Arid Zone Journal of Basic and Applied Research
Faculty of Science, Kashim Ibrahim University
Maiduguri, Nigeria
Journal homepage: https://www.azjournalbar.com

Research Article

Compositional Characteristics and Economic Appraisal of the Pibata Marble within the Basement Complex, Part of Paiko Sheet 185NE, Nigeria

Yunusa Adinoyi OMANAYIN[1*], Muhammed Ademu USMAN[1], Sharon Mercy MICHAEL[1], Mutari LAWAL[2], and Adegbe MAMODU[1]

[1] Department of Geology, School of Physical Sciences, Federal University of Technology, P. M.B. 065, Minna, Nigeria
[2] Department of Geology and Gemology, Faculty of Science, University of Abuja, P.M.B. 117, FCT Abuja, Nigeria
***Corresponding author's Email:** o.adinoyi@futminna.edu.ng; doi.org/10.55639/607.020100146

ARTICLE INFO:
Keywords:
Marble,
Geochemistry,
Characteristics,
Lime,
Aggregate.

ABSTRACT

This study characterises the mineralogy, geochemistry, and economic potential of marble deposits in the Pibata area, part of Paiko Sheet 185NE, Nigeria. Field mapping reveals a migmatite-gneiss-schist-quartzite complex terrain, the marbles occur as pods and lensoids within mica schist of the Precambrian Basement Complex, structurally controlled by NE-SW trends associated with the Pan-African Orogeny. X-ray diffraction analysis showed a mixed composition averaging 66.80% calcite and 16.61% dolomite, with significant impurities including quartz, anthophyllite, and orthoclase. Geochemical data indicate moderate CaO (avg. 43.83%), elevated SiO_2 (avg. 12.60%), and high loss-on-ignition (avg. 35.41%). The marble is classified as siliceous, calcitic to dolomitic, derived from an impure limestone protolith that was metamorphosed under low- to medium-grade conditions. Trace element enrichment (e.g., Zr, V) reflects detrital sedimentary input. Economic appraisal demonstrates that, in its natural state, the marble may not meet purity standards for cement production, pharmaceuticals, chemicals, or high-value construction due to excessive silica, alkalis, and volatile content except if it is upgraded. However, its total carbonate content (85.10%) aligns with requirements for agricultural fertiliser and soil conditioning. The deposit is potentially suitable for use as agricultural lime based on its carbonate content, and for cement feedstock following beneficiation. This research provides a critical assessment framework for the sustainable utilisation of low-grade marble resources in similar settings.

Corresponding author: Yunusa Adinoyi Omanayin, **Email:** o.adinoyi@futminna.edu.ng
Department of Geology, School of Physical Sciences, Federal University of Technology, Minna, Nigeria

INTRODUCTION

Marble, one of the most widely used industrial minerals, a metamorphic product of sedimentary rocks such as limestone and dolostone, is widely deposited across Nigeria. Marble, a carbonate rock, is composed mainly of calcite, dolomite and in some cases both, and its texture ranges from fine to coarse-grained. The physical property of marble, such as colour, often varies depending on the presence of impurities during its formation. For example, marble produced from limestone with lesser impurities tends to be whitish in colour, compared to those with impurities such as iron oxides and clay minerals, which would be darker (Omodeni, 2023). Also, marble associated with metasediments and metavolcanics is often fine-grained, grey in

colour and shows fine dark and light grey lamination, whereas marble intruded by igneous bodies is usually coarse-grained and characterised by various shades of colour, such as white, blue, orange or grey (Grant et al., 1989). The calcite ($CaCO_3$) mineral dominant type is referred to as calcitic, while the magnesium dominant [$CaMg(CO_3)_2$] type is described as dolomitic. This carbonate rock occurs in rocks of different geological ages (Boggs, 2009). Limestone is the dominant carbonate rock in the Mesozoic and Cenozoic sequences, whereas dolomite is the dominant carbonate unit of the Precambrian and Palaeozoic age (Ronov, 1983). Brownlow (1996) posited that an MgO value greater than 1% in limestone is an indication that the mineral dolomite is present. A pure dolomite is composed of 45.7% $MgCO_3$ and 54.3% $CaCO_3$ or 21.8% Magnesia (MgO) and 30.4% lime (CaO), while pure marble is essentially composed of the mineral calcite or aragonite with a sum $CaCO_3$ content of between 97-99% (Boynton, 1980).

Marble plays an important role in the industrial applications of any nation. These applications, dependent on their inherent properties, range from construction, cement production, chemical and paint, ceramics, agriculture and metallurgical industries. Other areas it is found useful include as fillers in paper production, pharmaceuticals, cosmetics and as a supplement in poultry feed (Omodeni, 2023). In Nigeria, marble occurrence spans both the sedimentary basins and the basement complex terrain of the country. The marble occurrence within the basement complex of Nigeria, particularly within the migmatite-gneiss-schist-quartzite complex, is considered a relic of sedimentary carbonate rocks. Such marble deposits are reported to be confined to the western portions of the south and central parts of the country (Fatoye and Gideon, 2013). The Pibata area in Niger State, part of North-Central Nigeria, is endowed with marble occurrences whose study has been limited and piecemeal. The present research aims to contribute to knowledge by integrating the mineralogy and geochemistry of the Pibata marble to appraise its economic potential.

Pibata area is located in the northeastern part of the topographic map of Paiko Sheet 185, bounded by Latitudes 9°23'00"N - 9°25'00"N and Longitudes 6°53'30"E - 6°55'30"E, covering an area of approximately 14 km^2. The area is surrounded by villages like Baidna, Shikpna and Kwakuti within the Paikoro Local Government Area of Niger State, North-central Nigeria (Figure 1). The area is easily accessible through the Suleja-Minna expressway and hosts some primary and secondary footpaths.

The geology of Nigeria has been established to consist of Basement Complex rocks, Younger Granites and the Sedimentary Basins of different ages (Figure 1). In a similar vein, the geology of the region (Niger State), of which the study area is a part, is characterised by two principal rock types: the younger Sedimentary and the Precambrian Basement Complex. This geological foundation fundamentally governs the state's distribution of natural resources and the evolution of its terrain. The sedimentary terrain, occupying roughly 40% of the state, comprises Palaeozoic to Cenozoic deposits. A prominent unit within this sequence is the Nupe/Bida Sandstone, which includes sandstones, siltstones, conglomerates, and claystones (Kogbe, 1989).

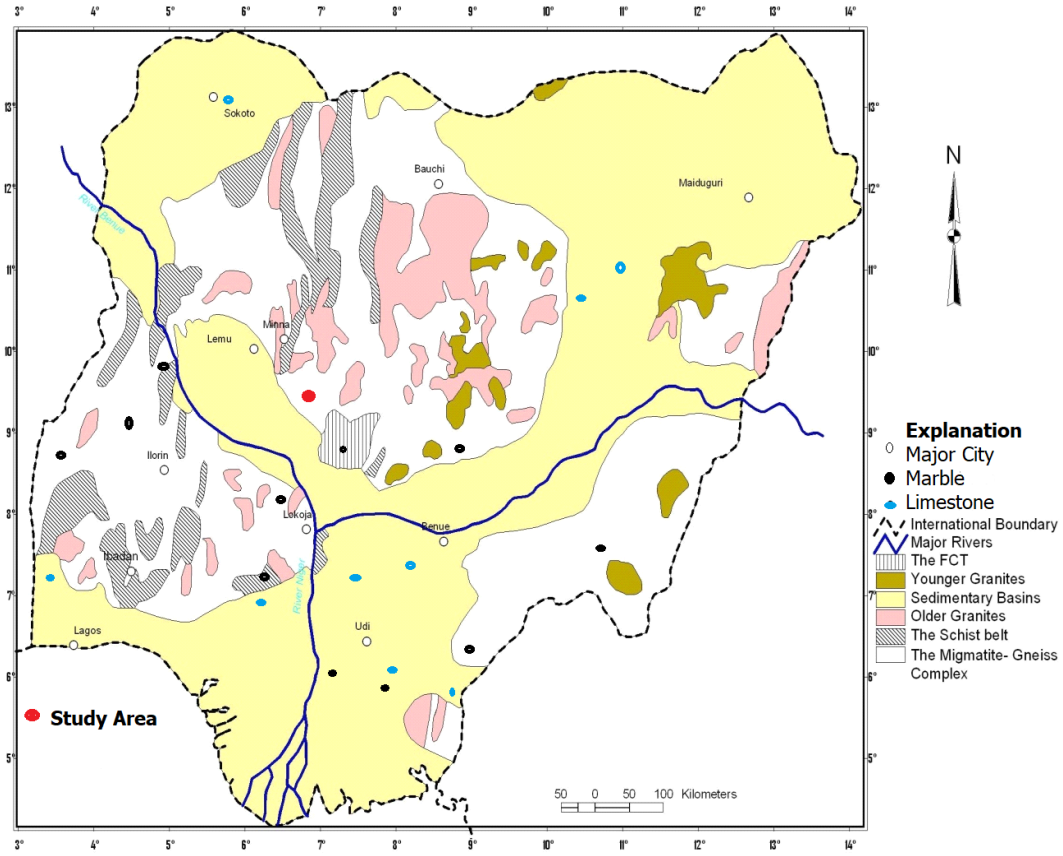


Figure 1: Geological Map of Nigeria showing marble and limestone deposits (Modified after Ajibade and Woakes, 1983)

The basement complex aspect of the state consists of solid rocks dating back over 541 Ma and spans approximately 60%. The major rock types in the area, similar to those in the rest of northern Nigeria, are deformed Archean migmatite-gneisses, meta-volcanosedimentary rocks (including schists, amphibolite, quartzite, and marble), and Pan-African granitoids (Goodenough et al., 2014; Omanayin et al., 2023). The gneisses were formed through high-grade metamorphism of igneous and sedimentary protoliths (Rahaman, 1988). The schist, a metamorphic rock mostly derived from mica-rich parent materials (Odeyemi, 1988) and the quartzites, a metamorphosed sandstone, are primarily exposed in the western region (Akinola and OlaOlorun, 2022). Similarly, the migmatites of the Minna region fall into two principal categories: those formed by high-grade metamorphic anatexis and those created through magmatic injection (Abolade, 2015). Dominating the local granitic geology are the Minna Batholiths, which form a continuous NE-SW trending ridge consisting of eight major plutons (Unuevho, 2009). The study area forms part of the area underlain by the basement complex rocks.

