Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Structural Controls and Mineralization Style of Baryte Deposits in the Azara Area, Central Benue Trough, Nigeria: Implications for Mineral Exploration

Diyelmak Victor Bulus

bulusv@unijos.edu.ng

University of Jos https://orcid.org/0009-0009-3644-6139

Research Article

Keywords: baryte, hydrothermal veins, structural control, anticline, radiometric, MVT-like

Posted Date: April 1st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9277014/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Structural Controls and Mineralization Style of Baryte Deposits in the Azara Area, Central Benue Trough, Nigeria: Implications for Mineral Exploration

Diyelmak, Victor Bulus [1] and Ifeanyi, Andrew Oha [2]

[1]Department of Geology, University of Jos, Plateau State, Nigeria

[2]Department of Geology, University of Nigeria Nsukka, Enugu State, Nigeria

*Correspondence: bulusv@unijos.edu.ng

Abstract

Baryte mineralization in the Azara area, central Benue Trough, Nigeria, occurs with base metals and considered generally as part of an epigenetic, structurally controlled hydrothermal system hosted mainly by Cretaceous siliciclastic rocks with minor carbonate interbeds. This study evaluates the structural controls, vein geometry, and mineralization style of the Azara deposits to unravel ore-fluid pathways and predict exploration targeting. Integrated surface mapping, satellite-image processing, airborne radiometric analysis, and lithologic-structural log data of available exploration drill core were used to assess vein distribution, continuity, and host-rock relationships. The results show that baryte occurs in discrete vein clusters along a major NE–SW structural corridor which coincided with a topographic ridge inferred to be an anticlinal crest. Radiometric data revealed an elongate K-enriched zone which was also corroborated by ternary diagram of the presence of a major structural corridor recognized as Keana anticline extention, while structural analysis indicates a dominant NW–SE vein set with subordinate E–W and minor N–S sets. Drill-core intersections reveal steep to subvertical, bedding-discordant mineralization occuring as massive fissure-fill lodes, breccia infill, stockwork veinlets, and open-space cavity fills. The principal assemblage is baryte with siderite and associated minor chalcopyrite–pyrite, followed by late sphalerite in dilational sites. These relationships indicate a multi-stage hydrothermal system controlled by fold-related fracture connectivity and repeated reactivation of fractures. Although the K anomaly may partly reflect lithologic exposure, the combined structural and radiometric evidence highlights anticlinal crests, vein-set intersections, and dilational jogs as key exploration targets in the central Benue Trough.

Keywords: baryte; hydrothermal veins; structural control; anticline; radiometric; MVT-like.

1.0 INTRODUCTION

1.1 Background to the Study

The baryte–lead–zinc mineralization of the central Benue Trough is widely recognized as epigenetic, structurally controlled, hydrothermal Pb–Zn–Ba mineralization hosted within Cretaceous carbonate and siliciclastic successions of an intracontinental rift basin (Olade, 1985). Across the trough, mineralization is predominantly localized along faults and fracture systems trending NW–SE, NE–SW, and N–S (Akande et al., 1989). These structures developed

during the Early Cretaceous rifting associated with the opening of the South Atlantic Ocean and were later modified by transcurrent tectonics, producing a complex network of wrench faults, normal faults, and fracture corridors along the basin axis (Benkhelil, 1989).

The axial fault system of the Benue Trough comprises NE–SW oriented shear zones, pull-apart basins, and fault-bounded horsts, reflecting alternating compressional and extensional stress regimes (Benkhelil, 1989). Such deformation zones are known to localize hydrothermal fluid flow and vein-hosted mineral assemblages, including Pb–Zn–Cu–Ba–F systems (Murphy et al., 2011; Pe-Piper et al., 2018). Within the central Benue Trough, baryte commonly occurs as veins, veinlets, stockworks, and locally strata-bound lenses along faults, fractures, and bedding planes. These ores are associated with low-temperature saline basinal brines and are commonly classified as Mississippi Valley-type (MVT) or MVT-like carbonate-hosted Pb–Zn–Ba systems (Akinlua, 2015; Nwachukwu et al., 2017; Fatoye et al., 2023; Bute, 2024).

Although regional-scale structural controls on Pb–Zn–Ba mineralization in the central Benue Trough are well established, the district-scale relationships among baryte veins, associated base-metal occurrences, host lithologies, and specific structural domains in the Azara district remain poorly constrained. Previous mapping in the Arufu–Akwana–Azara district (Aladesanmi et al. (2018) and Labe et al. (2018), Figure 1) has shown a strong spatial association between baryte veins and NW–SE- and N–S-trending fracture zones within the Cretaceous Keana Formation and related units, but it has not fully resolved whether baryte and Pb–Zn mineralization formed within the same hydrothermal system or represent structurally distinct mineralizing events. In addition, the relative roles of major rift-related faults, subsidiary fractures, and reactivated structures in controlling ore emplacement remain uncertain. This study addresses these gaps by integrating detailed surface mapping with scout drill-core observations, thereby providing new subsurface constraints on vein geometry, host-rock relationships, shallow geology, and mineralization style.

Therefore, this study aims to determine the structural controls and mineralization style of baryte deposits in the Azara area, Central Benue Trough, Nigeria. To achieve this, the study integrates surface mapping and available drill-core data to: (i) characterize baryte vein style and geometry; (ii) define the hierarchy of vein and fault orientations and evaluate their relationship to the anticlinal architecture; and (iii) assess how host lithology and structural intersections influence mineralization continuity and associated sulphide-carbonate phases. The study ultimately seeks to refine the genetic interpretation of the Azara baryte system and improve exploration targeting for structurally controlled Pb-Zn-Ba mineralization in the central Benue Trough.

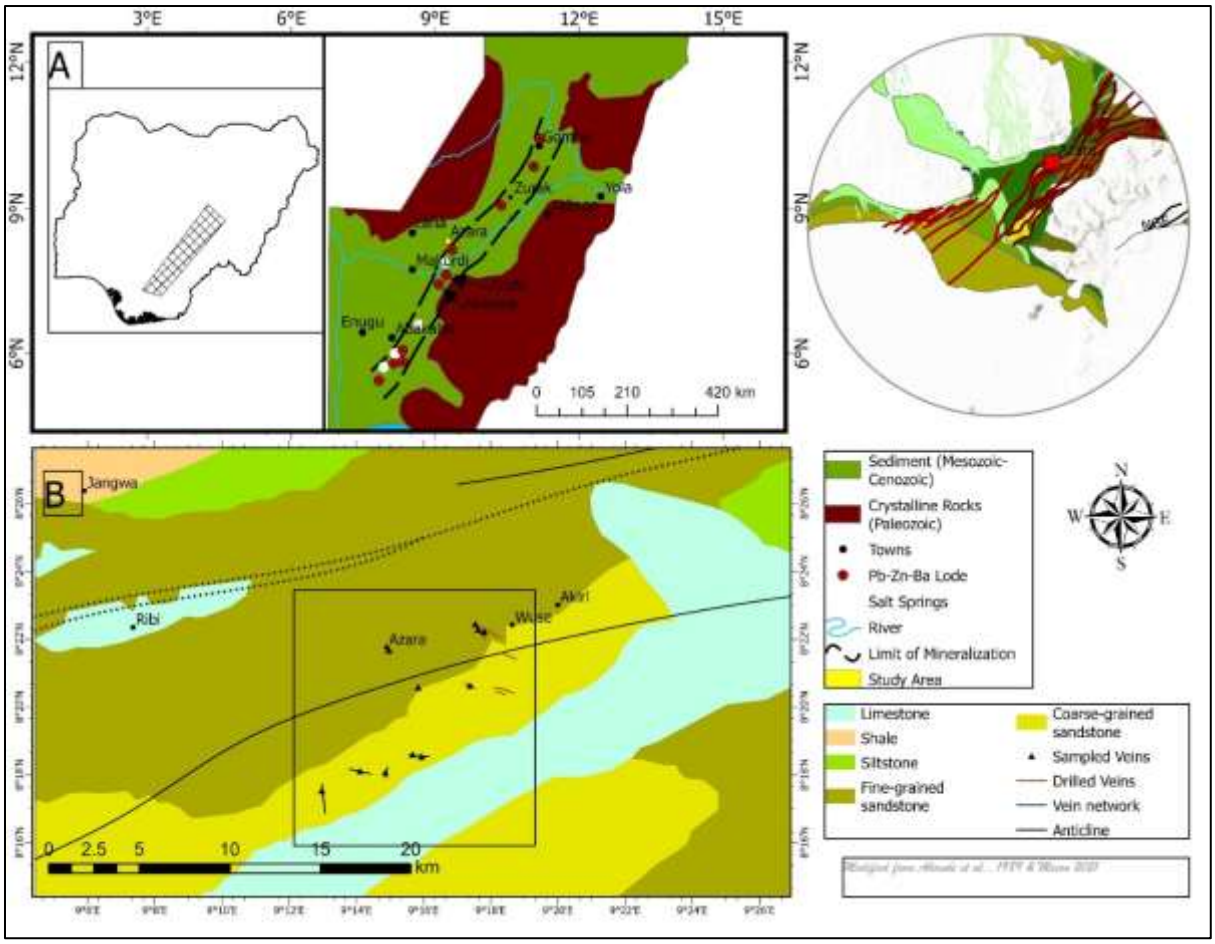


Figure 1: (A) Regional distribution of Pb–Zn–Ba mineralization within the Cretaceous sedimentary basin. (B) Geological and structural map of the Azara district. (Inset) Regional structural configuration of the central Benue Trough (Modified from Akande et al., 1989 and MECON 2021)

1.1 Geologic Setting

The Benue Trough is a NE–SW trending intracontinental rift basin extending for over 1000 km across Nigeria and forming part of the West and Central African Rift System (WCARS) (Benkhelil, 1989; Olade, 1985). The basin developed during the Early Cretaceous in response to the separation of the African and South American plates and the opening of the South Atlantic Ocean (Benkhelil, 1989). Rifting commenced during the Aptian–Albian and was accompanied by crustal extension, lithospheric thinning, and the development of fault-bounded depocenters (Figure 2).

The structural architecture of the trough is dominated by an axial fault system characterized by NE–SW–trending transcurrent and normal faults, which define grabens, half-grabens, pull-apart basins, and basement ridges (Benkhelil, 1989). These structures reflect multiphase tectonic deformation involving early extensional rifting followed by wrench faulting and later compressional inversion, particularly during the Santonian tectonic event (Benkhelil, 1989; Akande et al., 1989). Reactivation of earlier rift faults during subsequent tectonic episodes further modified the structural fabric of the basin.

Sedimentation within the Benue Trough began during the Aptian–Albian with predominantly continental to marginal marine deposits, followed by progressive marine transgression during

the Cenomanian–Turonian (Olade, 1985; Akande et al., 1989). In the central Benue Trough, the Albian–Cenomanian sequences are composed mainly of sandstones, shales, siltstones, and subordinate limestones of the Keana Formation and related stratigraphic units (Olade, 1985). The Turonian–Maastrichtian interval is characterized by marine shales, siltstones, and carbonates, reflecting deeper marine conditions during peak subsidence (Akande et al., 1989). Paleocene–Eocene deposits record a transition toward more continental sedimentation in the northern sector of the basin while marine conditions persisted locally in the south (Benkhelil, 1989, Table 1).

In the Azara area, Cretaceous siliciclastic rocks dominate the stratigraphy and consist of fine- to coarse-grained sandstones, shales, and siltstones with minor carbonate intercalations. These lithologies provide both mechanical contrasts and chemically reactive horizons favourable for vein-hosted mineralization, particularly along structurally prepared zones.

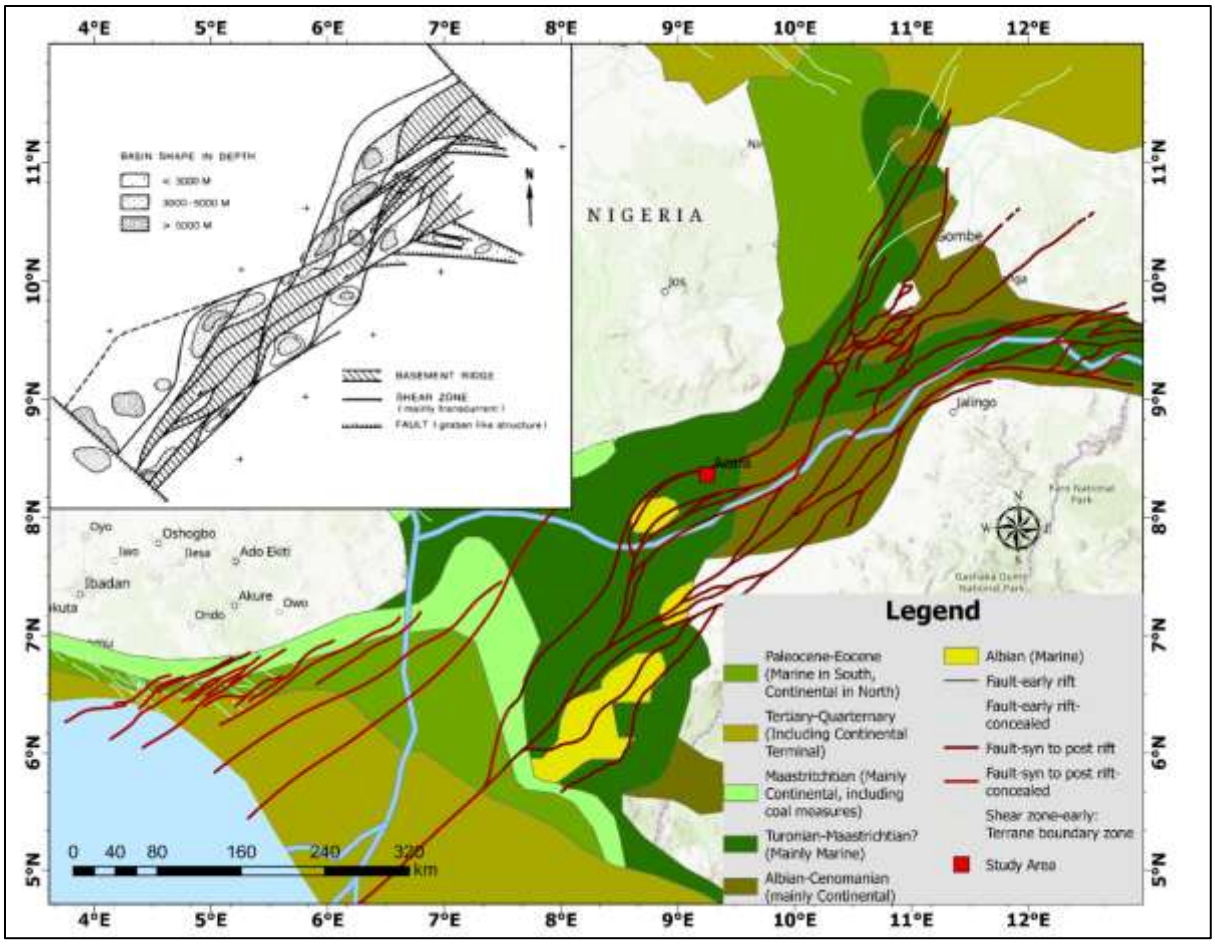
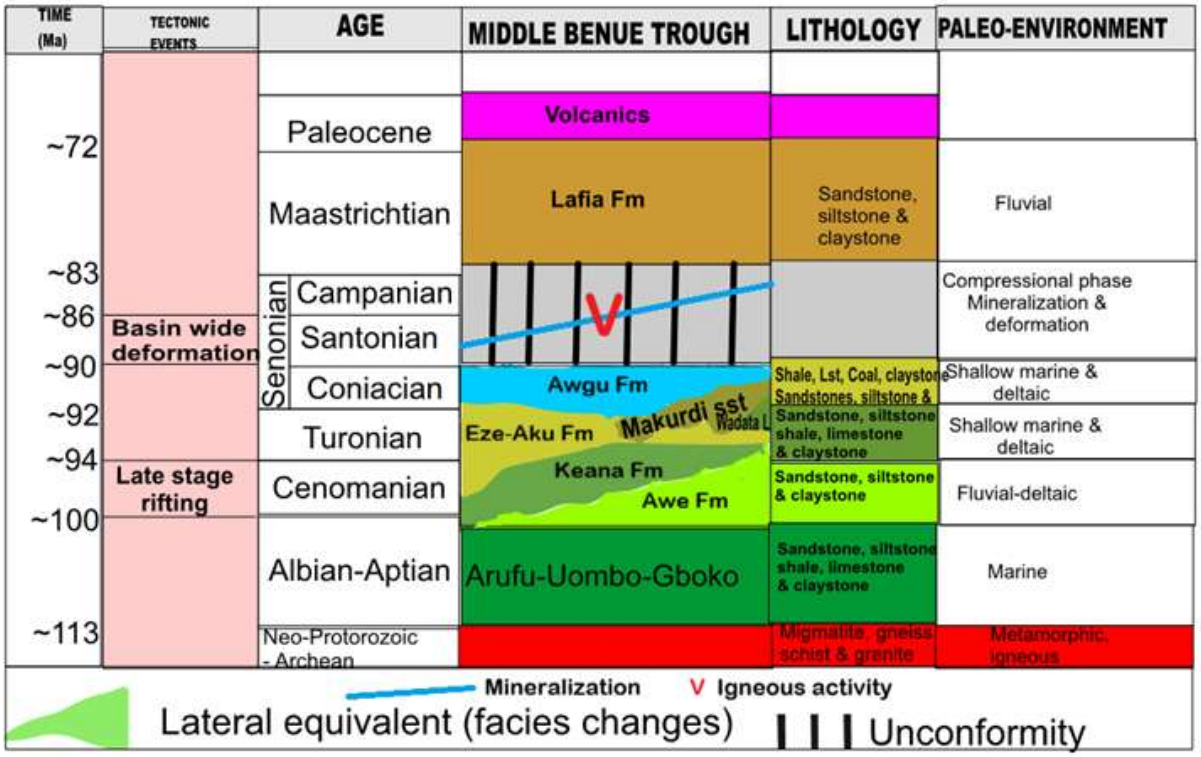


