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Geology, Geochemistry, and Economic Potential of Hydrothermal Baryte Mineralization in the Gombe Inlier, Upper Benue Trough, Nigeria

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Abstract

The Gombe Inlier, located in the Upper Benue Trough, Nigeria, hosts significant hydrothermal baryte mineralization within altered Bima Sandstone. This study investigates the geology, geochemistry, and structural controls of the baryte occurrences in the Gombe-Liji area to evaluate their economic potential and compare them with other Nigerian and global deposits. Field observations reveal that the mineralization is structurally controlled, occurring in NE-SW trending veins along major fault systems within the inlier. The geochemical analysis shows BaO content ranging from 70.87% to 71.46%, indicating high purity, while SiO₂wt.% levels (15.55–15.60%) suggest quartz contamination. The baryte exhibits elevated Sr concentrations (10,540.5 ppm), comparable to Peruvian and Moroccan deposits, suggesting hydrothermal origins. Comparative analysis with other Nigerian occurrences shows that the Gombe-Liji baryte is geochemically similar to deposits in Azara and Duguri but contains higher SiO₂ than Lower Benue Trough deposits, which are more industrially suitable. The mineralization is associated with hydrothermal basinal brines, with structural controls facilitating fluid movement and precipitation. Despite the lack of isotopic and fluid inclusion studies in this research, previous studies in the Benue Trough indicate thermochemical sulfate reduction (TSR) and seawater-derived fluids as key sources of baryte mineralization. The Gombe-Liji baryte deposit meets industrial requirements for drilling fluids in the oil and gas sector but may require beneficiation to reduce silica content. This study enhances the understanding of baryte mineralization in the Upper Benue Trough and highlights its economic significance within Nigeria's growing mineral sector.

Keywords

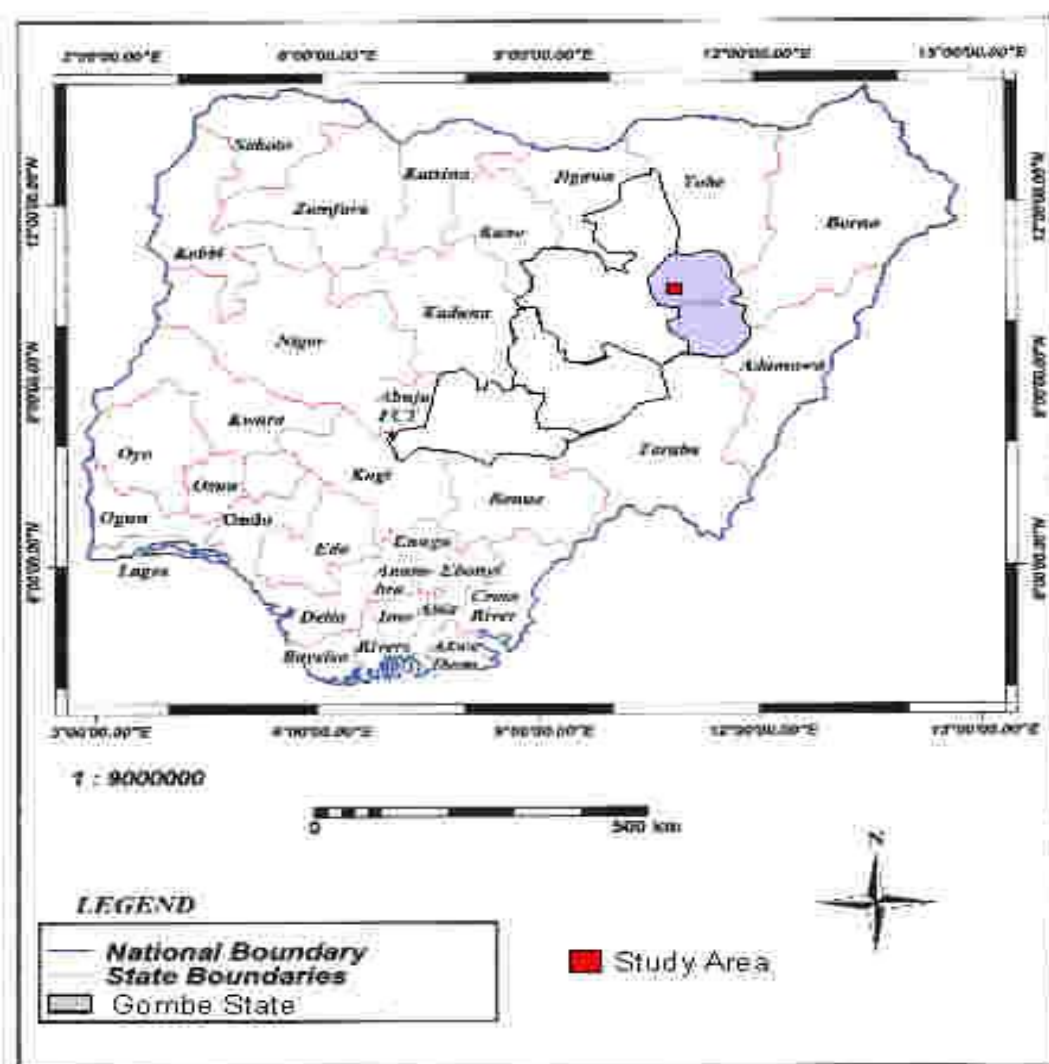
Baryte mineralization, Gombe Inlier, Upper Benue Trough, hydrothermal processes, economic geology

1. Introduction

Baryte (BaSO_4) is an industrially significant mineral primarily used in oil and gas drilling, chemical production, and paint manufacturing. It has a high specific gravity ($\sim 4.5 \text{ g/cm}^3$) and variable coloration due to impurities. Baryte commonly occurs in association with minerals such as celestine (SrSO_4), galena (PbS), and sphalerite (ZnS), and is often found in hydrothermal veins and sedimentary formations. The Gombe Inlier, a basement dome within the Gongola Basin of the Upper Benue Trough, exposes stratigraphic sequences such as the Bima Sandstone, Yolde Formation, Pindiga Formation, and Gombe

Sandstone. The geochemical characteristics of these surrounding rocks provide critical insights into the baryte mineralization process.