MATERIALS AND METHODS

The underlying lithologic units within the limit of the study area were revealed by traverse geological mapping at a scale of 1:12,500. A global positioning system (GPS), compass clinometer, geologic hammer, hand lens, and measuring tape aided the mapping exercise and plotting of the outcrops located on the base map. The marble and other host rocks located were studied *in situ*, describing their mineralogy, texture and structural features. Twenty-five (constituting 10 marbles and 15 surrounding rock) samples were taken from the field. Seven (7) representatives out of the 10 marble samples were prepared and subjected to mineralogical and geochemical studies at the National Geoscience Research Laboratory of the Nigeria Geological Survey Agency, Kaduna. The selection of these representative marble

samples was done based on similarities in colour, texture and hand specimen mineralogy. At the laboratory, the samples were crushed to size, homogenised, pulverised and ground to ensure over 95% of the powder samples pass a 150-micron sieve. These prepared powder samples were duplicated and subjected to the analytical methods for X-ray diffraction and X-ray fluorescence to reveal their mineralogical and geochemical (major and trace elements) compositions.

The mineralogical composition of the marble samples was determined using a Rigaku Miniflex X-ray diffraction spectrometer following the estimated semi-quantitative method using peak intensities. The system, equipped with a Cu-Kα radiation source (λ = 1.5406 Å), was operated at 40 kV and 30 mA. Diffraction patterns were collected over a 2θ range of 5° to 70° at a scanning speed of 2°/min. The resulting diffractograms, which serve as unique fingerprints of the crystalline phases, were analysed by comparing peak positions with standard reference patterns from the Joint Committee on Powder Diffraction Standards (JCPDS) database for mineral identification purposes. The "GENIUS IF XENEMETRIX" X-ray fluorescence spectrometer was used to determine the geochemical composition of the marble samples under optimized voltage settings (35-40 kV), with major oxides and trace elements quantified using XRS-FP software. Blank and duplicate samples were inserted to determine the integrity of the analysis and all returned with about 99 % accuracy). To prevent leaks on the thin film layer, the ground samples were filled to one-third of the sample cup, placed inside the thin film cup, and covered. The samples were subsequently put into the XRF machine's sample turret. The equations (i) and (ii) below were used to calculate $CaCO_3$ and $MgCO_3$ from CaO and MgO in the geochemical results of the studied marbles.

$$\%CaCO_3 = \%CaO\ x\ \left(\frac{Molar\ Mass\ of\ CaCO_3}{Molar\ Mass\ of\ CaO}\right) \text{----------} \quad \text{(i)}$$

$$\%MgCO_3 = \%MgO\ x\ \left(\frac{Molar\ Mass\ of\ MgCO_3}{Molar\ Mass\ of\ MgO}\right) \text{----------} \quad \text{(ii)}$$

RESULTS AND DISCUSSION

Geology

The subsurface geology of the research region comprises migmatite, meta-volcanosedimentary, and minor pegmatite intrusive rocks in various proportions (Figure 2), as indicated from the field mapping. The major joint direction in the study area reveals NNW-SSE and minor in the NE-SW, the latter appears to influence the intrusion of pegmatite into the migmatite, and the alignment of marble with the strike of its host schist rock (Figure 3).

The migmatites, intruded by pegmatites, outcropped at the western, southern and southeastern portions of the study area, covering approximately 52% (Figure 2). The migmatite rock unit exhibits complex petrology. The rocks range from light to dark in colour and are medium- to coarse-grained. Their composition varies, with some portions displaying a weak to strong gneissic fabric, while others show colour banding due to the interlayering of paleosome and neosome minerals in patches and foliations of varying thickness. In hand specimens, they are composed of quartz, feldspars, muscovite, and biotite. Foliation, lineation, joint, fault, ptygmatic fold, and quartz veins in various locations trending northeast characterise the migmatites. In a few locations, where migmatite dominates, granite outcrops were observed. This is suspected to have been the ripple effects of the magma that invaded the initial surrounding rock (gneiss). Thus, this intruding magma, perhaps, may have separately solidified into forming granite at some point and, on the other hand, inflicted partial melting and solidified into forming the migmatites. This rock seems to be the oldest in the area, considering its structural imprint and reports form literature (Rahaman, 1988; Eleuze et al., 2015).

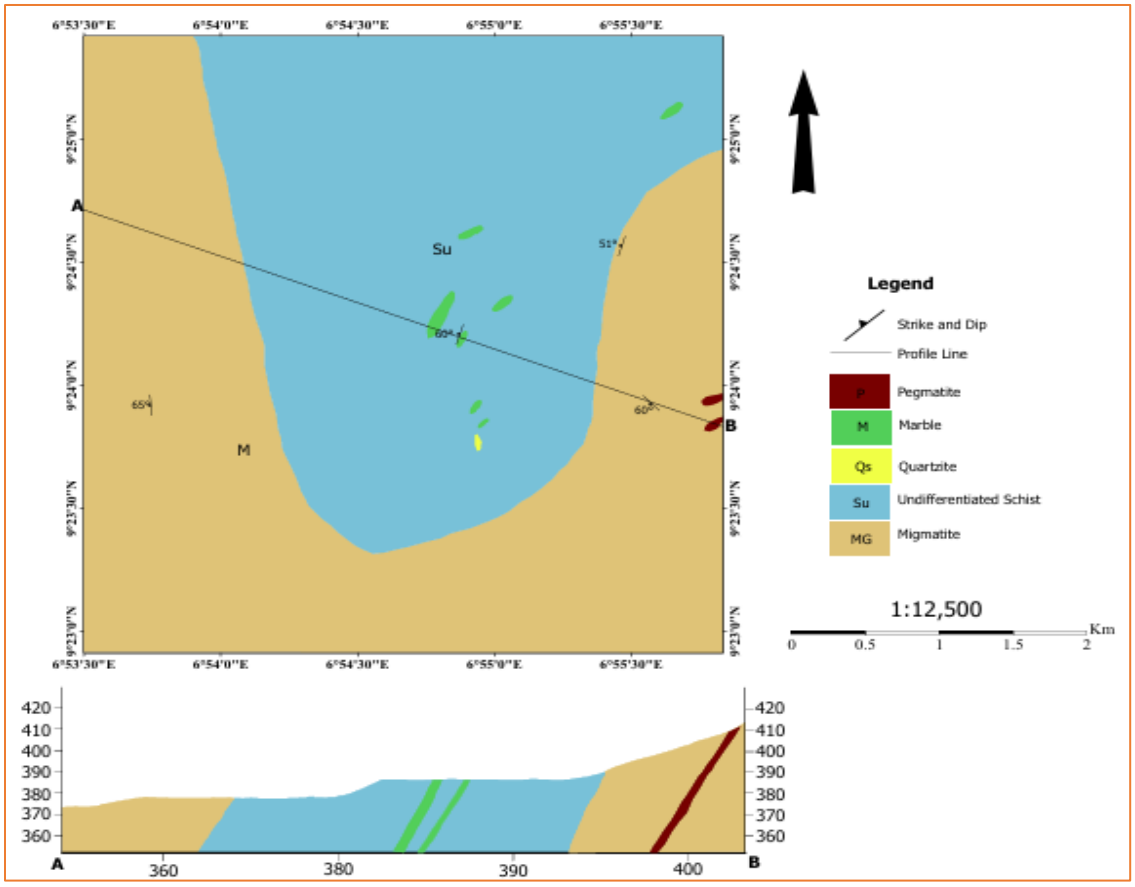


Figure 2: Geology of the Pibata area, North-Central Nigeria

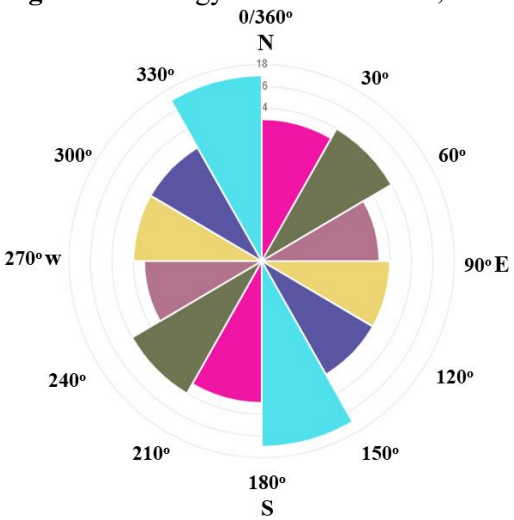


Figure 3: Rose plot of joint directions from the Pibata area

The meta-volcanosedimentary (mica schist, amphibolite, quartzite and marble) rocks occupy the central and northern portions, covering about 48% of the study area. The mica schist occupies the lowland, strikes NE-SW direction and dips to the east, highly weathered, exposed along the stream channels, making detailed description and sampling difficult. The amphibolite, quartzite and marble bodies interlayered with this intensely weathered mica schist in the central portion, making their visibility easier. The amphibolite, though not a mappable unit, appears green to dark-green in colour, fine-grained and lacks foliation. The quartzite shows association with the marble as they

both interbedded with the schist while occurring at the southern part in a N-S strike. The marbles occur as pods and lensoids within the mica schist, with a major strike direction NE-SW, which corresponds to the foliation trend observed on the mica schist. Such similar trends between schist rocks and marble bodies within the Nigerian basement complex have been reported in the literature (Onimisi et al, 2013; Eleuze et al., 2015; Akinola and OlaOlorun, 2021). The marbles show varieties of colours (white, grey and a mixture of the two), granoblastic texture and some show foliation (Figure 4). This is an indication that the protolith, which metamorphosed to birth the marble, contains impurities. Most of the marble bodies were made visible due to the ongoing artisanal workings within the vicinity of the study area.



