Geology, Geophysics & Environment 2021, vol. 47 (4): 203–216

X-ray diffraction studies of onshore mud volcanoes in parts of the Upper Benue Trough, northeastern Nigeria

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Received: 6 May 2021; accepted: 23 December 2021; first published online: 30 December 2021

Abstract: The mineralogical studies of clay from the onshore mud volcanoes discovered in parts of the Upper Benue Trough of Nigeria provide a clue about the geological formation from which the extruded mud originates. The study area is a part of the Cretaceous Upper Benue Trough filled with Early Cretaceous continental deposits and Late Cretaceous marine deposits, having a history of magmatism dating from the Albian to the Pleistocene. The study approach involves integrated inorganic geochemical analysis of the samples to reveal their composition and origin. The results of XRD analysis of the fresh clays from the mud volcano revealed the presence of quartz, kaolinite, and other clay minerals (illite-smectite), feldspars, and in a much lower quantities, other accessory minerals including muscovite, evaporites, calcite and dolomite, trona, barite, goethite. The saprolite samples are composed mainly of quartz, kaolinite, smectite-illite associations, and feldspars, traces of goethite, calcite, and evaporate minerals (sylvite, halite). The presence of calcite, dolomite, sylvite, and halite suggests the marine origin of the rocks, while trona mineral is a non-marine evaporate. The coexistence of these minerals in some of the analyzed samples suggests the deposition of sediments in a transitional environment of deposition. Traces of marine minerals are present in some of the samples but completely absent in others collected from another site. This suggests that the source rock formations from which the material originated are within the Upper Bima Sandstone interpreted as being deposited in a non-marine environment or the Yolde Formation, which is known as a transitional unit (transitional between the outcropping continental Upper Bima Sandstone and marine Pindiga Formation).

Keywords: mud volcano, weathered rocks, soft overburden, mineral composition

INTRODUCTION

The middle Benue Trough is the central segment of the Nigerian Benue Trough, a stretched large intracratonic rift structure that originated within the Precambrian to Early Palaeozoic crustal basement of the Pan-African mobile belts in the Late Jurassic to Early Cretaceous (Olade 1975, Obaje 2009, Nwajide 2013). Consequently, Offodile (1984) reported the occurrences of brine fields in

Middle Benue Trough within the Awe Formation (Awe brine fields), Lower Benue Trough within the Amasiri I Ezeaku Formation (Azara and Ribi brine fields), and the Upper Benue Trough within the Yolde Formation (Ayaba and Todi salt springs). This author described the origin of brines in these areas as enigmatic, issuing from geological formations, deposited in environments transitional between marine and non-marine ones, invariably of about Albian to Cenomanian in age. Furthermore, the Nigerian inland mud volcanoes were first described by Musa et al. (2014, 2015). They reported that the mud volcanoes are located within Cretaceous Upper Benue Trough, filled with Early Cretaceous continental deposits and Late Cretaceous marine deposits, having a history of magmatism dating from Albian to Pleistocene. The onshore mud volcanoes are located in parts of the Upper Benue Trough, southwest from the Kaltungo inlier (Figs. 1, 3) mostly on Yolde Formation and Upper Bima Sandstone. The globally renowned mud volcanoes are either subaerial or submarine sedimentary structures whose surface morphology resembles that of an igneous volcano but on a much smaller scale.

They are of small sizes – from 0.5 m to several meters in diameter (max. of 5 m) at the base and with heights not usually exceeding a meter (max. of 1.5 m), but they occur in large numbers close to each other, so that the areas of their concentration (kind of clusters) have been described as mud volcano fields. The volcano fields are usually about 3000 m^2 in area; the largest one was found in Lallapido, where about 28 mud volcanic cones are located over a surface area of 4500 m^2. They occur along the NE-SW trending Kaltungo fault zone and other minor N-S and NW-SE trending faults.

They form as a result of the emission of depressurized pore water, gases, and argillaceous material from deep-seated sources and manifest either on the earth's surface or seafloor as piercing shale diapirs, sometimes along faults and fractures (Dimitrov 2002, Kopf 2002). The material extruded from the deeper units of formations consists of fine-grained sediments, water, gases, and sometimes rock fragments and even mud breccia in the case of huge mud volcanoes. The depth of the parent bed from which material is extruded forming mud diapirs and volcanoes can be estimated from seismic reflection surveys; the offshore giant mud volcanoes in many sites, like the Mediterranean Sea, Alboran Sea, Nile Delta (Savini et al. 2009), Gulf of Mexico (MacDonald & Peccini 2009) and a few within the Nigerian part of Gulf of Guinea (Graue 2000) have been subjected to acoustic, laser, video and other study techniques. Seismic soundings are usually carried out in areas where mud volcanoes of huge dimensions occur in hydrocarbon exploration areas. In those cases, the depth of material-bearing beds can be as deep as several kilometers.

The smaller mud volcanoes, particularly the onshore ones which are beyond the focus of resource exploration, are usually not subjected to costly detailed geophysical examination and their depth in most cases is unknown. However, in the case of small mud volcanoes (with a diameter up to several meters), it is expected that the parent-bed is at a much shallower depth (Musa et al. 2016). The mud volcanoes in the Upper Benue Trough, as they are the small size type, probably draw up liquid material from not very deep parent beds. No geophysical studies have yet been conducted to recognize the source of the mud underground, but the other, geological approach has been applied to find out more about the nature of the volcanoes. However, from a qualitative and quantitative examination of the mineral composition as presented in Table 1 (both the material extruded from volcanic mud slurry and the saprolite), it was assumed that if the mud slurry and the saprolite picked from the particular location are similar in mineral content, the material extruded from the volcano originates from the interval of saprolite occurrences, probably not deeper than several dozen meters. In the study area, the Upper Bima Sandstone or Yolde Formation directly underlies the weathered overburden (Ejiga et al. 2021). The characterization of the formations is presented further in this paper. Studies of the mineralogical content of mud slurry and its comparison to the results obtained for the saprolite reveal the origin and mechanism of the mud volcanic activity within the Upper Benue Trough.