Figure 2: Regional tectono-stratigraphic framework of the Benue Trough, Nigeria, showing the distribution of major sedimentary successions and fault systems controlling basin evolution and mineralization (Modified from Benkhelil, 1989)

Table 1: Generalized stratigraphic, tectonic, and paleoenvironmental framework of the Central Benue Trough (Modified after Olade (1985), Akande et al. (1989), and Benkhelil (1989))



3.0 MATERIAL AND METHODS

3.1 Surface mapping and structural measurements

A reconnaissance study was carried out using satellite imagery derived from Google map to establish the veins distribution and spatial relationships. Also, airborne radiometric data was acquired from the Nigerian Geological Survey Agency (NGSA) and processed to understand the radiometric signatures associated with the host rocks and their relationship to mineralization. The natural gamma-ray spectrometric method has been utilized extensively in identification of alteration zones and lithological delineation using total potassium (K), thorium (Th) and uranium (U) determination (Elkhateeb & Abdellatif, 2019; Abd El Nabi 2013; Elawadi et al., 2004; Grasty and Shives 1997; Maden & Akaryali 2015; Shives et al., 2000 and Youssef & Eldkhodary, 2013). Additionally, the K/eTh ratio map was useful for delineating hydrothermally altered zones, because potassium enrichment accompanied by thorium depletion is commonly regarded as an indicator of hydrothermal alteration in ore-forming environments (Elkhateeb & Abdellatif, 2019). Finally, a ternary radiometric map was generated by combining the concentrations of the three radioelements in the red, green, and blue (RGB) colour channels. All analyses were performed with the aid of Oasis Montaj and Arcmap tools.

The veins were easily accessed through major/minor roads and paths. During the fieldwork, outcrops, active mine workings, and baryte stockpiles at operating mines were systematically examined. Rock-chip and grab samples were collected to identify the local lithologies and obtain representative ore samples from mineralized occurrences. At each sampling location,

coordinates were recorded together with vein geometry, thickness, orientation, and host-rock relationships in situ. Individual veins and vein clusters were mapped at scales of approximately 1:500 to 1:2000, depending on the dimensions and complexity of the exposed mineralization. To support the mapping, tape and compass survey methods was used to guide the vein traverse. Samples collected were assigned a unique identification number and recorded in a field notebook. A total of 50 samples were collected during the mapping exercise, of which 18 were identified as baryte-rich samples from the mineralized samples and were prepared for further geochemical analysis.

Airborne radiometric data were integrated with field mapping to better understand the radiometric signatures of the host rocks and their relationship to baryte mineralization.

3.2 Subsurface data compilation

Given the extensive surface evidence of mineralization and the presence of artisanal workings on several veins, coupled with the limited availability of good natural exposures in the study area, Mecon undertook a systematic scout drilling programme of up to 3,000m on the highest-ranked vein targets. The drilling programme was not designed for resource definition, but rather as an initial investigation to evaluate the quality of the baryte veins and the shallow subsurface geology.

All drill holes were located within approximately 5–9 km south and east of Azara, and targeted Veins 1, 2, 6, 17, 18, Sohon Rami, and Sauki Sarni (Figure 3). These targets are distributed within four main vein clusters, as shown in Figure 3. Collar locations were selected following field reconnaissance, guided by prior examination of Google Earth imagery. A key objective of the programme was to test as many priority targets as possible within the available timeframe. Except for the large Vein 1 system, all drill holes were less than 105 m deep. Collar positions were established using a hand-held GPS. Drill azimuths were measured along a line defined by a taut string extending from the drill stem to a pre-determined point fixed by GPS and checked with a compass. The drill rigs, sourced from India and France, were not equipped with wireline systems and therefore produced conventional core. Drilling generally commenced with 85 T2 core, yielding a core diameter of approximately 71 mm over the initial 6–20 m, after which 76 T2 rods were used to recover 61 mm core. However, a few holes were drilled entirely with 85 T2 rods using single-tube core barrels.

Core logging recorded not only depth and lithology, but also a range of geological and mineralization parameters, including weathering profile, grain size, nature of basal contacts, structural type and angle, texture, alteration type, style and intensity, and mineralization style. Approximate percentages of baryte, pyrite/marcasite, limonite, and galena were visually estimated and accompanied by brief comments relevant to mineralization and structural relationships. Core recovery was recorded for each drilling run and was generally high, averaging more than 96%, with negligible additional loss in mineralized intervals. This suggests that baryte sampling from the core is unlikely to be significantly biased by poor recovery. Drill depths were marked on wooden blocks during drilling. A double-tube core barrel was used, and run lengths varied from 0.9 m to 3.0 m.

Owing to the shallow nature of the drill holes and the lack of access to suitable down-hole survey equipment, no down-hole deviation surveys were conducted. However, given that the sedimentary host rocks are relatively soft but competent, and that no strong parallel joint systems were observed, drill-hole deviation greater than 1–2° is considered unlikely.

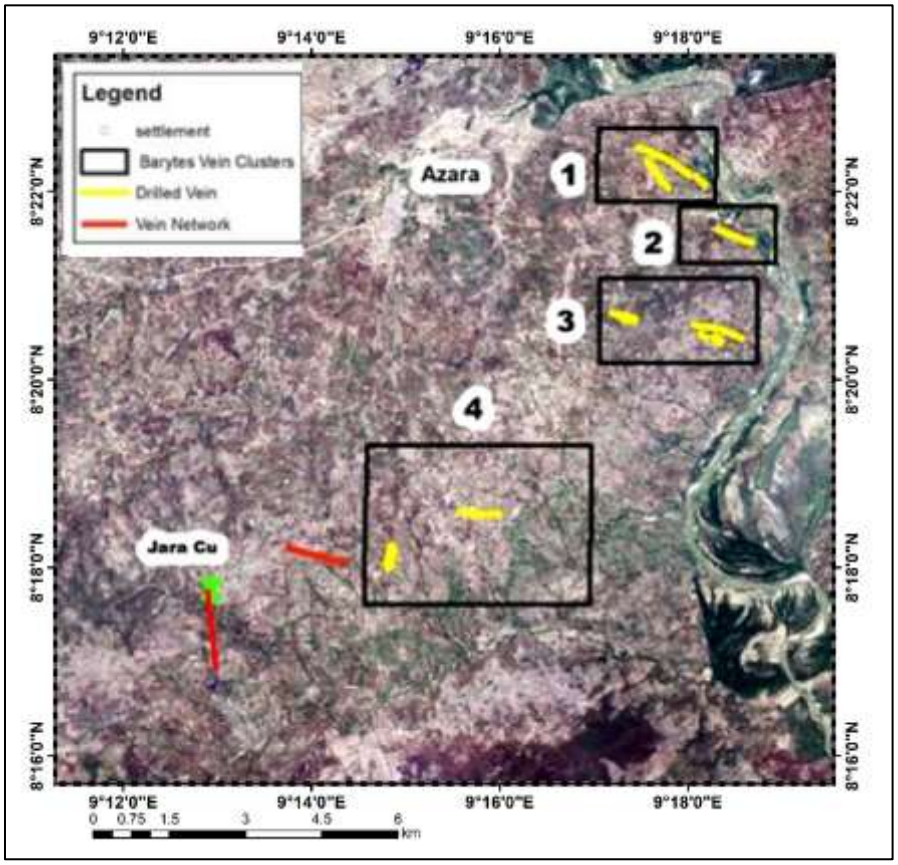


Figure 3: Baryte Vein Clusters within the study Area

4.0 RESULTS

4.1 District-scale distribution and structural zone

Baryte veins in the study area occur in spatially discrete clusters along a major NE-SW-trending corridor that coincides with a prominent ridge suspected to be the crest of an anticline (Figure 4). The clustering pattern reflects structurally controlled veins along the fold-related fracture network, with local dilation and segmentation controlling vein density.

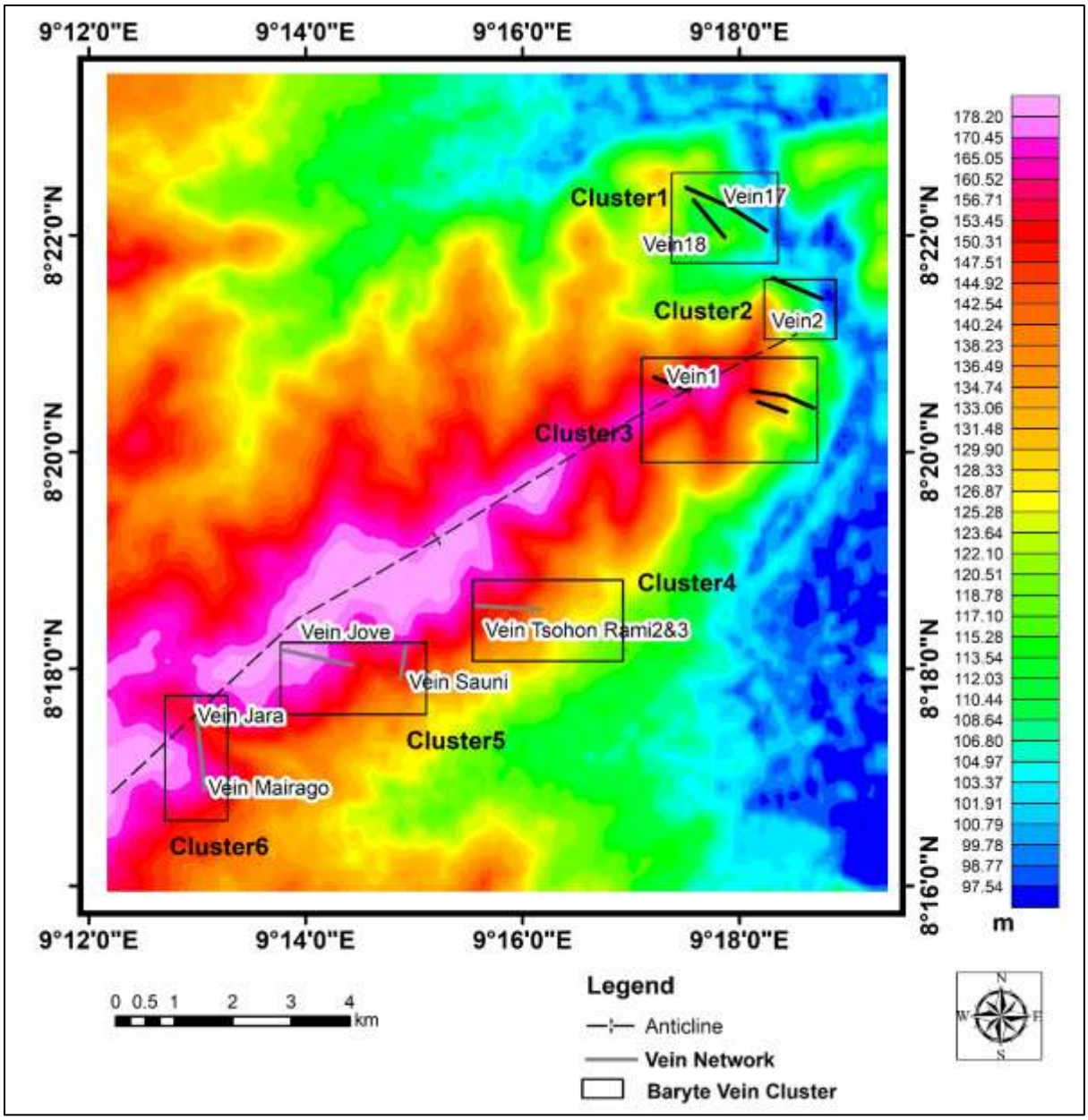


Figure 4: Elevation map of the Azara area, Central Benue Trough, showing the spatial distribution of baryte-mineralized veins and vein clusters (Clusters 1–6) in relation to regional structural lineament

4.2 Radiometric Characterization

Equivalent potassium mapping delineates an elongate NE-SW K-high zone which coincided with the ridge and vein distribution (Figure 5). The ternary K-eTh-eU image similarly highlights K-dominant domains along the same corridor (Figure 6). The spatial distribution of the veins along the K enrichment highlight deep processes of fluid-rock interaction within

fracture networks and preferential exposure of K-bearing lithologies on the uplifted crest, or a combination of both stages.