2. Location of Study Area and Regional Geologic Setting The study area is situated in northeastern Nigeria, within Gombe Local Government of Gombe State. It forms part of the Gombe Sheet 152 N.W, covering approximately 53 km^2 , between latitudes $10^\circ 16' \text{N}$ - $10^\circ 19' \text{N}$ and longitudes $11^\circ 11' \text{E}$ - $11^\circ 15' \text{E}$. (Figure 1) The Gombe-Biu trunk road traverses the area, with additional secondary roads and footpaths ensuring accessibility.



SOURCE: National Centre For Remote Sensing Joz, Nigeria

Figure 1. Location Map of the Study area

The Benue Trough, one of Nigeria's most significant Cretaceous sedimentary basins, has been extensively studied in terms of its origin and evolution. The trough lies on the Nigerian Basement Complex, which forms part of the Pan-African Mobile Belt. Its formation is linked to the opening of the South Atlantic Ocean and is believed to have been influenced by pre-existing structures of the West African Shield (Benkhelil, 1989).

The Benue Trough is divided into three sections: Upper, Middle, and Lower Benue Trough. The Upper Benue Trough bifurcates into a southwest-trending Yola Arm and a north-south-trending Gongola Arm (Carter et al., 1963). The Zambuk Ridge is the structural feature separating these two arms, characterized by prominent NE-SW trending sinistral strike-slip faults. The Upper Benue Valley has undergone two recognized folding events: the Cenomanian and post-Maastrichtian deformations (Barber, 1954).

The stratigraphy of the region includes the Bima Sandstone (Albian age), which unconformably overlies the Precambrian basement and is subdivided into Upper, Middle, and Lower Bima Sandstones. The

Yolde Formation (Cenomanian) lies unconformably on the Bima Sandstone and marks the onset of marine incursions into the Upper Benue Trough. This formation consists of sandstone, limestone, shale, and mudstone, indicative of a transitional coastal-marine environment. The Turonian-Santonian stratigraphic units in the Yola Arm include the Dukul, Jessu, Sekuliye Formations, Lamja Sandstone, and Numanha Shales, which correlate with the Gongola and Fika Formations in the Gongola Arm. These formations are largely marine, consisting of dark gray carbonaceous limestone, shales, and pale-colored sandstone.

The Gongola Formation is well-exposed at Ashaka Cement Factory, while the Fika Shale contains bluish-green carbonaceous limestone. The Santonian period marked significant deformation and folding across the Benue Trough. Post-folding deposits include the continental Gombe Sandstone (Maastrichtian) and the overlying Kerri-Kerri Formation (Tertiary age), both representing post-orogenic sedimentation.

AGE	LOWER BENUE		MIDDLE BENUE	UPPER BENUE	
Quaternary	NIGER DELTA	Benin		Yola sub	Gongola sub
Pliocene		Agbada	Volcanics		
Miocene					
Oligocene		Akata		Volcanics	Kerri-Kerri
Eocene		Nanka	Hiatus		
Paleocene	ANAMBRA BASIN	Ameka/Imo/ Nsukka			
Maastrichtian		Ajalli/Owelli/ Mamu	Lafia	Hiatus	Gombe
Campanian		Nkporo/Enugu			Fika
Santonian					
Coniacian	Cross River Group	Agbani	Makurdi	Lamja	Fika ?
Turonian		Nkalagu	Awgu	Numanha	Pindiga
Cenomanian		Agala	Ezeaku/Konshisha/ Wadata	Sekuliye	Gongola
		Odukpani	Keana / Awe	Jessu	
Albian	Asu River Group	Mfamosing Abakaliki	Arufu/Uomba/Gboko	Yolde	
Pre-Albian	B a s e m e n t C o m p l e x				

Figure 2: Stratigraphic succession of the Benue Trough. (Obaje, 2009).

3. Methodology A detailed geological field mapping was conducted, involving ground traversing along footpaths, cattle tracks, farmlands, stream channels, and other accessible routes. Outcrops were accurately located on a base map using GPS, and their orientations were recorded in the field. Representative rock samples were collected along and across the baryte mineralized veins and surrounding host rocks for petrographic and geochemical studies.

A total of 18 representative samples were selected for geochemical analysis. Five baryte samples were analyzed for whole-rock characterization (major oxides, trace elements, and rare earth elements), while six surrounding rock samples underwent ultra-trace geochemical multi-acid digestion. Sample preparation, including pulverization, was

conducted at the Department of Geology, University of Jos, before being transported to Acme Laboratory, Vancouver, Canada, for analysis.

