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Research Article

Quality assessment of some baryte ores in Benue state area, Nigeria for oilfield drilling

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Abstract

The massive exploration and production well drillings in Nigerian oilfield indicate the demand for drilling fluid supplements such as baryte, in managing over-pressured formations and preventing hazardous blowouts. The underdevelopment of Nigerian solid minerals has created a wide gap between the demand and supply of the local resource, whereas there exist some assertions that the Nigerian baryte quality is below the American Petroleum Institute, API, standard. This study aimed at testing and evaluating qualitatively, based on API standards, some baryte ores from the Benue area, Nigeria, to establish their usefulness or otherwise in oilfield drilling operations. General field studies and sampling with laboratory studies were done including flame tests, X-ray Diffraction and X-ray fluorescence, to confirm mineralogy and chemical compositions of the barytes respectively and very importantly, the API tests prescribed for drilling grade barytes were carried out. The results showed impressive quality barytes with a specific gravity range from 4.10 to 4.49 and concentration of alkaline earth metals as calcium, Ca, 20 mg/kg to 48 mg/kg, particle sizes processed within API standard requirement, and the weight percentage of $BaSO_4$ composition of the ores ranged from 93.55% to 99.61%. There were no significant impurities of threat such as carbonates, iron ores, silicates and sulphides. The estimation of reserves and proper development of the resource is highly recommended as the quantity and quality might enhance the sustainability of local drilling grade baryte supply and save Nigeria the current huge capital flight and other plights.

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Introduction

Nigeria has played a prominent role in the global production and supply of petroleum resources. The rising energy demand has necessitated increasing exploration, development and production of oil and gas. This implies massive drilling, hence, continuous demand for baryte as the weighting agent in drilling fluids, basically needed for: controlling over-pressured formations by raising the mud density to 2.5g/cm^3 (Ariffin, 2004) – which prevents kicks and blowouts by creating borehole stability; and well control applications from solid-laden plugs. Due to the high technical hazards of drilling, there is a need for control and regulation of the entire drilling process and materials involved. There are baryte substitutes like haematite, celestite, galena, other iron ores, dolomites and calcite; and also a new synthetic haematite manufactured in Germany but baryte has been tested and proven over time, so it is widely used and preferred in the mud market, (Ariffin, 2004; McRae, 2016; 2020). Baryte is an additive in virtually all types of drilling fluids, (Bosch, 2016). It is no wonder a good drilling grade baryte is celebrated in any oilfield drilling.

Specifically, the baryte preference is traced to its unique physical and chemical qualities like high specific gravity (SG) up to 4.5, low solubility, chemical inertness, relatively low or modest cost, bulk availability (Darely and Gray, 1988; Foraminifera Market Research Limited, 2016; McRae, 2016), low abrasion with a hardness of 3-3.5, low oil absorption tendency, nontoxicity and environmental friendliness. It has also been noted for noninterference with magnetic measurements during logging-while-drilling and drilling in separate drill-hole logging (McRae, 2016; Pulidindi and Pande, 2017). Generally, Baryte is an industrial mineral composed of $BaSO_4$, it is colourless or white, but because of its impurity content like Fe, Sr, Pb and contaminants such as clay and sand, it may take various colours like pearly white, yellow, pink, green, grey, etc (Bonel, 2005; Mineral Galleries, 2001: Foraminifera Market Research Limited, 2016). Baryte of any colour can be used for drilling purposes (McRae, 2016). It has a white streak, vitreous or pearly lustre, perfect cleavage, unidirectional or parallel to the base (3 at right angles), uneven or irregular fracture, may be tabular, has molecular weight of 233.43, contains about 65.7% BaO and 34.3% SO_3, and sometimes forms isomorphic admixture with strontium and calcium (Betekhin et al., 1964). Depending on the quality, baryte is broadly used in several other industries including plastics, concrete and ceramic, metallurgical, paper and paint, pharmaceutical, glass, automobile, (Pulidindi and Pande, 2017); it is the main source of barium. Its largest consumption is, however in the oil and gas industry. The British Geological Survey Mineral profile records the petroleum industrial use (drilling muds) as 88% (Bonel, 2005).

Several researchers and government agencies have worked on Nigerian barytes and made recommendations for more work. A few examples are Bogue (1951) and Farrington (1952), who wrote on baryte occurrences, as gangue in galena and sphalerite veins. More recent documentation include the Ministry of Mines and Steel Development, MMSD, (2008) that reported 21,623,913metric tons of baryte inferred reserves in 7 Nigerian states; Nigerian Geological Survey Agency, NGSA (2011), estimated Nigerian baryte resources as 22,298,843 tons; Oden (2012), worked elaborately on Baryte veins in the Benue Trough; Bamalli (2013) worked extensively on some Nigerian Barytes deposits including beneficiation; Ebunu (2017), worked on 7 baryte samples from 6 states (including one sample from Benue State); Boamah (2019), worked broadly on comparative studies across some African States; and so on. More research on the subject of baryte in Nigeria, a country with enormous petroleum and other resources cannot be overemphasized. Stakeholders including some major oil companies like Chevron Nigeria Ltd, Total E and P, etc. have at various times, made collaborative moves with academia and processing companies to encourage research and development on baryte. For example Chevron Nigeria Ltd. in the past donated $1.4 million worth of mining equipment and provided training on its use to the Association of Miners and Producers of Baryte in Gboko, a center of this research area, to increase quality local baryte production, reduce baryte imports, and create jobs for the local community (Chevron Nigeria Ltd., 2018; Energy Mix Report, 2019).

