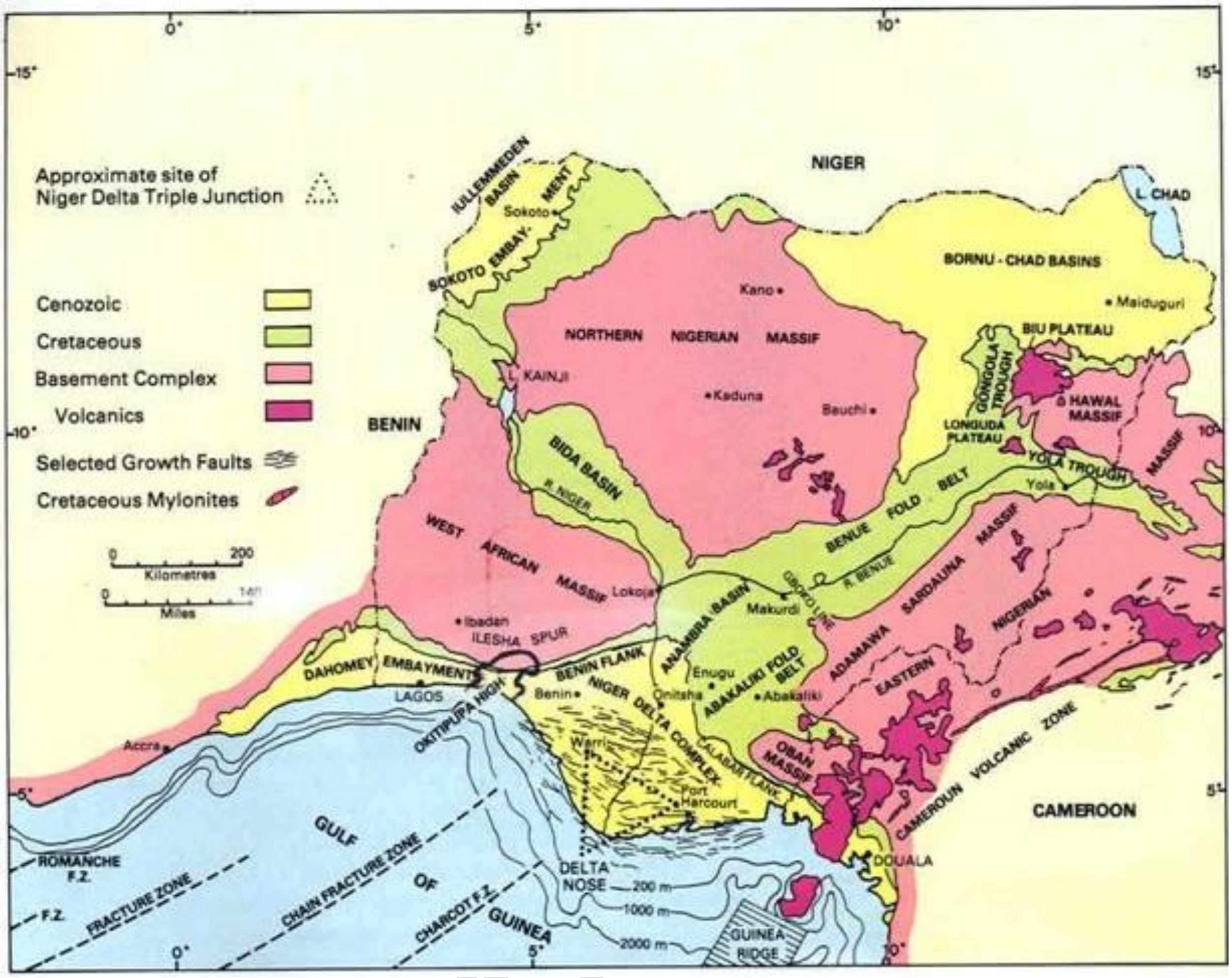


Figure 3a: Geological Map of Nigeria showing Romanche, Chain and Charcot extension fractures zones from Mid-Atlantic ridge to the Nigerian coastline, Benue Trough, Basement Complex and Volcanics,