4. Results

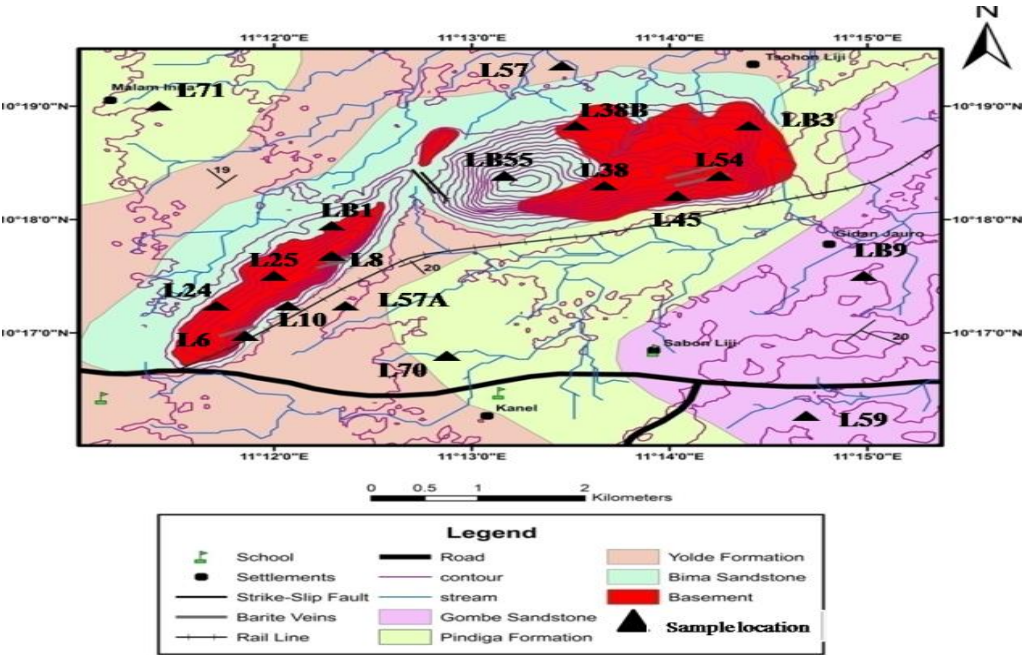
4.1 Field Geology

The study area comprises lithologic units from the Basement Complex and sedimentary formations, including Granite Gneiss, Bima Sandstone, Yolde Formation, Pindiga Formation, and Gombe Sandstone (Figure 2 a and b). The Basement Complex rocks, mainly granite gneiss and pegmatite and Quartzite (Plate 1), occur at the top of Gombe inlier and Liji Hill, exhibiting a NE-SW strike direction. The pegmatite veins result from hydrothermal processes. The Gombe Sandstone in the northeast is fine to medium-grained, with quartz, feldspar, and mica. The Pindiga Formation in the northwest consists of

bluish-dark shale, while the Yolde Formation in the southwest comprises light grey sandstones with cross-bedding and burrows. The Bima Sandstone, surrounding Gombe inlier and Liji Hill, has been thermally altered and hosts baryte

veins (Plate 1c). Quartzite formations (Plate 1c) near the Gombe inlier are dark gray, indurated, and granoblastic, with evidence of thermal alteration. Baryte mineralization occurs within quartzites and extends into granite gneiss.

A.



b.

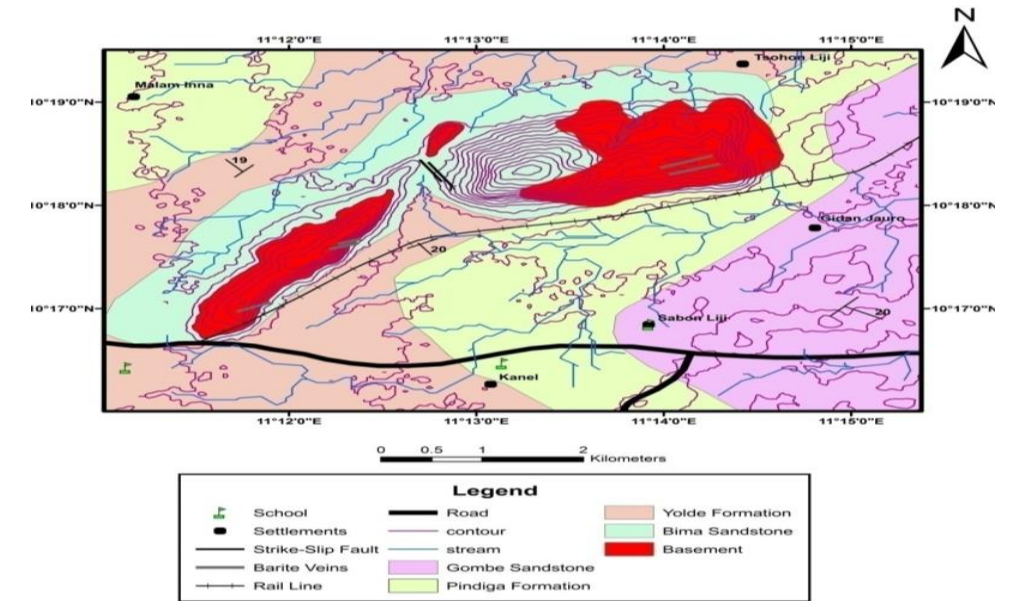


Figure 3a and b. Geological map of the study area (with sample locations in a)



Plate 1: Basement rocks exposure at Gombe Inlier (N 10° 18 07.3, E 11° 12 31.1) (a) Granite Gneiss (b) Quartzite



Plate 1c: Bima sandstone showing baryte sandwiched in Bima sandstone

4.2 Baryte Mineralization and Pegmatite Veins Two baryte fields, Gombe and Liji, have been identified, with numerous mining pits. The baryte veins trend E-W, NNW-SSE, NW-SE, and NE-SW.

4.2.1 Gombe Baryte Field Located at the crest of a ridge within (Plate 2) altered Bima Formation quartzites, baryte veins trend NW-SE, NNW-SSE, and NE-SW. The dominant vein follows a NE-SW strike (190°) over 1-2 km in length and 11 m in width, with smaller veins ranging from 0.3 to 0.8 m wide.

4.2.2 Liji Baryte Field Liji baryte mineralization occurs as fracture infillings within Bima Sandstone, exhibiting silicification. The veins strike 274° (NW) and extend 5-9.4 m, with widths of 1.8-2.7 m. The baryte is reddish to brown due to iron oxide impurities.

4.2.3 Pegmatite Vein Rock A pegmatite vein at Liji Hill intrudes the Basement Complex, trending NE-SW (200° SW). It extends 50-60 m in length and 3-5.2 m in width, appearing greenish-white and coarse-grained (Plate 3 a and b)



Plate 2a. A ridge of baryte vein at 'Gombe Inlier' (N10° 18 14.2, E 11° 12 58.7) and b. a section at the mining pit of Baryte mineralization in Liji (N 10° 18 16.8, E 11° 14 10.3).