Figure 4: Marble outcrops (A) boulders of marble bodies that fall off from the highly weathered schist (B) white variety marble experiencing workings (C) grey-dark coloured variety of marble from the study area

The observed structural feature, like the joints on rocks from the study area, was used to plot a rose diagram to determine the deformational history of the area. The principal joint direction is NNW-SSE, and closely followed by the NE-SW direction. This is an indication that the area may have experienced two major deformational processes corresponding to the Pan-African Orogeny (Uzuakpunwa, 1978; Ekwueme, 2003). Since the schist and marble show a structural trend of NE-SW, it therefore reveals they are controlled by it, and probably represent the youngest age compared to the oldest (NNW-SSE) within the study area.

Mineralogy of the Pibata marble

The X-ray diffraction mineralogical composition of marble samples from the Pibata area is presented in Table 1 and the diffractograms in supplementary pages. It reveals calcite (66.80%), dolomite (16.61%), anthophyllite (7.46%), quartz (3.63%), orthoclase (2.04%), kaolinite (1.30%), clinochlore (0.48%), and muscovite (0.46%) composition. This clearly reveals a mixed marbles; calcitic ($CaCO_3$) and dolomitic [$CaMg(CO_3)_2$] compositions, with the presence of impurities. The occurrence of anthophyllite in a marble deposit is an indication of the intense heat and pressure conditions a contaminated original rock rich in magnesium undergoes during the low-to-medium grade metamorphism. The muscovite is one of the common rock-forming minerals; its presence indicates a mica-rich host rock. Clinochlore appearance in marble body reveals an impure protolith rich in ferromagnesian minerals (biotite,

pyroxene, or amphibole) that metamorphosed at low-grade, particularly in the chlorite and greenschist facies. This was confirmed during fieldwork as mica schist, though highly weathered, serves as host to the marble deposit.

Table 1: X-ray mineralogical composition (%) of the Pibata marble

Minerals/Samples	Ya1	Ya2	Ya3	Ya4	Ya14B	Ya17	Ya19	Average
Calcite ($CaCO_3$)	94.0	51.30	42	34.0	78.30	86.0	82	66.80
Dolomite [$CaMg(CO_3)_2$]	-	36.3	28.0	49.0	-	-	3.0	16.61
Quartz (SiO_2)	4	8.0	-	-	11.40	2.0	-	3.63
Orthoclase ($KAlSi_3O_8$)	4	-	-	-	10.30	-	-	2.04
Kaolinite [$Al_2Si_2O_5(OH)_4$]	-	4.60	-	4.50	-	-	-	1.30
Anthophyllite [$(Mg,Fe)_7Si_8O_{22}(OH)_2$]	-	-	27	13.20	-	12.0	12.0	7.46
Muscovite [$(KAl_2(AlSi_3O_{10})(OH)_2$]	-	-	3.20	-	-	-	-	0.46
Clinochlore [$(Mg_5Al(AlSi_3O_{10})(OH)$]		-	-	-	-	-	3.40	0.48

Geochemistry of the Pibata marble

The geochemical results of the representative marble samples analysed reveal that SiO_2 ranges between 5.10 and 24.56 with an average of 12.6 %, which is higher than many Nigerian marbles. For instance, the value is higher when compared to Iluhagba calcitic (Omanayin et al., 2026), Ikpeshi calcitic (Madukwe and Obasi, 2016), Burum-Takalafiya dolomitic (Ako et al., 2012) and Igya grey/dolomitic (Aliyu et al., 2023) marbles (Table 3). However, silica content in the studied marble is similar to that of the Zambezi belt (Munyanyiwa and Hanson, 1988) and Igwe (Omodeni, 2023) calcitic marbles. Higher silica content in marble has a positive cost-effect on its utilisation for cement production, but the average value recorded in Pibata marble is less than the maximum required standard of 22.0 % (Rajput, 2008), with the exclusion of sample Ya3 (Table 2). CaO (36.50-51.50; avg., 43.83 %), and it is moderate compared to global standards. This average value is higher compared with Burum-Takalafia (Ako et al., 2012), Ikom (Ephraim, 2011), lower than Obajana (Elueze et al., 2015), Igwe calcitic (Omodeni, 2023), but similar to that of Ugya grey (Aliyu et al., 2023) marbles (Table 3). MgO constituent of the Pibata marble ranges between 0.01-8.76, with 3.46 % average indicating dolomite content. The average value is less than that of Igwe, Zambezi belt and Obajana calcitic marbles, but lower than Ikpeshi calcitic, Ugya grey and Burum-Takalafia marbles.

Table 2: Major oxides composition (%) of marble in the Pibata area

Oxides Composition (%)	Pibata Marble							Range	Average
	Ya1	Ya2	Ya3	Ya4	Ya14B	Ya17	Ya19		
SiO_2	5.10	8.78	24.56	12.4	18.34	8.92	10.1	5.10-24.56	12.60
CaO	51.5	42.45	36.6	36.5	44.12	48.8	46.87	36.50-51.50	43.83
MgO	0.56	6.67	4.8	8.76	0.05	0.01	3.4	0.01-8.76	3.46
K_2O	0.65	1.67	4.5	0.5	1.98	3.43	3.75	0.50-3.75	2.35
Na_2O	ND	0.05	0.21	0.06	0.65	0.65	0.54	0.05-0.65	0.36
MnO	0.33	0.25	0.24	0.81	0.33	ND	0.2	0.20-0.81	0.36
P_2O_5	0.02	0.05	0.36	0.16	ND	ND	0.14	0.02-0.36	0.15
Fe_2O_3	0.19	0.77	0.1	0.58	0.19	0.2	0.91	0.10-0.91	0.42
Al_2O_3	0.02	0.05	0.06	0.52	0.04	0.02	0.05	0.02-0.52	0.11
SO_3	nd	nd	nd	nd	nd	nd	nd	nd	nd
TiO_2	nd	nd	nd	nd	nd	nd	nd	nd	nd
LOI	40.65	38.8	28.0	34.78	34.0	37.75	33.89	28.00-40.65	35.41
Total	**99.02**	**99.54**	**99.43**	**99.55**	**99.7**	**99.78**	**99.85**	**99.02-99.87**	**99.55**
$CaCO_3$	91.67	75.56	65.15	64.97	78.53	86.86	83.43	64.97-91.67	78.02
$MgCO_3$	1.17	13.94	10.03	18.31	0.10	0.02	7.11	0.02-18.94	7.24
Total Carbonate	**91.67**	**89.50**	**75.18**	**83.28**	**78.63**	**86.88**	**90.54**	**75.18-91.67**	**85.10**
Trace Elements (ppm)									
V	285	285	508	408	390	520.5	715	285.0-715.0	444.5
Cu	80	50	50.8	310	90	60	12	12.0-310.0	93.25
Sr	265	430	377	548	650.5	450	320	265.0-650.5	434.36
Zr	500	5000	8900	9980	9870	4600	9980	500.0-9980.0	6975.71
Ba	587.6	433.5	344.5	467	600	440	448	440.0-600.0	474.37
Zn	612	156	185	21.6	80.5	180	0.001	0.001-612.0	176.44

nd: not detected.

The K_2O ranges between 0.50-3.75, with an average of 2.35 %. This average K_2O value supports that the studied marble is enriched in K-feldspar, as revealed in the mineralogy (Table 1). Oxides such as Na_2O, MnO, Al_2O_3, Fe_2O_3 and P_2O_5 all show average values of less than 1%. The loss-on-ignition (LOI) aids the assessment of organic matter content in sediments, and in the case of carbonate rocks, it is the loss of volatile inorganic substances like H_2O and CO_2. The LOI in the Pibata marble ranges between 28.00 and 40.65, with an average value of 35.41%. This average value is below the values recorded for Ikpeshi calcitic, Obajana calcitic, and Ugya grey/dolomitic marbles (Table 3), but a few of the studied marble samples (Ya1, Ya17, and Ya19) with higher CaO content show similar values. High LOI implies high carbonate content since it is analogous to the evolvement of carbon dioxide after heating at 900ºC (Olatunji, 1989), and such a high value constitutes a problem in marble usage for cement production.

