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Chapter

Is a Volcanic Eruption Possible in Nigeria?

Uriah Lar, Isah Lekmang, Cedric Longpia and Mohammed Tsalha

Abstract

The Jos and Biu Plateaux volcanic provinces occupy the northeastern half of Nigeria bordering the Cameroon Volcanic Line, dotted with conspicuously visible number of dormant volcanoes with no reported activity. These dormant volcanoes represent potential future eruption sites. The ejecta materials of these volcanoes are essentially basaltic in composition and consist of sequence of pyroclastic materials, basalts, scoria and ash and are formed by strombolian and effusive styles of eruption. The volcanoes are represented by well-preserved cones and lava flows. In places the lava flows have been lateritized and eroded leaving remnants of weathered basalt boulders and a number of plugs and dome-like outcrops lacking any preserved cones. The basalts display essentially similar compositions consisting of phenocrysts of both olivine, plagioclase (bytownite–labradorite), with minor pyroxene (diopside-augite) embedded in a groundmass of plagioclase laths (labradorite), and accessory magnetite, ilmenite, k-feldspars, and volcanic glass. Geochemical data shows that these basalts are mainly alkaline olivine basalts derived from the deep mantle source enriched in incompatible elements similar to that of the Ocean Island basalts (OIB). Preliminary $^{40}$Ar-$^{39}$Ar ages on the some of the basalts revealed Quaternary ages (Pleistocene epoch). The significant change in the composition of the Pidong Lake marked by decreasing pH is indicative of a probable input of juvenile fluids into the Lake. Also, the several incidences of volcanic eruptions along the close-by Cameroon volcanic line are pointers to the possibility for the reactivation of any of the dormant volcanoes in Nigeria. This work focuses on the need to assess the hazard level of some of these volcanoes for effective monitoring, disaster preparedness and land use planning as more people live and farm in these potentially endangered volcanic prone areas, unaware of the inherent risk.

Keywords: volcanoes, eruption, Jos Plateau, Biu Plateau, Nigeria

1. Introduction

An inventory of all the volcanic prone areas on the Jos and Biu Plateaux were carried out, followed by detailed update of the Geology of two major volcanic areas on the Jos Plateau volcanic provinces (Kassa and Kerang volcanoes). The geochemistry (major, trace and REEs compositions) of these volcanoes were determined and a few dating using $^{40}$Ar-$^{39}$Ar technique were performed on the Kassa basalts. Hydrogeochemical investigations of the Pidong Volcanic Crater Lake have also been carried out to constraint the chemical element sources into the Lake. Also, $^{40}$Ar-$^{39}$Ar
dating of the basalts of the Kassa volcanic field has revealed young ages spanning from 2.5, 1.97, 1.66, 1.39 to 1.34 Ma confirming the recent but short interval and multiple successive episodes of eruptions associated with volcanic activity in the region. Similar ages in the range of 2.1–0.9 Ma have been reported from basaltic rocks from the Benue Trough and a dolerite dyke from the region [1]. These same range of ages (of 2.83–0 Ma) have been obtained on basaltic rocks from the near-by Cameroon Volcanic Line (CVL) [1]. The Jos Plateau basalts vary in composition from basalt proper to trachyandesitic varieties of alkaline basalt magma series and some tholeiitic affinity [2]. Contrarily to the general notion that volcanoes are only associated with plate margins alone, the volcanoes in Nigeria are emplaced within the continent, associated with mantle Hot Spots. Records of gas emissions at Lakes Monoun and Nyos in Cameroon Republic in 1984 and 1986 respectively destroyed
lives and properties within 14 km radius to a large extent, affected some commu-
nities in Nigeria (Mambilla Plateau and Katsina-Ala River banks) [3]. This research
tries to provide answers as to whether it is possible that the dormant volcanoes
in Nigeria with no recorded history of eruption could roar back to life? Some
reported successive minor volcanic activities within the Cameroon Volcanic Line
(CVL) (1909, 1922, 1954, 1959 and 1982) are pointers to the possibility of the
reactivation of some dormant volcanoes in Nigeria.

2. Geologic settings

An understanding of the geology is important in studying natural hazards
related to volcanism because the geology influences tectonic movement which leads
to the disequilibrium of the ecosystem and other environmental components.