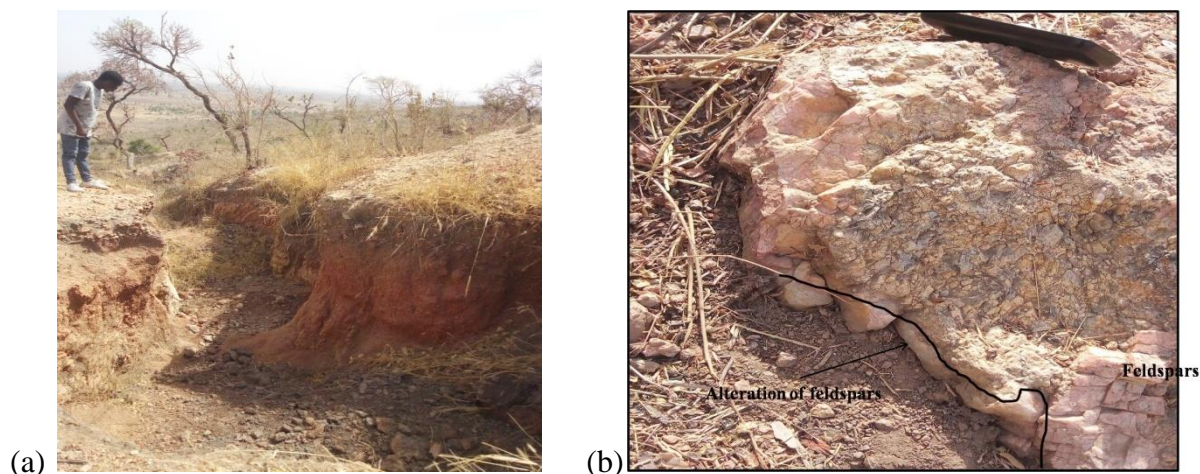


Plate 3: Pegmatite vein at Liji Hill (N 10° 18 67.9, E 11° 13 48.4) showing (a) Mining pit, (b) alteration processes of feldspars

4.3 Geochemistry of the Rocks

4.3.1 Major Elements of the Host Rocks

Geochemical analysis of the sandstones in the study (Table 1) area reveals variations in major oxide concentrations. SiO₂ content is highest in the Gombe Sandstone (93.39-98.12 wt. %, avg. 92.76 wt. %), followed by the Yolde Sandstone (79.48-90.27 wt. %, avg. 84.88 wt. %), and the Bima Sandstone

(65.57-92.37 wt. %, avg. 81.85 wt. %). The Yolde Sandstone has the highest Al₂O₃ (avg. 8.94 wt. %), Fe₂O₃ (avg. 1.70 wt. %), and TiO₂ (avg. 0.38 wt. %). The Bima Sandstone contains the highest MgO (avg. 0.70 wt. %), Na₂O (avg. 1.05 wt. %), and K₂O (avg. 3.64 wt. %). CaO concentrations are highest in the Yolde Sandstone (avg. 4.49 wt. %), while MnO is most abundant in the Gombe Sandstone (avg. 0.04 wt. %).

Shales in the study area (Table 1) are enriched in SiO_2 (63.86–71.25 wt. %, avg. 67.56 wt. %), CaO (avg. 4.87 wt. %), and K_2O (avg. 3.97 wt. %) but have lower Al_2O_3 , MgO , MnO , and P_2O_5 relative to North American Shale Composite (NASC) and Post-Archean Australian Shale (PAAS). The Fe_2O_3 and Na_2O concentrations exceed those reported for the Lower Benue Trough. P_2O_5 values are similar to NASC but lower than PAAS.

Based on Herron's (1988) classification diagram (Figure 4), the sandstones are categorized as wacke, litharenite, and

quartz arenite. $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios range from 3.06–13.69, indicating quartz-rich sandstones as per Crook's (1974) model. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios and Chemical Index of Alteration (CIA) values suggest differing degrees of weathering and provenance. The Bima Sandstone shows high $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios, indicative of a quartz-rich, mature sedimentary source, while the shales of the Pindiga Formation display lower ratios, reflecting less weathered, feldspar-rich sources. High Ba concentrations in the shale (1086 ppm) and gneiss (2514 ppm) suggest these lithologies could be potential sources for the baryte mineralization.

Table 1: Average Chemical Composition of Shale and Sandstone from the Study Area (all values in wt. %).

Major Oxides	Gombe Sandstone (n=2)	Shale (n=2)	Yolde Sandstone (n=2)	Bima Sandstone (n=3)
SiO_2	92.76	67.56	84.88	81.85
TiO_2	0.42	0.84	0.38	0.13
Al_2O_3	4.42	12.52	8.94	7.56
Fe_2O_3	1.53	4.68	1.70	1.52
MnO	0.04	0.05	0.03	0.03
MgO	0.18	0.77	0.23	0.70
CaO	4.35	4.87	4.49	6.13
Na_2O	0.16	0.29	0.72	1.05
K_2O	0.49	3.97	2.94	3.64
P_2O_5	0.02	0.02	0.02	0.01
LOI	0.06	0.40	0.21	2.06
TOTAL	100.43	99.97	100.54	102.68

Additional Geochemical Ratios;

Parameter	Gombe Sandstone	Shale	Yolde Sandstone	Bima Sandstone
$\text{SiO}_2/\text{Al}_2\text{O}_3$	20.99	5.40	9.49	10.83
$\text{K}_2\text{O}/\text{Na}_2\text{O}$	3.06	13.69	4.08	3.47
CIA*	46.92	57.83	52.31	41.13
$\text{Al}_2\text{O}_3/\text{TiO}_2$	10.53	14.9	23.53	58.15

*CIA (Chemical Index of Alteration) is a measure of weathering intensity

Table 2: Average Chemical Composition of Shale and Sandstone from the Study Area Compared to Other Sedimentary Basins in Nigeria and Worldwide (all values in wt. %).