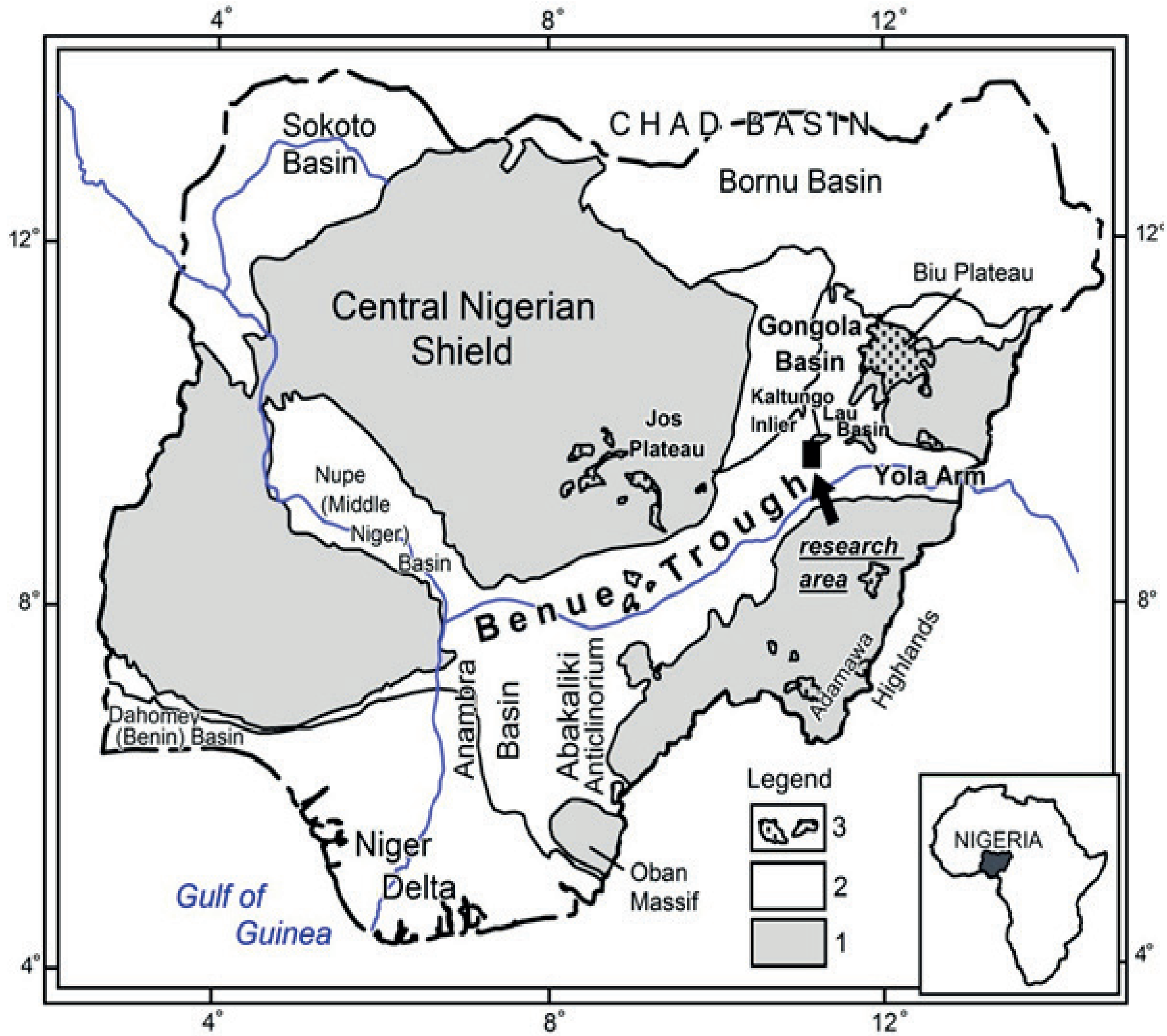

Fig. 1. Location map of the study area on the background of general geological division of Nigeria: 1 – Precambrian basement, crystalline rocks, 2 – sedimentary basins (Cretaceous-Cenozoic), 3 – Cenozoic volcanic

UPPER BENUE TROUGH – GEOLOGIC SETTING

The Benue Trough is a tectonic megastructure filled with Cretaceous sediments, developed upon a framework of mainly SW-NE trending major faults. The widespread model of the origin and tectonic development presents the Benue Trough as a part of a West Central African Rift System which was created during Africa – South America separation in the process of the disintegration of Gondwana (Cratchley et al. 1984, Popoff 1988, Binks & Fairhead 1992, Genik 1992). The major faults in the Benue structure were then interpreted as strike-slip faults. The fault and fold system formed within the trough and characterized by general SW-NE trend was explained as a wrench tectonics effect accompanied by compressional and extensional stages, resulted finally in forming a system of basins (pull-apart type) and uplifted blocks, especially well recognized in the northern part of the trough (Maurin et al. 1986, Guiraud 1990, Binks & Fairhead 1992). Tectonic, sedimentological, and geophysical studies led to the conclusion that the Benue Trough evolved in two major stages: (I) the initial stages of rifting (pre-rift stage during the terminal Jurassic to earliest Cretaceous) and (II) the latter stage (from Late Albian) including the succession of the three periods of rifting, then late rifting, the thermal sag of the basin with extension and transgressional inversion (Popoff 1988, Guiraud 1993). The folding episodes associated with the succession of marine, continental and transitional beds of middle Albian to Maastrichtian age have generated anticlinal structures which dominate the Benue Valley. The structures genetically are related, and are separated into the Abakaliki, Keana, and Lamurde anticlinoriums in the lower, middle and upper parts of the Benue valley respectively (Offodile 1984). The sedimentary succession of the Upper Benue Trough consists of Early Cretaceous continental classics and dominantly marine Late Cretaceous clastic and limestones formed during the latter three principal tectonic-sedimentary phases of Benue Trough development (Popoff 1988). The thickest sediments recorded in the Benue Trough were believed to have been deposited in rhomb grabens or pull-apart basins with sinistral strike-slip borders trending N40°E to N70°E ("Benue trend") and normal borders striking N120° to N160°E ("Chad trend") (Guiraud 1990).

The basic lithostratigraphic succession for the upper part of the Benue Trough, divided into Gongola Basin and Yola Arm with Lamurde-Lau Basin in-between (Fig. 1), was proposed by Carter et al. (1963), modified by Popoff et al. (1986), then Obaje et al. (2004) and Samaila et al. (2008) (Fig. 2).