There exists a clear gap between the supply and demand of Nigerian baryte as indicated by some reports (Foraminifera Market Research Limited, 2016; O'Driscoll, 2017; Adebayo, 2020; Oguche, 2020; Economic Confidential, 2020), owing to high demand but low quality and quantity of the supplied product – due to a general presumption and expressed difficulty that Nigerian baryte does not meet up to API standard (O'Driscoll, 2017; Energy Mix Report, 2019). Oilfield service companies applied for the waiver on baryte import ban, since 2013 when the demand was 70,590 tonnes, but local supply was only 39,181.35 tonnes. The implemented waiver has orchestrated continuous high importation of drilling grade (commercial) baryte, paradoxically resulting in huge capital flight as much as N5 billion annually, job exportation, underdevelopment of baryte resources (like other solid minerals), etc, (Energy Mix Report, 2019; Kadiri, 2020; Adebayo, 2020). Nigeria spends about $300 million/Annum to import baryte from Morrocco (Ukpe, 2020). With corresponding increasing demand, it was estimated that baryte consumption in 2020 would be 440,000 tonnes valued at $96 million (Energy Mix Report, 2019; Clarion Events Africa, 2020), while Nigeria's crude oil production would be 4,000,000 barrels/day, (Foraminifera Market Research Limited, 2016). According to the MMSD, (2008) report and NGSA (2011) (Figure1), Nigeria has over 21 million metric tons of baryte resources (inferred) concentrated in the Benue Trough, yet there is a demand-supply gap with some vendors having challenges in supplying API quality. Noting that baryte accounted for as much as 3.6% of total import (2016), the Nigerian Government recently initiated a road map to strategically develop the production of local baryte resources to a standard acceptable internationally and sustainably supply the industry (Kadiri, 2020; Adebayo, 2020). This will bridge the supply gap, forestall lost foreign earnings for the country, facilitate economic diversification and enhance indigenous jobs and wealth creation (Okeke, 2020; Oguche, 2020). There is, therefore, the need for proactive research evaluating the quality and quantity, as well as developing Nigerian Barytes.

This study was aimed at researching into the baryte quality issue, using some baryte ores from Benue State, Nigeria as case studies, primarily regarding API 13A (2004 and 2010) standard, to ascertain their suitability or otherwise, for use in oilfield drilling; and is further motivated by the underlying facts on Nigeria's losses due to import of API grade baryte, in a quest to bridge the supply gap. The study involved some desk work, field sampling, hand specimen and then laboratory studies which essentially included: the API 13A 2004 and 2010 prescribed tests and standards for drilling grade baryte, flame tests, as well as further mineralogical (XRD) and geochemical (XRF) analytical studies. The API specifications (2004 and 2010) for barytes are the same except the SG 4.2 minimum in API 2004 which was reviewed to accommodate SG 4.1 minimum in API 2010 due to baryte dwindling reserves (McRae, 2016). According to Johnson et al. (2017), two crucial requirements for drilling baryte set by API are the SGs 4.2 or 4.1 and the weight percent of the $BaSO_4$ which must be up to 90 in both the API 2004 and 2010 (Table 1a and b). Additionally, a few requirements as in Table 1b except oil absorption, were also tested.

Study area and geological setting

The study area is within the geographic location of Benue state, Nigeria, Figure 1. Geologically, the area is situated within the Benue Trough, specifically in the Middle Benue Trough. The BT is an NE-SW striking, vast structural basin of over 800km long and about 180-250 km wide, infilled with over 5,000 m thick Cretaceous sediments (having various mineral resources including baryte), underlain by the Pan African Basement rocks (Benkhelil 1982; Guiraud, 1993) (Figure 2). The baryte in the BT, including the area of study, are predominantly hydrothermal *vein and cavity filling,* formed by infilling and crystallisation of barium rich epithermal fluids in host rocks' points of weakness or openings like faults, voids, cavities, bedding planes, etc, even though in nature other forms like *residual deposits* and *precipitate (bedded) Stratotype also exist* (King, 2013). The host rocks of the baryte broadly include sandstones, limestones, siltstones, clay and so on (Figures 3a,b). However, there are indications that the barytes also formed along fault planes through the Precambrian Basement Complex underlying the Cretaceous sediments, as evidenced in Bunde – Lessel mine (near Orgba) where the vein walls are brecciated (Figures 4a,b) and the host rocks include some basement gneisses. There are several mineral gangue associations with baryte; among others, Lead-zinc-baryte mineralisation has been recorded in the BT (Ene et al., 2012; Labe et al., 2018) (Figure 2). Quartz, fluorite, talc, iron ores, antimony, etc were also noted in the study area. The talc (soapstone) presence in the area is also indicative of the hydrothermal activity (Figures 3a, b).