Table 3. A comparison of the chemical composition (%) in the Pibata marble with some typical calcitic and dolomitic marbles

Oxides (%)	1	2	3	4	5	6	7	8
SiO_2	12.60	9.69	4.58	1.6	11.9	3.80	2.31	1.90
CaO	43.83	51.96	42.92	46.42	45.0	31.03	35.79	53.31
MgO	3.46	1.86	7.80	6.22	0.67	20.72	16.70	1.10
K_2O	2.35	0.69	0.15	0.25	0.70	0.12	0.07	0.07
Na_2O	0.36	0.39	0.46	0.17	0.39	0.05	0.01	0.12
MnO	0.36	0.03	0.08	0.03	0.03	0.01	0.01	0.02
P_2O_5	0.15	0.16	0.03	0.07	-	0.02	0.07	0.06
Fe_2O_3	0.42	1.14	0.74	0.36	1.04	0.73	0.08	0.11
Al_2O_3	0.11	1.87	0.80	0.73	2.30	0.61	0.22	0.24
TiO_2	0.00	0.09	0.06	0.04	0.13	-	0.01	0.03
LOI	35.41	41.77	42.32	43.96	-	42.40	44.41	42.18

1. Pibata marble (Present study)
2. Igwe Calcitic marble (Omodeni, 2023)
3. Ugya grey/dolomitic marble (Aliyu et al., 2023)
4. Ikpeshi calcitic marble (Madukwe and Obasi, 2016)
5. Zambezi belt calcitic marble (Munyanyiwa and Hanson, 1988)
6. Burum-Takalafia dolomitic marble (Ako et al., 2012)
7. Ikom dolomitic marble (Ephraim, 2011)
8. Obajana calcitic marble (Elueze et al., 2015)

The calculated carbonate composition equivalents of CaO and MgO contents in the Pibata marble revealed: $CaCO_3$ (64.97-91.67; avg. 78.02%) and $MgCO_3$ (0.02-18.94; avg. 7.42%). The carbonate composition of any marble is crucial in determining its bearing on mineral calcite and dolomite. $MgCO_3$, whose value exceeds 2% implies the availability of mineral dolomite (Bathurst, 1975), while less than 8% indicates the presence of isolated dolomite crystals (Greensmith, 1978). Similarly, marble with less than 11% of $MgCO_3$ is considered calcitic, and those with greater than 40% of $MgCO_3$ are dolomitic marble (Brown, 2007). The range of $MgCO_3$ and $CaCO_3$ recorded (Table 2) indicates characteristics suggesting that within the Pibata marble, there is existence of both calcitic and dolomitic marbles. An indication of the dolomitic composition in the Pibata marble is revealed in samples (Ya2, Ya3 and Ya4; Figure 5), occupying the southern portion. The histogram graphically shows that the $CaCO_3$ (blue) content exceeds that of $MgCO_3$ (brown), with their combined total represented by the silver bar (Figure 5).

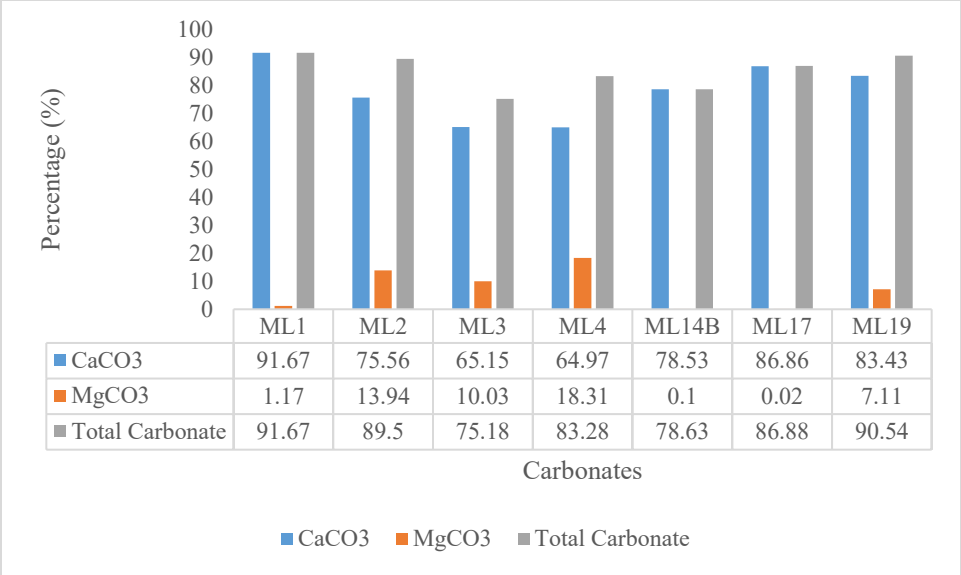


Figure 5: Histogram showing the calcitic and dolomitic nature of the Pibata marbles

Due to the presence of mixed (calcitic and dolomitic) compositions in the Pibata marble, further classification models are needed to put them in the right perspective. So, a ternary classification plot for marbles by Carr and Rooney (1983) was adopted for the studied marble and reveals: pure calcite marble (Ya1, Ya17, Ya19); impure calcite (Ya14B and Ya3); pure calcite-dolomite (Ya2); and impure dolomite (Ya4) marbles (Figure 6). In another classification system by Storey and Vos (1981), the Pibata marble is classified as: siliceous calcite (Ya1, Ya17 and Ya14B); siliceous dolomitic calcite (Ya19, Ya2 and Ya4); and calc-silicate dolomitic calcite (Ya3) marbles, respectively (Figure 7; Table 4). This classification scheme puts the Pibata marbles as dominantly siliceous calcite and siliceous dolomitic calcite types. Furthermore, the chemical constituents of the studied marbles were compared with the constituents of sedimentary carbonate rocks to constrain their possible protolith (Table 5), and are more consistent with the impure limestone protolith (Pettijohn, 1975). Lippman (1973) posited a total carbonate content of 70% and more as pure carbonates while impure carbonates are designated between 40-70%.

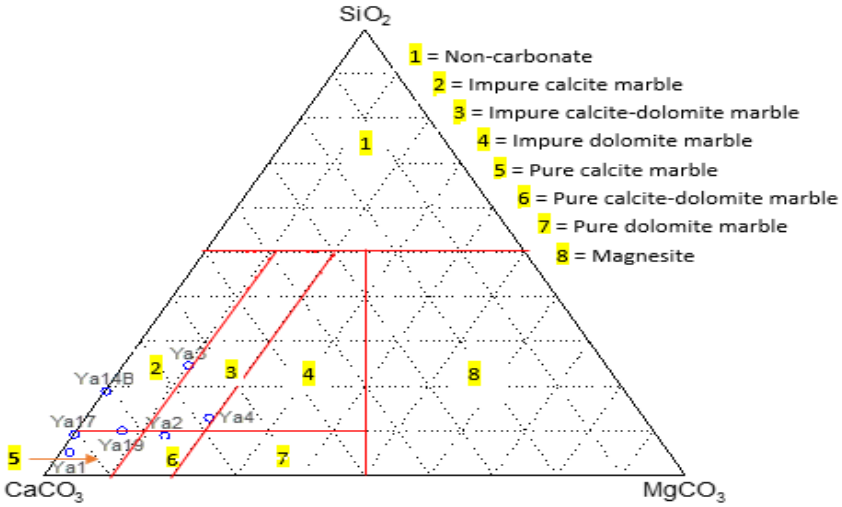


Figure 6: Ternary (CaO-MgO-SiO_2) diagram classification model for marbles (After Carr & Rooney, 1983)

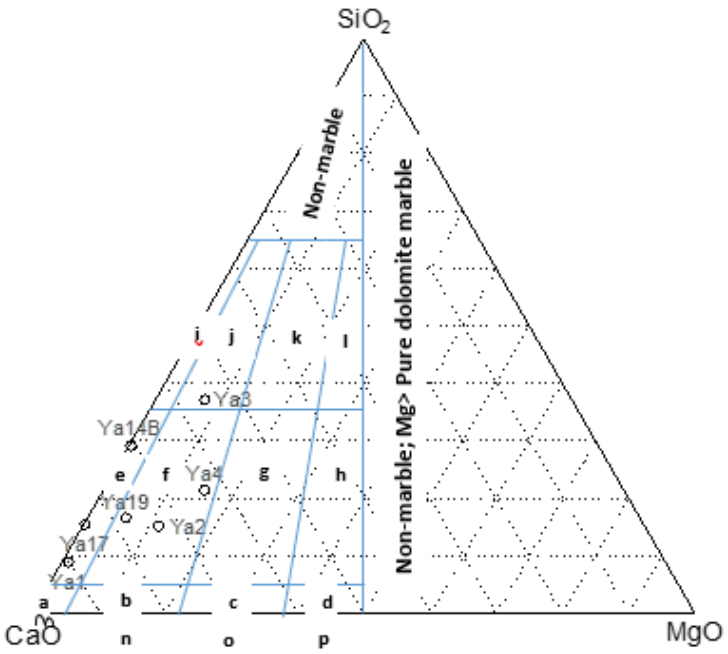


Figure 7: Classification diagram of the Pibata marbles (after Storey and Vos, 1981)

Table 4: Explanation of Figure 14 above

a	**Pure Calcite**	**Pure Marble**
b	Pure Dolomite Calcite	
c	Pure Calcite Dolomite	
d	Pure Dolomite	
e	Siliceous Calcite	Siliceous Marble
f	Siliceous Dolomite Calcite	
g	Siliceous Calcite Dolomite	
h	Siliceous Dolomite	
i	Calc-Silicate Calcite	Calcsilicate Marble
j	Calc-Silicate Dolomite Calcite	
k	Calc-Silicate Calcite Dolomite	
l	Calc-Silicate Dolomite	
m	Calcite Marble	Impure Marble
n	Dolomitic Calcite Marble	
o	Calcitic Dolomite Marble	
p	Dolomite Marble	

Table 5: Constituents of Pibata Marbles compared with constituents of sedimentary carbonate rocks

Major Oxides (%)	Pibata Marble (mean)	Relatively Pure Limestone (Pettijohn, 1975)	Impure Limestone (Pettijohn, 1975)	Dolostones (Pettijohn, 1975)
SiO_2	12.60	1.88	10.61	3.98
CaO	43.83	50.89	41.9	29.09
MgO	3.46	2.75	2.01	20.26
K_2O	2.35	0.01	0.56	0.04
Na_2O	0.36	0.06	1.35	0.14
MnO	0.36	0.01	0.22	0.02
P_2O_5	0.15	0.01	0.21	0.32
Fe_2O_3	0.42	0.26	2.97	0.64
Al_2O_3	0.11	0.83	4.30	0.78
TiO_2	0.00	0.01	0.07	0.04

Thus, based on the field, mineralogical, geochemical and classification evidence, the Pibata marble is considered to be mixed types (calcitic-Ya1, Ya14B, Ya17, Ya19; and dolomitic-Ya2, Ya3, Ya4), that is, siliceous and possibly of impure carbonate sediments protolith. This may have occurred under the influence of certain impurities and/or replacement of calcium by magnesium during metamorphism in the region. Such metamorphism could be described as low- to medium-grade metamorphism, which aligns with the established metamorphic grade of the regional basement complex to which the study belongs. Similar conditions were reported for Nigerian basement marbles (Akinola and OlaOlorun, 2021) and East African marbles (Melezhik et al., 2008).