The sedimentary succession of the Upper Benue Trough consists of Early Cretaceous continental clastic of the Bima Group deposited directly on the Precambrian basement floor and an overlying, dominantly marine Late Cretaceous series.

The Bima Group is usually divided into the Lower (1), Middle (2), and Upper Bima (3) Sandstone formations (e.g., Carter et al. 1963, Guiraud 1990, Zaborski 1998), however, some authors suggested dual division into the Lower and Upper Bima Sandstones (Tukur et al. 2015). Despite the structural and textural differences between the particular units, the deposited material originated from eroded crystalline/granitic foundation, as shown in the results, the Bima Formation is in general feldspathic (Carter et al. 1963).

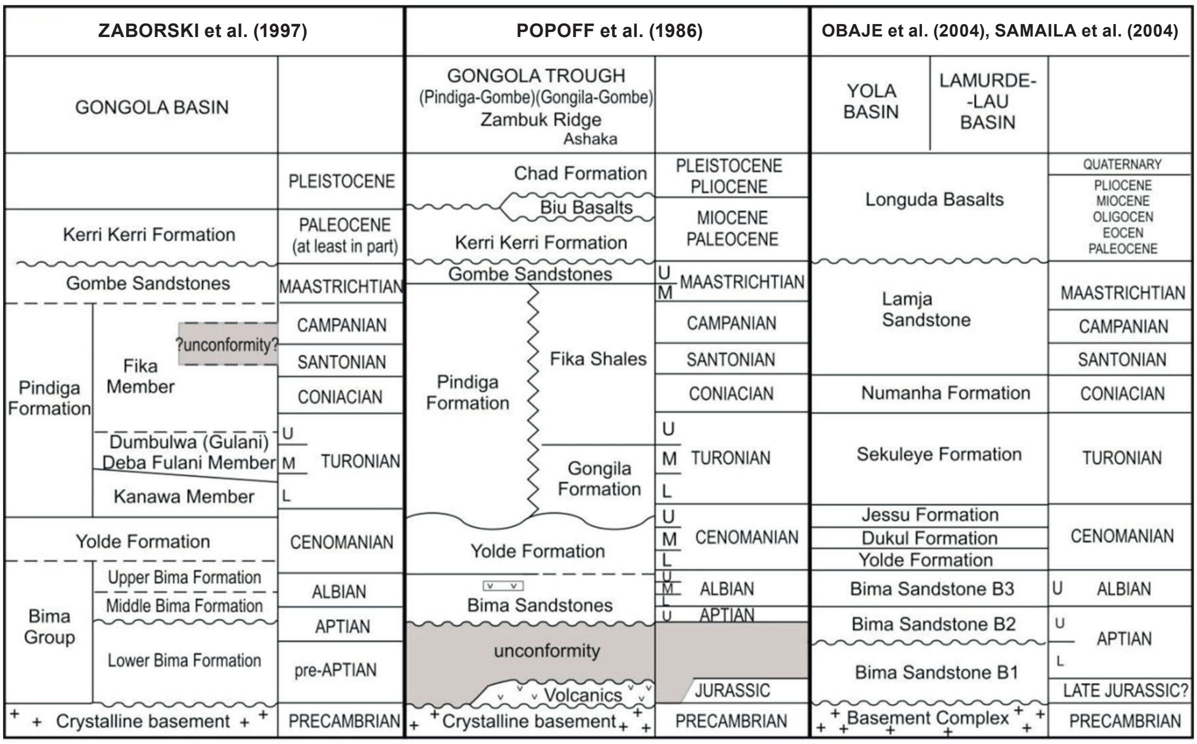

***Fig. 2.** Lithostratigraphic subdivision of the Upper Benue basins as proposed by Popoff et al. (1986), Zaborski et al. (1997), Obaje et al. (2004), and Samaila et al. (2008)*

The mineralogical composition of the Bima Formation (general) from Yola Basin consists of quartz (averagely 66.6%), feldspars (21%), and rock fragments (12.4%) (Overare et al. 2015). However, the lithological characteristics of Bima rocks are highly variable as the depositional environments were different in different parts of the sedimentary basins and were changing over time. The Lower Bima is a highly variable unit, from 0 to over 1500 m thick, mainly coarse-grained, forming fanglomerates deposited in an early, syn-rift phase of deposition. Furthermore, it reveals a grading up to sandstones intercalated locally with fine-grained material, deposited in a braided river environment. Between Bima (1) and Bima (2–3), a regional separating unconformity has been distinguished. The Middle Bima unit includes tabular cross-bedded sandstones formed as fining- upward sets of 5–10 m thick, sometimes with clay and palaeosols at the top of each set. The uppermost Bima (3) consists of fine to coarse-grained sandstones formed in sets, up to a few meters in thickness, characterized by tabular, convolute, and overturned cross-bedding (Guiraud 1990, 1991, Zaborski 1998.

Bima Formation is overlain by Cenomanian continental to marine Yolde Formation, usually described as a “transition” unit. It consists of sandstones, usually deposited as thin cross-bedded and ripple-bedded layers, intercalated with sandy mudstones and shales, in upper parts of the series – calcareous sandstones and shelly limestone (Carter et al. 1963, Zaborski 1998). According to Sarki Yandoka et al. (2015) Yolde shales contain quartz as a dominant mineral (about 50–61%) and kaolinite, glauconite, montmorillonite, pyrite, illite, chlorite, hematite and calcite. The Yolde Formation represents an initial phase of Late Cenomanian to Early Turonian transgression. The signs of following transgressive and regressive episodes are observed within subsequently deposited formations: marine Turonian to Campanian Pindiga subdivided into Kanawa, Deba Fulani, Dumbulwa, and Fika Members in the Gongola subbasin (Zaborski 1998) and their lateral equivalents in Lau-Yola sub-basins: the Dukul, Jessu and Sekule, Numanha and partly Lamja Formations. The Maastrichtian Gombe Sandstone and Santonian-Maastrichtian Lamia Sandstone were deposited at the top of the Upper Cretaceous succession. These marine units are represented by alternating shales, siltstones, mudstones, sandstones, and limestone; additionally, within Numaha members the signs of lava flows were found (Carter et al. 1963, Whiteman 1982, Zaborski 1998). The Paleocene Kerri-Kerri Formation ended the deposition in the west portion of the Gongola sub-basin. During the Cretaceous tectonic and sedimentary development of the basins, several magmatic/volcanic episodes took place in the Upper Benue Trough. The first is dated on Late Jurrasic to Albian (Coulon et al. 1996), then in Santonian times andesitic volcanism and granodioritic intrusions affected the Yola and Gongola sub-basins (and other parts of Benue Trough) (Whiteman 1982), finally, the Cenozoic volcanism affected Cretaceous formations as in Biu and Longuda areas.