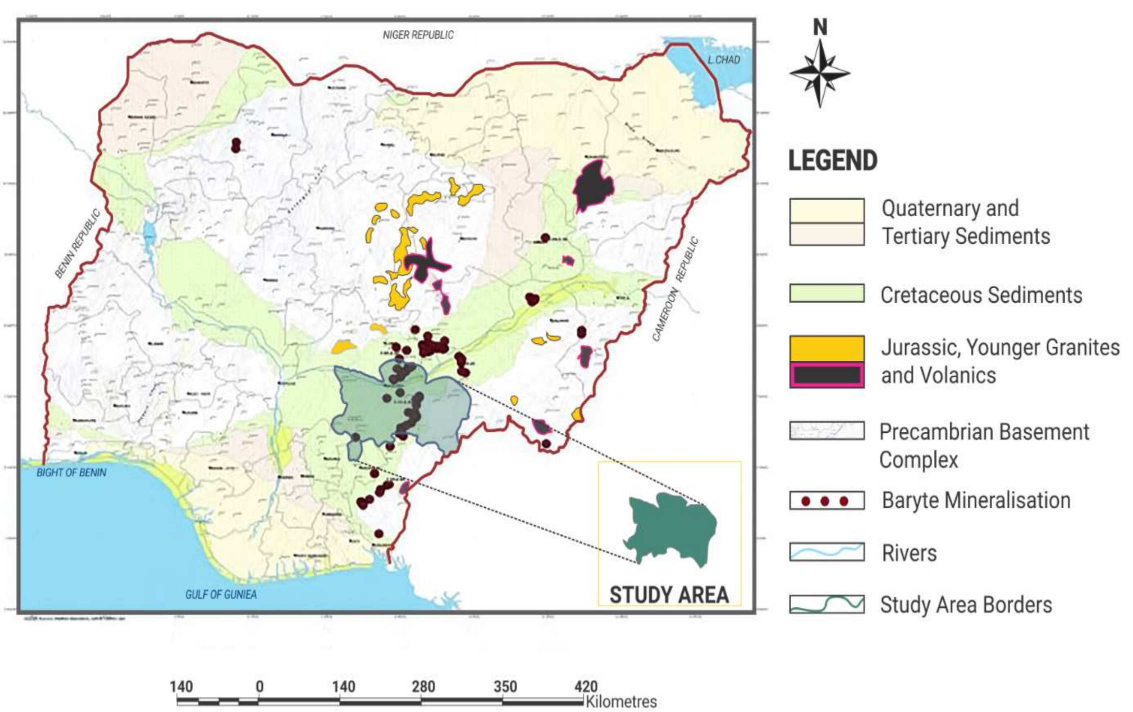

Figure 1. Simplified geological map of Nigeria showing baryte deposits locations and the study area. Source: (modified after NGSA), map retrieved from Kadiri (2020).

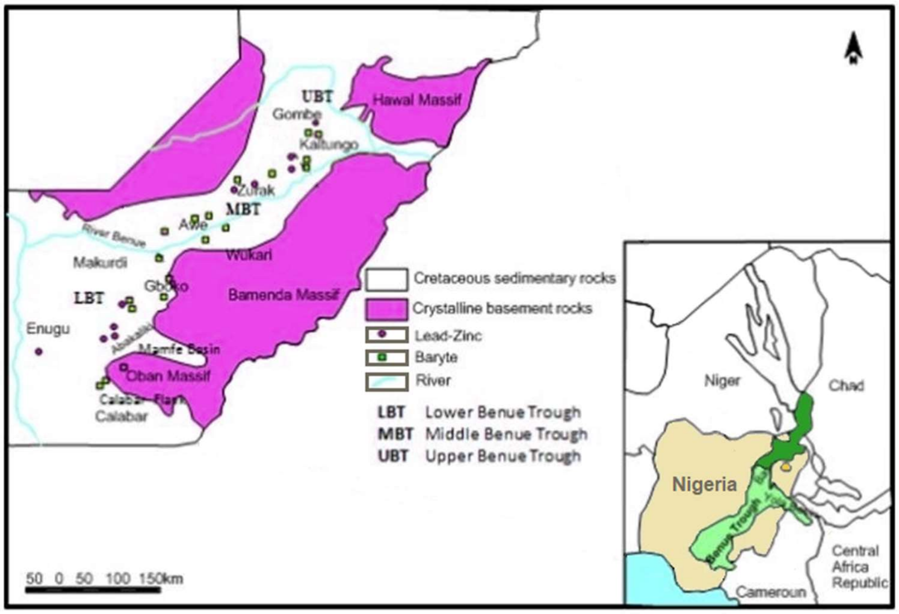

Figure 2. Distribution of lead-zinc-baryte mineralisation along the Benue Trough (modified from Ene et al., 2012 -after Cratchley and Jones, 1965; and Labe et al., 2018).

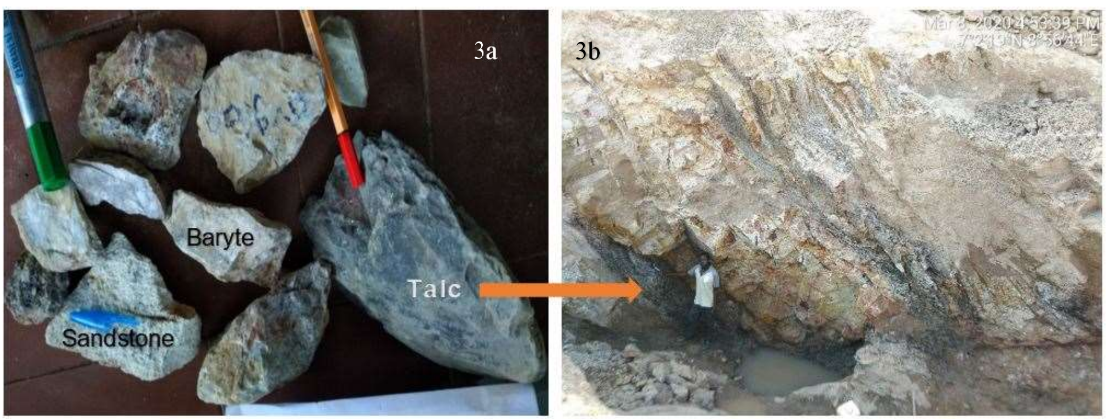

Figure 3. (a) Orgba baryte, associated talc, quartz and other minerals. (b) Orgba baryte mine showing black talc bands (veins) in clayey sandstone and some other host rocks. The man by the black talc is about 1.8 meters tall.