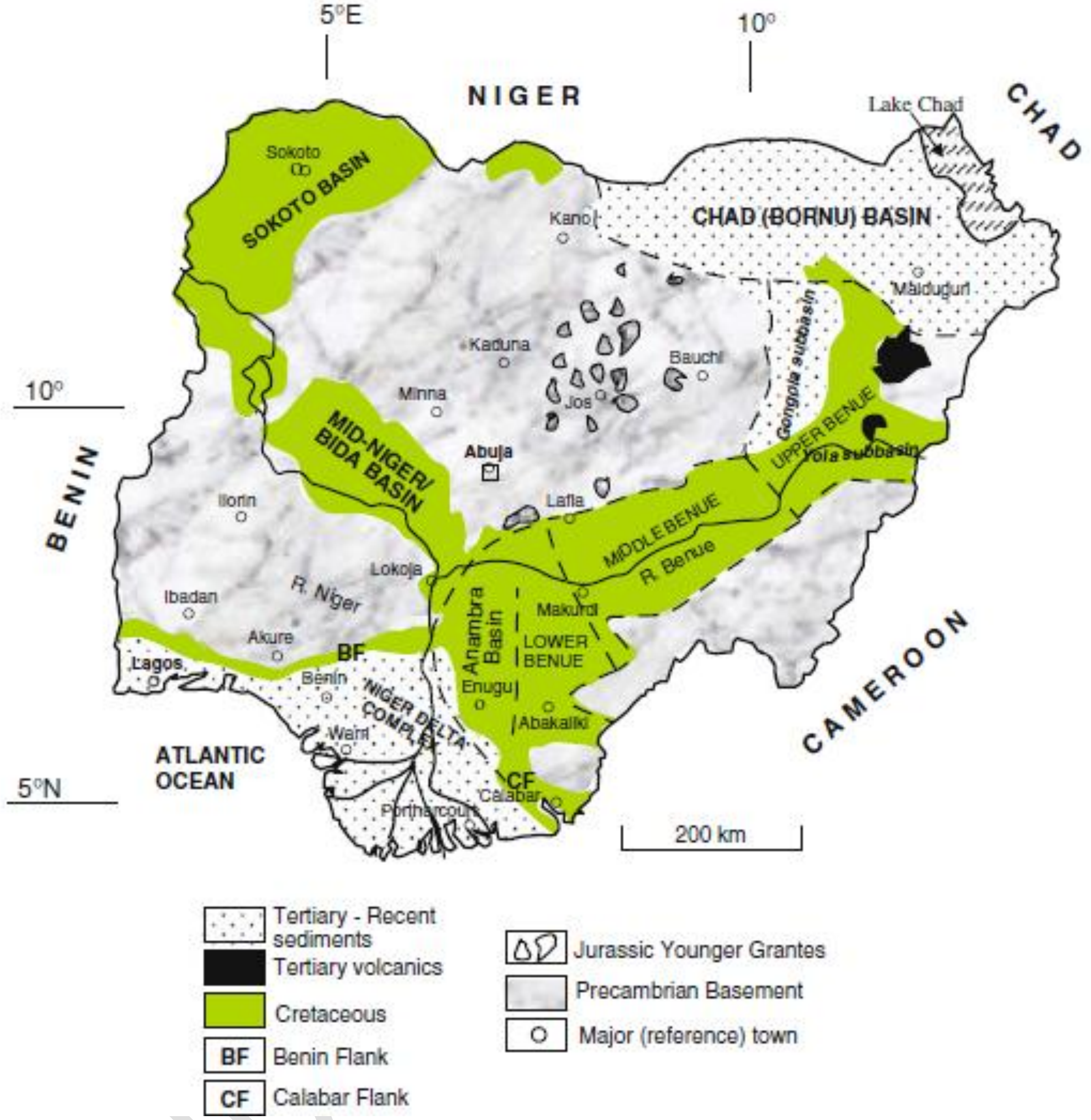


Figure 3b: Geological Map of Nigeria showing majorly shows the arbitrary partitioning of Benue Trough with other sedimentary basins, Basement Complex and Younger Granites (after Whiteman, 1982; Obaje, 2009).

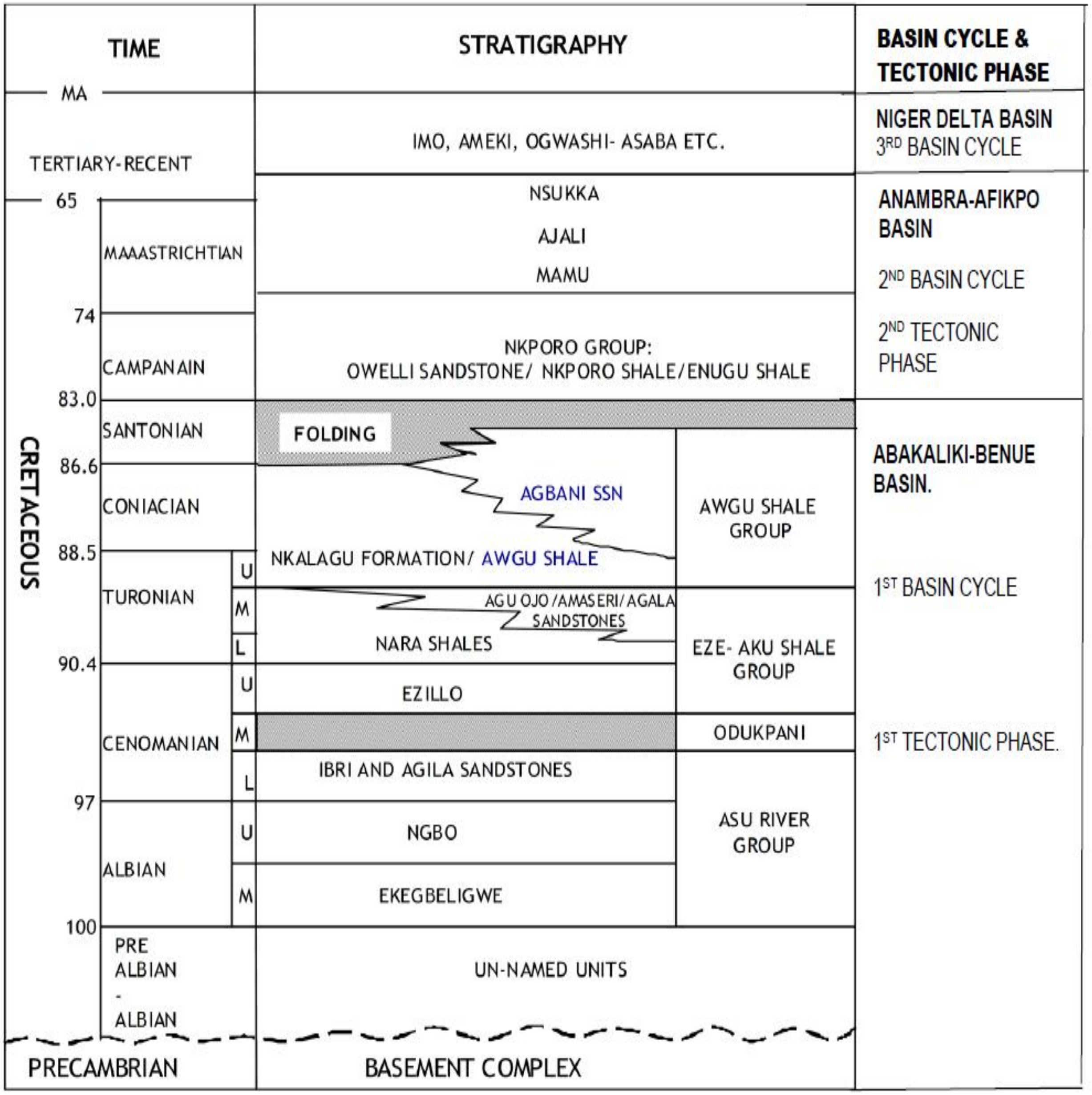


Figure 4: Summarized Stratigraphy of the Southern Benue Trough and Anambra Basin (Modified after Reyment, 1965; Ojoh, 1992; Okoro et al, 2016).