In the study area, which covers the land of mud volcanoes occurrence to the north-west, west, and southwest of Kaltungo inlier, only the Bima Sandstone, Yolde, and Pindiga Formations were found and mapped (Benkhelil 1985, Guiraud 1989, Musa et al. 2015). The geology of the area is shown on the map in Figure 3. The Upper Bima outcrops cover the central, northeastern, and southern portions of the area. Towards the south of Todi, the Upper Bima Sandstone is characterized by tabular cross-bedded sandstone. The Yolde Formation constitutes about 30% of the study area, outcropping in the central, southwestern, northwestern, and southern portions. The Kanawa Member of the Pindiga Formation constitutes less than 15% of the study area and is restricted to the north-western portion. This unit usually forms flat topography, characterized by dark clays with blocks of fossiliferous limestone. Most often, the upper surfaces of the limestone show Thalassinoides burrows. In addition to the sedimentary rocks, there are dark-colored basalts that intruded in most cases into the Bima Sandstone and Yolde Formation. In topography, they form prominent hills in the study area and are of Neogene to Quaternary age (Zaborski et al. 1997). The model of geological structure known from previous works and shown on the map in Figure 3 has been supplemented by the location of mud volcanoes fields described for the first time by Musa et al. (2014).

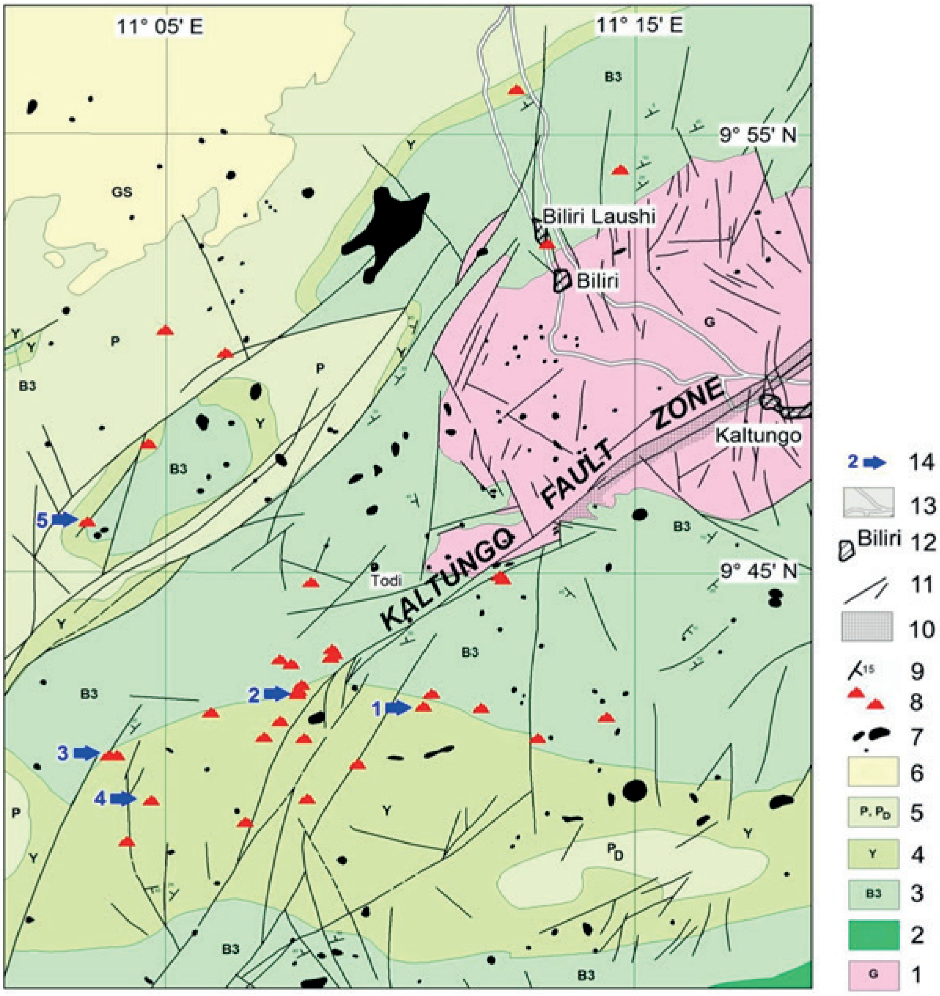

Fig. 3. Geological map of the part of Upper Benue Trough, southwest from Kaltungo inlier (modified after Benkhelil, 1985) with the location of the mud volcano fields: 1 – Precambrian basement (mainly granites) of Kaltungo inlier, 2 – Middle Bima Sandstone (Middle Aptian), 3 – Upper Bima Sandstone (Upper Albian), 4 – Yolde Formation (Cenomanian), 5 – Pindiga Formation (Turonian-Santonian), PD – Dukul Formation (the lowest member of Pindiga Formation, Turonian), 6 – Gombe Sandstone (Maastrichtian), 7 – Neogenic volcanic, 8 – mud volcano fields, 9 – dip and strike of beds, 10 – mylonites, cataclastic in the main fault zone, 11 – faults, 12 – major settlements, 13 – main roads, 14 – sampling sites described in Table 1

Table 1
Characteristics of the sampled mud volcano fields with numbers shown on the geological map in Figure 3