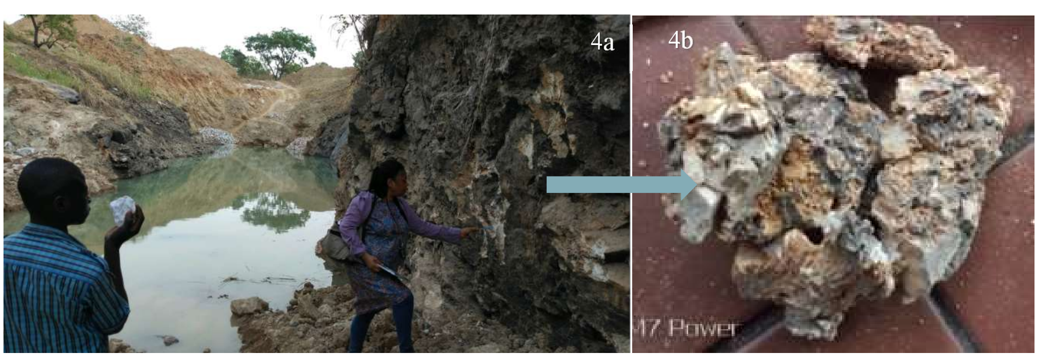

Figure 4. (a) Bunde baryte mine showing brecciated vein walls, (b) Bunde baryte breccia.

Materials and Methods

There was fieldwork involving ore sampling from baryte mines, physical or hand specimen examination, and laboratory studies such as a flame test to establish $BaSO_4$ presence in the samples; API standard prescribed tests (details as per API 13A 2004 and 2010) comprising determination of Specific Gravities (SGs); Alkaline earth metals as Ca, and particle sizes; further X-Ray diffraction, (XRD) analysis for sample mineralogical identity confirmation and X-Ray fluorescence (XRF) geochemical analysis to determine purity and confirm the percentage composition of $BaSO_4$ in the ore samples.

Fieldwork

The representative samples taken from various mines for this study include those from Ute 1&2 - Guma, Tombo- Buruku, Pilla – Yadev, Bunde - Lessel, Gbughla - Lessel, Orgba - Ushongo, Mbaakune-Ihugh, Ansha- Korinya 1&2. Preliminary samples identification as baryte was made (subject to further confirmation of mineralogical and chemical quality), by examination of properties like cleavage, colour, weight by heft tests, etc. The sampled ores were taken from shallow (under 5 m depth) to deep (5 m - >20 m depth) hydrothermal veins through predominantly sedimentary rocks overlying the basement complex. There were active and inactive mines, including some abandoned ones. Figure 5 shows the sampled areas.

Flame test

The samples were subjected to flame tests. When sample dust or chip of few grams held into the gas flame changes the flame to yellowish-green, it indicates barium, Ba presence from barium sulphate, $BaSO_4$ (baryte). This test significantly differentiates baryte from other similar heavy mineral associations like celestite, SrO_4 with which Baryte, $BaSO_4$ commonly forms a solid solution, $BaSrSO_4$; the baryte group isomorphs include anglesite $PbSO_4$ and anhydrite, $CaSO_4$ (Hanor, 2000). Celestite has a similar structure and crystals with baryte so it is difficult to differentiate ordinarily, but with a flame test, the strontium, Sr in celestite, $SrSO_4$ reacts to produce red flame; conversely the Ba in baryte, $BaSO_4$ reacts to produce the yellowish-green flame (Mineral Galleries, 2001), indicating, the heavy mineral sample is baryte. This is not conclusive of the percentage composition of the $BaSO_4$ in the sample, but another quick and good indication of its presence. Thus, confirmative XRD and XRF analysis were done subsequently.

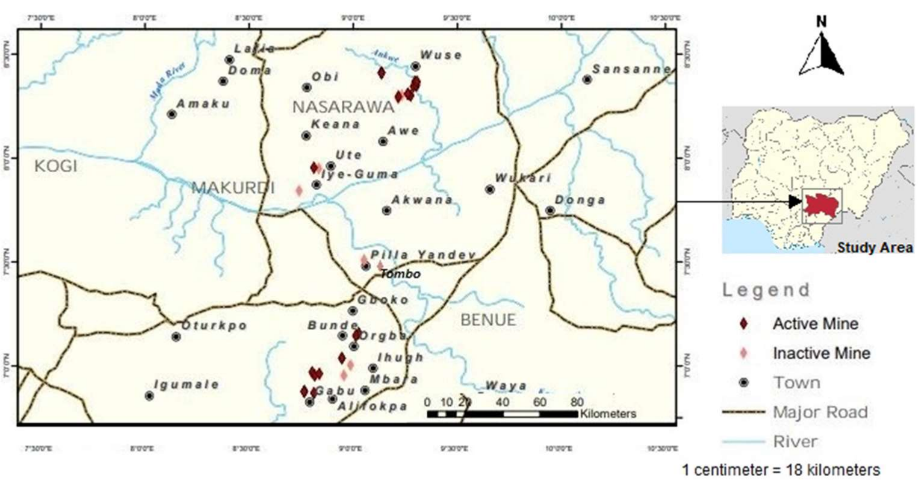

Figure 5. Map of study area showing sampled locations and some mines status in Benue State.