The Nigeria-Cameroon Volcanic Provinces lie within the Pan-African collision
belt of West Africa (Figure 1). In Nigeria, the volcanic provinces (Jos Plateau, Biu
Plateau, Benue Valley, etc.) are confined to the northeastern and central regions
[4]. The volcanic provinces are characterized by numerous volcanic cones and lava
flows consisting of alkaline olivine basalts together with less important trachyte and
phonolite intrusive rocks [5].

Apparenty, the large volcanic province of Nigeria suggests that volcanic activity
during the Quaternary, was intense on the Jos Plateau, the Benue trough and along
the northeast to southwest Cameroon line. Like the Jos Plateau volcanic regions,
most of the main volcanic provinces such as the Bamenda Highlands, the Mambilla
Platue and the Adamawa Plateau are characterized by basement uplift [5].

The Cameroon Volcanic Line which extends from the Gulf of Guinea, Island of
Annobon, Sao Tome and Principe and Fernando Po splits into two branches, one
extending into northern Nigeria forming the Biu Plateau while the other extending
eastward forming the Ngoude Plateau of Eastern Cameroun (Figure 1). Thus, in
Nigeria, the volcanic provinces occur as relicts of volcanism in the form of scattered
volcanic plugs and cones in some cases [5]. On the relatively uplifted Jos Plateau
region, volcanic rocks are represented by volcanic cones and calderas [2].

Some of these cones generally rise only few hundred meters above the Plateau
surface and are steep-sided with a central crater which may measure up to 450 m
usually emerging at a breached in the crater wall. They are mainly built of basaltic
scoria, volcanic ash, lava and with some variety of inclusions.

3. Materials and methods

3.1 Field mapping

Reconnaissance visits were carried out to past volcanic eruption sites where a
careful and systematic mapping of each of the volcanoes visited were carried out so
as to determine its nature, size and composition. Other information acquired was
their physical surface weathering features, morphology, outcrop patterns and the
extent of vegetation cover.

3.2 Petrographic and geochemical studies

Rock samples were collected for petrography, geochemistry and geochronology.
Both petrographic and geochemical studies were done in the Department of
Geology, University of Jos, Nigeria. $^{39}$Ar-$^{37}$Ar dating on the basalts was done in
Netherlands, Geological Survey Laboratory. For quality control, a duplicate geochemical analysis on the same basaltic rocks was carried out at the University of Cardiff, Wales using the Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES).

3.3 Hydrogeochemical monitoring study

A constant monitoring of the Pidong Crater Lake through continuous water sampling 24–36 calendar months was done. The following physical parameters were recorded in the field using MT 806/pH/EC/TDS/Temp portable meter (pH, Temperature, Electrical Conductivity (EC), Total Dissolved Solids (TDS)). The water samples were collected in 100 ml polyethylene plastic bottles for cations and anion analysis. The sample for cations analysis was acidified with 0.1 M Nitric acid to prevent precipitating and bacterial growth. The following cations: Mg, Ca, Na, K, Cr, Ni, Co, Sc, V, Cu, Pb, Zn, Bi, Cd, Sn, W, Ma, As, Sb, Rs, Cs, Ba, Sr., Ga, Li, Ta, Nb, Hf, Zr, Y, Th, U, B, Fe & REEs were analyzed using ICP-MS method at Bureau Veritas Minerals Laboratory Limited, Canada while the anions: SO$_4$, Cl, HCO$_3$, NO$_3$, F, Br and PO$_4$ were carried out using colometry method at Maxxam Laboratory, Vancouver, Canada (subsidiary of Bureau Veritas Ltd).

3.4 Isotope study

Oxygen-18 ($\delta^{18}$O) and deuterium ($\delta^2$H), and ($\delta^3$H) and Carbon-14 ($^{14}$C) isotopes of the Pidong Crater Lake, Bwonpe Volcanic Spring and rainfall were analyzed at Activation Laboratory Ontario, Canada using cavity Ring down spectroscopy (CRDS) model L11 02-1 California, USA with V-SMOW standards with typical standards deviation for $^{18}$O ± 0.1% and 1% for Tritium unit (TU).

4. Field investigations

Field investigations have revealed the existence of about 22 dormant volcanoes on the Jos Plateau region alone (Table 1) and are generally aligned in series of NNW–SSE trend [6–8] (Figure 2). None of these volcanoes have record of any activity in recent past [8, 9]. They are composed mainly of basaltic scoria and pyroclastic materials.