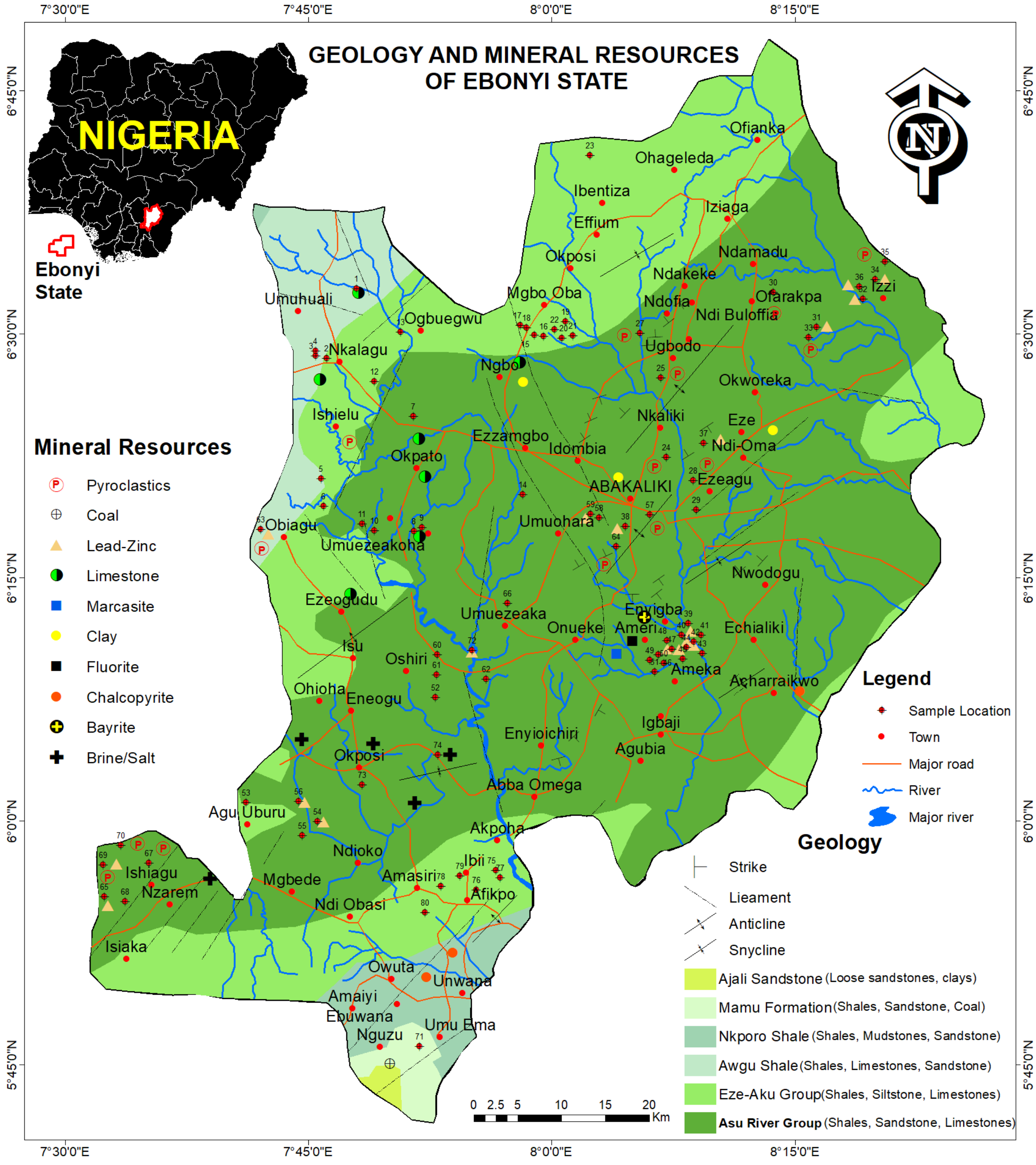


Figure 5: Geology, Structural and Mineral Resources of the Study area.