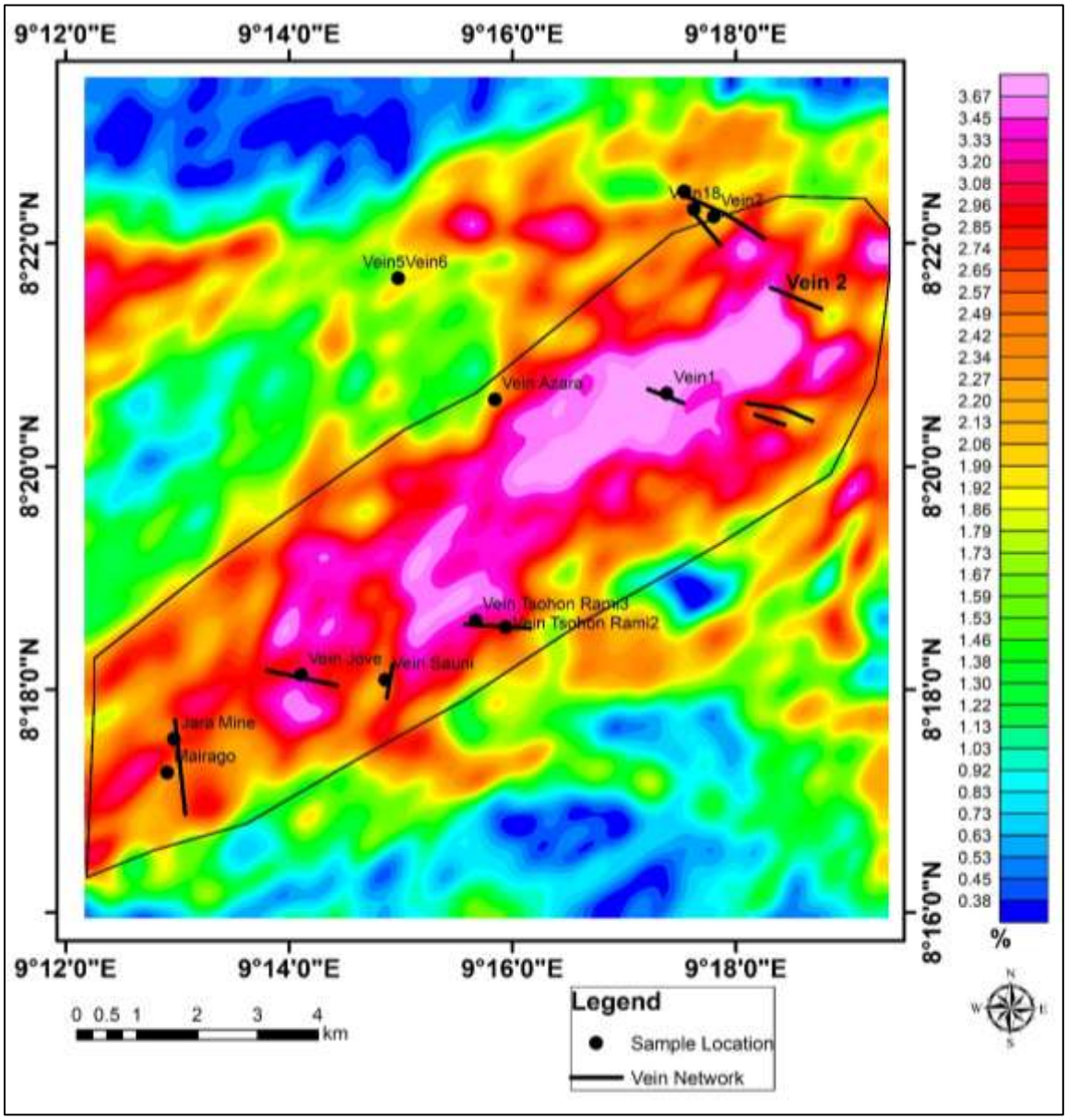


Figure 5: Equivalent potassium (eK%) radiometric map of the Azara area showing a NE–SW trending K high-anomaly corridor coinciding with the anticline axis and the distribution of baryte veins

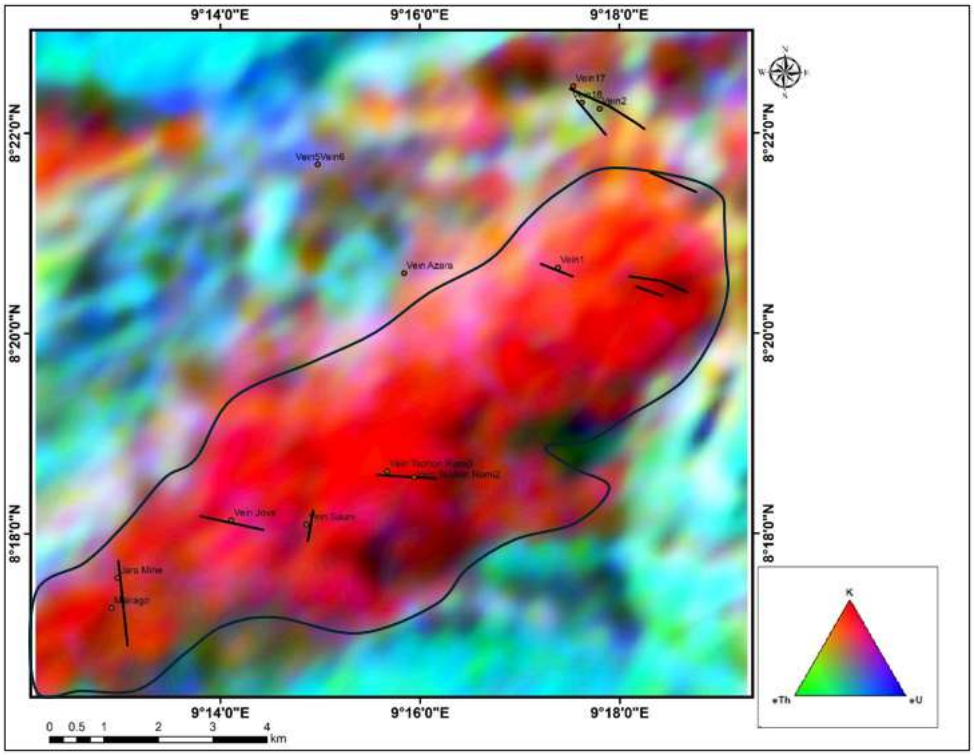


Figure 6: Ternary radiometric (K–eTh–eU) image of the Azara area showing potassium-dominant zones aligned along a NE–SW trending structural corridor corresponding with the anticline axis and baryte vein distribution

4.3 Vein-sets Occurrence and Orientations

Three principal vein sets are common within the study area (Figure 7): (i) a dominant NW-SE set (Veins 1, 2, 6, 17, and 18), (ii) a subordinate E-W set (Vein 5, Vein Sarki Sauni, and Vein Sohon Rami), and (iii) a minor N-S set (Mairago and Jara veins) (Fig. 8). The geometric relationship of these vein sets to the anticlinal axis reflects progressive deformation, with vein development partitioned between syn-folding fractures, post-folding shear-related fractures, and late brittle adjustment structures.

The distribution of barytes veins in the study area are often in distinct clusters characterized by local structural controls due to deep seated features permitting preferential fluid mobilization or mixing of brines in shallow fractures within favourable permeable sandstone units (Figure 8)

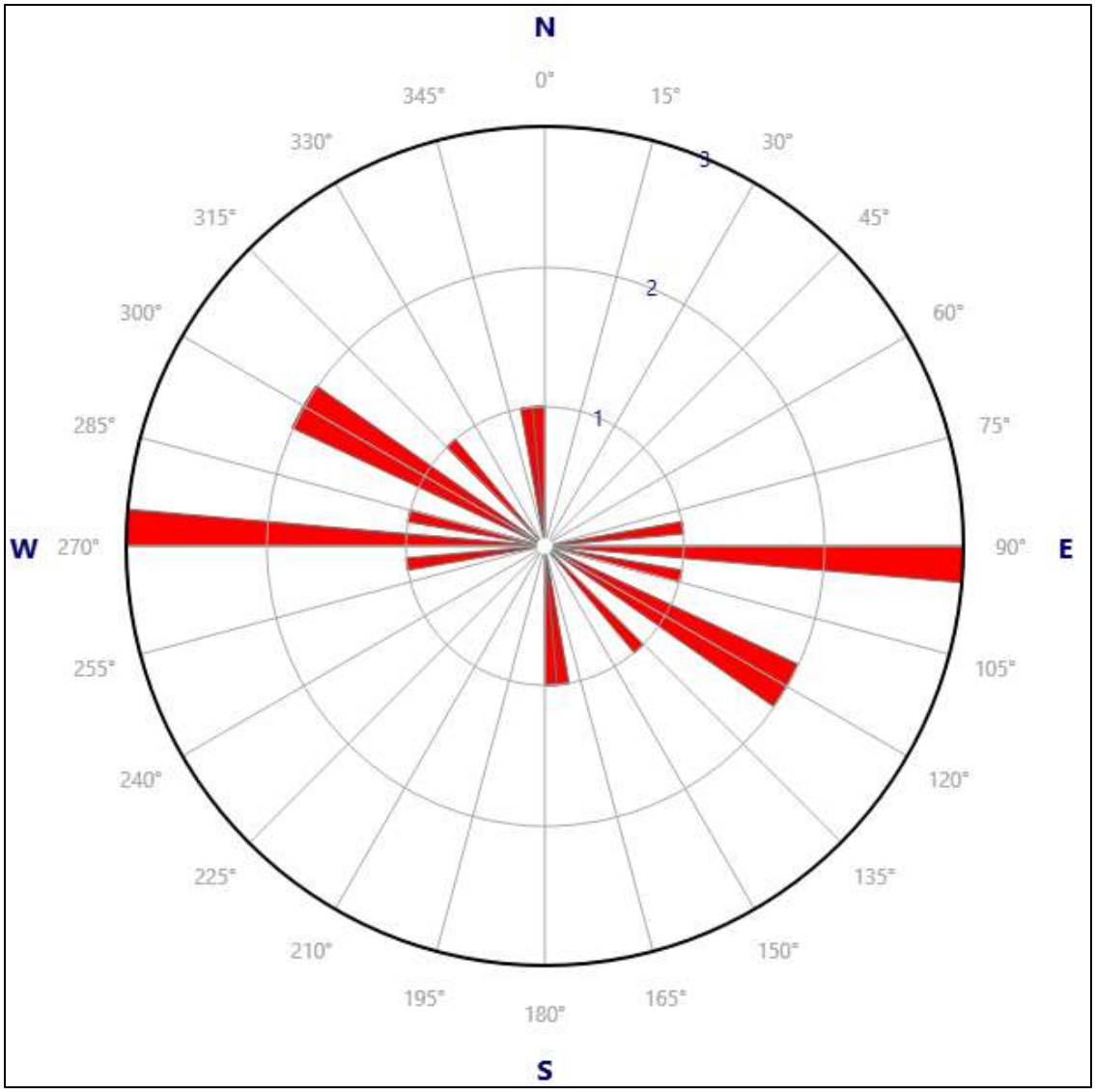


Figure 7: Rose diagram of measured baryte-vein orientations in the Azara area, Central Benue Trough, Nigeria (Source: Author)

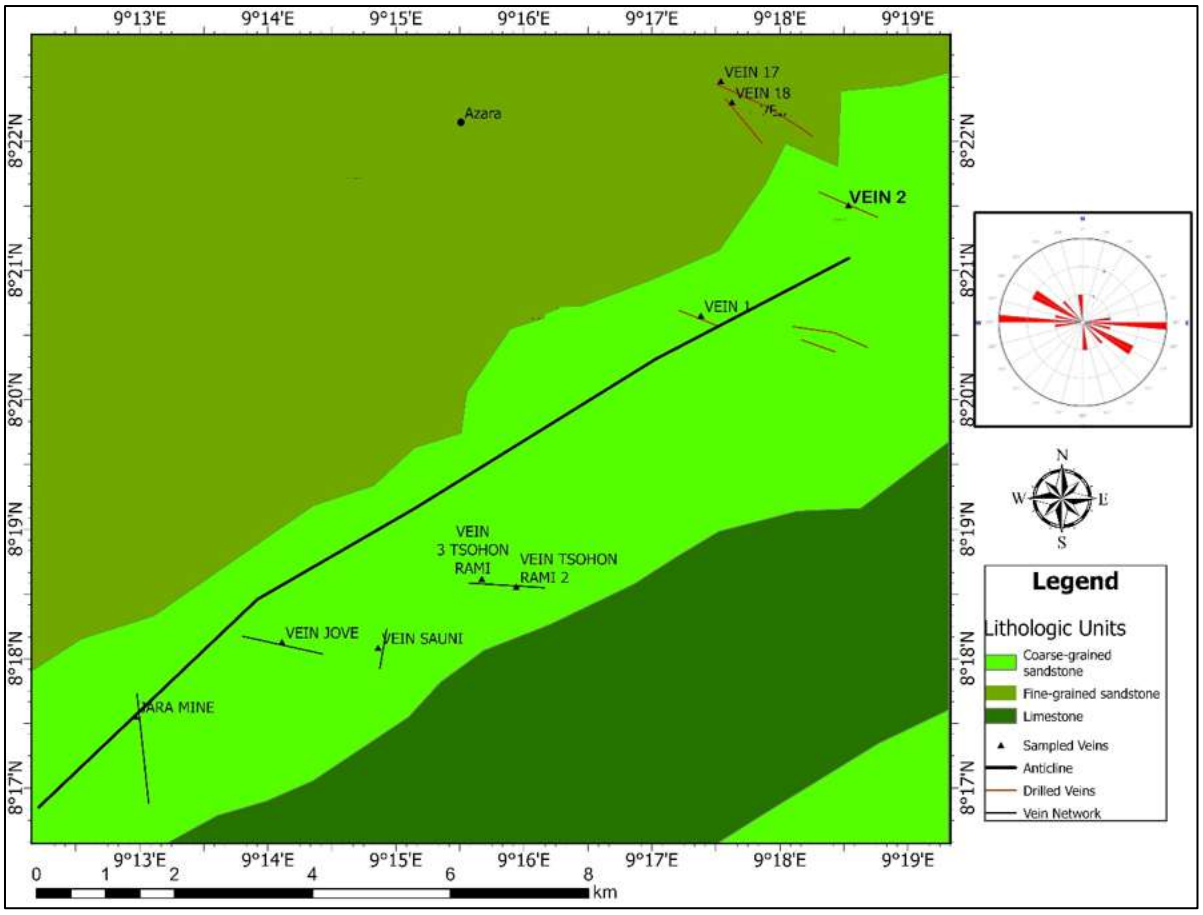


Figure 8: Geological map and Baryte veins of the study area showing lithologic units, the SW–NE trending anticline axis, vein network, and vein orientations displayed on the rose diagram inset (Modified from MECON 2021, Unpublished)

4.4 Vein Geometry and Mineralization Styles from Drill-Core Constraints

4.4.1 Cluster 1

Cluster 1 (Veins 17 and 18) shown in Figure 9 comprises steeply dipping to subvertical veins hosted within discrete fracture/fault zones (Figures 10 and 11). The Drill-core intersections show bedding-discordant mineralization occurring as massive vein fill, breccia-hosted infill (Fig. 12), stockwork veinlets (Fig. 13), and open-space cavity fills. The principal mineral baryte is commonly associated with siderite, minor chalcopyrite and/or pyrite locally observed toward the base of mineralized zones (Fig. 14).