Mineralogy

X-Ray Diffraction, XRD, technique was employed to study the samples' mineralogy, using the National Geoscience Research Lab (NGRL), Nigeria's Panaltical Empyrean diffractometer with cupper anode material and other accessories. This is a nondestructive analysis and the diffractometer which is connected to a computer workstation using a data collector software made easy generation of automated results. The samples were washed and dried, pulverized in steel and agate mortar. The finely ground mill (<75 micron) was homogenised, then about 5grams of each sample was put and compressed to a smooth surface on a sample holder, mounted on sample rack and placed on the sample stage in the goniometer, which is the central unit of the diffractogram. In brief, X-rays are generated and passed through the targeted samples. The characteristic output intensity, d-spacing and 2Theta and the automated result of the analysis showing the identified minerals were recorded in a table and general diffractograms in the result section.

Geochemical analysis

The geochemical technique employed here is the Energy Dispersive X-Ray Fluorescence (EDXRF) using a Minipal (4EDXRF) from NGRL Kaduna, Nigeria. The ore samples were washed and well dried, pulverized in a motorized agate mortar to about 53 microns and about 10grams of the mill was mixed with 1gram steric acid to bind; and then the sample was pelletized through a hydraulic pressure press and used for the analysis of major element oxides. Loss on ignition, LOI, was done by gravimetry using the furnace. The analysis provided % values of BaO and SO_3 in all the samples which further became the basis for calculating the weight percent composition of the $BaSO_4$ in the samples, using the standard molecular weights of the components. The geochemical analysis is a useful tool for also indicating the presence of some undesired materials in baryte for drilling muds. The rejection of certain materials in drilling fluids is due to various reasons like their abrasive, soluble or insoluble nature, depending on their chemical reactivity, that might alter or pose a challenge to the mud systems. However, generally, there are no Standards regulations on the concentrations of the impurities that have insoluble nature (McRae, 2016).

API requirement: some physical and chemical tests on the baryte ore samples

After the preliminary confirmation of sample identities, the samples were then tested based on API standard following the procedures detailed in API 2004 (Table 1), the standard reference for this research – from the SGs determined using Le Chatelier SG flask, alkaline earth metals as calcium, Ca and particle sizes to the determination of particles sizes <3 µm which was done by sedimentation method. The SG being the most crucial factor was determined in two separate and independent laboratories to confirm and establish the authenticity of results. Additionally, the pH tests were carried out on the samples using pH Test Strips dipped in baryte sample suspension in distilled water, and the moisture contents, determined by weight difference before and after furnace heating.

Table 1a. API physical and chemical specification for drilling grade baryte.

Requirement	API Specification
Specific Gravity (API 2004)	4.2 minimum
Specific Gravity (API 2010)	4.1 minimum
Water-soluble Alkaline Earth Metals as Ca,	250 mg/kg maximum
Residue > 75 microns (µm)	maximum mass fraction 3.0%
Particles < 6 microns (µm), in equivalent spherical diameter	maximum mass fraction 30%

Source: API 13A (2004) 16th Edition and API 13A (2010), 18th Edition.

Table 1b. Some other additional requirements.

Requirement	API Specification
Moisture content	1%
Oil Absorption	9%
pH	7
$BaSO_4$	90% Minimum

Source: Musaed et al. (2000), Mineral Galleries (2001), Johnson et al. (2017).

Results and Discussions

Field results

The barytes identified from the study area were white, pearly white, pink, grey, and light brown in colour (Figures 6 to 13). A number of the samples showed good cleavage typical and diagnostic of baryte especially where there were fairly prominent crystals like in Ute, Pilla-Y and Tombo Samples (Figures 6 to 9), while some had but little sizes reflective cleavage. All samples passed the characteristic relative heft tests subject to further analytical investigations. Although there are some mineral association like galena, antimony, etc found within the vicinity of the project area, part of the Benue Trough, they were not particularly observed in the mines except, some quartz, talc, fluorite and haematite. Brecciation was observed around the host rocks vein walls of the Bunde mine (Figures 4a and b), which also had some basement rocks (granite gneiss) exposures.

Laboratory results and discussion

The Flame Tests Results: All the ore samples tested turned the gas flame to pale yellowish-green indicating that $BaSO_4$ is present - the samples are baryte. The sampled Benue barytes are unassuming, having a generally modest and sometimes dull appearance, but proved very impressive after testing.

The XRD result

The XRD results (Table 3 and Figures 14) show baryte dominance in all the samples, with associated quartz as the 2nd mineral in all except Ute1 -Guma and Ansha - Korinya, and the presence of fluorite as 3rd in the Bunde - Lessel baryte sample. The latter is from the field area that showed baryte veins through basement hard rock with brecciated vein walls, (Figure 4) unlike the other samples whose host rocks outcrops were basically of sedimentary origin. Integrating this result with the API 2004 Test for particle sizes, the presence of quartz being an abrasive mineral however did not show significant threat as the milled samples were sieved through 75 micron mesh before being tested for 'sandy' residue >75 microns; the range under the 3.0% prescribed by API standard also shows that no significant beneficiation is required.