Sample	Name of site	Geographic coordinates	No. of cone in volcano field	Physical feature *D* – diameter at base [m] *H* – height of cone [m]
1	Lashadar saprolite Lashadar mud slurry	N09°41'51.7", E11°10'29.3" N09°41'55.6", E11°10'29.7"	11	*D*: 1.0–3.5 *H*: 0.1–0.2
2	Lakaturu saprolite Lakaturu mud slurry	N09°42'08.7", E11°07'44.4" N09°42'12.4", E11°07'42.8"	15	*D*: 0.5–2.5 *H*: 0.2–0.4
3	Pamadu mud slurry Pamadu saprolite	N09°40'44.4", E11°03'56.2" N09°40'49.6", E11°03'56.2"	27	*D*: 1.5–5.2 *H*: 0.2–0.6
4	Jenye saprolite Jenye mud slurry	N09°39'48.3", E11°04'39.7" N09°39'47.4", E11°04'39.6"	11	*D*: 1.8–4.5 *H*: 0.6–0.8
5	Kurum saprolite Kurum mud slurry	N09°46'15.1", E11°03'04.4" N09°46'16.5", E11°03'06.1"	21	*D*: 0.8–1.0 *H*: 0.2–0.6

MATERIALS AND METHODS

A total of ten samples, one each from dry mud and overburden material selected from five fields of onshore mud volcanoes were sent for XRD laboratory analysis at the Faculty of Earth Sciences, University of Silesia, Poland. The sampling sites are shown in Figures 4 and 5. Furthermore, some physical features of sampled mud volcano fields are presented in Table 1 as well.

The X-ray diffraction (XRD) was obtained using a Panalytical X'Pert PRO MPD PW 3040/60 diffractometer with filtered Cu-Kα radiation ($\lambda = 1.542$) operating at a beam voltage and current of 45 kV and 30 mA respectively. The XRD patterns were recorded in the range of $2\theta = 2.5–65°$ using a step size of 0.008° and scan step time of 200 seconds. The resultant XRD spectra were then analyzed with the aid of expert hgh-score plus software. Also, the analysis of the five samples of dry mud and five samples of the overburden was conducted at room temperature.

Fig. 4. *Mud volcanoes at various sampling sites*

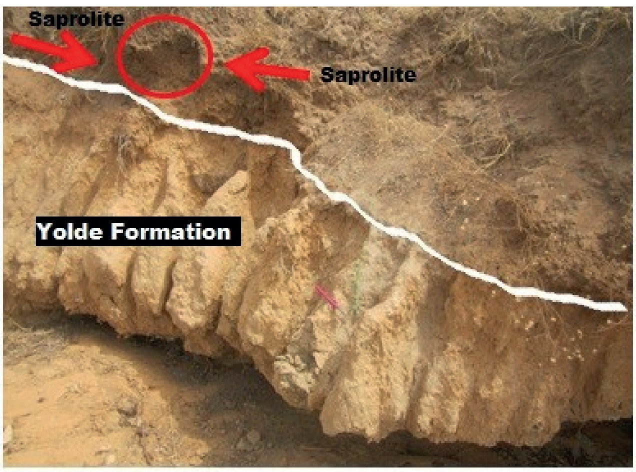

Fig. 5. *A sample of saprolite taken along a river channel at Lakaturu (N09°42'08.7", E11°07'44.4")*

RESULTS AND DISCUSSION

XRD results shown in Figures 6–10 revealed that the dry mud from the mud volcanoes and the saprolite from surrounding areas are composed mainly of quartz, kaolinite, and microcline. Also, other clay minerals (mixed-layer smectite-illite) were noticed in most of the samples. Furthermore, traces of other minerals including different types of feldspars, goethite, and evaporites were present.

Lashadar saprolite and mud slurry

The Lashadar saprolite (Fig. 6) is dominated by quartz (90% ±3%). In addition, there are other minerals: microcline (5% ±1%) and kaolinite (3–4% ±1%). The rest of the composition constitutes traces of evaporite minerals (less than 1%). There are trace amounts of smectites and illite, a very small amount of sodium feldspar (plagioclase variety). The mineral composition in the Lashadar mud slurry includes quartz (90.6%), microcline (5%), and kaolinite (3.5%). In addition, there is less than 1% of sylvite, with traces of barite (3.44 Å). There is a small quantity of the smectite-illite packages as well. Kaolinite and microcline occur in very similar quantities in both samples while traces of barite are only found in the mud slurry in low concentrations.

Lakaturu saprolite and mud slurry

The Lakaturu saprolite (Fig. 7) shows the following minerals: quartz (approx. 40%) and a relatively large amount of potassium feldspars: microcline (27%), orthoclase (24%). In addition, kaolinite (approx. 8%) has been detected. Different silica types are also present: cristobalite and tridymite (4.034 Å) (approx. 2%). On the diffractograms, these types of silica are represented by clear but much lower than ordinary quartz peaks. In the sample traces of evaporite minerals (3.107 Å) occur. There may also be a trace amount of calcite. The flat bulge at the beginning of the diffractogram (Fig. 6) shows the range of 11–15 Å and it indicates the presence of disordered clay minerals, arranged in a mixed-layered structure (smectite-illite). In the Lakaturu mud slurry (Fig. 6), quartz content is approximately 65% and a large content of feldspars is 25% including microcline (17%) and orthoclase (8%); there is also a significant amount of kaolinite (11%).

Just as in the other samples, on the left side of the diffractogram there is a bulge observed in the range of 10–12 Å, indicating the presence of clay minerals (illite-smectite). Reflection 3.07 Å is evidence of sylvite admixture with trona. In addition, 3.07 and 2.64 Å reflections indicate the presence of trona mineral – approx. 1% by weight.

Pamadu mud slurry and saprolite

In the Pamadu saprolite (Fig. 8) the mineral composition is dominated by quartz (approx. 87%), feldspars (mainly microcline – 11%), clay minerals (1.5%), and traces of sylvite or barite. In the Pamadu mud volcano slurry, the mineral composition is dominated by quartz (72%), potassium feldspars (approx. 16%), clay minerals: kaolinite (11%) and signs of disordered, mixed-layered clay minerals (smectite-illite), as well as reflections of goethite (1–2%).

Jenya mud slurry and saprolite

In the Jenye saprolite (Fig. 9) there is quartz (approx. 91%), the other minor minerals include microcline (8%), as well as small amounts of kaolinite and mixed-layered other clay minerals (illite-smectite).

The Jenye mud slurry (Fig. 9) is dominated by quartz (89%). Also present are microcline (6–8%), kaolinite (2–3%), and a small quantity of illite and smectite packages. The quantities of kaolinite and microcline are similar both in saprolite and mud volcano slurry; the clay mineral association in the overburden material is also similar to that from the mud volcano.