Field observation at the central part of Vein 17 is characterized by intense tectonic activity, resulting in strong brecciation and deformation of the vein material (Fig. 15). Toward the terminal end of the vein, deformation is typically associated shearing, but the rocks are less tectonized than in the central portion. This reflects a variation in structural intensity along the vein, with the central zone being more disturbed than the terminal zone.

Figure 9: Satellite image of Cluster 1 showing Veins 17 & 18, with associated drill collar locations (DV1701, DV1702, DV1703, DV1704, DV1801 and DV1802) in the study area (Source: Google Earth)

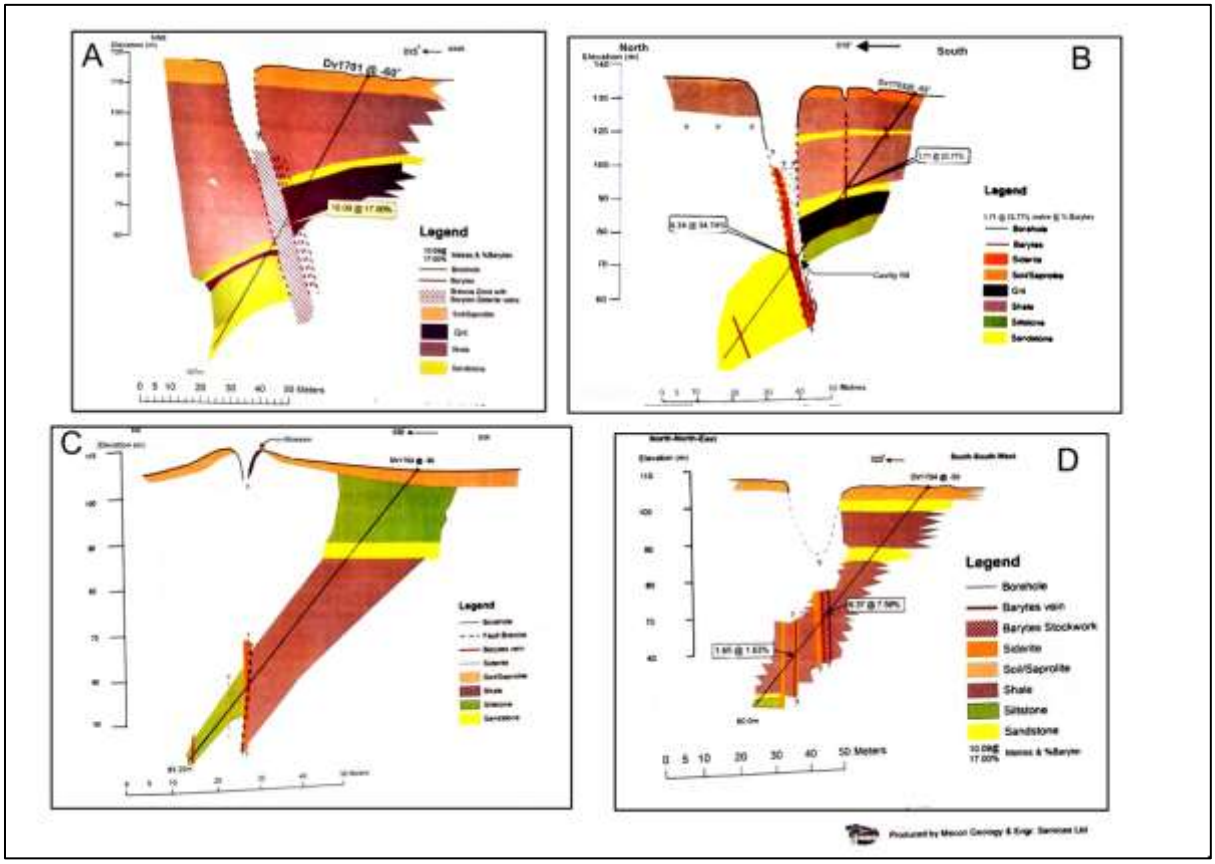


Figure 10: Cross sections of Vein 17 (DV1701–DV1704), showing vein geometry, breccia, stockwork, and cavity-fill textures

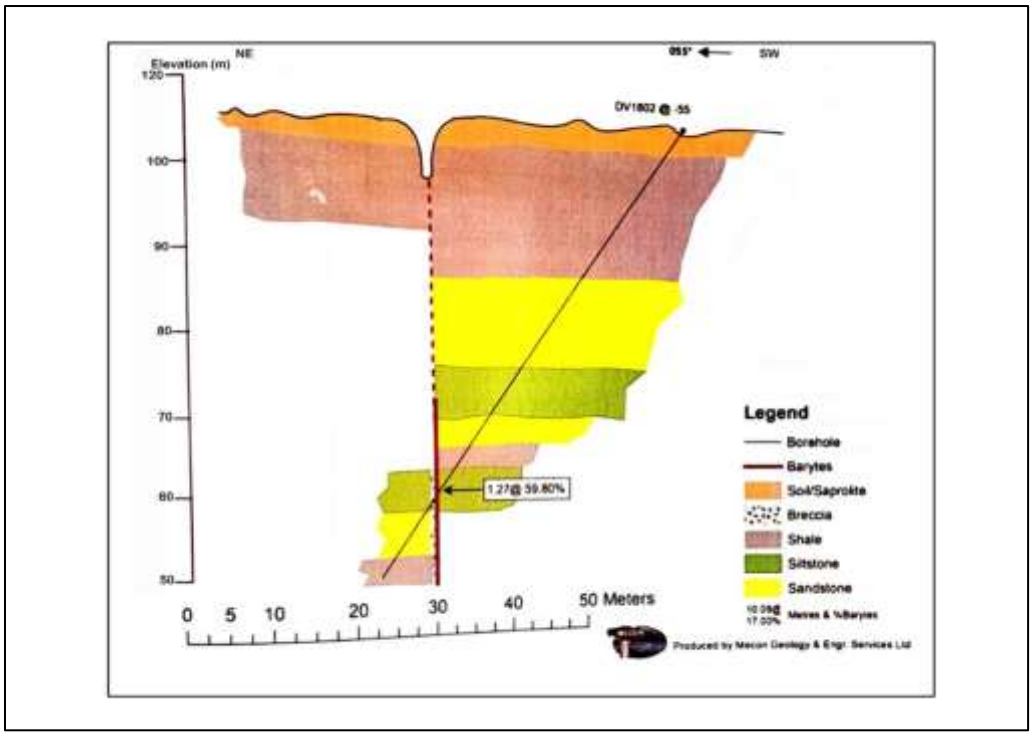


Figure 11: Cross section of Vein 18 (DV1802), showing steep vein geometry

Figure 12: Core photograph of the DV1701 main lode intersection showing massive and brecciated baryte within the shear zone.

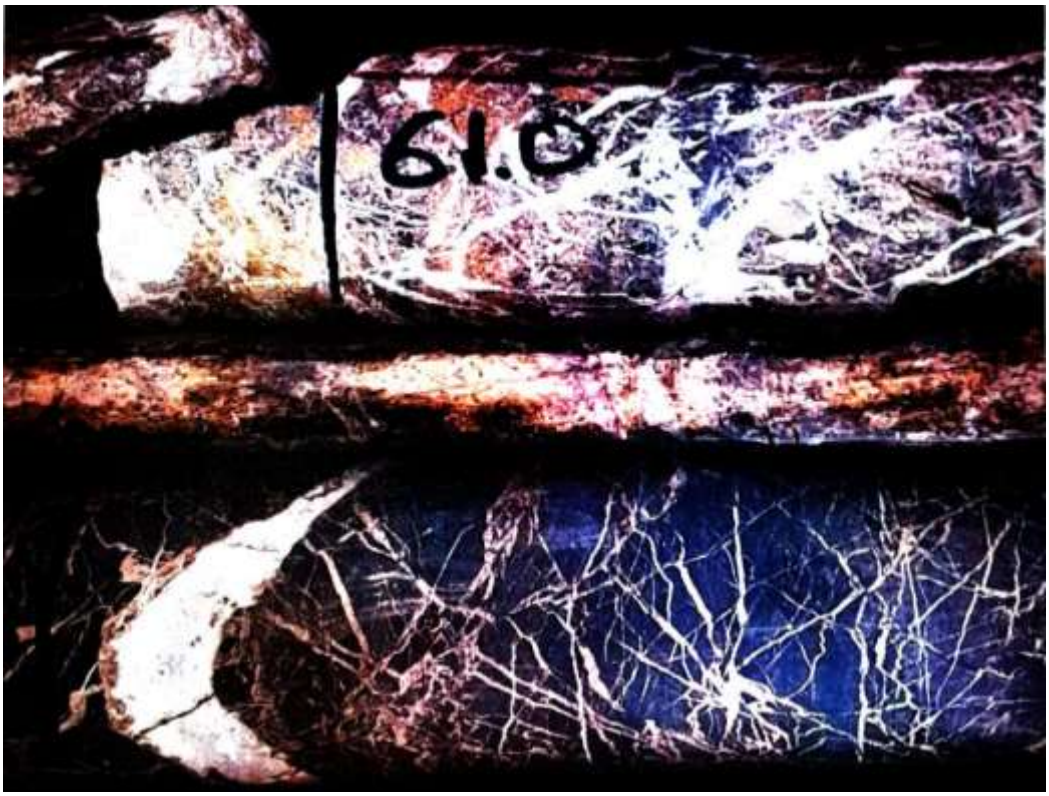


Figure 13: Drill core (DV1701; ~61.0 m downhole) showing dense baryte–siderite stockwork within dark siltstone.

Figure 14: Chalcopyrite in younger siderite breccia, DV1702, 68.3m

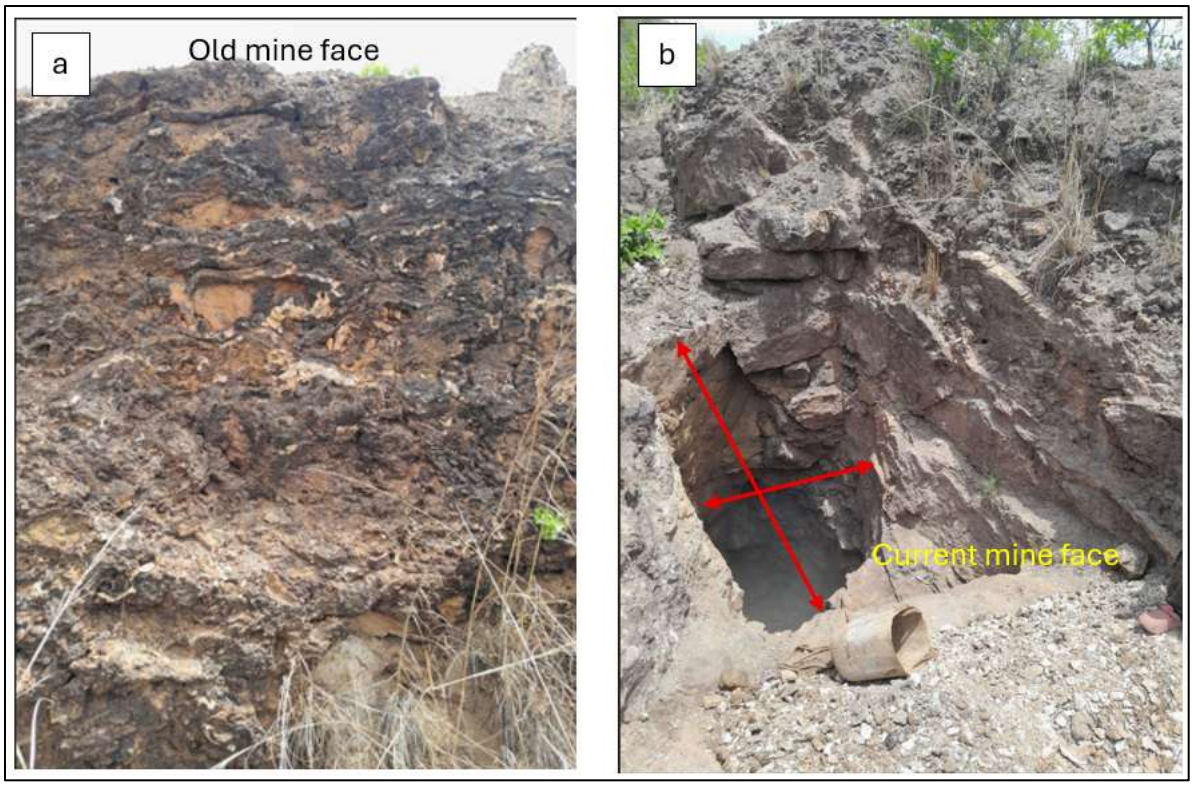


Figure 15: Old and current mine face a) Brecciated and Tectonized zone in Central Part of Vein 17. b) Shearing effect but less tectonized at the terminal of the vein compared to the central part of the vein

4.4.2 Cluster 2

Cluster 2 (Vein 2) forms a continuous NNW-SSE to NW-SE-trending vein (Figure 16) that is steep to near vertical with local displays of splays, multi-vein arrays, stockwork zones, and brecciation (Figures 17&18). A notable paragenetic relationship is indicated by bedding-parallel silicification carrying very fine chalcopyrite ± pyrite adjacent to the main lode (Figure 17B), which pre-dates siderite-baryte veining. Also, coarse sphalerite occurs within baryte veins as infills vugs/veinlets during late-stage Zn enrichment at dilational sites (Plate 5).

The slickensided vein-wall (Plate 6) at Vein 2 shows evidence of structural movement, with affirmation from the polishing and striations formed due to frictional slip along the vein surface.