Figure 6. Ute 1- Uvii baryte.


Figure 7. Ute 2 - Kaseyo, Uvii baryte.


Figure. 8 Pilla -Y baryte.


(9a)


(9b)


(9c)

Figure 9. Tombo – Buruku barytes.


Figure 10. Bunde baryte.


Figure 11. Gbughla baryte.


Figure 12. Ihugh baryte.


Figure 13. Ansha baryte.

Table 2. XRD results of some Benue samples (peak values at 100% intensity, I).

No.	Sample	Minerals	Spacing d, (Å)	2Θ	Diffractogram Reference
1.	Ute1	Baryte	3.10244	28.753	Similar to Figure 14a
2.	Ute2	i. Baryte	3.10391	28.739	
		ii. Quartz	3.34836	26.600	
3	Tombo	i.Baryte	3.10244	28.753	Similar to Figure 14a
4	Pilla -Y	i Baryte	3.10244	28.753	Figure 14a
5.	Bunde	i. Baryte	3.10244	28.753	Figure 14b
		ii. Fluorite	1.93146	47.009	
		iii. Quartz	3.34255	26.647	
6.	Gbughla	Baryte	3.10244	28.753	Similar to Figure 14a
7.	Orgba	i. Baryte	3.10244	28.753	
		ii. Quartz	3.34542	26.624	
8.	Mbaakune Ihugh	i. Baryte	3.10244	28.753	
		ii. Quartz	3.34255	26.647	
9.	Ansha Korinya	Baryte	3.10244	28.753	Similar to Figure 14a

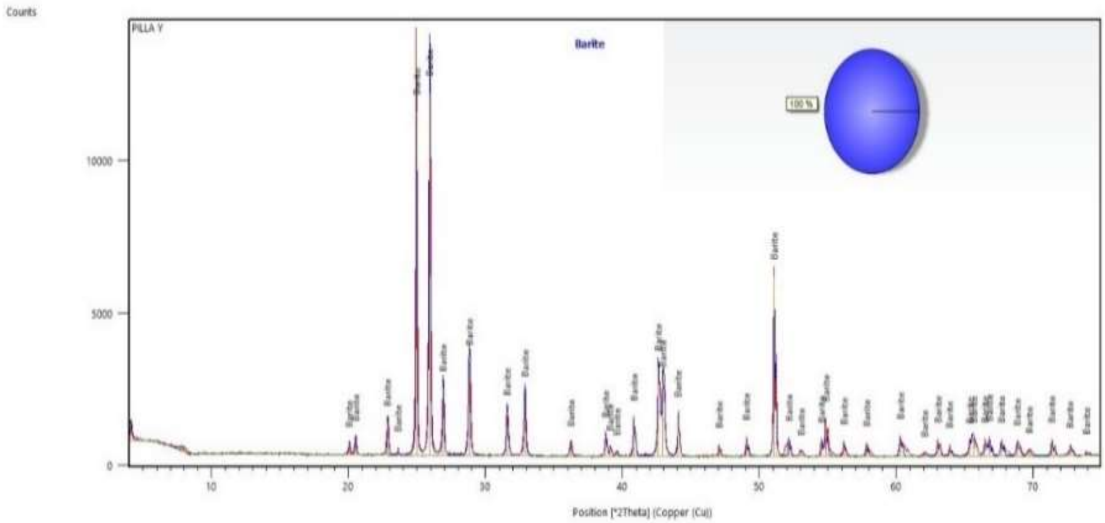

Figure 14(a). Pilla-Y samples' representative general diffractograms: pure baryte.

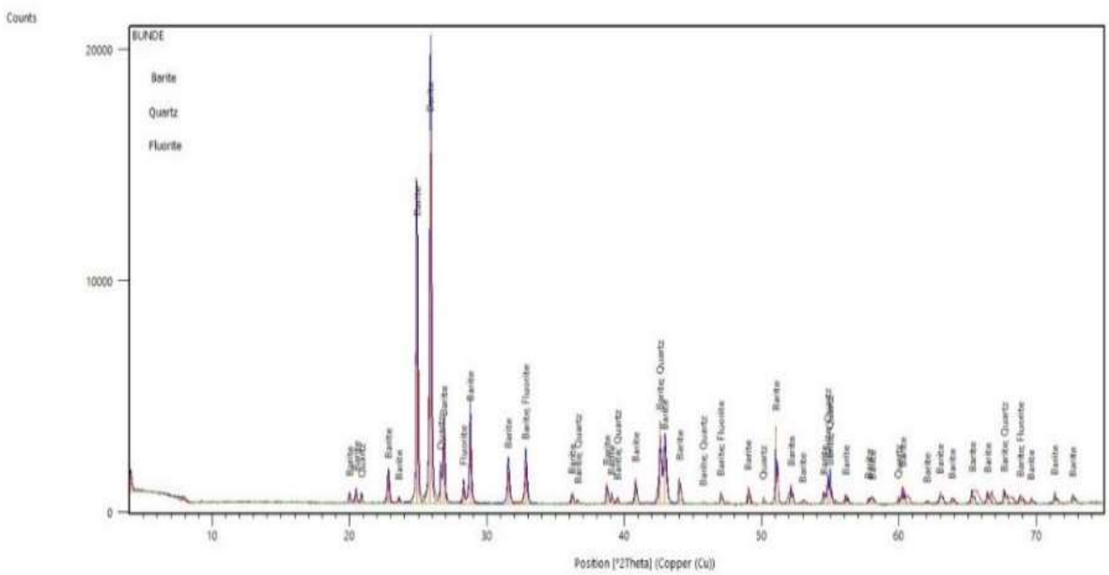

Figure 14(b) Bunde Lessel samples' representative general diffractograms: baryte, quartz and fluorite.