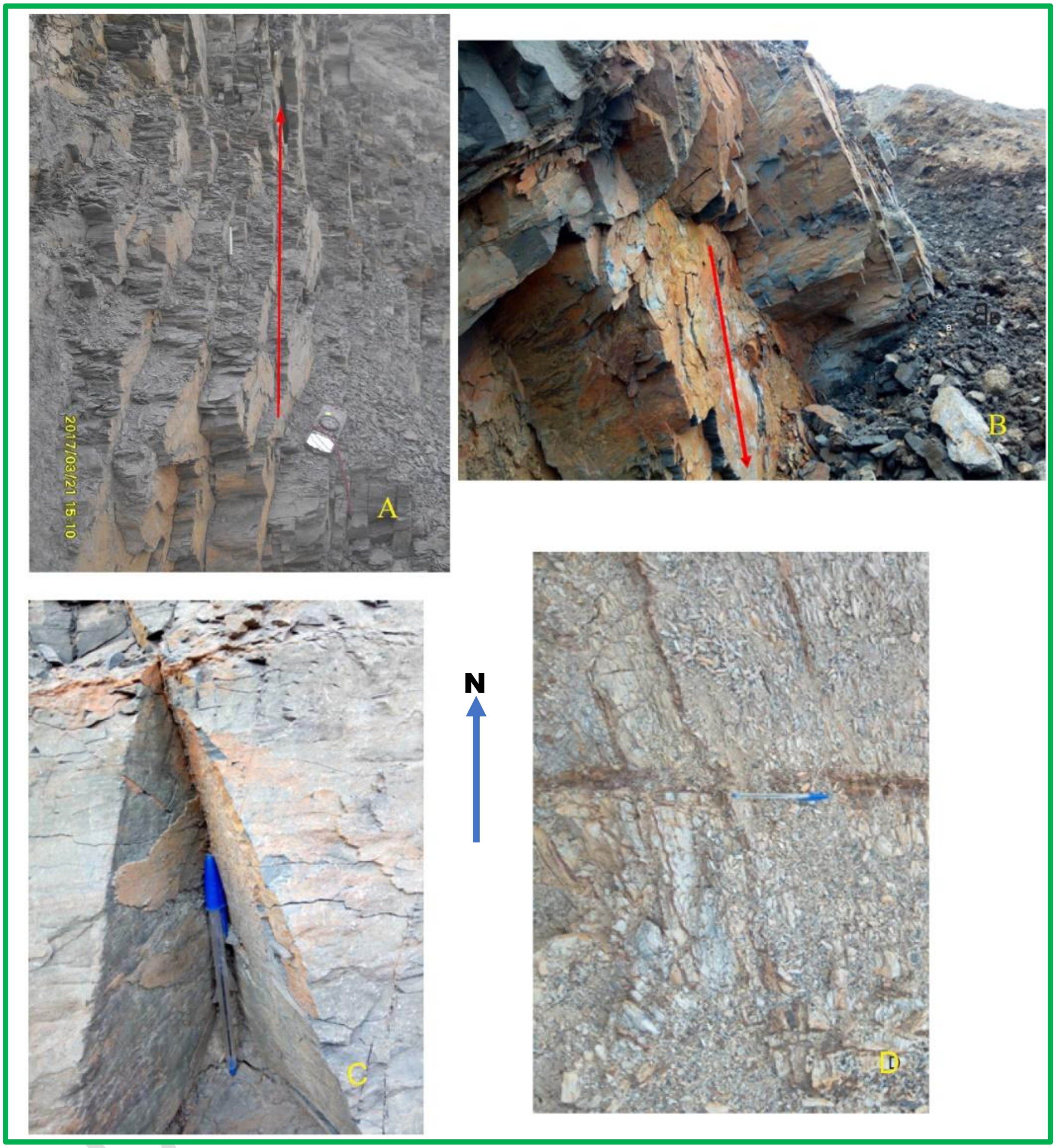


Figure 6: Style of fracture occurrences (a) vertical long trending fractures (b) steep dip of fracture (c) conjugate fractures, (d) cross fractures.

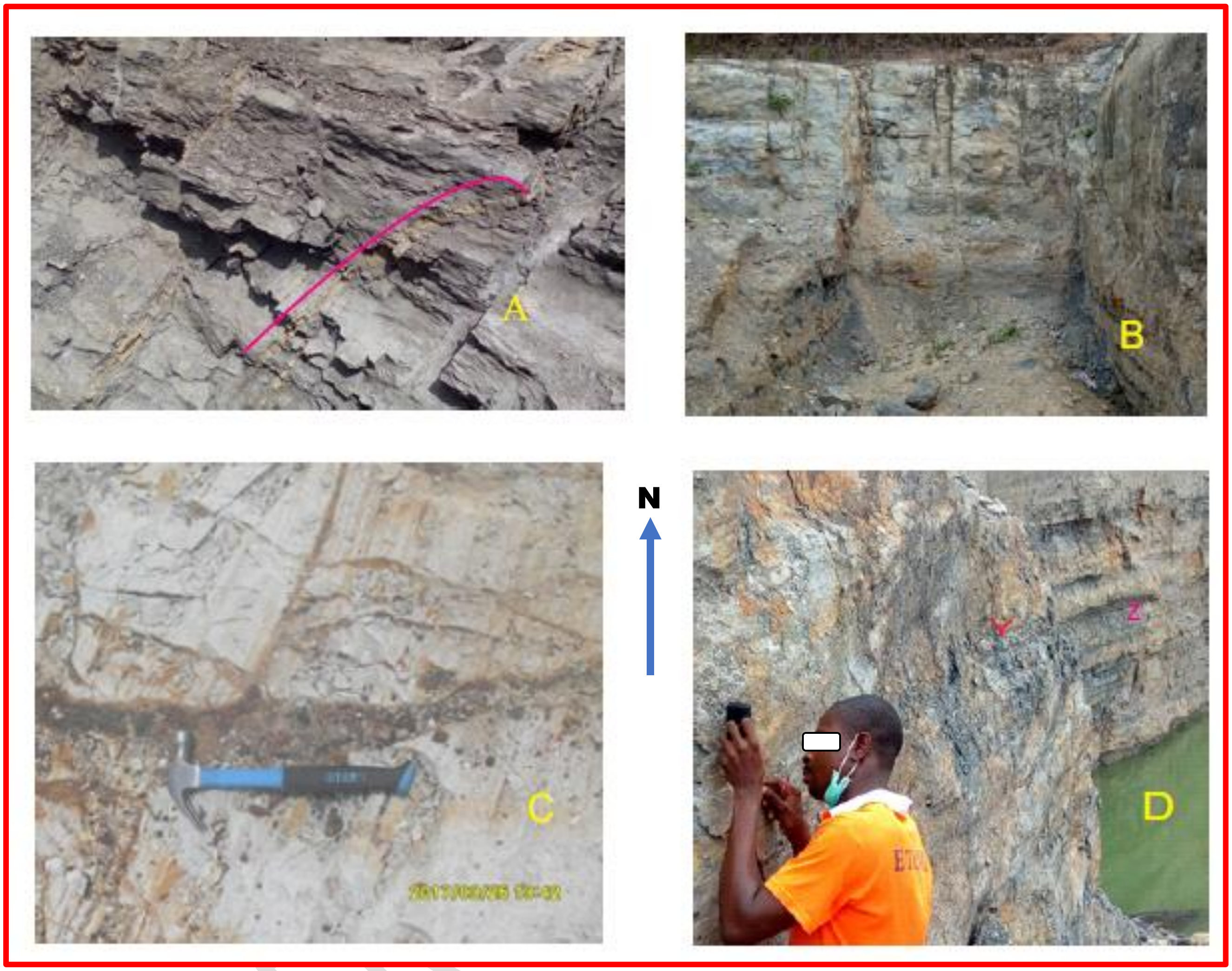
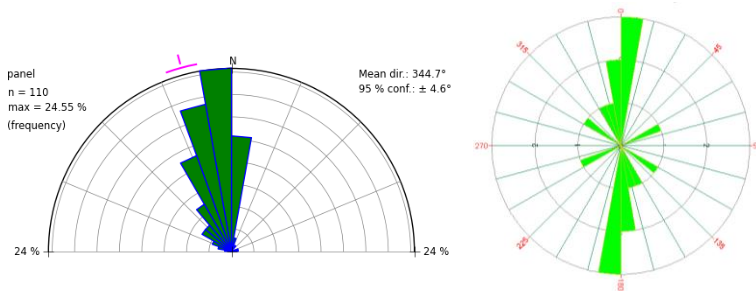