Kurum saprolite and mud slurry

The Kurum saprolite analysis (Fig. 10) revealed the following minerals: quartz (87%), feldspars (8%), and kaolinite (5%). There are very small amounts of other minerals such as smectite-illite association and traces of evaporite minerals. The mineralogical composition of the mud volcano slurry (Fig. 10) shows the following minerals: quartz (62%), kaolinite (18%), high content of microcline (16%), muscovite (1–3%), and a lot of mixed-layered clay minerals (illite-smectite).

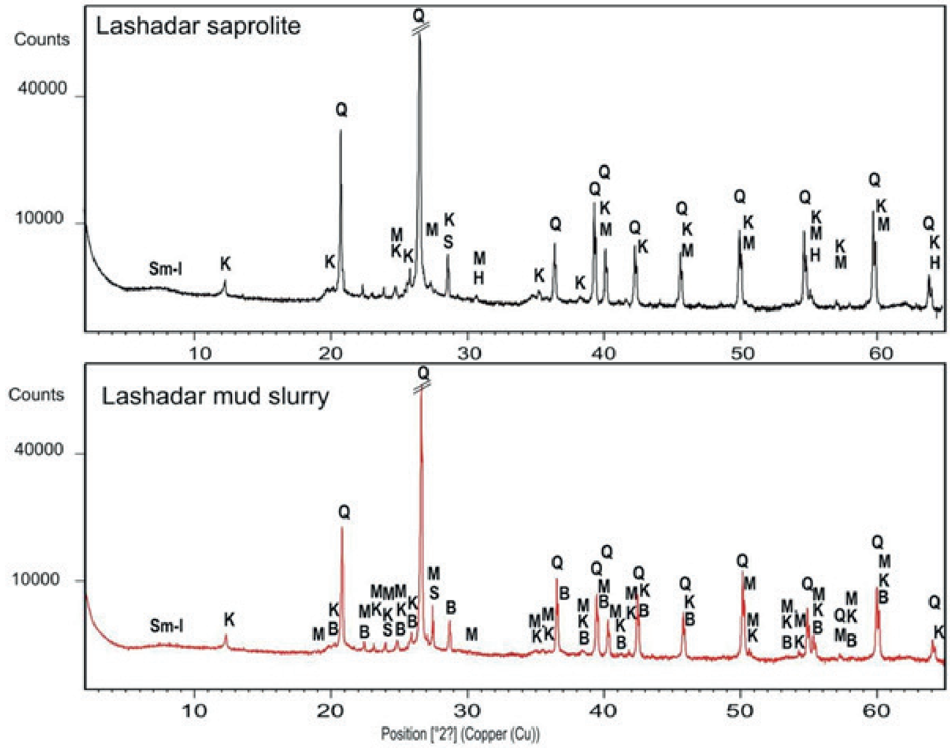

Fig. 6. *Measured XRD pattern (diffractogram) showing minerals from mud volcanoes and saprolite at Lashadar: Q – quartz, K – kaolinite, M – microcline, B – barite, Sm-I – smectite and illite*

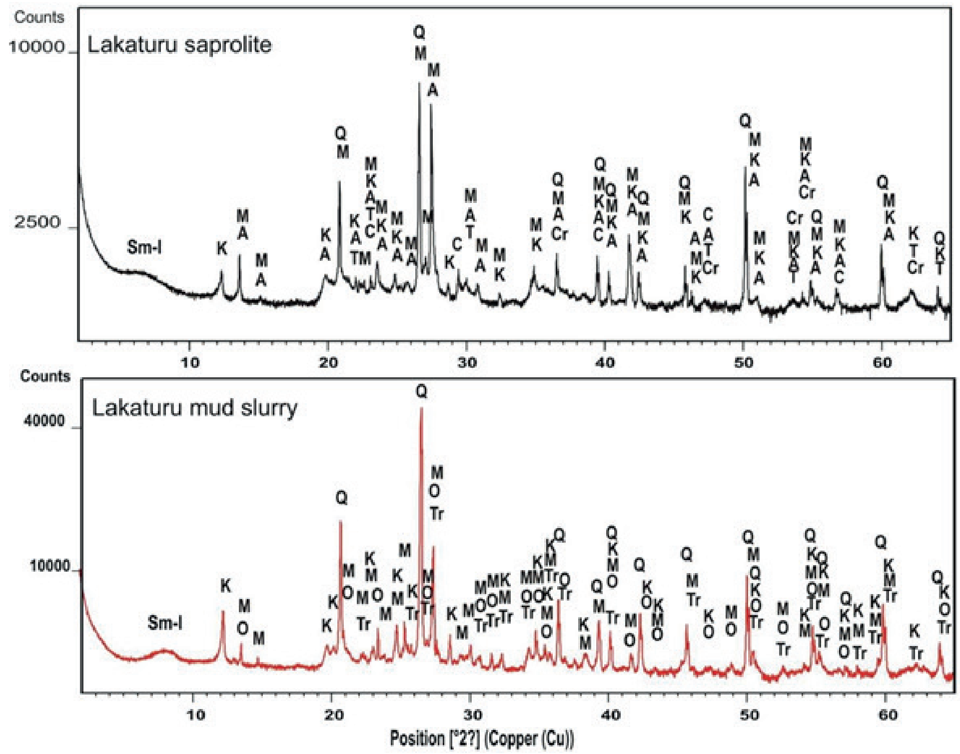

Fig. 7. *Measured XRD pattern (diffractogram) showing minerals from mud volcano and saprolite at Lakaturu: Q – quartz, K – kaolinite, M – microcline, O – orthoclase, T – tridymite, C – calcite, Cr – cristobalite, Tr – trona, Sm-I – smectite and illite*