Tables 1 and 2 present the inventory of the dormant volcanoes on the Jos Plateau and the Biu Plateau, respectively. From the NNW end are the Ganawuri volcanic line, Hoss volcanic line, Panyam (Sura) volcanic line and Gu (Jiblik) volcanic line (Figure 2). The Ganawuri line comprises from the north to south of the Bum, Jal, and Kwakwi volcanoes. The Hoss volcanic line consists of two volcanoes; Miango in the north and Hoss volcano in the south. The Miango line consists of five volcanoes from the north to the south viz.: Rukuba, Miango north, Miango south, Vom and Kassa volcanoes. The Southern-most end members are namely the Panyam and Gu volcanic lines. The Panyam volcanic line consists of seven volcanoes aligned in a NNE–SSW trending directions along a hypothetical fracture line [6, 10]; Dai volcano (referred to as Wushik volcano), Amshel volcano (referred to as Kugol volcano), Dutsin volcano, Kerang volcano, Tingyaras volcano, Ampang volcano (referred to as Mufil volcano), Pidong Crater Lake.

The Kerang twin volcanoes are located at Kerang town and its environs in the present Mangu Local Government Area, about 120 km from Jos, Plateau State (Figure 1). The Kerang I (Dustin) volcano has a peak of 1456 m above sea level and a crater diameter of 300 m. The volcanic pile consists of ash, lapilli, scoria, pumices,
| S. No. | Name/ locality          | Coordinates | Estimated population of people at risk | Type of volcano | Diameter of crater | Elevation (ASL) | Materials deposited                                      |
|-------|-------------------------|-------------|----------------------------------------|-----------------|--------------------|-----------------|----------------------------------------------------------|
| 1     | Bum                     |             | 200,000                                | Cone            |                    |                 | Basaltic                                                |
| 2     | Jal                      |             | 150,000                                | Cone            |                    |                 | Basaltic                                                |
| 3     | Kwalawi                  |             | 250,000                                | Cone            |                    |                 | Basaltic                                                |
| 4     | Miango volcano I         | N09° 51' 36.5" E008° 43.961" | For 1 & 2 250,000 | Cone           | 350 m              | 1297 m          | Scoraceous basalt/ pyroclastics                        |
| 5     | Miango volcano II        | N09° 51.05" E008° 44° 19.1" | Cone | 650 m              | 1303 m          |                 |                                                         |
| 6     | Kassa volcanoes          | Highest Peak: N09° 36° 11.9" E008° 53° 52.1" | 100,000 | Cluster (6 overlapping volcanoes) | Average 300 m | Average 1342 m | Olivine basalt, scoria, tuff, breccia/volcanic bomb    |
| 7     | Sha 1                    | N09° 10° 54.3" E008° 47° 95.5" | 20,000 | Dome               | 200 m             | 1310 m          | Pyroclastics (granite fragments/lava)                   |
| 8     | Sha 2                    | N09°10.846" E008° 48° 05" | 10,000 | Dome               | 200 m             | 1294 m          | Weathered basaltic materials capped by iron concretions |
| 9     | Passakai                 | N09° 10° 54.3" E008° 47° 95.5" | 10,000 | Dome               | 300 m             | 1375 m          | Lateritized                                             |
| 10    | Wushik (Lakas) volcano   | N09° 24° 165° E009° 10° 55.4" | 10,500 | Cone               | 250 m             | 1300 m          | Scoria/pyroclastics                                     |
| 11    | Kogal (Nyeis) volcano    | N09° 22° 57.3" E009° 11° 06.8" | 80,000 | Cone               | 250 m             | 1250 m          | Scoria/pyroclastics                                     |
| 12    | Kerang I                 | N09° 20° 286° E009° 11° 643" | 1 to IV put together 200,000 | Cone           | 600 m             | 1400 m          | Scoria/basaltic rocks with large phenocrysts of olivine, garnet and pyroxene |
| 13    | Kerang II                | N09° 20° 392° E009° 11° 502" | Cinder | Cone               | 1000 m            | 1450 m          | Scoria/basaltic rocks with large phenocrysts of olivine, garnet and pyroxene |
| 14    | Kerang III volcano (Swan junction) | N09° 20° 306° E009° 10° 56.1" | Cone | 1000 m            | 1486 m          |                 | Scoria/pyroclastics                                     |
| 15    | Kerang IV                | N09° 11° 283° E008° 12° 547" | Cluster (with 2 craters) | 1.5 km           | 1372 m          |                 | Pulverised basement and lava                           |
breccias, basalts, boulders, and pyroclastic materials of various sizes. The Kerang II (Kerang) volcano has three craters with a peak height of 1510 m above sea level with a crater diameter ranging from 600 m to 1 km (Table 1). This volcano (Kerang II) is the second largest volcano on the Jos Plateau compared to the Jiblik volcano which has a peak height of 1670 m above sea level. The volcanic pile of the Kerang II volcano is composed of ash, lapilli, scoria, breccias, bombs, basaltic boulders and pyroclastic materials (lapilli, granitic and lava flows).