Recent studies on marble deposits worldwide emphasise the role of protolith purity, metamorphic grade, and post-metamorphic alterations in determining marble quality. Siliceous marbles similar to the Pibata, marbles from the Zambezi Belt (Munyanyiwa and Hanson, 1988) and Igwe, Nigeria (Omodeni, 2023) also show elevated SiO_2, attributed to detrital input and metasomatic processes. The presence of dolomite (up to 49% in Ya4) aligns with global dolomitic marble formations such as those in the Precambrian of India (Kumar et al., 2022) and Turkey (Ince et al., 2021), where Mg-enrichment is linked to hydrothermal alteration or Mg-rich fluids. Anthophyllite presence indicates medium-grade metamorphism and Mg-rich protolith, similar to marbles in the Appalachian Belt, USA, where amphibole-group minerals signify impure carbonate precursors. Protolith inference by considering the geochemical signature (SiO_2, Al_2O_3, K_2O) aligns with impure limestone or marl, consistent with Pettijohn (1975). Similar siliceous-dolomitic marbles in Brazil (Azevedo et al., 2024) and Oman (Ambrose et al., 2021) are also interpreted as metamorphosed impure carbonates with detrital input.

The trace element content in the Pibata marbles, such as zircon (Zr), vanadium (V), strontium (Sr), copper (Cu) and zinc (Zn), shows elevated concentrations when compared with the upper continental crust (UCC) background values (Zr=193 ppm; V=97 ppm; Sr=320 ppm; Cu=28 ppm and Zn=67 ppm) given by Rudnick and Gao (2003; Table 2). Zr shows extreme

concentration, which ranges from 500-9980 ppm and averages 6975.71 ppm. Though, this Zr value is very high perhaps due to the analytical technque used, but suggests that the marble metamorphosed from sedimentary protolith, likely limestone, with detrital zircon grains incorporated during either metamorphism or metasomatic alteration. This high zircon recorded in the studied marbles is similar to the study conducted in the Himalayan region (Cui et al., 2024), where it indicates zircon inheritance from detrital sediments. V ranges from 285-715 ppm with an average of 444.5 ppm, affirming detrital input, which may suggest reducing conditions during marble formation, comparable to Turkish marbles (Cengiz et al., 2025). Sr values range from 265-650 ppm with an average of 434.36 ppm. Sr often incorporates into carbonate minerals; its moderate value is an indication of diagenetically aided metamorphism, and that seawater has no major influence, akin to metamorphosed lacustrine carbonates in China (Li et al., 2008). Similarly, Cu (12-310; avg. 93.25 ppm) and Zn (0.001-612; avg. 176.44 ppm) are often naturally distributed in carbonates.

Economic appraisal of the Pibata marble

The applicability of marble in various uses is influenced by its constituent physical, mineral and chemical characteristics. Their quality is dependent on the amount of CaO, MgO and SiO_2 concentrations. The following subheadings present some of the common areas' marbles are found useful; thus, the constituents in the Pibata marbles are compared with known specifications to assess their status as shown below.

Cement production

The major standard for cement production of carbonate rocks is in the range of: CaO not more than 63.0%, MgO not more than 3%, Al_2O_3 not more than 6%, Fe_2O_3 not less than 3.0%, SiO_2 not more than 22.0%, total alkalis not more than 0.5%, but $CaCO_3$ should be more than 82% (Rajput, 2008). Constituents of the studied marble are: CaO (43.83%), MgO (3.46%), Al_2O_3 (0.11%), SiO_2 (12.60%), total alkalis (K_2O+Na_2O=2.71%), and $CaCO_3$ (78.02%) (Table 2). So, the Pibata marble does not meet these standards, and so cannot be used directly in cement production, except if beneficiated to the desired specifications. Such a beneficiation practice is adopted for low-grade marbles in India (Kumar et al., 2022).

Chemical industry

Based on specifications, chemical industries make use of lime products from carbonate minerals like marble in the manufacture of calcium carbide, sodium carbonate, insecticide dust and bleaching powder. Such chemical specification includes SiO_2 (<3.0%), MgO (<1.0%), CaO (>53%), total carbonate (($CaCO_3$ + $MgCO_3$; >94.6%) (Boynton, 1980). The Pibata marble does not meet these criteria, as they differ from standards.

Pharmaceutical industry

The specifications required for marble use in the pharmaceutical industry include SiO_2 (< 0.12 %), Fe_2O_3 (< 0.1 %), MgO (< 0.42 %), CaO (> 54 %), and $CaCO_3$ (> 96%). This is important as a neutraliser and filtration agent in the manufacture of antibiotics, antacids and tablets (Harrison, 1993). The studied marbles again fall short of these important requirements and so, cannot be used in the field of pharmaceuticals. World over, only high-purity calcitic marbles (e.g., from Italy, Greece, and Turkey) are often used in the pharmaceutical sector (Polaris Market Research, PMR, 2025).

Paint, paper and plastic industries

Physical and chemical properties of marble complement each other in its use in paint, paper and plastic productions. Pure white or pinkish marble with fine (98 % passing 325 sieve) particle sizes constitutes the required physical properties. The chemical standard for paint production includes SiO_2+MgO (> 75%), and Al_2O_3 (≥ 2%), (Boynton, 1980). A few of the studied marbles from the Pibata area partly satisfy the physical requirements, but are chemically unsuitable for paint production based on the specifications. Though some manufacturer of paints may have their varied specification and as such could decide to process. The required standards for marble as filler/extenders in paper and plastic productions include SiO_2 (< 3%), CaO (> 53%), Al_2O_3 (< 0.2%), MgO (<

3%), and Fe_2O_3 (< 0.2%) (Boynton, 1980). Based on the standards given, the Pibata marble falls below it (Table 2), except for alumina content; thus, it is considered unsuitable in the production of paper and plastic as well.

Glass manufacturing

Marble composition requirements for glass manufacturing are $CaCO_3$ (>96%) and Fe_2O_3 (0.05-0.2%), with the lowest value for colourless and the highest value for coloured glass. The calcium carbonate and ferric oxide recorded in the Pibata marble are above these stated specifications, thus, are not fit for the manufacture of glass except if otherwise specifically stated by companies.

Construction industry

Metamorphic rocks, marble inclusive, maintain significant commercial value for decorative flooring (tiles and slabs), and artistic sculptures (Ofulume, 1991). In terms of construction, marble is used as ballast, road base, and concrete aggregate. For concrete, the key requirements are low alkalis (K_2O+Na_2O), CaO+MgO (60% and above), and freedom from surface organic matter. For other aggregate applications, suitability is determined by physical and mechanical properties. The Pibata marble with total alkalis (2.71%) and CaO+MgO (47.29 %) (Table 2), is considered chemically unsuitable raw material for high-value construction (e.g., tiles, slabs) due to impurities and colour variation (Barron, 2018). However, mechanical properties and polishability are also important criteria to be considered too.

Fertiliser industry

The use of marble as a critical material in fertiliser manufacturing cannot be overemphasised. Its suitability for use in calcium ammonium nitrate (CAN) fertiliser manufacturing and for neutralising pH imbalances requires a total carbonate content ($MgCO_3$+$CaCO_3$) of 85%. The Pibata marble (85.10%) is considered suitable for fertiliser manufacturing based on the carbonate content (Boynton, 1980; FAO, 1991). However, other qualities such as neutralizing value, fineness, and reactivity are also factors to be considered but are not within the scope of this work. Impure marbles like Pibata are comparable to low-grade deposits in Pakistan, Iran, and Nigeria, which are primarily used in low-value construction and agriculture (Raza et al., 2024).

CONCLUSION

The Pibata area is underlain predominantly by the Precambrian basement complex rocks, specifically within a migmatite-gneiss-schist-quartzite complex. The marble occurs as pods and lensoids within the highly weathered mica schist, strikes NE-SW, conformable with the regional structural trend of the host rock (schist). The joint directions of NNW-SSE and NE-SW recorded in the surrounding rocks indicate a regional deformation event corresponding to the Pan-African orogeny. Field relationships and mineral assemblages suggest formation under low- to medium-grade metamorphic conditions affecting an impure sedimentary protolith. Mineralogically, the marbles are heterogeneous mixtures rather than pure carbonates. X-ray diffraction reveals average compositions of 66.80% calcite and 16.61% dolomite, with significant impurities including anthophyllite (7.46%), quartz (3.63%), and orthoclase (2.04%). This mineralogy points to a magnesium-rich, siliceous precursor rock subjected to metamorphism. Geochemically, the deposits exhibit moderate calcium oxide (average 43.83%) and elevated silica (12.60%) contents compare with pure marble. High loss-on-ignition values (35.41%) reflect substantial carbonate decomposition upon heating. Classification schemes identify the marbles primarily as siliceous calcite and siliceous dolomitic calcite types, derived from impure limestone or marl protoliths enriched with detrital sediments.

Economic evaluation indicates limited suitability for high-value applications. The marbles fail to meet industrial specifications for cement production (excessive alkali; low $CaCO_3$), pharmaceuticals and chemicals (insufficient purity), glass manufacturing (elevated iron oxides), and paper/plastic fillers (high silica content). Their variable colouration and impurity levels also restrict use in decorative construction apart from other considerations. However, the

preliminary assessment based on mineralogical and geochemical composition of the Pibata marble it aligns with agricultural requirements, making fertiliser production and soil conditioning the most viable immediate applications. Additionally, the material with beneficiation may serve as potential cement feedstock.

Conflict of Interest

The authors declare that they have no competing interests.