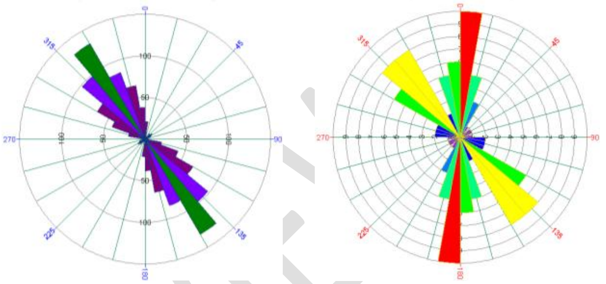
Figure 7: Fracture occurrences at the sandstone zones. (a) curved fracture at the shale, (b) long trending vertical fractures, (c) T-junction fracture, (d) terminating fracture at Uburu.



Dominant Trends

Joints: NW-SE, NNE-SSW, NE-SW, E-W   Vein: NNE-SSW, NW-SE, NE-SW

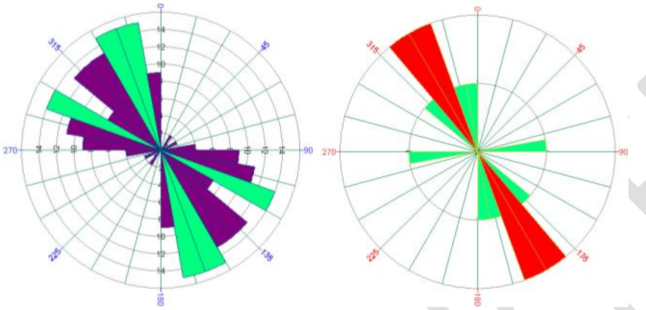
a) Abakaliki Zone



Dominant Trends

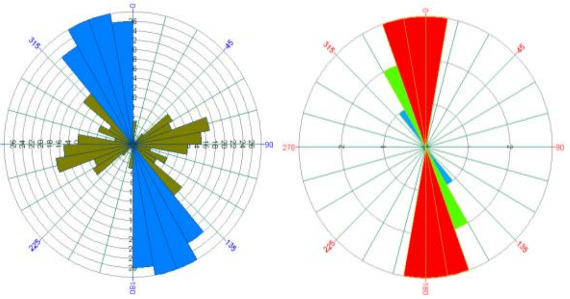
Joints: NW-SE, NNE-SSW, NE-SW   Vein: NNE-SSW, NW-SE, WNW-ESE, NE-SW

b) Enyigba Zone



Dominant Trends

Joints: NW-SE, N-S, WNW-ESE, NE-SW, E-W   Vein: NW-SE, N-S, E-W



Dominant Trends

Joints: NW-SE, N-S, WNW-ESE, NE-SW, E-W   Vein: NW-SE, NNE-SSW, N-S

c) Izzi Zone

Joint Rose diagram

Vein Rose diagram
N

Joint Rose diagram

N

Vein Rose diagram

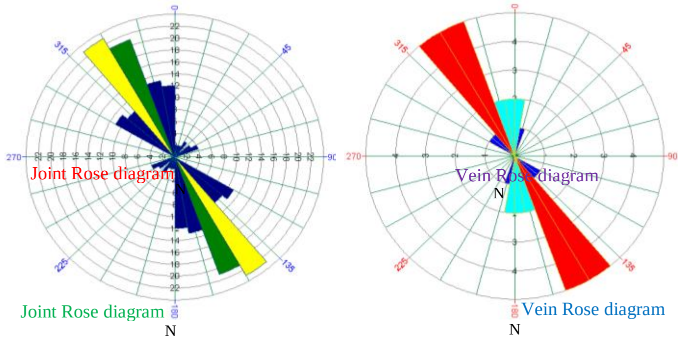
N

Figure 8: Joints and Mineral Vein sets Rose Diagram of (a) Abakaliki zone, (b) Enyigba zone, (c) Izzi zone, (d) Uburu zone and (e) Ishiagu zone of the study area indicating the dominant