The Pidong volcano (Maar) has a series of three craters and aligned along the general North-South trend of the Panyam Volcanic Line [10]. The Pidong Maar consists of a sequence of pyroclastic materials (mixture of large fragments of basement rocks/pyroclastics, scoria and ash) and indicative of violent eruption [9]. The Gu volcanic line consist of five volcanoes from NW to SW namely Jiblik, Kagu, Katul and Lagdak volcanoes. The volcanic cones are composed essentially of volcanic ash, lapilli, scoria, breccias, bombs, basaltic boulders and pyroclastic materials (lapilli, granitic and lava flows).

Also, the relatively large sizes of some of these volcanoes (Miango, Kassa, Jiblik, Kerang, etc.) suggest that quite a large volume of ejecta materials were spewed out covering quite a large landmass (valleys and low-lying plains) as lava flows. Lava flows apparently from the Jiblik volcanic can be traces to several kilometers south of the Jos Plateau escarpment. If any of these volcanoes erupt today with the same intensity and volume presumed, a large expanse of land would be buried and about 2 million people living around these volcanoes are potentially at risk.

The volcanoes of the Biu Plateau (Table 2) present similar physical and petrographic characteristics as those of the Jos Plateau region. The volcanoes also form near linear alignments from the north to the south and extend right through the low-lying Basement complex into the sedimentary formations of the Benue valley (Garkida-Gombi-Song areas in Adamawa State). The volcanoes are simple and never in clusters, but with very large craters of greater than 1 km, (Caldera). The volcanoes extruded directly the basement rocks and therefore are of lower

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**Table 1.**

*Inventory of the volcanoes of the Jos Plateau, Nigeria.*

| No. | Name/ locality | Coordinates | Estimated population of people at risk | Type of volcano | Diameter of crater | Elevation (ASL) | Materials deposited |
|-----|----------------|-------------|----------------------------------------|----------------|-------------------|----------------|---------------------|
| 16  | Pidong volcano | N09°17’650;E009°12’312’ | 50,000 | Crater Lake | 700 m | 1378 m | Scoria/ pyroclastics |
| 17  | Jiblik volcano | N09°16’591;E009°16’890’ | 100,000 | Cinder Cone | 1 km | 1228 m | Scoraceous basalt +garnet/ pyroclastics |
| 18  | Kagu volcano | N09°13’901;E008°16’383’ | 50,000 | Cone | 1 km | 1060 m | Scoraceous basalt/ pyroclastics |
| 19  | Katul volcano | N09°11’264;E009°15’795’ | 5000 | Cone | 700 m | 976 m | Scoraceous basalt/ pyroclastics |
| 20  | Lakdak | | 7000 | cone | | | Scoraceous basalt/ pyroclastics |

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**Forecasting Volcanic Eruptions**
altitude above sea level relative to those of the Jos Plateau, which extruded the already high-level Younger Granite bodies.

Also, unlike the volcanoes of the Jos Plateau, those of Biu Plateau are constituted by a large volume of volcanic ash and pyroclastic materials (for example, at Gwamya, Tilla Crater Lake, Gadam, Batadeka, Buratai, Katla volcanoes, etc.) ('Table 2'), suggesting that there was a tremendous spewing of ejecta materials (ashes and gases) into the atmosphere prior to the violent eruptions and/or in-between the eruptions.