REFERENCES

Abolade, O. S. (2015). Petrographic study of rocks in the south-western part of Paiko Sheet 185, Northwestern Nigeria [Unpublished Undergraduate Thesis]. Federal University of Technology Minna, Nigeria.

Ako, T. A. Onoduku, U. S., and Abdulfatai, I. S. (2012). Economic evaluation of Burum Takalafia marble deposit, Federal Capital Territory, Abuja, Nigeria. *Research Journal of Science and IT Management,* 1(12), 23-32. http://repository.futminna.edu.ng:8080/jspui/handle/123456789/6698

Ajibade, A. C., and Woakes, M. (1983). Proterozoic crustal development in the Pan-African regime of Nigeria. In: Kogbe, C. A (Ed.). *Geology of Nigeria*, Rock View Ltd., Jos, 57-63.

Akinola, O. O., and OlaOlorun, O. A. (2022). Morphological attributes, petrochemistry and origin of quartzite units in Ekiti, Southwestern Nigeria. *International Journal of Geography, Geology and Environment,* (2): 42-51. https://doi.org/10.22271/27067483.2022.v4.i2a.116

Akinola, O. O., and OlaOlorun, A. O. (2021). Lithological features and chemical characterization of metamorphosed carbonate rocks in Igue, Southwestern Nigeria. *Journal of Geology and Mining Research, 13(1), 11-20.* http://www.academicjournals.org/JGMR

Aliyu, A. I., Unuevho, C. I., Yohanna, A., Sanusi, I. M., Aliyu, S., Jabo, J. N., Okkoh, A. I., and Yahaya, M. (2023). Assessment of industrial potentials of marble deposits in Ugya, North Central Nigeria based on mineralogical and chemical studies. *Science Forum (Journal of Pure and Applied Sciences)* 23, 951 – 964. https://atbu.edu.ng/science-forum/

Ambrose, T. K., Waters, D. J., Searle, M. P., Gopon, P., and Forshaw, J. B. (2021). Burial, accretion, and exhumation of the metamorphic sole of the Oman-UAE Ophiolite. *Tectonics,* 40(4). https://doi.org/10.1029/2020TC006392

Azevedo, J. M. N., Hühn, S. R. B., Freire, J. V. O., Mattos, I. C., Silva, I. M. (2024). Lithostructural mapping and 3D modelling in a dolomitic marble deposit, Canta-Galo District (Acarape-CE), Borborema Province, Northeastern Brazil. *Brazilian Journal of Geology*, 54(2), e20240022. https://doi.org/10.1590/2317-4889202420240022

Barron, A. J. M. (2018). Report on the carrara marble deposit in Italy. *Mercian Geologist,* 19(3), 188-194. https://www.mercian2018v19p188CarraraMarbleBarronAJM.pdf

Bathurst, R. G. C. (1975). Carbonate sediments and their diagenesis. Developments in sedimentology. Amsterdam-Elsevier. p. 620. https://www.scirp.org/reference/referencespapers?referenceid=3499415

Boggs, S. Jr. (2009). Petrology of Sedimentary Rocks, Second Edition. Cambridge University Press, UK, 2009; 600. https://doi.org/10.1017/CBO9780511626487

Boynton, R. S. (1980). Chemistry and technology of lime and limestone. New York: John Wiley and Sons, Inc., 300pp.

Brown, T. (2007). Setting the standard in the natural stone industry. Marble Institute of America. p. 278.

Brownlow, A. H. (1996). Geochemistry (2nd Ed.). Prentice Hall, New Jersey. 1996; 580.

https://archive.org/details/geochemistry0000brow

Carr, D. D., and Rooney, L. F. (1983). Limestone and dolomite. In: Lefond, S.Y. (Ed.) Industrial minerals and rocks (5th edition). New York: (America Inst. Met. And Petr. Engr. Inc), 833- 868.

Cengiz, O., Kiray, D., and Ozegdemir, E. (2025). Petrography and geochemistry of the middle Jurassic–lower Cretaceous limestones from the Mustafakemalpaşa Quarries, Bursa, Turkey: The depositional environmental and diagenetic processes. *Minerals, 15(11),* 1135. https://doi.org/10.3390/min15111135

Cui, H., Wang, C., Su, M., Lei, Y., Zeng, L., and Jia, J. (2024). Detrital zircons record the provenance and source-to-sink process in the northwestern margin of the South China Sea. Frontiers in Marine Science, 11:1427579. https://doi.org/10.3389/fmars.2024.1427579

Ekwueme, B. N. (2003). Regional metamorphism of pelitic rocks SE Lokoja. *Nigerian Journal of Mining and Geological Science*, 20, 17-24.

Elueze, A. A., Jimoh, A. O., and Aromolaran, O. K. (2015). Compositional characteristics and functional applications of obajana marble deposit in Precambrian basement complex of central Nigeria, *Ife Journal of Science*, 17(3), 591–603. https://www.researchgate.net/publication/325575803.

Ephraim, B. E. (2011). Compositional appraisal and quality implications of a metacarbonate deposit occurring in parts of southeastern Nigeria. *RMZ – Materials and Geoenvironment*, 58 (4), 405 – 420.

Fatoye, F. B., and Gideon, Y. B. (2013). Geology and Occurrences of Limestone and Marble in Nigeria. *Journal of Natural Sciences Research*, 3(11), 60-66. https://www.iiste.org/Journals/index.php/JNSR/article/view/7663

Food and Agriculture Organization (FAO) of the United Nations. (1991). Economic and social development paper: manual on fertilizer statistics. Report, 45p.

Goodenough, K. M., Lusty, P. A. J., Roberts, N. M. W., Key, R. M. and Garba, A. (2014). Post-collisional Pan-African granitoids and rare metal pegmatites in western Nigeria: age, petrogenesis, and the 'pegmatite conundrum'. *Lithos,* 200: 22-34. https://doi.org/10.1016/j.lithos.2014.04.006

Grant, W. T., Papertzian, V. C., and Kingston, P. W. (1989). Geochemistry of Grenville marble in southeastern Ontario; Ontario Geological Survey, *Mineral Deposits Circular 28*, 1989; 266.

Greensmith, J. T. (1978). Petrology of the sedimentary rocks, 6th edition, Vol. 2 George Allen and Unwin Ltd., London, pp. 124-172.

Harrison, D. J. (1993). High-purity limestone in England and Wales, *Quarterly Journal of Engineering*. https://doi.org/10.1144/gsl.qjegh.1993.026.004.05

Ince, Z., Atakoglu, O, O., and Yalcin, M. G. (2021). Multivariate and spatial statistical analysis of geochemical data of dolomite: The case of industrial raw materials' differentiation. *Montes Taurus Journal of Pure and Applied Mathematics*, 3 (2), 8–28. https://www.mtjpamjournal.com

Kogbe, C. A. (1989). Paleozoic and Mesozoic stratigraphy of the Nupe Basin, Nigeria. *Journal of African Earth Sciences*, 8(2), 151-164.

Kumar, M., Singh, H. P., Sakale, R. (2022). Utilization of marble powder in making of cement concrete and analysis of its strength characteristics. *International Journal of Trend in Scientific Research and Development,* 6(3), 1673-1679. https://www.ijtsrd.com

Li, M., Kang, S., Zhu, L., You, Q., Zhang, Q.,Wang, J. (2008). Mineralogy and geochemistry of the Holocene lacustrine

sediments in NamCo, Tibet, China. *Quaternary International,* 187(1), 105-116. https://doi.org/10.1016/j.quaint.2007.12.008

Lippmann, F. (1973). Sedimentary carbonate minerals. Berlin, Heidelberg, and New York (Springer-Verlag), 228 pp. https://doi.org/10.1180/minmag.1974.039.306.19

Madukwe, H., and Obasi, R. (2016). Geochemical and petrogenetic characteristics of the marble deposit at Ikpeshi southern Nigeria. *Nature and Science,* 14(9), 1-11. https://doi.org/10.7537/marsnsj140916 01

Melezhik, V. A., Bingen, B., Fallick, A. E., Gorokhov, I. M., Kuznetsov, A. B., Sandstad, J. S., Solli, A., Bjerkgård, T., Henderson, I., Boyd, R., Jamal, D., and Moniz, A. (2008). Isotope chemostratigraphy of marbles in northeastern Mozambique: Apparent depositional ages and tectonostratigraphic implications. *Precambrian Research,* 162 (3–4), 540-558. https://doi.org/10.1016/j.precamres.2007.11.002

Munyanyiwa, H., and Hanson, R. E. (1988). Geochemistry of marbles and calcsilicate rocks in the Pan- African Zambezi belt, Zambia. *Precambrian Research*, 38, 177-200.

Odeyemi, I. B. (1988). Lithostratigraphic and structural relationships of the upper Precambrian metasediments in Igarra area, western Nigeria. In: P.O. Oluyide, W.C, Mbonu, A.E., Ogezi in the Precambrian Geology of Nigeria. *Geological Survey of Nigeria*, Kaduna. pp. 111-123.

Ofulume, A. B. (1991). The Jakura marble as filler and extender in paints, paper and plastic industries. *Journal of Mining and Geology,* 27(2), 187-193.

Olatunji, J. A. (1989). Chemical characterization of Isale osin marble, Kwara state. Geoscience Consultancy Report for Ministry of Commerce and Industry, Ilorin, Kwara State. 1989.

Omanayin, Y. A., Lawal, M., Bolaji, I. B., and Muhammad, A. (2023). Field and petrographic studies of Basement Complex rocks in Saigbe and environs, North-Central, Nigeria. *Nigerian Journal of Basic and Applied Sciences (NJBAS),* 31(1), 49 – 59. http://dx.doi.org/10.4314/njbas.v31i1.6

Omodeni, J. N. (2023). The Geochemistry of carbonate rocks in Igwe Igarra, Southwestern Nigeria. *International Journal of Geosciences,* 14, 505-514, https://doi.org/10.4236/ijg.2023.146027

Onimisi, M., Obaje, N. G., and Daniel, A. (2013). Field geologic occurrence and petrographic characteristics of Precambrian marble body in Itobe area, Central Nigeria. *Advances in Applied Science Research,* 4(5), 58-71.