n = 9

n = 602

n = 63



Joint Rose diagram
N

Vein Rose diagram
N

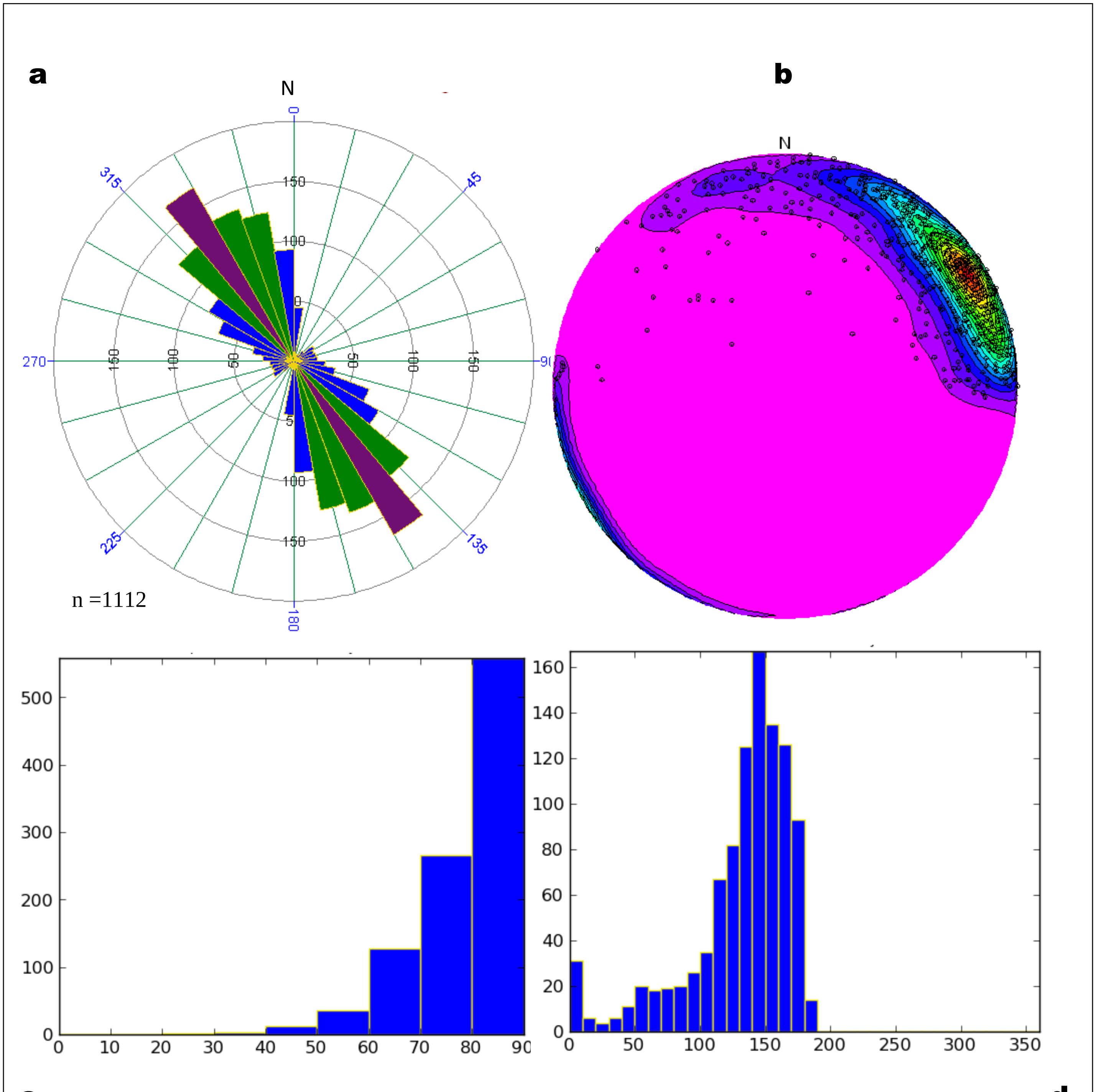
d) Uburu Zone

Dominant Trends

Joints: NW-SE, N-S, NNW-SSE, NE-SW   Vein: NW-SE, NNE-SSW, N-S

e) Ishiagu Zone

orientations of the vein minerals as well as the fracture orientations.



Histogram of joints/fractures dips values

Histogram of joints/fractures strike values

Figure 9: Composite Joints and Fractures diagrams. The true joints are >70^0 dips, 30-60^0 dips are fractures (a) Composite rose diagram of joints and fractures, (b) Composite Stereogram showing poles to joint and fracture planes, lower hemisphere projection, (c) Composite dip Diagram of joints and fractures (d) Composite strike frequency diagram

Figure 10: Lithologies hosting the mineralization, see text for description. Picture scale: 2.99” x 3.98”

Unit B

Description	Unit
Top lateritic ironstone	B
Greyish brown to pinkish red calcareous fissile, thinly laminated, fractured, weathered but leached shale.	


2017/04/03 12:22
a
2017/04/08 22:54
b
c
d
e
2017/04/06 04:14
f

Figure 11: Vein mineral of the study area, (a) calcite and quartz minerals alignment parallel to the vein walls, as indicated by the arrow, scale: 2.75"x 3.16" (b) Quartz vein growing inward from the wall rock, scale: 2.76"x 3.65" (c,