The samples' XRF Results (Table 4): Though some baryte deposits like the Pilla and Tombo are in a geological environment of limestones, and others associated with quartz, from the XRF and XRD results, there were no significant unwanted materials, like the insoluble but abrasive silicates like quartz and cherts, insoluble materials which in presence of hydroxyl ions are capable of releasing deleterious anions like carbonates, e.g. dolomites, ($CaMg(CO_3)_2$), and sulphides, e.g. Pyrrhotite ($Fe_{1-x}S$), and there were no obvious threats of soluble materials like gypsum (calcium sulfate dihydrate, $CaSO_4.2H_2O$), capable of releasing excess alkaline earth metals as calcium in presence of hydroxyl ions, (King, 2013), the iron and silica contents are moderate. Loss On Ignition, LOI, values are also reasonable, following API value of 1% for moisture content (Table 1b).

Table 3. XRF results for the Benue baryte ore samples from various fields.

% Oxide	Samples and % Oxide Composition								
	Ute 1 *Guma*	Ute 2 *Guma*	Tombo *Buruku*	Pilla-Y *Gboko*	Bunde *Lessel*	Gbughla *Lessel*	Orgba *Lessel*	Ihugh *Mbaakune*	Ansha *Korinya*
SiO_2	0.31	4.60	0.30	0.261	5.21	0.24	3.64	4.52	0.27
TiO_2	Nd	0.110	<0.001	Nd	0.093	Nd	0.22	0.130	Nd
Al_2O_3	<0.001	1.90	<0.001	<0.001	2.04	<0.001	1.70	1.81	<0.001
Fe_2O_3	0.06	0.75	0.025	0.022	0.273	0.041	0.67	0.99	0.012
CaO	0.18	0.39	0.023	0.10	0.69	0.17	0.16	0.36	0.024
MgO	0.034	0.072	0.016	0.060	0.030	0.20	0.064	0.070	0.012
Na_2O	0.08	0.100	0.020	0.024	0.212	0.04	0.10	0.111	0.023
K_2O	0.120	0.132	0.011	0..041	0.041	0.025	0.024	0.231	0.187
MnO	0.002	0.017	0.033	0.002	0.015	0.004	0.02	0.010	0.003
BaO	65.40	61.46	65.45	65.40	62.54	65.38	62.73	61.86	65.44
SO_3	33.45	29.27	33.73	33.90	28.43	33.70	30.26	28.19	33.82
SrO	0.011	0.30	0.04	0.03	0.23	0.004	0.27	0.41	0.004
L.O. I	0.35	0.90	0.18	0.16	0.20	0.20	0.10	1.30	0.20

The XRF results also facilitated the calculation of the overall weight % $BaSO_4$, [(1) and (2)] ranging between 93.55% and 99.63%, which is excellent being above the 90% requirement (Figure 15). This quality of baryte could as well be exploited in other industries that require higher purity.

(1) $BaSO_4 = BaO + SO_3$

Where, Molecular Weight are: 233.39 = 153.33 + 80.06

(2) Weight% $BaSO_4$ in any Sample S with a given weight %BaO is: $\frac{\%\,BaO \times 233.39}{153.33}$

Therefore $\%BaSO_4$ in the Ute1 and Pilla-Y Samples *each* e.g. is: $\frac{65.40\% \times 233.39}{153.33} = 99.55\%$

API 2004 Prescribed Tests Results (Table 2)***:*** The SGs range from 4.06 to 4.49, the lower values being the Ihugh baryte with SG of 4.10 and the Tombo baryte SG range 4.06 to 4.17 implying that there is a need for very little or no beneficiation for both; and that virtually all the sampled barytes studied are suitable for drilling purpose based on API requirement 13A 2004 and 2010 (Table 1a). The Ihugh baryte sample was taken from a very shallow pit of about 2.5 m deep of a new, underdeveloped mine. From observation, deeper levels might have relatively higher SGs. The Ansha Korinya samples were very dark and also taken from, shallow >3 m- 5 m depths, also not extensively developed mines, but results show acceptable drilling grade. Likewise, the Ute2 Guma sample was a newly opened shallow mine <2 m deep but is of drilling grade. The alkaline earth metals as Ca range, the particle sizes >75 µm, and < 6 µm for the milled samples were all, within API acceptable limits, (Table 1). The pH of the barytes is adequate. A very interesting observation was made on the Tombo baryte. For comparative analysis, the SGs of the Benue Samples were matched with their % $BaSO_4$ composition. Two samples from Tombo ore were tested in two different and independent labs 1 and 2, giving a total of 4 results for Tombo SGs.