Major Oxides	Present Study Shale	Ihugh & Lessel Shale (a)	NASC (b)	PAAS (c)	Ihugh & Lessel Sandstone (a)	Cross River Group (d)	Present Study Sandstone
SiO ₂	67.56	77.6	64.2	62.4	83.1	79.6	86.50
Al ₂ O ₃	12.52	14.4	17.1	18.8	8.2	7.7	6.97
Fe ₂ O ₃	4.68	4.0	5.7	7.2	4.2	1.4	1.58
MnO	0.05	0.1	-	-	0.1	0.1	0.03
MgO	0.77	1.1	2.8	2.2	1.2	0.3	0.37
CaO	4.87	0.4	3.5	1.3	0.3	1.5	4.99
TiO ₂	0.84	0.8	0.8	1.0	0.4	0.4	0.31
Na ₂ O	0.29	0.1	1.1	1.2	0.4	0.3	0.64
K ₂ O	3.97	1.5	3.9	3.7	2.0	2.0	2.39
P ₂ O ₅	0.02	0.1	0.2	0.2	0.1	0.1	0.01
TOTAL	95.57	100.0	99.4	97.9	100.0	93.4	100.79

Notes:

- (a) NASC (North American Shale Composite) - Haskin et al. (1966)
- (b) PAAS (Post-Archean Australian Shale) - Taylor and McLennan (1985)
- (c) Cross River Group - Adeigbe and Jimoh (2013)
- (d) Lessel-Ihugh Sandstones and Shale - Ngukposu (2015)

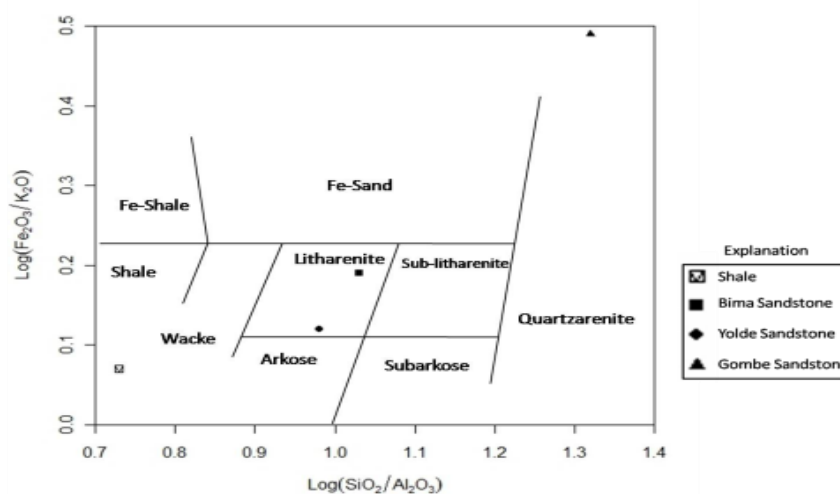


Figure 4: Geochemical classification diagram using $\log (\text{SiO}_2/\text{Al}_2\text{O}_3) - \log (\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ (Herron, 1988).

4.3.2 Trace Elements Composition of the Host Rocks

The trace element composition of the surrounding rocks (Table 2) shows variations between distal (unaltered) and proximal (hydrothermally altered) sandstones. Ferromagnesian elements such as Cr, Ni, Co, Sc, and V exhibit decreasing concentrations from distal to proximal sandstones and baryte veins. Cr ranges from 24-245 ppm (average 108 ppm) in distal sandstones and 3-101 ppm (average 61.3 ppm) in proximal sandstones. Similarly, Ni averages 40 ppm in distal sandstones and 23.8 ppm in proximal sandstones. These values are lower than the average crustal abundances reported by Taylor (1964),

indicating fractionation and weathering effects. Trace elements of economic interest—Ba, Sr, and Rb—show significant variations. Ba content increases from 245-2514 ppm (average 1281.67 ppm) in surrounding rocks to 601-2107 ppm (average 1134 ppm) in host rocks, reflecting hydrothermal alteration. Sr follows a similar trend, while Rb shows depletion in altered rocks, suggesting leaching by hydrothermal fluids. Ba/Sr ratios range from 3.9-19.5 ppm. Normalized trace element concentrations align with upper continental crust values (Taylor & McLennan, 1985), with notable enrichment in Rb, Ce, and Ba but depletion in K, Ti, and P.

Table 2: Trace Element Concentration (in ppm) of the Surrounding Rocks (ppm)

Trace Elements	Distal			Proximal		
	Shale L70 (Pindiga Formation)	Sandstones				Gneiss L25 Basement Complex
		L59 Gombe Sandstone	L57A Yolde Sandstone	L10 Bima Sandstone	L24 Bima Sandstone	
Ba	1086.00	245.00	2514.00	2107.00	601.00	695.00
Mo	0.53	0.30	3.22	0.60	17.48	2.05
Cu	18.3	7.20	13.00	5.00	6.60	5.20
Pb	30.32	9.66	33.86	15.95	14.37	28.26
Zn	17.70	15.90	13.3	2.60	7.40	19.00
Ag	<20.00	<20.00	24.00	35.00	348.00	162.00
Ni	29.00	13.70	77.90	0.60	31.50	39.30
Co	15.30	2.80	3.70	<0.20	3.10	1.50
Mn	134.00	79.00	58.00	7.00	34.00	54.00
As	0.40	0.60	<0.20	1.20	1.60	<0.20
U	4.10	0.80	1.50	0.30	1.00	3.80
Th	12.80	6.90	8.80	1.30	2.40	23.30
Sr	118.00	23.00	159.00	108.00	63.00	178.00
Cd	<0.02	<0.02	0.02	<0.02	<0.02	0.04