ines

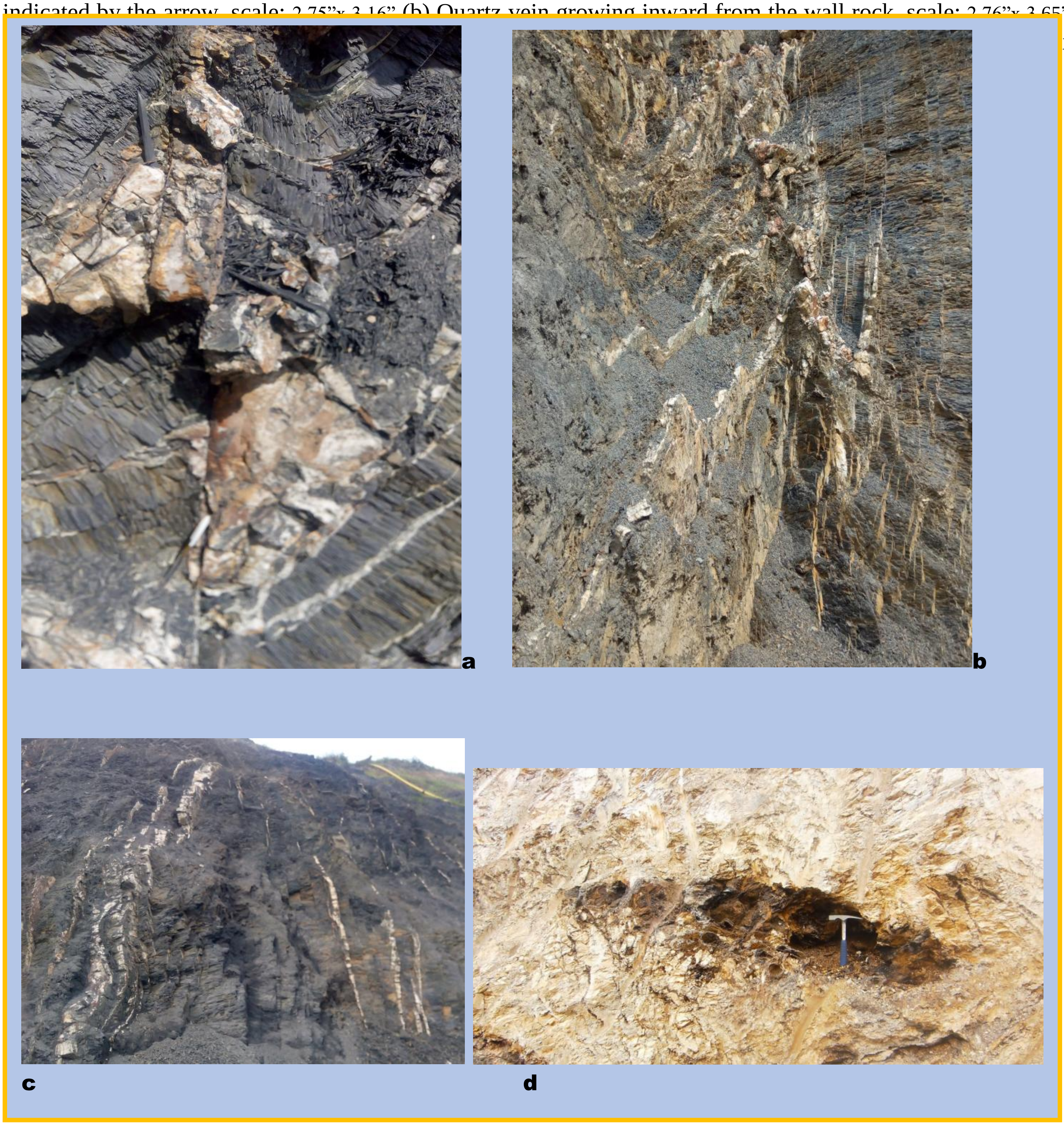


Figure 12: (a) Faulted vein deposit, scale: 4.49" x 3.07". (b) Tight folded vein deposit, scale: 4.45" x 3.21". (c) Anticlinal folded vein deposit, 2.27" x 3.08". All were observed at Enyigba axis. This indicates that faults and folds also control the mineralization. (d) Concordant type of vein occurrence, ellipsoidal in shape, scale: 2.06" x 3.97"