5. Geochemical results and interpretations

The major and trace elements geochemical compositions of the basaltic rock samples collected from the various volcanic cones in the Jos Plateau volcanic
| S/No. | Name/locality                           | Coordinates                  | Estimated population of people at risk | Type of volcano | Diameter of crater | Elevation (asl) | Materials deposited |
|-------|-----------------------------------------|------------------------------|----------------------------------------|-----------------|--------------------|----------------|---------------------|
| 1     | Tasha Village                           | N10°17'388"E011°24'406"     | 5000                                   | Cluster of 3 volcanic cones | 50 m               | 426 m asl        | Massive basaltic rocks |
| 2     | After Tasha Village                     | N10°16'661"E011°27.143"     | 5000                                   | Dome            |                    | 427 m           | Massive/vesicular basaltic rocks |
| 3     | Tagwaye (twin volcanoes (In Kwaya Kusar LGA of Borno State)) | N10°30'530"E011°30'402"     | 15,000                                 | 2 Cones         | 200 m              | 512 m           | Olivine basaltis/Agglomerates. |
| 4     | Gadam Volcano (Kwayar Kusar LGA, Borno State) | N10°31'951"E011°53'485"     | 30,000                                 | Cone            | 250 m              | 479 m asl        | Olivine Basalt |
| 5     | Location 5                              | N10°30'.279"E011°50'.726"   | Inhabited Plug                         |                 |                    | 683 m           | Basaltic boulders/Agglomerates/tuff |
| 6     | Location 6                              | N10°30'.279"E011°50'.726"   | Inhabited Dome                         |                 |                    | 826 m           | Vesicular Basaltic boulders/Agglomerates/tuff |
| 7     | TUM                                     | N10°36'.254"E012°06'.564"   | 10,000                                 | Dome            | 643 m asl          |                | Scoraceous basalt with olivine/zeolite/Columnar basalt |
| 8     | Wakama (a) (BCG Village)                | N10°36'.472"E012°07'.126"   | 2500                                   | Cone            | 1 km               | 677 m           | Scoraceous basalt |
| 9     | Wakama (b)                              | N10°37'.211"E012°08'.886"   | 2500                                   | Caldera         | 10 km              | 701 m           | Scoraceous basalt |
| 10    | Gwamya Volcano                          | N10°33'.496"E012°06'.341"   | 6000                                   | Cone            | 500 m              | 752 m           | Scoraceous basalt/pyroclastic pile |
| 11    | Tilla Volcanic Hill                     | N10°32'.549"E012°08'.477"   | 2500                                   | Cone            | 500 m              | 910 m           | Scoraceous basalt/pyroclastic pile |
| 12    | Tilla Crater Lake                       | N10°32'.336"                | 10,000                                 | Caldera         | 2 km               | 751 m           | Scoraceous basalt/ |
| S/No. | Name/ locality | Coordinates | Estimated population of people at risk | Type of volcano | Diameter of crater | Elevation (asl) | Materials deposited |
|-------|----------------|-------------|---------------------------------------|----------------|--------------------|----------------|-------------------|
| 13    | Versu Volcano  | N10° 39.759' E012° 08.457" | 3000 | Seasonal Crater Lake | 700 m | 782 m asl | Olivine basalt |
| 14    | Dragna Volcano | N10°27.132’ E012° 05’.820” | 5000 | Caldera filled up by collapsed materials. | 3 km | 750 m asl | Weathered scoraceous basalt Basalt |
| 15    | Marama Volcano | N10° 27.746’ E012° 09’.093” | 150,000 | Cone | 1 km | 735 m | Scoraceous basalt/ pyroclastics |
| 16    | Gwaram volcanic hill | N10° 39’.214’ E012° 09’.092” | 8000 | Cone | 1 km | 942 m | Boulders of scoraceous basalt |
| 17    | Batadeka (i) Volcanic hill | N10° 41’.673’ E012° 07’.707” | 3000 | Cone | 700 m | 884 m | Weathered scoraceous basalt |
| 18    | Batadeka (ii) Volcanic hill | N10° 42’.067’ E012° 07’.542” | 3000 | Cone | 1 km | 1053 m asl | Weathered scoraceous basalt |
| 19    | Kwatla Crater Lake | N10° 42’.117’ E012° 06’.433” | Inhabited | Seasonal Crater Lake | 1.5 km | 752 m asl | Weathered scoraceous basalt |
| 20    | Maldau | N10° 43’.500’ E012° 06’.979” | Inhabited | Cone | 350 m | 907 m asl | | |
| 21    | Buratai Volcanic Hill | N10° 53’.926’ E012° 02’.800’ | 5000 | Dome | 700 m | 718 m asl | Weathered scoraceous basalt/ pyroclastics |
| 22    | Kona Uku Volcanic hills | N10° 49’.814’ E012° 07’.062” | 10,000 | 3 Cones clustered together | 2 km | 879 m asl | Weathered scoraceous basalt/ pyroclastics |
| 23    | Dutsen Kura (Bogur) Volcanic hill | N10° 49’.313’ E012° 05’.978” | 5000 | Seasonal Crater Lake | 1.2 km | 1011 m asl | Weathered scoraceous basalt/ pyroclastics |
| 24    | Kukuwa (Gabai lga Yobe State) | N11° 06’.387’ E011° 53’.689” | 5000 | Plug | 200 m | 429 m asl | Columnar basalt |
province are presented in Tables 3 and 4. The volcanic cones situated at the northern end of the volcanic line here referred to as the north-western group are represented by Miango (M1 & M2) and Kassa (K1–5), while the south-eastern end group are represented by Jiblik (G1 & G2), Tingyaras (S1), Ampang (S2), Pidong (S3), Wulshik (S4), Kugol (S5) and Kerang (S6).