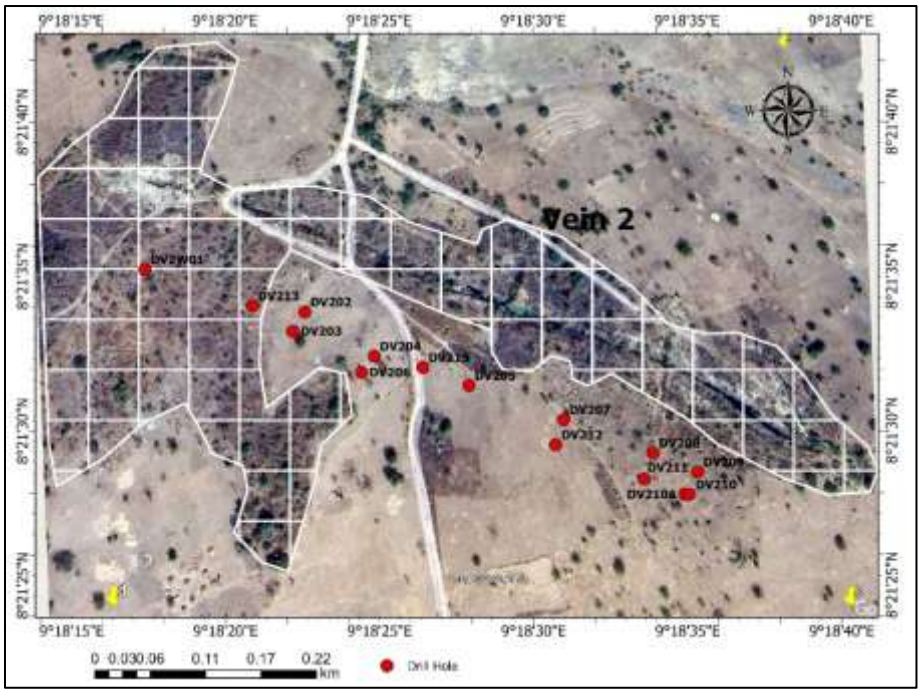


Figure 16: Drill collar location map of Cluster 2 (Vein 2) (Source: Google Earth)

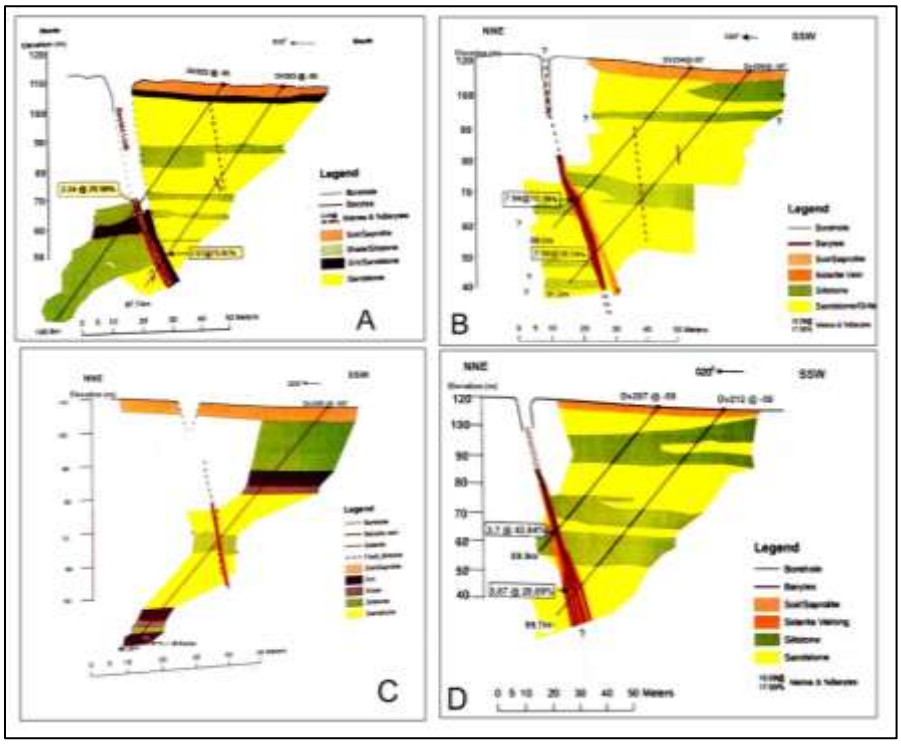


Figure 17: Cross sections of Vein 2 (A-C) showing lithological relationships, vein geometry, breccia zones, stockwork development, and oxidation features

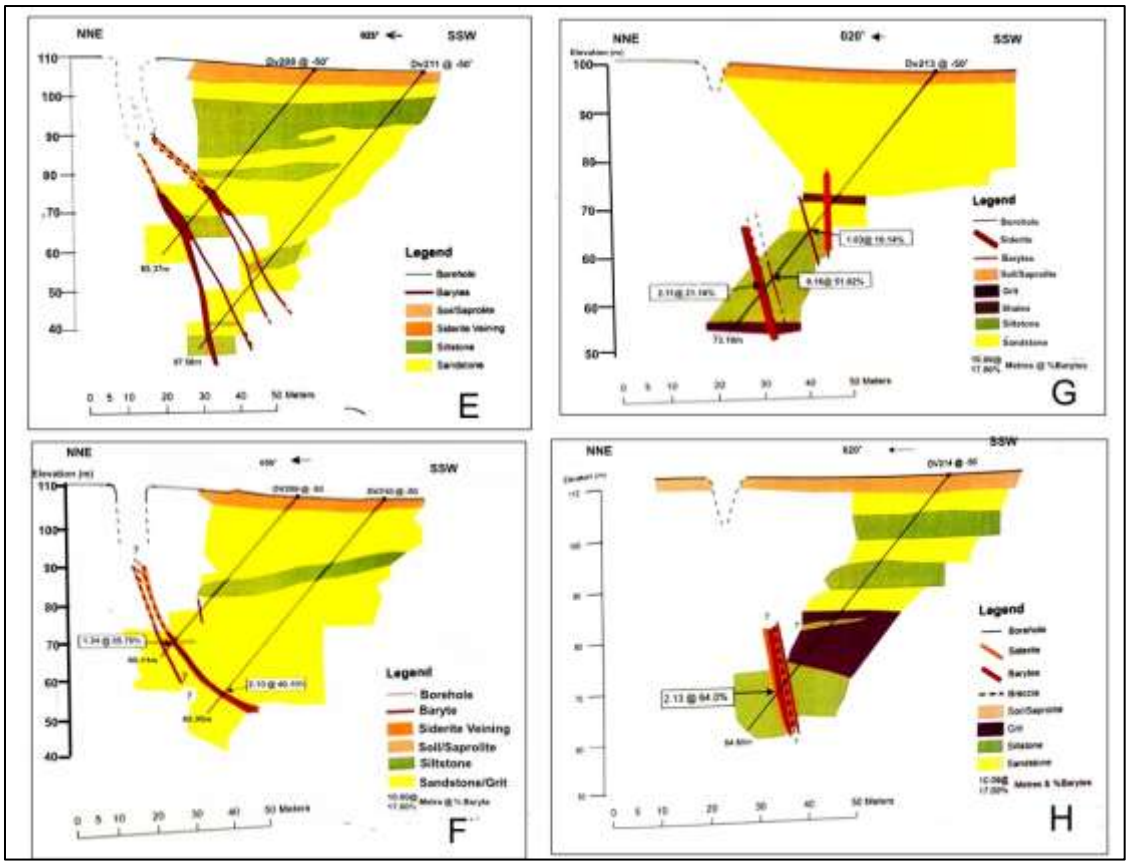


Figure 18: Cross sections of Vein 2 (D-G) showing lithological relationships, vein geometry, breccia zones, stockwork development, and oxidation features

Figure 19: DV210 (72-75m). Note Sphalerite cutting barytes below 73 & 74m

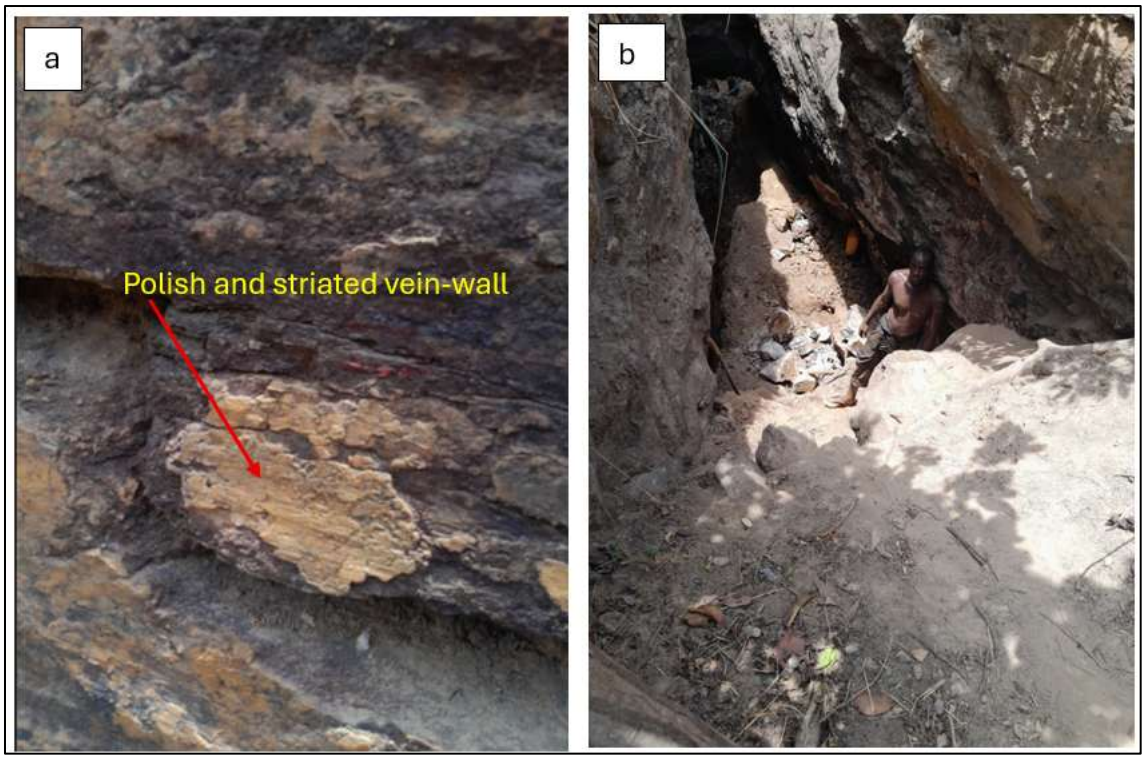


Figure 20: a) Slickenside surface on Vein 2. The polished and striated vein-wall surface records slip along the vein plane. b) Mine pit within Vein 2

4.4.3 Cluster 3

Cluster 3 (Veins 1 and 6) shows two contrasting but structurally similar systems (Figure 21): Vein 1 is composite, with multiple subparallel strands and breccia/veinlet arrays typical of repeated reactivation (Figure 22A-B), whereas Vein 6 is more planar and discrete with stronger strain localization along a single mature fracture. Also, Near-surface gossan/limonite development is common along the structural zones. (Figure 22C-D)

The host rock is predominantly strongly weathered Keana feldspathic sandstone. Mineralized zones range from <0.3 m to >4 m in width. However, relatively competent barytes is intermingled with limonite-goethite gossan in veins ranging from a few centimetres to 0.75 m wide (Figure 23). Occasional brecciation is observed, and minor quartz veinlets post-date the barytes mineralization.

The three drill holes completed on Vein 6 are representative of only a very limited area. Nevertheless, the core confirms what is observed in outcrop and underground workings: a 5 m wide main gossan zone containing less than 25% barytes, occurring as irregular veins and stockworks cut by erratic, fine quartz veinlets (Figure 24), together with a narrow hanging-wall gossan zone that is almost devoid of barytes (Figure 22D). However, zones of fine, loose sand are highly anomalous, particularly as mining has not advanced to any significant depth. The origin of this cavity fill remains uncertain, although it may reflect a semi-karstic process related to preferential dissolution of the host sandstone cement.

The mine face exposed within Vein 6 shows spatial variation in baryte mineralization from Zone A through Zone D (Figure 25). Samples collected across these zones show differences in the specific gravity of baryte which is attributed to changes in mineral purity and local depositional

conditions along the vein. This zonation reflects the heterogeneous nature of mineralization along the vein and offered key opportunity for understanding the ore quality distribution in the field.

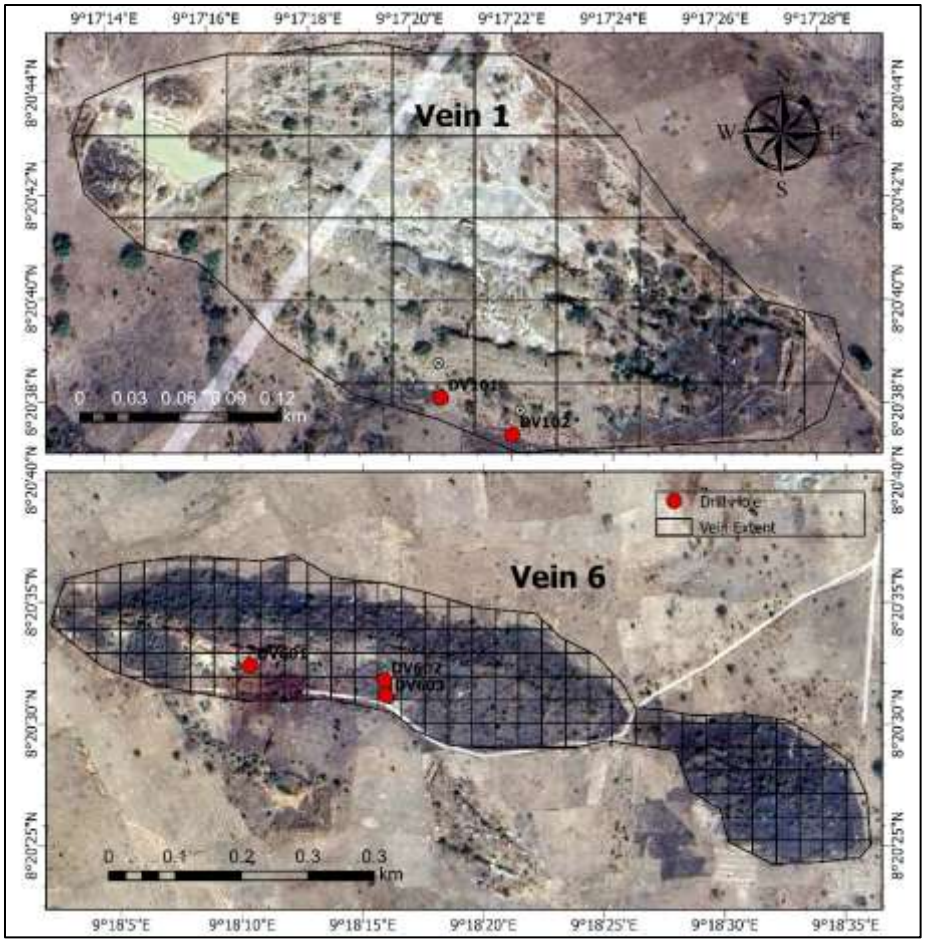


Figure 21: Satellite view map of Cluster 3 showing the surface expression and extent of Vein 1 and Vein 6 (Source: Google Earth)