Sb	0.20	0.05	0.10	0.09	0.34	0.14
Bi	0.16	<0.04	<0.04	<0.04	0.04	<0.04
V	73.00	25.00	22.00	4.00	4.00	17.00
W	2.30	0.40	0.90	0.10	0.40	0.90
Cr	55.00	24.00	245.00	3.00	101.00	80.00
Zr	113.6	43.10	54.00	17.60	20.90	76.20
Sn	3.90	0.70	2.50	1.10	1.10	5.10
Be	5.00	<1.00	1.00	<1.00	<1.00	4.00
Sc	9.80	3.40	2.80	0.40	0.30	2.50
Y	16.10	5.90	7.10	1.60	1.90	7.70
Hf	3.37	1.27	1.71	0.46	0.58	2.53
Li	10.30	8.30	42.40	86.10	103.40	29.30
Rb	603.00	18.90	193.90	148.70	87.60	255.00
Ta	1.90	0.40	0.70	0.20	0.10	0.50
Nb	28.01	6.25	10.26	3.05	1.91	8.71
Cs	47.20	1.20	6.00	1.20	0.70	6.20
Ga	31.99	7.90	14.42	6.94	3.95	25.82
In	0.05	0.01	0.03	0.01	<0.01	0.03
Re	<0.002	0.003	0.003	<0.002	<0.002	0.004
Se	0.90	0.60	<0.30	1.50	<0.30	0.80
Te	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Ti	4.08	0.19	1.44	1.55	3.66	2.19
Ratio						
Th/U	3.12	8.63	5.86	4.30	2.40	-
Ba/Sr	9.20	10.65	15.81	19.51	9.54	3.90
V/Cr	1.33	1.04	0.09	1.33	0.04	0.21
Ni/Co	1.90	4.89	21.05	-	10.16	26.2
Cu/Zn	1.03	0.45	0.98	1.92	0.89	0.27
Zr/Nb	4.06	6.90	5.26	5.77	10.94	8.75
Th/Sc	1.31	2.03	3.14	3.25	8.00	9.32
Zr/Hf	33.53	33.93	31.58	38.26	36.03	30.12
Cr/Ni	1.90	1.75	3.15	5.00	3.21	2.04
Rb/Sr	5.11	0.82	1.22	1.38	1.39	1.43
Nb/Y	1.75	1.06	1.45	1.91	1.01	1.13
Zr/Th	8.88	6.25	6.14	13.54	8.71	3.27
Cr/Th	4.30	3.48	27.84	2.31	42.08	3.43

4.3.3 Geochemistry of Baryte

4.3.3.1 Major Elements

The major element composition of baryte veins (Table 3) indicates significant variation across the study area. SiO₂ concentrations range from 6.71-38.66 wt.%, showing a decreasing trend from the southwest to the northeast, whereas Fe₂O₃ (0.04-0.23 wt.%) and CaO (0.99-6.96 wt.%) increase in the same direction. BaO and SrO concentrations in baryte veins range from 43.4-65.9 wt.% and 0.59-0.9 wt.%, respectively. Compared to host rocks, the baryte veins exhibit lower concentrations of major oxides, suggesting hydrothermal alteration, possibly involving plagioclase feldspar and epidote formation.

Pegmatite veins show very low SiO₂ and high CaO levels, further emphasizing hydrothermal activity. The geochemical analysis of baryte samples from Gombe and Litji reveals that BaO is the predominant oxide, constituting approximately 71.46% to 70.87% of the samples. This high BaO content aligns with findings from other Nigerian baryte deposits, such as those in Torkula and Kaseyo, Benue State, where BaO values

range between 48.37% and 60.1%. The SiO₂ content in the Gombe and Litji baryte samples varies between 15.55% and 15.60%, which is higher than the SiO₂ content reported in other Nigerian baryte deposits, indicating potential silica contamination that may require beneficiation.

4.3.3.2 Trace Elements

Trace element results (Table) reveals that baryte samples are enriched in Ba, Sr, Rb, and Ta but depleted in Hf, Zr, Ce, Nb, Nd, Y, and Ti. Normalization to average lower continental crust values indicates similar geochemical trends between the Gombe and Liji baryte deposits. The Ba/Sr ratio in baryte veins (6.58-10.00) is lower than that of the host rocks (3.90-19.50), implying Ba leaching due to hydrothermal fluid interaction. Notably, baryte veins contain exceptionally high Ba concentrations (388,700-590,000 ppm), confirming the economic significance of the deposit. Other notable trace elements include Pb (0.70-6.40 ppm), Zn (1.00-7.00 ppm), and Ni (0.30-19.50 ppm), reflecting possible metallogenic influences from hydrothermal processes.

Table 3: Major Oxides Concentration of Mineralized Baryte Veins (wt.%)

	Gombe	Liji			
	Vein 1 (L6)	Vein 2 (L8)	Vein 3 (L45)	Vein 4 (54)	
SiO ₂	18.02	38.66	18.55	6.71	12.84
TiO ₂	0.04	0.03	0.01	<0.01	0.02
Al ₂ O ₃	1.48	0.97	0.36	0.05	0.61
Fe ₂ O ₃	0.34	0.14	0.14	<0.04	0.23

MgO	0.09	<0.01	<0.01	<0.01	0.01
CaO	60.53	2.90	0.99	1.39	6.96
MnO	<0.01	<0.01	<0.01	<0.01	<0.01
Na ₂ O	0.16	0.04	0.01	<0.01	0.04
K ₂ O	0.74	0.51	0.05	<0.01	0.22
P ₂ O ₅	0.02	0.01	<0.01	<0.01	<0.01
BaO	-	65.9	43.40	55.9	46.5
SrO	-	0.73	0.89	0.90	0.59
Cr ₂ O ₃	<0.002	<0.002	<0.002	0.004	0.010
LOI	4.1	2.00	1.4	3.9	3.4
TOTAL	84.44	102.89	65.80	68.85	68.04

Table 4: Trace Elements (in ppm) Concentration of Mineralized Baryte Veins

	Gombe	Liji			
	Vein 1 (L6)	Vein 2 (L8)	Vein 3 (L45)	Vein 4 (54)	
Ba	314	388,700	590,000	500,700	416,700
Mo	0.30	1.10	0.90	0.50	0.70
Cu	0.60	1.50	0.70	1.90	6.40
Pb	0.40	4.00	0.80	0.70	2.30
Zn	6.00	7.00	1.00	1.00	2.00
Ag	<0.10	0.20	<0.10	<0.10	0.10
Ni	<0.10	1.60	1.30	13.80	19.50
Co	0.60	1.10	0.30	1.70	0.70
As	<0.50	0.90	9.20	<0.50	1.00
U	<0.10	<0.10	<0.10	<0.10	<0.10
Th	0.90	0.80	0.50	<0.20	0.70
Sr	83.40	6219.20	7533.00	7597.10	5000.80
Cd	<0.10	<0.10	<0.10	<0.10	<0.10
Sb	<0.10	0.10	0.30	<0.10	<0.10
Bi	<0.10	<0.10	<0.10	<0.10	<0.10
V	<8.00	17.00	<8.00	<8.00	<8.00
W	<0.50	<0.50	<0.50	<0.50	<0.50
Zr	12.90	16.30	3.60	0.70	6.30