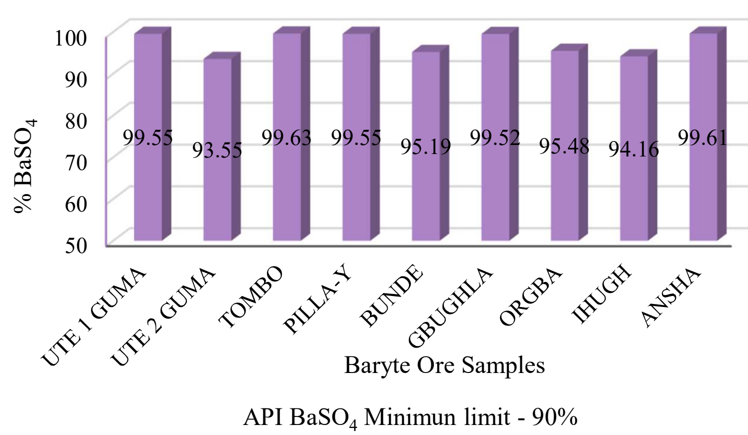

Figure 15. Bar chart showing % weight composition of $BaSO_4$ in the Benue baryte ore samples.

Table 4. API physical and chemical tests results of the Benue baryte ore samples.

Requirement	API Specification	Results of Samples								
		Ute 1 ***Guma***	**Ute 2** ***Guma***	**Tombo Buruku**	**Pilla-Y Gboko**	**Bunde** ***Lessel***	**Gbughla** ***Lessel***	**Orgba Ushongo**	**Ihugh** ***Mbaakune***	**Ansha** ***Korinya***
Density Lab 1	4.20 g/cm^3, Minimum	4.49	4.34	4.17 4.08	4.42	4.3	4.37	4.40	4.10	4.30
Density Lab 2	4.20 g/cm^3, Minimum	4.35	4.21	4.16 4.06	4.40	4.27	4.32	4.23	4.10	4.42
Alkaline Earth Metals, as Ca	250mg/kg Maximum	20	30	16	20	32	36.2	30	22	48.0
Residue >75 µm	3.0% Weight Maximum	0.64	0.82	0.54	0.54	0.56	0.32	0.66	0.66	0.70
Particles <6 µm	30% Weight Maximum	14.42	16.98	22.39	28.36	20.12	28.2	20.02	23.04	20.10
Moisture Content %	NI	1.8	2.0	0.90	0.88	1.4	1.6	1.10	1.00	1.3
pH	7 (Neutral)	7	7	7	7	7	7	7	7	7

Physically, the ore chunks from the Tombo field have very well defined baryte crystals marked with clear distinct basal reflective cleavage, typical of a standard baryte; the chemical analysis showed about 99.63% $BaSO_4$ which is the highest of all the analysed sampled; however, the SG happens to be the lowest in its range. This is attributed to the individual crystals (also used for XRD and XRF analysis) having a higher concentration of $BaSO_4$ than the bulk mineral (chunk) pulverized and used for the SG test. This mine has portions of clean baryte (Figure 9a) and portions with the crystals aggregate which appears to have contaminants like clay in the matrix (Figure 9b and c). Further examination might reveal more. This was collaborated by comparative laboratory sieving analysis results. The same volume of Tombo baryte and the same volume of Pilla baryte pulverized and sieved through the same process and timing produced more mill from the Tombo than the Pilla Baryte. Although the degree of weathering and localized effects could contribute to such results, it was observed that this was more of a matrix content effect, as both Pilla and Tombo (Figures 8 and 9) samples have good crystals. It was observed that the crystal arrangement of baryte ores could permit other materials influx into the matrix. This can also be collaborated with the brecciated samples having a matrix composed of other minerals and clayey/rock between baryte crystals fragments, clearly observed at Bunde baryte mines (Figure 4a and b). Analysis of an individual baryte fragment from the breccia will yield higher $BaSO_4$ % composition and higher SG values than those from analysis of a bulk brecciated baryte chunk. Taking this to an industrial scale, where bulk baryte is milled makes beneficiation justifiable. If the bulk baryte is not 'cleansed' to get rid of the contaminants, the actual SG may be altered (higher or lower) depending on the contaminant present in the ore and this will adversely compromise the drilling mud efficiency. This again makes the API prescribed tests very necessary and justifiable before drilling mud is subjected to any bulk milled barytes.

Conclusion

This work evaluated the quality of some baryte ores from Benue State Nigeria, a part of the Middle Benue Trough, in a quest to ascertain their suitability for use as a weighting material in drilling fluids. The assessment was based on the standard API specification and tests for drilling fluids used in the oil and gas industry. The study was systematically carried out both in the field and laboratory. The field study revealed several hydrothermal veins of baryte with active and inactive mines operated by artisanal and small-scale companies.

Field sampling and preliminary identification of the hand specimens revealed good baryte prospects for drilling mud material. Subsequently, with the flame tests, XRD mineralogy and XRF geochemical analysis, baryte was confirmed as the principal mineral with $BaSO_4$ weight percent composition of over the 90% standard set by API, without significant deleterious contaminants. The API 2004 and 2010 specified physical and chemical tests requirement, showed that the ores are as fit as commercial baryte, for oilfield drilling, especially as all samples met the SG requirement of 4.2 and 4.1 set by API. However, the Tombo baryte might need little beneficiation like blending with a higher grade baryte as the SG was variable and might be slightly inconsistent on bulk exploitation. It was noted that some samples like the Ihugh baryte taken from shallow depth, approximately 2.5m, prone to more weathering, might likely have higher SG and quality at deeper levels.

It is concluded that the bulk of the sampled baryte ores from Benue State, Nigeria, are of high economic potentials, as they meet the API drilling grade standard. They are recommended for use as weighting material additive in drilling fluid for Nigerian oilfield and beyond. Estimation of the reserves is also highly recommended, as it will take both good quality and quantity for the baryte to sustainably meet the demand of the Nigerian petroleum industry.

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