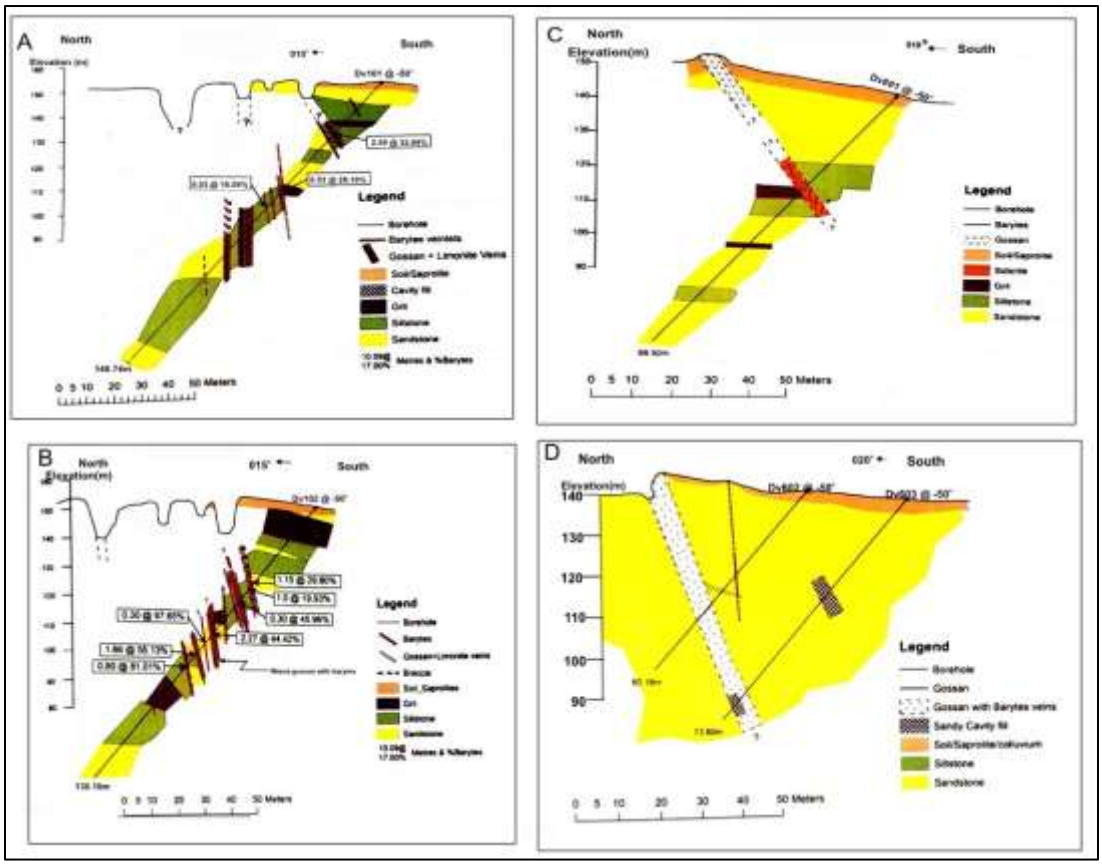


Figure 22: Geological cross-sections (A–D) through Cluster 3 showing the structural geometry and mineralization style of Veins 1 and 6

Figure 23: DV102 Gossan and Barytes below 68m

Figure 24: DV603 Baryte veins in gossan with fine quartz stockwork

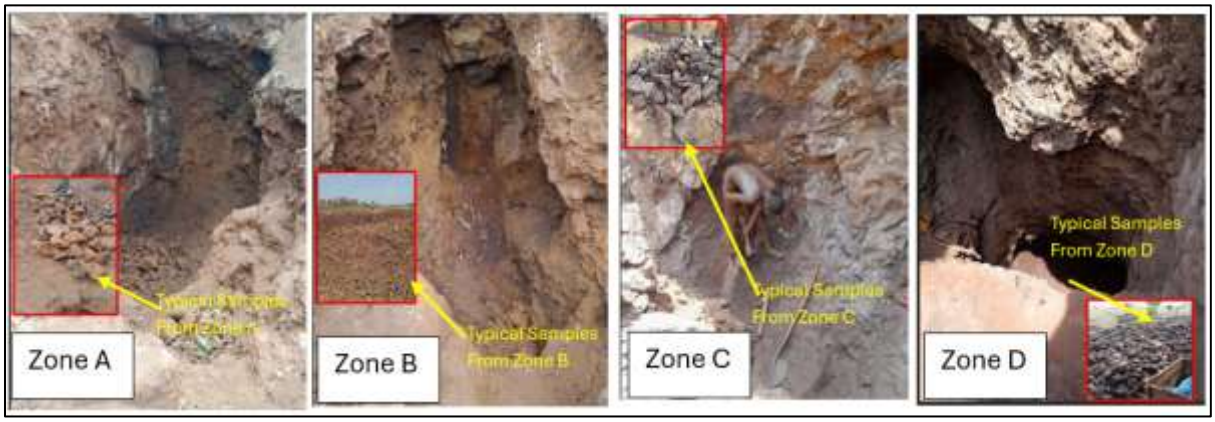


Figure 25: Active mine face with variations in baryte specific gravity along the vein within Vein 6, shown by samples collected from four mineralized zones (A–D) from SE towards NW

4.4.4 Cluster 4

Cluster 4 (Sauni Sarki and Sohon Rami) shows variability between a narrow, laterally persistent vein (Figure 25) with a mature fracture/fault strand and more segmented mineralized lenses (Figure 26A-C) while Figure 27D-E has a distributed deformation domain with fracture partitioning. Both occur within sandstone to greywacke dominated successions with subordinate siltstone/shale and show steep fissure-fill geometries.

The Sarki Sauni vein is exposed in the central part of the mine pit along the contact between siltstone and baked, competent sandstone, with lithologic contrast playing an important role in

controlling vein development (Figure 28). The Sohon Rami mine pit also follows a mineralized vein and shows that vein emplacement which are strongly controlled by local structural and lithologic conditions are prime target by artisanal miners.

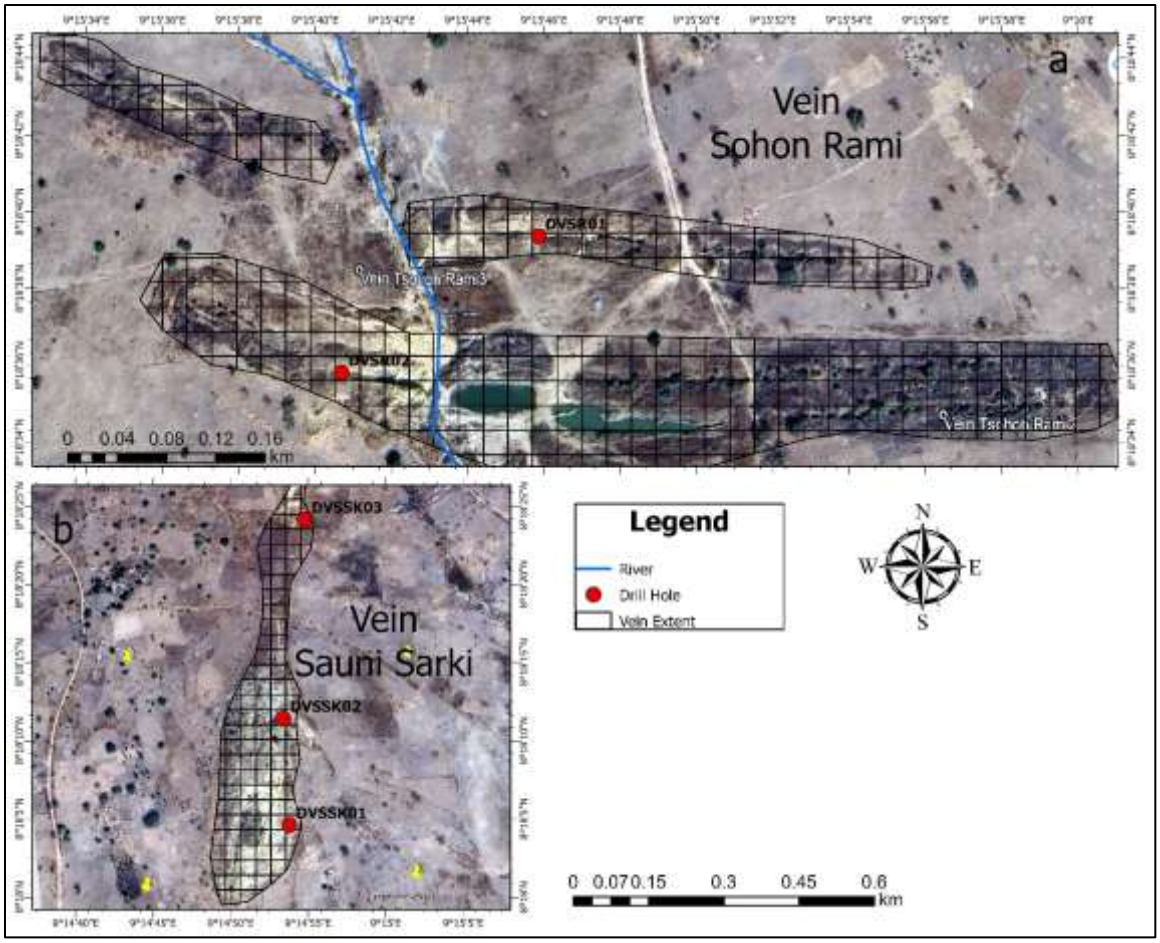


Figure 26: Plan-view satellite imagery showing the surface extent and structural geometry of the Sohon Rami (a) and Sauni Sarki (b) veins (Source: Google Earth)

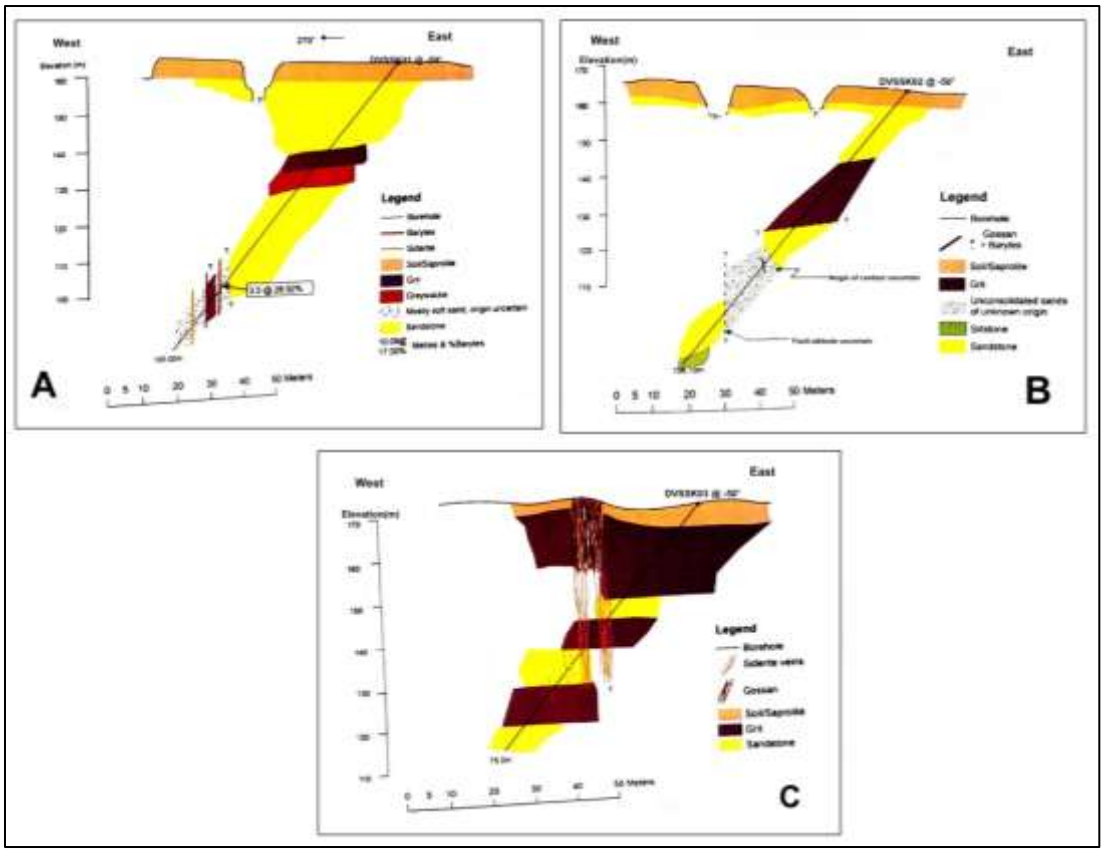


Figure 27: Geological cross-sections (A–C) through the Sauni Sarki vein illustrating steeply dipping, structurally controlled mineralization developed within sandstone, grit, and greywacke units

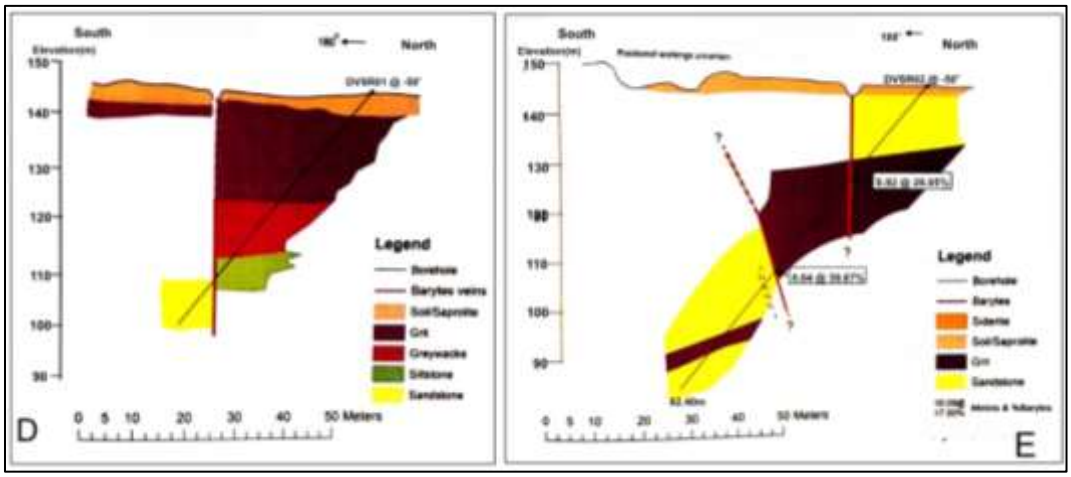


Figure 28: Geological cross-sections (D–E) through the Sohon Rami vein showing a steeply dipping mineralized corridor developed within sandstone and greywacke

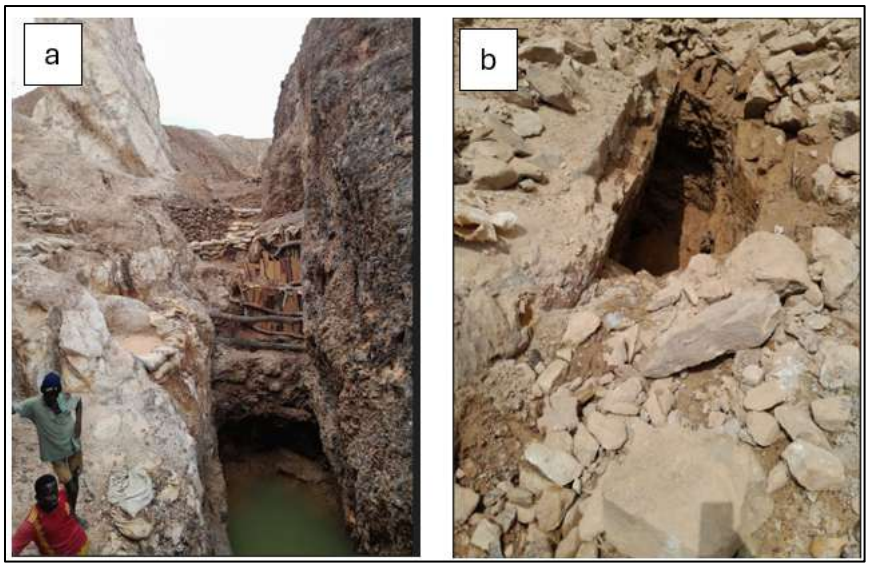


Figure 29:a) Vein Sarki Sauni mine pit at the central part of the vein along the contact between siltstone and baked, hard and indurated sandstone b) Mine pit at Sohon Rami vein

4.5 Paragenesis and relationship to base-metal mineralization

Core observations are broadly consistent with the interpreted paragenesis for the Azara veins. This comprises an early silicification phase, followed by Stage 1 mineralization characterized by open-space filling and crusti-form to vein-style deposition of siderite, baryte, quartz, calcite, galena, and sphalerite. In some veins, subsequent fluid pulses were accompanied by brecciation (Stage 2), followed by renewed deposition of baryte and siderite, with lesser calcite and minor late quartz infill during Stage 3 (Figure 30). A further brecciation event is inferred locally in Stage 4, accompanied by late quartz, possible baryte, and galena. Veins 17 and 2 appear to record the most complex paragenesis, including one or more brecciation phases, whereas clusters 3 and 4 commonly show only Stage 1 mineralization.