Sn	<1.00	<1.00	<1.00	<1.00	<1.00
Be	2.00	2.00	<1.00	<1.00	<1.00
Sc	<1.00	<1.00	<1.00	<1.00	<1.00
Y	109.00	7.20	2.50	3.10	21.10
Hf	0.30	2.00	2.40	2.10	1.70
Rb	30.50	20.20	2.60	<0.1	10.00
Ta	<0.10	5.50	5.80	4.70	3.50
Nb	1.70	0.70	0.20	<0.10	0.50
Cs	0.70	0.70	0.10	<0.10	0.30
Ga	0.60	<0.50	1.30	<0.50	<0.50
Au	<0.50	<0.50	<0.50	<0.50	<0.50
Hg	<0.01	0.01	0.13	0.03	0.01
Se	0.80	<0.50	<0.50	<0.50	<0.50
Ti	0.30	0.30	0.10	<0.10	<0.10

Element Ratios

Ratio	Gombe Vein 1	Gombe Vein 2	Liji Vein 3	Liji Vein 4
Ba/Sr	8.04	6.64	6.58	10.00

5. Discussion

5.1 Field Geology and Host of Baryte Mineralization

The study area is underlain by granite gneiss of the Basement Complex at the core of the Gombe inlier, surrounded by Cretaceous sedimentary formations including the Bima, Yolde, Pindiga, and Gombe Formations. The dominant structures observed are NE-SW and NW-SE trending faults, joints, and veins, with baryte mineralization occurring mainly along fractures parallel to the Gombe fault, similar to those in the Middle Benue Trough (Farrington, 1952; Akande & Abimbola, 1987; Ford, 1989; Oden, 2012). Petrographic studies show fractured quartz and microcline in

altered Bima sandstone, facilitating the infiltration of hydrothermal fluids responsible for baryte mineralization. The sandstones display subangular to subrounded grains, indicating variable degrees of sorting and weathering.

5.2 Source of Ore-Bearing Fluids

The baryte mineralization in Gombe-Liji is structurally controlled, occurring in NE-SW trending veins within altered Bima Sandstone. Geochemical and isotopic studies suggest a hydrothermal basinal brine origin, similar to other deposits in the Benue Trough (Akande & Abimbola, 1987; Oden, 2012). High Sr concentrations (~10,540 ppm) indicate prolonged fluid interaction with Sr-rich sediments. $\delta^{34}\text{S}$ values (+12‰ to +20‰)

suggest thermochemical sulfate reduction (TSR) as the primary sulfur source (Oden, 2012), while Pb isotopes hint at possible basement contributions (Akande et al., 1989).

Fluid inclusion studies from Benue Trough barytes (Ekwueme et al., 2015; Daspan & Imagbe, 2017) indicate homogenization temperatures of 90–150°C, consistent with deep-seated hydrothermal circulation along fault zones. Global analogs, such as the Mississippi Valley-Type (MVT) baryte deposits (Leach et al., 2010) and hydrothermal barytes in China (Liu et al., 2016), exhibit similar Ba-Sr geochemistry and fault-controlled precipitation. Overall, the Gombe-Liji baryte deposit is linked to hydrothermal basinal brine migration, with structural controls facilitating mineralization. The presence of high-temperature alteration and isotopic signatures supports a mixed sedimentary and basement-derived fluid source, reinforcing its economic potential within the Benue Trough metallogenic province.

5.3 Comparative Analysis of Baryte Occurrences

Baryte mineralization in the Gombe-Liji area shares similarities and differences with other occurrences in the Benue Trough and worldwide. In the Upper Benue Trough, baryte is predominantly hydrothermal and associated with fault-controlled systems, similar to Gombe-Liji. The Middle Benue Trough hosts stratabound baryte deposits, with some occurrences influenced by syngedimentary processes (Akande &

Abimbola, 1987; Akande et al., 1989). In the Lower Benue Trough, baryte mineralization is more extensive and occurs in vein-type and disseminated forms, with higher BaO content and better industrial suitability (Ibrahim et al., 2018). Globally, hydrothermal baryte deposits in Iran (Ehya, 2012) and China exhibit similarities in REE fractionation patterns and mineralization controls. However, Nigerian baryte deposits generally contain higher impurities such as Fe and Sr, requiring beneficiation for industrial use. The quality of baryte from the Gombe-Liji area falls within the mid-range of global standards, necessitating processing for high-end applications.

5.4 Origin and Controls of Baryte Mineralization

Petrographic and geochemical evidence supports an epigenetic hydrothermal model for baryte mineralization, with seawater-derived fluids migrating through fault-controlled fractures. The enrichment of Ba and Sr, depletion of Pb, Zn, Cu, and the REE signature suggest similarity with Lower Benue Trough barytes and seawater-dominated hydrothermal systems (Ehya, 2012; Alireza et al., 2014; Auwalu et al., 2024; Kamale et al., 2021). The strong depletion of Ti in host rocks and baryte veins indicates hydrothermal alteration at low temperatures, further supporting the seawater-derived hydrothermal model. The mineralization likely occurred at temperatures of 95–200°C, as

suggested by fluid inclusion studies from similar settings (Akande et al., 1989; Ibrahim et al., 2018). The main controls of baryte mineralization include faulting, lithological variation, and hydrothermal fluid migration. NE-SW and NW-SE trending fractures provided pathways for fluid movement and subsequent precipitation of baryte. The structural framework of the Gombe-Liji area, particularly its association with the Santonian tectonic events, facilitated the remobilization of ore-bearing fluids and their precipitation along favorable sites. The role of lithology in controlling mineralization is evident in the higher concentration of baryte within fractured sandstones and fault zones, where permeability was enhanced (Akande & Abimbola, 1987; Akande et al., 1989; Ford, 1989).