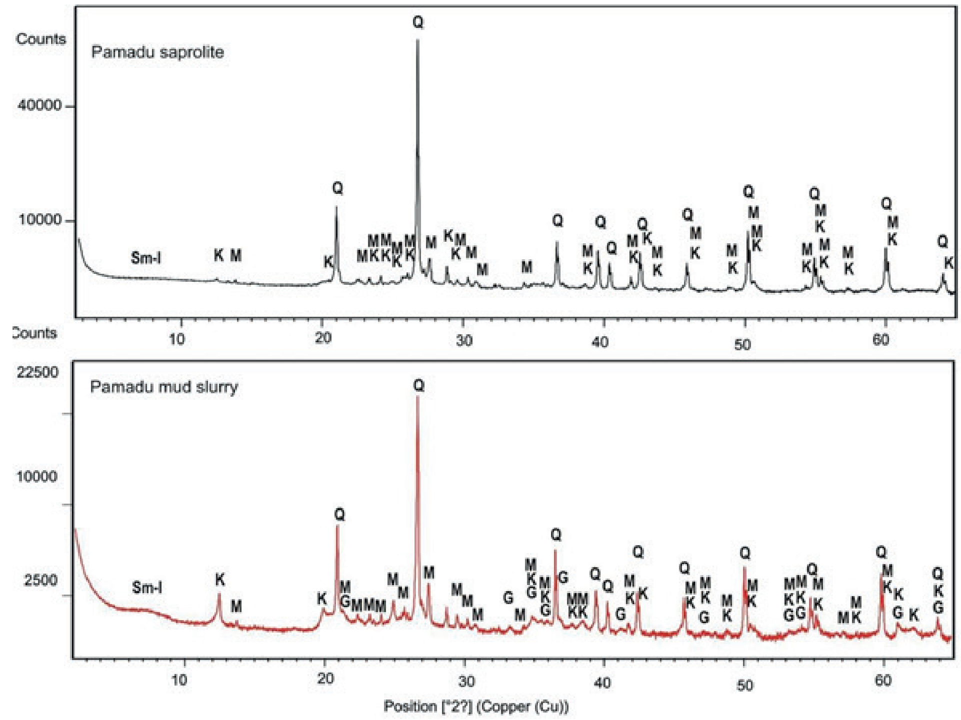

__Fig. 8.__ Measured XRD pattern (diffractogram) showing minerals from mud volcanoes and saprolite at Pamadu: Q – quartz, K – kaolinite, M – microcline, G – goethite, Sm-I – smectite and illite

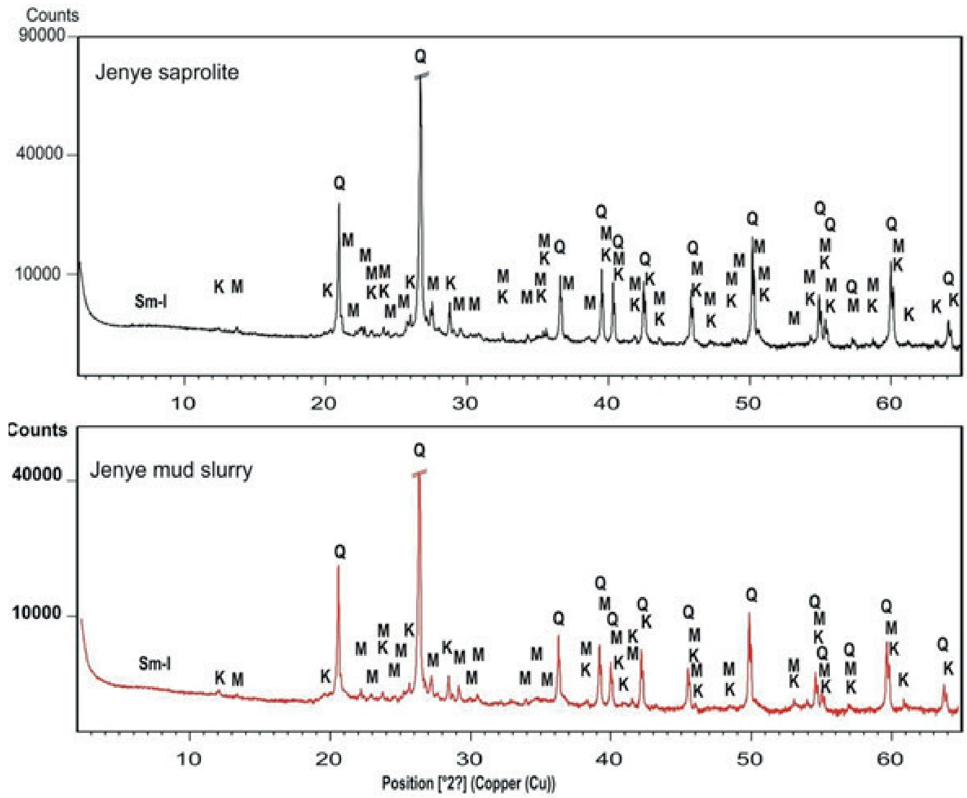

__Fig. 9.__ Measured XRD pattern (diffractogram) showing minerals from mud volcanoes slurry and saprolite at Jenye: Q – quartz, K – kaolinite, M – microcline, Sm-I – smectite and illite