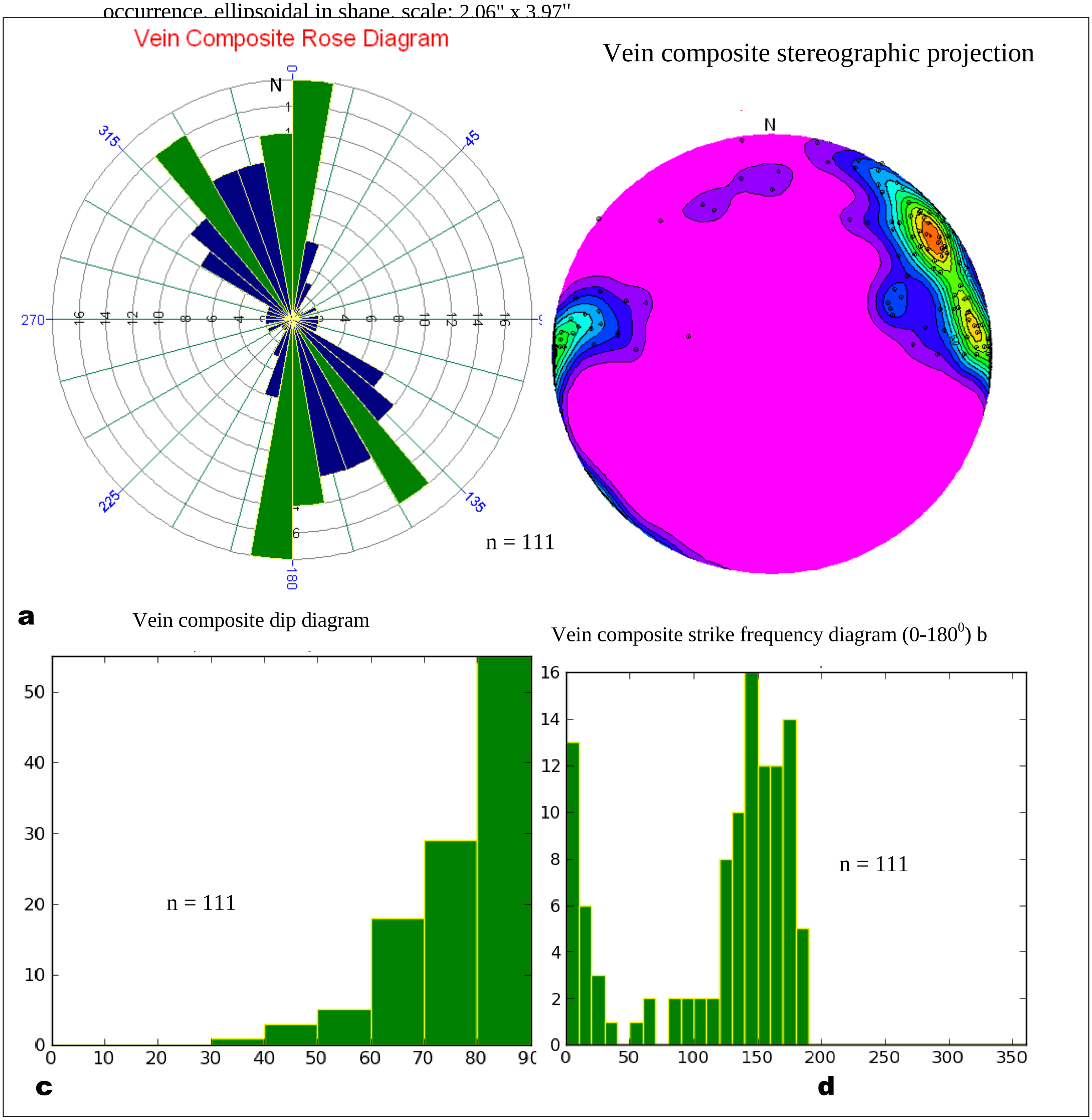


Figure 13: Vein composite digrams, (a) rose digram (b) sterographic projrction of poles to planes (c) dip diagram and (d) strike frequency digram of n = 111 measured vein minerals.

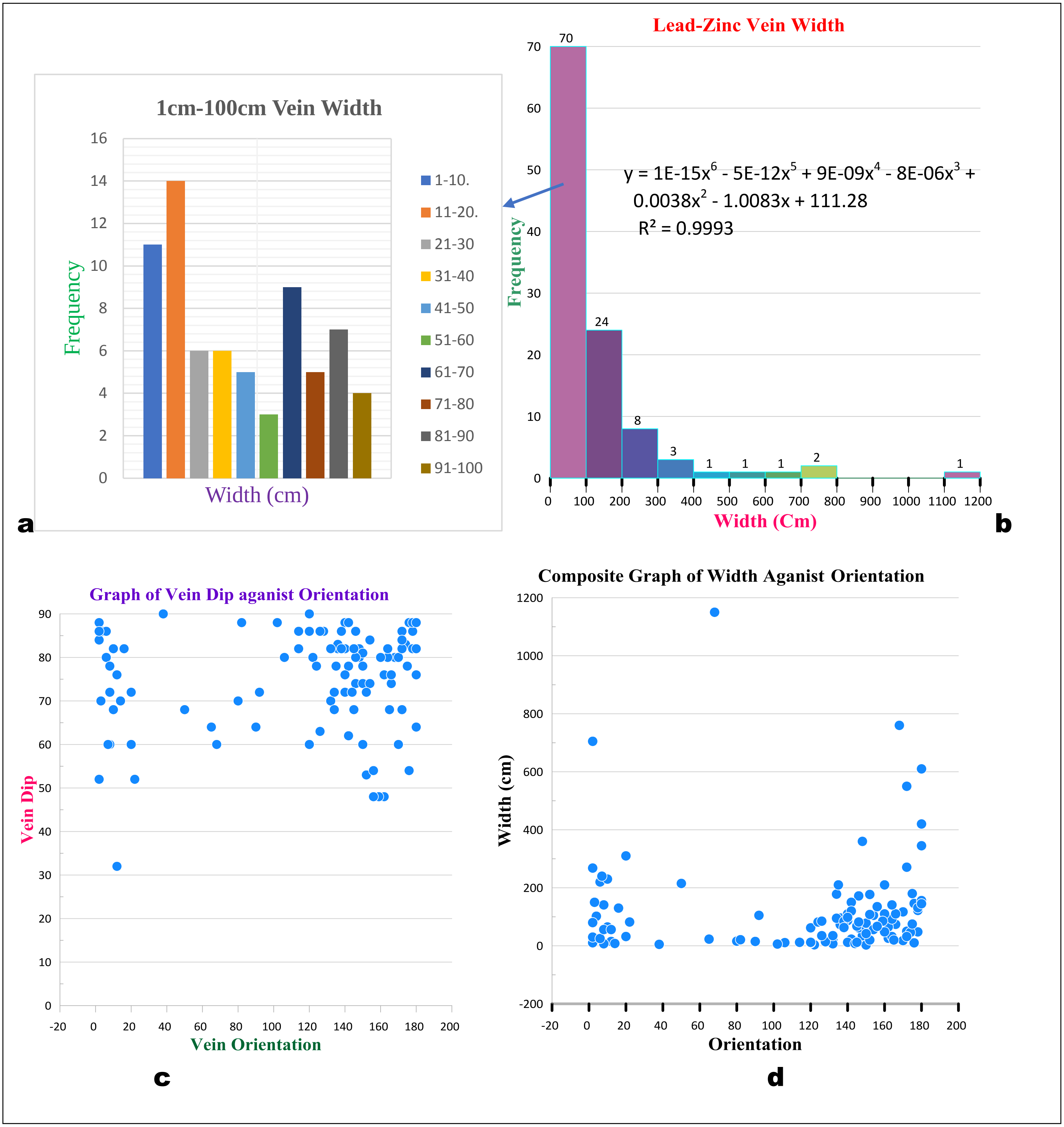


Figure 14: Vein width, dip and orientation description. (a) Histogram of vein width distribution between 1cm-100cm highest occurring vein width. (b) Histogram of Pb-Zn vein width. Note the exponential distribution. (c) Vein dips above 60^0 are more common than less. (d) Two main vein orientations ($0\text{-}20^0$) and ($140\text{-}180^0$), i.e., NNE-SSW and NW-SE