Pettijohn, F. J. (1975). Sedimentary Rocks. 3rd Edition, Harper and Row, New York, 628 p. https://www.scirp.org/reference/referencespapers?referencei=20473471

Polaris Market Research (PMR) (2025). Marble market size, share, trends, and industry analysis report by colour (white, black, yellow), by product, by application, and by region, *Market Forecast*, 2025–2034. https://www.polarismarketresearch.com/industry-analysis/marble-market

Rajput, R. K. (2008). Engineering materials. S. Chand and Company. 3rd Ed. New Delhi, India. pp. 89-94.

Rahaman, M. A. (1988). Recent advances in the study of the Precambrian geology of Nigeria. *Journal of African Earth Sciences*, 7(3), 529-536.

Raza, M., Ahmed, W., Qazi, M. S., Azam, S., and Sajid, M. (2024). Characterization of Buner marble from Pakistan for construction purposes. *International Journal of Mining and Geo-Engineering*, 58-2 (2024) 135-143.

https://doi.org/10.22059/IJMGE.2024.364177.595094

Ronov, A. B. (1983). The Earth's Sedimentary Shell: AGI Reprint Series 5, 1983.

Rudnick, R. L., and Gao, S. (2003). Composition of the continental crust. In: Rudnick, R.L. (Ed.), Treatise on Geochemistry, 3, 1-64. https://doi.org/10.1016/b0-08-043751-6/03016-4

Storey, C. C., and Vos, M. A. (1981). Industrial minerals of the Pembroke-Renfrew area, Part 1: Marble; Ontario Geological Survey, *Mineral Deposits Circular 21*, 132.

Unuevho, C. I. (2009). Graphic determination of depth to fresh crystalline basement from Schlumberger sounding curves: Applicability in Minna Niger State, Nigeria. *Journal of Science, Technology, Mathematics and Education (JOSTMED),* 191-210.

Uzuakpunwa, A. B. (1978). The polyphase nature of the Nigerian basement complex. *Proc. 14th Annual Conf. Nigerian Mining and Metallurgical Society*, 1978.

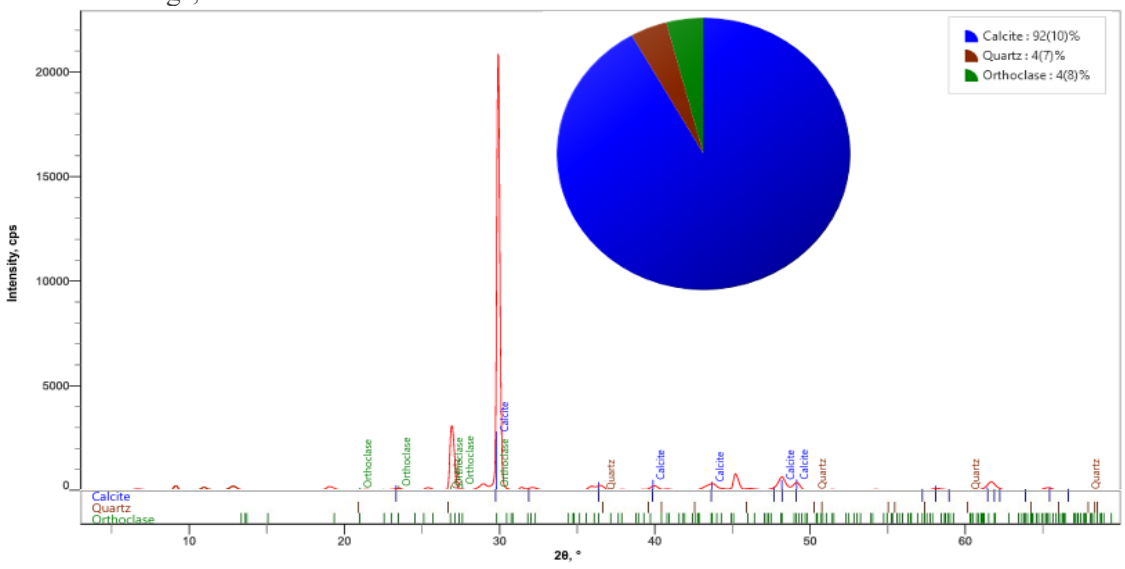
Funding

The research was funded from the authors savings, with no external financial influences affecting the study's design, execution, or conclusions.

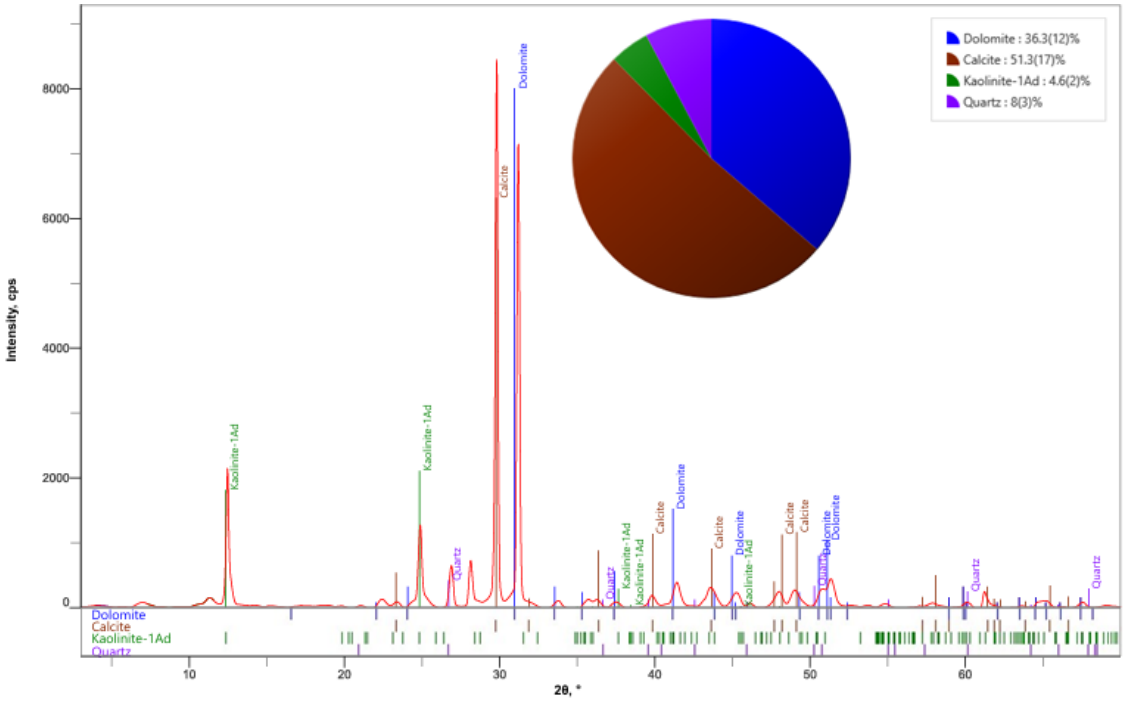
Author's contribution

Yunusa Adinoyi Omanayin (PhD, Senior Lecturer, Economic Geology): Writing– original draft, Research organization, Methodology, Investigation, Resources, Formal analysis, Data curation, Conceptualization, Analysed the findings, critically reviewed the manuscript draft, and offered valuable technical recommendations. **Muhammed Ademu Usman** (B.Tech Geology): Writing– original draft, review & editing, Visualization, Resources, and Validation of the XRF results aspect of the study. **Sharon Mercy Michael** (B.Tech Geology): Writing– original draft, review & editing, Visualization, Resources, and Validation of the XRD results aspect of the research. **Mutari Lawal** and **Adegbe Momodu** both contributed to the technical review and recommendations.