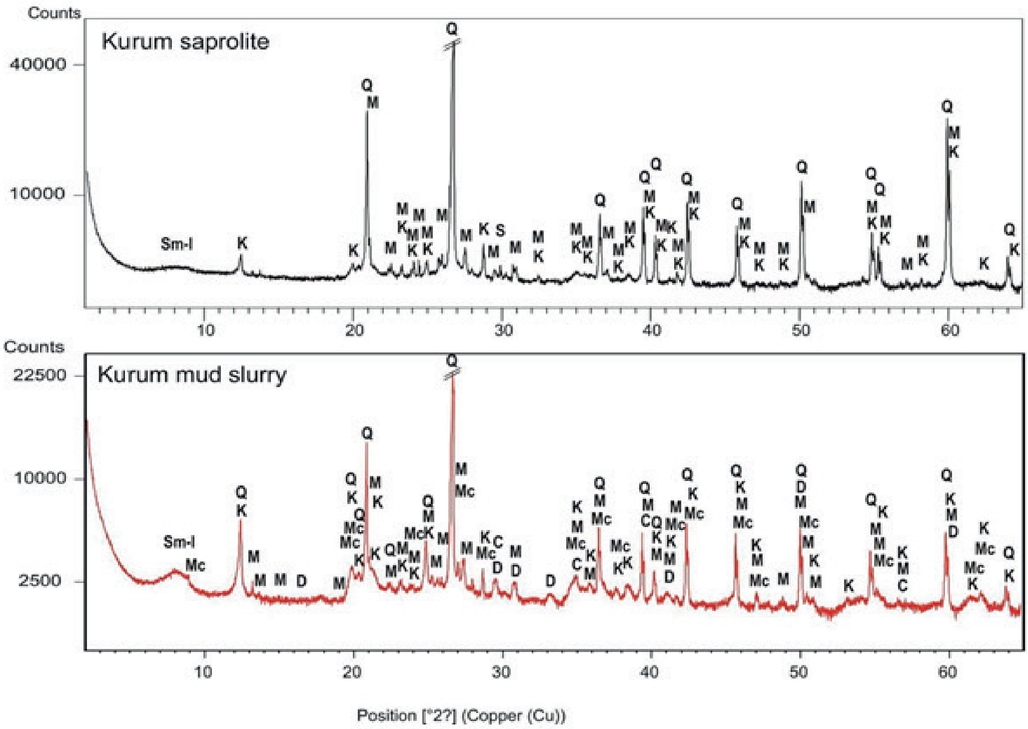

Fig. 10. *Measured XRD pattern (diffractogram) showing minerals from extruded mud and saprolite at Kurum mud volcano field: Q – quartz, K – kaolinite, M – microcline, C – calcite, D – dolomite, Mc – muscovite, S – sylvite, Sm-I – smectite and illite*

In addition, there is the presence of dolomite (1.6%), a trace amount of calcite (max. 1%), and a very small amount of sodium feldspar (plagioclase).

The high content of quartz in all samples – both the saprolite and the mud slurry – is an indication of the high content of quartz in the primal rock from which the mud slurry or saprolite originated. The high percentage of quartz is also a consequence of the fact that it is the most resistant to weathering, so it is durable in the environment. In most of the samples, the amount of quartz is about 60–90 %, with the Lakaturu mud slurry being an exception (40%). Feldspars and mica usually weather to clay minerals like kaolinite, smectite, and illite under humid and warmer conditions. This chemical weathering proceeds very rapidly with the removal of cations from feldspars through rapid leaching and subsequent formation of kaolinite (Cita et al. 1981). Kaolinite is one of the most common soil-derived clay minerals which can form under intensive, tropical weathering conditions within 50 years. All the samples analyzed contain feldspars and clay minerals, albeit in different proportions; their amount ranges between 5–25% of feldspars in volcano slurry and 5–51% in saprolite, 1.5–20% of clay minerals (kaolinite and smectite-illite) in volcano slurry and from less than 1–11% in saprolite. The difference in the minerals content may reflect different stages of alteration of feldspars into clay minerals as well as results of the external factors influence on the weathering material (rain, flowing water transport, wind). The other minerals found in some of the samples are represented by very small or trace amounts. The presence of traces of calcite, dolomite, or evaporites could suggest a marine origin which further provided a clue to the transitional nature of the formation from which the extruded mud originates. The traces of trona mineral in mud slurry from Lakaturu site are an indication of non-marine evaporation. On the other hand, the occurrence of sylvite or barite in the same sample might be the indication of ancient hydrothermal activity in that area; this hypothesis might be supported by the presence of traces of cristobalite and tridymite which may originate from hydrothermal phenomena connected to the tectonism of the Kaltungo fault zone.

The last mineral found in very small quantities is goethite (in Pamadu saprolite). Goethite is a common product of weathering from other minerals containing iron in a tropical climate. It occurs in Nigerian residual soils quite often and might be a sign of transition zone from saprolite to laterite – the parts of the typical profile of tropical weathering cap rock. Considering the qualitative and quantitative difference of mineral composition in paired samples it can be observed that in the case of Lashadar and Jenye the volcano mud slurry is very similar to the saprolite, not to say that almost the same. Hence it can be stated that the mud slurry originates from the surface weathered zone which is probably not thicker than 100 m, so the mud volcano's roots are not deeper than this. At the remained sampled sites there are no significant differences between mud slurry and saprolite and the major mineral components are quartz, feldspars, kaolinite; the paired samples differ in the content of trace amounts of carbonates, evaporates, and goethite. There are no drastic differences in mineral composition which could suggest that mud volcano slurry originates from the deeper, different beds (e.g., shale, as it is known from larger and deeper mud volcanoes and diapirs worldwide). In the tested samples, the content of minor components, as well as slight differences in the number of main components, could be explained by the zonation of the weathered mantle, which may result from both bedding of weathered rock and the influence of external factors in the weathering and erosion processes and after that. Thus, the source of material extruded from mud volcanoes can still come from the weathered layer of soft overburden.

There is one pair of samples, from the Lakaturu area, which is slightly different quantitatively from the remaining tested samples; their composition is characterized by less quantity of quartz and a much higher content of feldspars in both samples tested. The location of the Lakaturu mud volcano field within the south-western portion of the Kaltungo fault zone may be a reason for some mineral alterations; on the other hand, the tested material can originate from weathered Bima or Yolde bed zonally enriched with feldspars.

CONCLUSIONS

Results of the X-ray diffraction analysis on the clay extruded from the onshore mud volcanoes in the Upper Benue Trough show the presence of quartz, kaolinite, and other clay minerals like mixed-layered smectite-illite associations, microcline, orthoclase and traces of barite, marine minerals, such as calcite, dolomite and evaporate minerals (sylvite, halite, and traces of trona). A composition of saprolite from the sampled sites includes minerals such as quartz, kaolinite, smectite-illite associations, feldspars, and traces of calcite, goethite, and evaporate minerals (sylvite, halite).

The onshore mud volcanoes documented in the Upper Benue Trough are located within the Albian to Cenomanian Upper Bima or Cenomanian transitional Yolde Formation outcrops. The presence of traces of marine minerals (evaporites, carbonates) in both saprolite and mud slurry samples from Kurum, Lashadar, and associated minerals, as well as non-marine minerals in the extruded mud, reveals that the clays are mostly from the transitional Yolde Formation, a unit between the underlying Albian continental Bima Sandstone and the overlying Late Cenomanian to Early Turonian Marine Pindiga Formation. Also, since there are no significant differences in terms of mineral composition between mud volcano clays and the soft overburden samples from mud volcano's surroundings, it can be concluded that parent beds for the mud volcanoes material can be rather shallow depths, being a part of a surface weathered zone.

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