5.5 Modes of Transport of Ore-Bearing Fluids

The transport of ore-bearing fluids was facilitated by fault-controlled hydrothermal systems. The primary mechanism of fluid movement was advection along faulted and fractured lithologies, allowing mineralizing solutions to migrate over considerable distances. Fluid inclusions suggest that baryte was transported as Ba^{2+} and SO_4^{2-} in chloride-rich solutions at moderate salinities and low to moderate temperatures (Auwalu et al., 2024; Kamale et al., 2022; German & Elderfield, 1989). Precipitation occurred due to changes in temperature, pressure, and

fluid chemistry, with the mixing of different fluid sources playing a key role. The reduction in solubility of baryte was likely triggered by cooling, dilution, and changes in pH and oxidation state. The association of baryte with iron oxides in some veins suggests episodic fluid-rock interaction leading to oxidation and precipitation of baryte.

5.6 Comparison with Other Baryte Occurrences.

The geochemical characteristics of the Gombe and Litji baryte deposits were compared with other occurrences in the Upper, Middle, and Lower Benue Trough as well as global deposits (Table 6). The result shows Benue Trough baryte deposits show BaO content variations (54.6-73.4%), with Gombe-Liji, Azara, and Duguri exceeding 70%, while Moroccan and Mississippi Valley-Type (MVT) barytes surpass 75% (Oden, 2012; Leach et al., 2010). Gombe-Liji's high SiO_2 (15.55-15.60%) suggests quartz contamination, unlike Moroccan and Chinese deposits (3.5-9.3%) (Liu et al., 2016). Elevated Sr (10,540.5 ppm) in Gombe-Liji indicates hydrothermal influence, comparable to Peruvian and Moroccan barytes (Akande & Abimbola, 1987). Nigerian barytes are fault-controlled vein-type deposits, similar to Moroccan and Peruvian occurrences but differing from MVT deposits (Ekwueme et al., 2015). Gombe-Liji is suitable for drilling fluids but may require beneficiation due to high SiO_2 (Daspan & Imagbe, 2017).

Table 6: Comparison of Baryte Occurrences in the Upper, Middle, and Lower Benue Trough and Other Global Deposits

Location	BaO (%)	SiO ₂ (%)	Sr (ppm)	Host Rock	Structural Control	Reference
Gombe-Liji (This Study)	71.46-70.87	15.55-15.60	10,540.5	Quartzite (Altered Bima Sandstone)	Fault-controlled, NE-SW trending veins	Present Study
Torkula-Kaseyo, Benue State	48.37-60.1	5.5-10.3	6,800	Sandstone, Shale	Fracture-controlled, faulting	Ekwueme et al. (2015)
Azara, Middle Benue Trough	63.1-72.4	10.5-18.2	7,900	Sandstone, Shale, Carbonate Rocks	N-S trending veins, fracture filling	Offodile (1976)
Ibi Area, Lower Benue Trough	55.3-68.2	12.4-14.9	8,320	Sandstone, Limestone	Hydrothermal veins along faults	Akande & Abimbola (1987)
Duguri Area, Bauchi State	65.2-73.4	8.9-16.3	9,210	Shale, Limestone	NW-SE trending veins, silicified zones	Obaje et al. (2005)
Lessel & Ihugh, Lower Benue Trough	67.8-72.1	9.8-13.5	8,950	Sandstone, Shale, Dolomite	Fault and fracture-controlled veins	Ibrahim et al. (2018)
Tungan Kudaku, Upper Benue Trough	54.6-67.8	10.1-14.6	9,720	Sandstone, Shale	Vein-type mineralization, fracture-hosted	Daspan & Imagebe (2020)
Mississippi Valley-Type (USA)	75.4-80.1	2.1-7.5	12,000	Carbonate Rocks	Fault and stratabound deposits	Leach et al. (2010)
China Baryte Deposits	68.5-74.2	5.2-9.3	11,500	Carbonate-hosted	Hydrothermal veins, fault-controlled	Liu et al. (2016)
Peru Baryte Deposits	70.5-76.3	4.0-10.0	10,900	Limestone, Sandstone	Fracture-controlled veins	Rodriguez et al. (2018)
Moroccan Baryte Deposits	73.2-79.8	3.5-8.5	11,700	Carbonate Rocks	Hydrothermal veins, faulting	Bouabdellah et al. (2014)

Location	BaO (%)	SiO ₂ (%)	Sr (ppm)	Host Rock	Structural Control	Reference
India Baryte Deposits	68.0-75.5	4.5-11.2	9,950	Sandstone, Limestone	Fault-controlled veins, stratiform	Ramakrishna et al. (2012)

6. Conclusion

- i. Baryte mineralization in Gombe-Liji is structurally controlled, occurring along NE-SW and NW-SE trending faults within altered Bima Sandstone. The high Sr content (~10,540 ppm) and $\delta^{34}\text{S}$ isotopic values (+12‰ to +20‰) indicate a hydrothermal basinal brine origin, similar to other Benue Trough deposits.
- ii. The Gombe-Liji baryte deposit contains BaO (70.87-71.46%) within acceptable industry limits but has relatively high SiO₂ (15.55-15.60%), suggesting quartz contamination that may require beneficiation. Compared to Moroccan and Mississippi Valley-Type (MVT) deposits (>75% BaO, <9.3% SiO₂), Nigerian barytes generally have higher impurities, affecting their direct industrial application
- iii. Nigerian baryte deposits, including Gombe-Liji, are primarily vein-type, fault-controlled occurrences, akin to Moroccan and Peruvian deposits but differing from stratabound MVT deposits. The strong structural influence aligns with global hydrothermal baryte mineralization trends
- iv. The isotopic and geochemical characteristics suggest baryte precipitation occurred from hydrothermal fluids derived from a mixture of deep-seated basinal brines and basement-derived fluids. The Sr enrichment and Pb isotope signatures indicate prolonged fluid interaction with Sr-rich sediments and basement rocks, similar to other deposits in the Benue Trough and global analogs such as hydrothermal barytes in China and Iran
- v. While Gombe-Liji baryte is suitable for drilling fluids, further research on beneficiation techniques, fluid inclusion studies, and REE fractionation is needed to enhance its economic value. Understanding the lithological and structural controls can aid in future exploration efforts within the Benue Trough, supporting sustainable mineral resource development

7.0 References

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