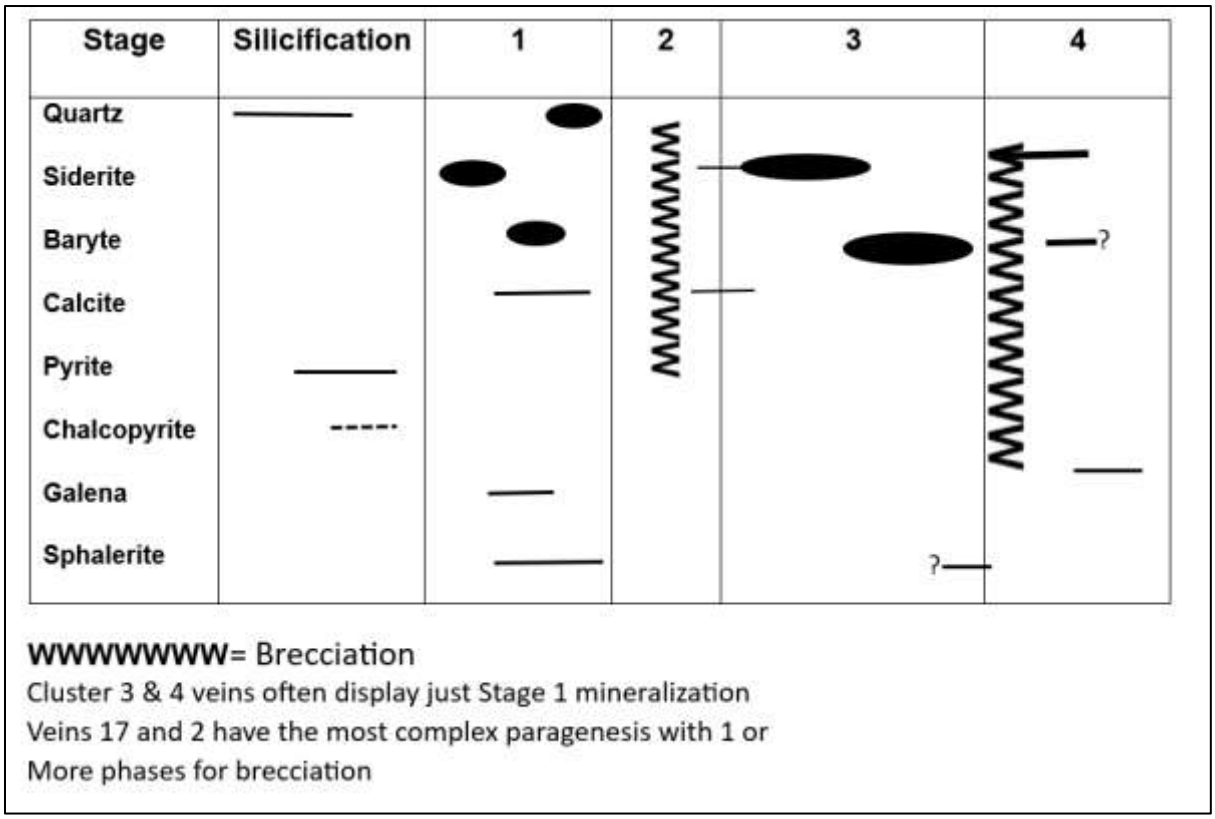


Figure 30: Generalised mineral paragenesis for the Azara veins

5.0 DISCUSSION

5.1 Fluid pathways development and structural evolution

The Azara vein clusters' district-scale alignment along a NE–SW corridor suggests that ore deposition was restricted by a long-lasting structural architecture formed from Benue Trough rifting and frequently reactivated during post-rift deformation. According to regional syntheses (Olade and Morton, 1985; Bute et al., 2024), the Nigerian Pb–Zn–Ba belt is a fault-guided hydrothermal system where saline basinal fluids are concentrated by transcurrent faults, extensional fractures, and structurally formed pathways. The fact that the primary vein path in Azara coincides with the ridge, which is thought to be an anticlinal crest, further implies that folding improved permeability by causing fracture dilation and crest-parallel extension rather than just serving as a passive geologic feature. In structurally focused MVT and MVT-like systems around the world, such connections between regional fault architecture and local fold-related permeability are becoming more widely acknowledged. This includes thrust-belt and transpressional settings where fluid pathways are repeatedly opened during tectonic readjustment (Song et al., 2023).

Thus, a hierarchy-based framework can be supported by the Azara dataset where local fracture intersections, splays, bends, and fold-crest dilation regulated mineral growth at the deposit scale, while regional NE–SW underlying faults produced the primary fluid distribution system. Similarly, in South Chinese districts of Nayongzhi and Wusihe, where weaker and more dispersed mineralisation was found in more distant or less permeable locations, the high-grade mineralisation was concentrated in conduit-style breccias, faults, and open-space infill zones

near principal fluid pathways (Luo et al., 2020; Wei et al., 2024). For Azara, the vein clusters are not just parallel fissures with equal prospectivity, but rather unevenly mineralised sections of a structurally controlled path where permeability was severely divided over time as observed from vein geometries and textures. Also, episodic fluid overpressure and cyclic fracture reactivation are indicated by steep to subvertical, bedding-discordant lodes, breccia-hosted infill, cavity fill, stockworks, and repetitive sealing-reopening textures. The Azara core records align with the conventional structure of hydrothermal breccias in vein systems, which frequently indicate transitory permeability increases during pressure fluctuations (Jébrak, 1997). Field evidence shows that fluid access and ore precipitation were not uniform along strike but were increased where deformation periodically regenerated permeability and the more severely brecciated portions of Veins 17 and 2 are of particular importance. This is similar to MVT systems in South China, where fault-proximal ores, breccia pipelines, and open-space infill are indication of repeated hydraulic fracturing or reactivation and concentrated fluid ascent (Wei et al., 2024).

The subordinate E–W and minor N–S sets, along with the major NW–SE veins, suggest that mineralisation occur along fracture array created under shifting local stress conditions overlaid on the regional trough fabric. These sets are better understood as kinematically linked structures that were variably reopened throughout subsequent deformation processes rather than as unrelated generations. While more comprehensive analyses of Nigerian deposits highlight the function of transfer structures and fracture corridors as fluid conduits across the metallogenic belt, studies from the Gombe segment of the northern Benue Trough similarly demonstrate that baryte–fluorite mineralisation is concentrated where lineament intersections and reactivated fault zones create enhanced structural connectivity (Auwalu et al., 2024). This model gains a significant district-scale line of evidence from the K-enriched NE–SW radiometric corridor. The signal's tight spatial congruence with the anticlinal ridge and vein clusters indicates that radiometric anomalies are also tracking structurally concentrated alteration and accelerated weathering above the mineralised corridor, even though some of it may reflect lithologic exposure. In other mineral systems, it has been shown that airborne gamma-ray data can be used to identify potassic or structurally modified hydrothermal corridors (Grasty and Shives, 1997; Shives et al., 2000; Maden and Akaryalı, 2015). In the Benue context, this method enhances rather than replaces direct structural mapping. Therefore, the radiometric response at Azara is best understood as an exploration-scale proxy for the same fault-fold architecture found in drill core and outcrop.

A multi-stage hydrothermal system as opposed to a single mineralising pulse is further supported by the paragenetic sequence. In reopened fractures, early silicification with little chalcopyrite ± pyrite, siderite–baryte veining, and later sphalerite–galena indicates changes in fluid composition, wall-rock contact, and redox state over time. This is consistent with recent basin-scale syntheses for the Benue Trough, which contend that hot saline brines flow through pre-existing structures and change because of mixing, sulphate reduction, and fluid-rock interaction (Bute et al., 2024; Walter et al., 2026). The Azara sequence is similar to multistage MVT systems found elsewhere, where late sulphides are concentrated in reopened cavities or structurally rejuvenated zones, and early Fe-rich or silica-bearing alteration comes before main-

stage gangue and sulphide precipitation (Luo et al., 2020; Tavazzani et al., 2024).

5.2 Vein thickness and style controls

Variations in vein style and thickness throughout the Azara district are influenced not only by fluid supply, but also structural location, fracture-segment geometry, host-rock competence, and repeated reactivation. Where there is evidence of splays, stockworks, brecciation, or orientation changes along strike, the veins are the thickest and most texturally complex. These features are commonly recognized as indicators of localized dilation in hydrothermal vein systems because they enhance fracture aperture, fluid residence time, and accessible surface area for precipitation. While simpler distal fractures are thinner and less texturally diversified, fault-linked breccias and conduit zones in MVT settings typically include the highest-grade mineralisation or the thickest gangue deposition (Wei et al., 2024; Niu et al., 2024). This notion is most well illustrated by the disparity between Vein 1 and Vein 6. While Vein 6 is more flat and rather distinct, Vein 1 consists of several subparallel strands with veinlet arrays and breccia formation. In South China, where structural segmentation controls whether mineralisation develops as breccia-hosted open-space fill, stockwork, or more strata-bound and replacement-like bodies, a similar distinction between conduit-proximal complex mineralisation and simpler planar or distal lodes has been highlighted (Wei et al., 2024). This indicates that thickness in Azara is a structural reaction rather than a merely stratigraphic characteristic with stepovers, jogs, splays, and vein crossings being the most likely causes of local thickening. Both mechanical opening and recurrent mineral sealing would have been possible at these locations, where dilatation would have been greatest during slip or fracture reactivation. The slickensided vein wall in Vein 2 indicates a post-opening movement on mineralised structures and shows that some veins remained mechanically active after initial infill. The most mineralised areas typically correspond with locations of fault interaction or renewed dilatation, and such evidence is frequently employed in global MVT systems to differentiate passive fracture fill from reactivated ore conduits (Song et al., 2023; Niu et al., 2024). Vein architecture was further regulated by mechanical stratigraphy. While mixed lithologies and weaker intervals influenced brecciation, wall-rock inclusion, and local stockwork formation in the Azara region, competent sandstone and greywacke horizons tended to preserve sharper-walled fissure fills. This is typical of sediment-hosted systems in Nigeria and other countries where competence contrasts influence whether fluid flow disperses into fracture swarms and replacement fronts or stays confined in discrete fractures (Akande and Mühl, 1989; Samaila et al., 2025). For instance, Samaila et al. (2025) found that fracture-controlled emplacement within favourable siliciclastic host rocks significantly influences baryte mineralisation in the Faya area of the Middle Benue Trough, supporting the idea that Azara is a member of a larger class of structurally emplaced baryte systems in the middle trough.

Vein thickness was increased throughout time by reopening and resealing, according to drill-core evidence for cavity fill, crack-seal textures, and breccia cementation. Every reactivation event has the potential to expand an already-existing fracture, produce additional wall-rock pieces, and produce new precipitation surfaces for sulphides, baryte, and siderite. This clarifies why certain Azara veins are thicker than would be predicted from a single opening event. Using

U–Pb geochronology of hydrothermal carbonates in the San Vicente district, Tavazzani et al. (2024) showed that MVT systems may continue to be sporadically active for extended periods of time, with recurring carbonate growth associated with tectonic events. However, the textural evidence from Azara is entirely consistent with a protracted, episodic mineralising history, despite the absence of direct geochronologic restrictions.

The apparent lode thickness was likewise altered by mineralogical sequencing. While later pulses characterised by carbonate and baryte added the majority of the visible vein volume, early silicification and Fe–Cu-bearing stages reinforced portions of the wall rock and may have prepared favourable fracture zones. By overprinting previous gangue-rich zones, late sphalerite–galena concentration in vugs, veinlets, and breccia matrices enhanced particular portions without necessarily producing thick lodes. In more general MVT, the highest base-metal grades and the largest gangue volumes are not always synchronous because metal-rich pulses may follow earlier gangue deposition once the fluid system evolves chemically or hydraulically (Luo et al., 2020; Niu et al., 2024).

5.3 Paragenesis and relationship to base-metal mineralization

The paragenetic sequence found in the Azara region suggests a multi-episode hydrothermal history that included wall-rock alteration, early sulphides, a dominating siderite–baryte event, and later Zn–Pb enrichment in dilational sites that were reopened. Compared to merely categorising the veins as "baryte-rich" or "Pb–Zn-bearing," this approach is more complex. Rather, the Azara system seems to be a local manifestation of the larger Benue Pb–Zn–Ba metallogenic province, where the ratio of late sulphide enrichment to sulphate-rich gangue precipitation varied from structure to structure. Nigerian deposits range from base-metal-rich to gangue-dominant hydrothermal veins depending on fluid evolution, host rocks, and structural emphasis, according to recent syntheses for the Benue Trough (Bute et al., 2024; Walter et al., 2026).