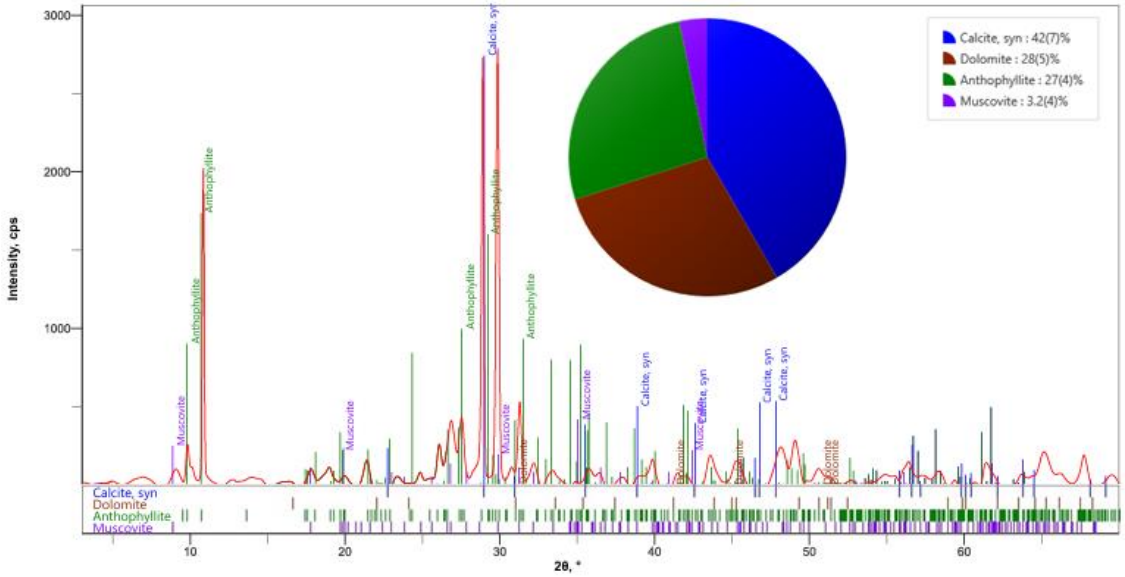
SUPPLEMENTARY PAGE



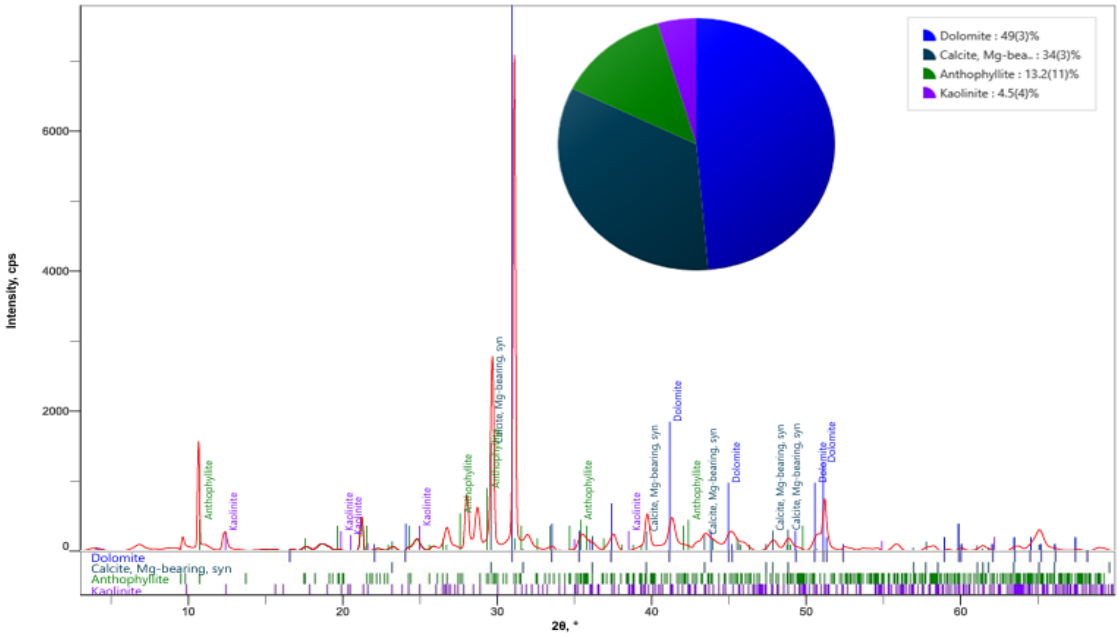
XRD pattern of the sample Ya1 from the Pibata area, North-central Nigeria



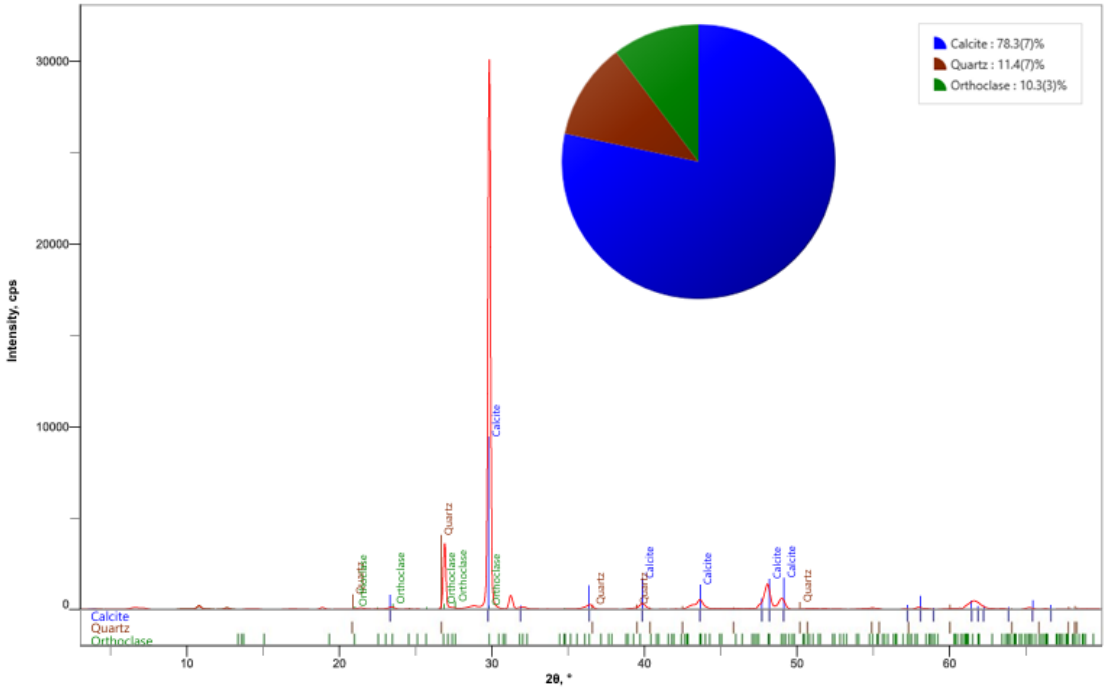
XRD pattern of the sample Ya2 from the Pibata area, North-central Nigeria



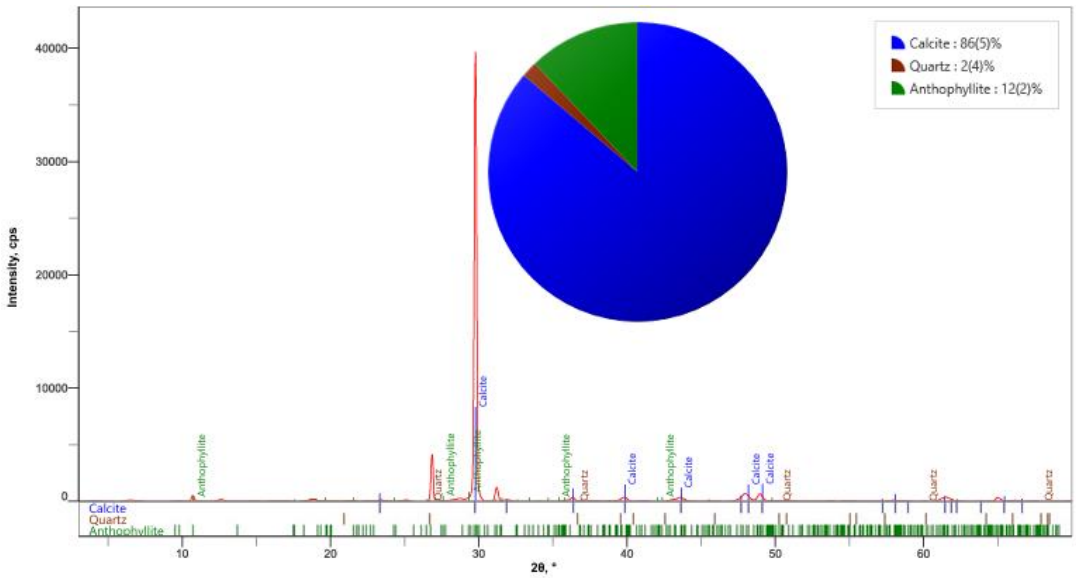
XRD pattern of the sample Ya3 from the Pibata area, North-central Nigeria



XRD pattern of the sample Ya4 from the Pibata area, North-central Nigeria



XRD pattern of the sample Ya14B from the Pibata area, North-central Nigeria



XRD pattern of the sample Ya17 from the Pibata area, North-central Nigeria

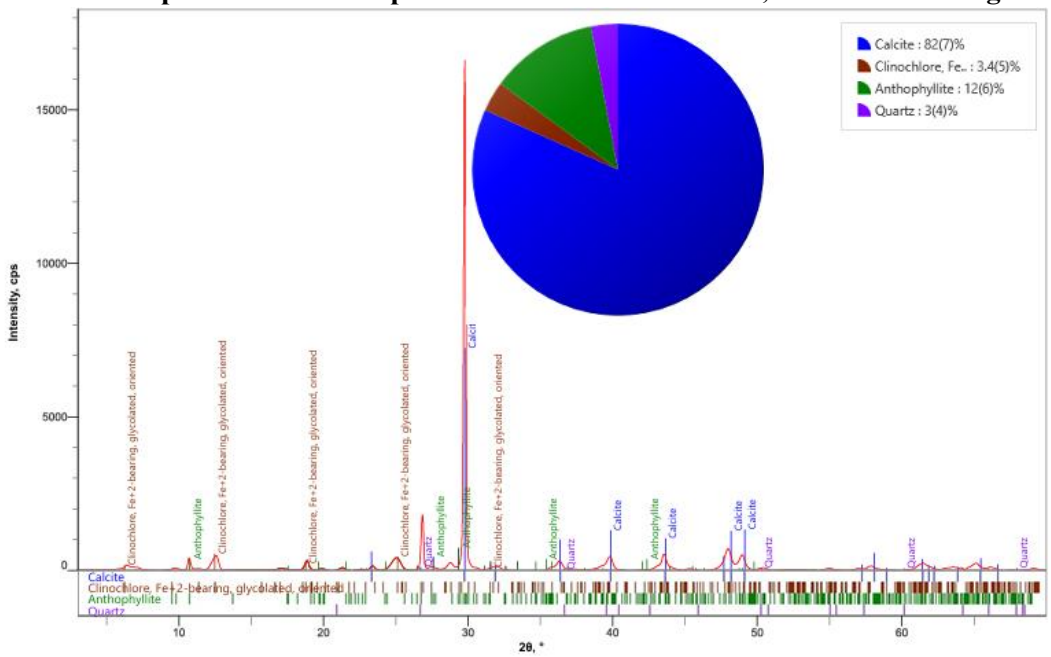


Figure 11: XRD pattern of the sample Ya19 from the Pibata area, North-central Nigeria