1) Pre-vein modification: silicification using early Fe–Cu sulphides

Silicification accompanied by weak pyrite and modest chalcopyrite is the oldest identifiable stage in Azara. This alteration probably represents pre-ore or early-ore fluid infiltration along porous stratigraphic surfaces connected to the later vein system since it is locally bedding-parallel and happens next to important lodes. This suggests that the ore system was chemically active prior to significant baryte deposition. Similar early alteration halos have been found in several MVT districts which are evidence of warm basinal brines that first interacted with wall rocks before conditions were favourable for large-scale gangue or sulphide deposition (Luo et al., 2020; Walter et al., 2026).

2) Stage 1: siderite–baryte (± calcite) dominates the primary fissure-fill event, with little Pb–Zn

Widespread siderite–baryte ± calcite, subordinate quartz, and very little galena or sphalerite are indicative of the primary mineralising stage. Most of the visible lodes emerged during this period, which also defines Azara's baryte-dominant nature. This implies that sulphate availability, fluid mixing, redox evolution, and possibly the timing of sulphur reduction differed

from more traditional Zn–Pb-dominant MVT systems, the dominance of baryte over sulphides is noteworthy. While Ogundana (2024) also highlighted the importance of highly saline brines throughout the Benue belt, Walter et al. (2026) demonstrated that Nigerian fluorite–baryte–base metal veins may record mixing among bittern brines, halite-dissolution brines, and oilfield brines. In such case, Azara might be an area of the system where high amounts of sulphide were partially or completely replaced by abundant baryte precipitated by sulphate-rich fluids.

3) Brecciation as the catalyst for restored permeability and textural diversity in stages 2 and 4

Brecciation was crucial in the later stages because it restored permeability and enhanced textural complexity. Brecciation recorded fracture reopening following prior sealing in the more intricate Azara veins, particularly Veins 17 and 2, and generated the voids where baryte and sulphides eventually gathered. This sequence is similar to conduit-style MVT mineralisation elsewhere, where structural renewal creates complex open-space textures and breccia-hosted ore shoots from simple fissure fills (Jébrak, 1997; Wei et al., 2024). Permeability during the hydrothermal system's dying stages was maintained. Meanwhile, brecciation at Azara was not only destructive but also ore generative.

4) Stage 3 to Stage 4: late Zn–Pb enrichment in dilational locations and baryte-dominant infill

Later Zn–Pb enrichment in reopened voids, vugs, and veinlets followed a baryte-rich pulse with reduced siderite. Despite the fact that many veins are gangue-dominant, this late-stage association is one of the best indications that Azara is a member of the larger MVT-like Pb–Zn–Ba family. Luo et al. (2020) and Niu et al. (2024) demonstrated in South China that as fluid mixing increases or redox and pH conditions change, economically significant sulphide accumulation may occur after earlier gangue or Fe-rich stages. At a smaller and more baryte-rich scale, the Azara cores maintain the same general logic where the most promising base-metal zones are the reopened, brecciated, and texturally diverse intervals rather than the thickest massive baryte sections.
This connection explains why numerous isolated veins are still predominantly baryte-rich even though the Azara district is part of the larger Pb–Zn–Ba province of the Benue Trough. Although local physicochemical conditions favoured sulphate mineral precipitation over widespread sulphide deposition, the district most likely occupied a portion of the broader hydrothermal system where fluid focussing was powerful enough to form massive fissure-fill veins. Despite having a similar tectono-hydrothermal framework, certain areas are gangue richer and others are metal richer, which is consistent with the larger Benue Trough (Olade and Morton, 1985; Labe et al., 2018; Bute et al., 2024).

5) District implication: why certain veins have Pb–Zn signatures while others are baryte-dominant

Veins that retain indications of reactivation, brecciation, and open-space infill are more promising for related base metals. Therefore, structurally complicated portions where late-stage permeability was preserved are the highest priority objectives. Additionally, MVT system exploration target prioritises fluid conduits, breccia zones, and fault intersections over

uniformly mineralised but texturally simple bodies because they are more likely to contain metal-rich deposits (Wei et al., 2024; Song et al., 2023).

5.4 Exploration Implications

Exploration targeting in the Azara district should prioritize (i) the NE-SW structural corridor and anticlinal crest zone, (ii) intersections of the dominant NW-SE vein set with E-W fractures and fold-related structures, and (iii) local dilational jogs, splays, and breccia zones that record repeated reactivation and enhanced permeability. Radiometric K anomalies can serve as a first-pass proxy for structural corridors and/or alteration but should be integrated with field structural mapping and subsurface constraints.

6.0 CONCLUSIONS

This study investigated the structural controls and mineralization style of baryte deposits in the Azara area, central Benue Trough, Nigeria, by integrating surface mapping, radiometric data, and scout drill-core observations. The results show that baryte mineralization is concentrated within discrete vein clusters along a major NE–SW structural corridor, spatially associated with an anticlinal ridge, and that ore emplacement was controlled by fracture connectivity, repeated structural reactivation, and localized dilation.

- Baryte mineralization in the Azara area is epigenetic and strongly structurally controlled, occurring mainly as steep to subvertical, bedding-discordant veins localized within fault- and fracture-dominated corridors.
- The district-scale distribution of veins along a NE–SW corridor coincident with an anticlinal ridge indicates a first-order structural control on fluid flow and ore emplacement. This links the mapped vein pattern, topographic expression, and radiometric K-enrichment to a common fault-fold architecture.
- Three principal vein sets were identified: a dominant NW–SE set, a subordinate E–W set, and a minor N–S set. Their geometry suggests progressive deformation and repeated reopening of structurally favourable pathways during mineralization.
- Drill-core observations show that the main mineralization styles are massive fissure-fill lodes, breccia infill, stockwork veinlets, and open-space cavity fills. These textures demonstrate episodic fracture opening, sealing, and reactivation, and explain the uneven distribution of ore thickness and continuity across the district.
- The mineral assemblage of baryte with siderite, minor chalcopyrite-pyrite, and late sphalerite indicates a multi-stage hydrothermal system. The paragenetic sequence shows that early alteration and sulphide phases were followed by dominant baryte-siderite deposition, with later Zn-Pb enrichment focused in reopened and dilational sites.
- The clearest exploration targets are anticlinal crest zones, intersections between the dominant NW–SE veins and subsidiary fractures, and brecciated or dilational segments

of the vein system. These are the locations where the structural data, radiometric response, and subsurface vein textures most clearly converge.

Overall, this work contributes to the broader understanding of structurally controlled Pb-Zn-Ba systems in sedimentary basins by showing how fold-related permeability, fracture reactivation, and vein-set intersections govern baryte emplacement in the central Benue Trough. Beyond Azara, the findings provide an exploration framework that can be applied to comparable MVT-like baryte and base-metal districts elsewhere, making the study relevant to international readers interested in hydrothermal ore systems, structural controls on mineralization, and mineral exploration targeting.

Acknowledgements

I would like to immensely thank MECON Engineering Ltd for access to exploration drill logs and TETfund for my PhD scholarship support.

Funding

This work was supported by Tertiary Education Trust Fund (TETfund) and Mecon Engineering Ltd.

Declaration of generative AI use

During the preparation of this work, the authors used ChatGPT 5.4 to assist with language editing, improving readability, and preparing supporting submission documents, including the cover letter and manuscript highlights. After using this tool/service, the authors reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Authors' contributions

Victor Bulus Diyelmak was responsible for Conceptualization, field mapping, analysis, Data curation, Visualization, Writing and original draft while Ifeanyi Andrew Oha Supervises, review & editing.

References

[1] A.O. Aladesanmi, A.K. Ogundana, A.A. Olowookere, L. Jenakumo, Geological characterization of Azara barite mineralization, Middle Benue Trough, Nigeria, J. Environ. Earth Sci. 8 (2018) 39-50.

[2] S.O. Akande, A. Mücke, Mineralogical, textural and paragenetic studies of the lead-zinc-copper mineralization in the Lower Benue Trough (Nigeria) and their genetic implications, J. Afr. Earth Sci. 9 (1989) 23-29.

[3] S.H. AbdElNabi, Role of gamma-ray spectrometry in detecting potassic alteration associated with Um Ba'anib granitic gneiss and metasediments, G. Meatiq area, Central Eastern Desert, Egypt, Arab. J. Geosci. 6 (2013) 4135-4147.

[4] D. Auwalu, A.I. Haruna, A.S. Maigari, T.P. Bata, U. Abubakar, A. Yusuf, A.S. Sulaiman, The structural attributes of Gombe lineaments in relation to baryte-fluorite mineralization in the Gongola Sub-basin of the

Northern Benue Trough, Nigeria: A study using remote sensing data, Bima J. Sci. Technol. 8 (1B) (2024) 50-63. https://doi.org/10.56892/bima.v8i1.613.

[5] J. Benkhelil, The origin and evolution of the Cretaceous Benue Trough (Nigeria), J. Afr. Earth Sci. 8 (1989) 251-282. https://doi.org/10.1016/S0899-5362(89)80028-4.

[6] S.I. Bute, J.-X. Zhou, K. Luo, M.B. Girei, R.T. Peter, Pb-Zn-Ba deposits in the Nigerian Benue Trough: A synthesis on deposits classification and genetic model, Ore Geol. Rev. 168 (2024) 105947. https://doi.org/10.1016/j.oregeorev.2024.105947.

[7] S.O. Elkhateeb, M.A.G. Abdellatif, Delineation of potential gold mineralization zones in part of the Central Eastern Desert, Egypt, using airborne magnetic and radiometric data, NRIAG J. Astron. Geophys. 7 (2018) 361-376.

[8] E. Elawadi, A. Ammar, A. Elsirafy, Mapping surface geology using airborne gamma-ray spectrometric survey data: A case study, in: Proc. 7th SEGJ Int. Symp., Sendai, Japan, 2004, pp. 45-52.

[9] F.B. Fatoye, M.A. Ibitomi, J.I. Omada, Lead-zinc-barytes mineralization in the Benue Trough, Nigeria: Geology, occurrences and economic perspective, Adv. Appl. Sci. Res. 5 (2014) 11-18.

[10] R.L. Grasty, R.B.K. Shives, Applications of gamma ray spectrometry to mineral exploration and geological mapping, in: Proc. Exploration 97, Fourth Decennial Int. Conf. on Mineral Exploration, Toronto, 1997, pp. 147-166.

[11] M. Jébrak, Hydrothermal breccias in vein-type ore deposits: A review of mechanisms, morphology and size distribution, Ore Geol. Rev. 12 (1997) 111-134. https://doi.org/10.1016/S0169-1368(97)00003-0.

[12] N.A. Labe, P.O. Ogunleye, A.A. Ibrahim, Field occurrence and geochemical characteristics of the baryte mineralization in Lessel and Ihugh areas, Lower Benue Trough, Nigeria, J. Afr. Earth Sci. 142 (2018) 35-49.

[13] D.L. Leach, R.D. Taylor, D.L. Fey, S.F. Diehl, R.W. Saltus, A deposit model for Mississippi Valley-Type lead-zinc ores, U.S. Geol. Surv. Sci. Investig. Rep. 2010-5070-A (2010). https://doi.org/10.3133/sir20105070A.

[14] K. Luo, J.-X. Zhou, Z.-L. Huang, J. Caulfield, J.-X. Zhao, Y.-X. Feng, H. Ouyang, New insights into the evolution of Mississippi Valley-Type hydrothermal system: A case study of the Wusihe Pb-Zn deposit, South China, using quartz in-situ trace elements and sulfides in situ S-Pb isotopes, Am. Mineral. 105 (2020) 35-51. https://doi.org/10.2138/am-2020-7021.

[15] N. Maden, E. Akaryalı, Gamma ray spectrometry for recognition of hydrothermal alteration zones related to a low-sulfidation epithermal gold mineralization (eastern Pontides, NE Türkiye), J. Appl. Geophys. 122 (2015) 74-85.

[16] P.-P. Niu, S.-Y. Jiang, M. Muñoz, Formation of the giant Maoping Mississippi Valley-type Pb-Zn (Ge) deposit via fluid mixing: Evidence from trace element and sulfur isotope geochemistry of pyrite, Ore Geol. Rev. 169 (2024) 106110. https://doi.org/10.1016/j.oregeorev.2024.106110.

[17] A.K. Ogundana, Origin of the brines associated with the lead-zinc-barite-fluorite deposits in Benue Trough, Nigeria: Evidence from stable isotope studies, Vegetos 37 (2024) 725-730. https://doi.org/10.1007/s42535-023-00773-4.

[18] M.A. Olade, R.D. Morton, Origin of lead-zinc mineralization in the southern Benue Trough, Nigeria: Fluid inclusion and trace element studies, Mineral. Deposita 20 (1985) 76-80.

[19] N.K. Samaila, I.A. Ekeleme, F.A. Ajol, T. Aga, A.P. Adelabu, et al., Baryte mineralization in Faya area and environs, Langtang South, Middle Benue Trough, Northcentral Nigeria: Inferences from geology, petrography and trace element geochemistry, J. Afr. Earth Sci. 231 (2025) 105714. https://doi.org/10.1016/j.jafrearsci.2025.105714.

[20] R.B.K. Shives, B.W. Charbonneau, K.L. Ford, The detection of potassic alteration by gamma-ray spectrometry—recognition of alteration related to mineralization, Geophysics 65 (2000) 2001-2011.

[21] Y. Song, Z. Hou, Y. Liu, L. Zhuang, G. Hu, Mississippi Valley-type Zn-Pb deposits in orogenic thrust belts: Ore formation in response to synorogenic crustal transpression or extension, Mineral. Deposita 58 (2023) 1333-1350. https://doi.org/10.1007/s00126-023-01185-9.

[22] L. Tavazzani, M. Guillong, A. Giuliani, L. Fontboté, C. Chelle-Michou, Not so fast: Million-years of metal precipitation in Mississippi Valley type deposits inferred from in-situ petrochronology of hydrothermal carbonates, Earth Planet. Sci. Lett. 632 (2024) 118718. https://doi.org/10.1016/j.epsl.2024.118718.

[23] B.F. Walter, N. Egesi, M. Raza, M. Agbebia, F. Adamu, R.J. Giebel, M.A.W. Marks, E.C. Ugbaja, G. Markl, Unconformity-related fluorite-baryte-base metal mineralization in the Benue Trough, Nigeria: A multifluid origin triggered by the separation of Pangaea, J. Afr. Earth Sci. 235 (2026) 105964. https://doi.org/10.1016/j.jafrearsci.2025.105964.

[24] C. Wei, L. Ye, Z. Huang, Y. Hu, Z. Yan, Z. Xiang, Transition from breccia pipe to stratabound mineralization in Mississippi Valley-type hydrothermal systems: The Nayongzhi Zn-Pb deposit, world-class Sichuan-Yunnan-Guizhou triangle, South China, GSA Bull. 136 (2024) 217-233. https://doi.org/10.1130/B36630.1.

[25] M.A.S. Youssef, S.T. Elkhodary, Utilization of airborne gamma ray spectrometric data for geological mapping, radioactive mineral exploration and environmental monitoring of southeastern Aswan, Egypt, Arab. J. Geosci. 6 (2013) 1867-1879.