The rocks display similar SiO$_2$ wt% contents (44.84–50.06 wt%) for the north-western group of volcanoes (M1 & M2 and K1–5) and 45.26–46.25 wt% for S1–6 and 49.69 wt% for the Jiblik volcano (G1). However, the sample G2 from Jiblik with high SiO$_2$ content of 64.21 wt% is exceptionally acidic and does not seem to be a basalt. Many of the rocks from the Kassa volcanoes (K1, K3, K4, and K5) display the highest SiO$_2$ content (46.99–50.06 wt%) as opposed to those from Miango volcanoes (M1 & M2) and the southern volcanoes (S1–6) whose SiO$_2$ contents are typical of a normal basalt (45.26–46.25 wt%). The Miango and the Kassa volcanoes display higher Fe$_2$O$_3$ contents (12.33–12.61 and 10.42–11.35 wt% respectively). The southern group (S1–6) displays lower Fe$_2$O$_3$ content; 9.83 wt% for the Jiblik volcano (G1); and a relatively higher but similar concentrations of between 11.25 and 11.92 wt% for the Panyam Volcanic line members (S1–6).

In general, the Al$_2$O$_3$ contents of all the basalts from the different volcanic cones are significantly high but vary narrowly inter/intra the volcanic cones (13.87–18.07 wt% for the north-western group and 12.41–18.07 wt% for the southern group (G1 & S1–6)). In terms of the MgO content, the southern group (S1–6) presents relatively higher values of between 10.71 and 12.58 wt% as against an average of 8.00 wt% for the northern group (M1–2 & K1–5). The CaO, Na$_2$O, K$_2$O and TiO$_2$ contents for all the volcanoes vary narrowly; averagely 8; 3; 1.5 and 2 wt%, respectively.

Their Al$_2$O$_3$/TiO$_2$ ratios vary narrowly and could be on that basis be subdivided into two groups; those with ratios between 5.53 and 5.69 and then those between 6.39 and 6.62 for the entire volcanic line (N-S) (Figure 3). This is further a
| Analyte symbol | unit | SiO₂ (%) | Al₂O₃ (%) | Fe₂O₃ (%) | MnO (%) | MgO (%) | CaO (%) | Na₂O (%) | K₂O (%) | TiO₂ (%) | P₂O₅ (%) | LOI (%) | Total (%) | Al₂O₃/ TiO₂ | CaO/ TiO₂ | Al₂O₃/ CaO |
|----------------|------|-----------|-----------|-----------|---------|---------|---------|---------|---------|---------|----------|---------|-----------|----------------|----------|-----------|
| M1             |      | 44.84     | 15.02     | 12.33     | 0.166   | 8.50    | 8.86    | 4.09    | 1.88    | 2.668   | 0.76     | < 0.01   | 98.83     | 5.63      | 3.32      | 1.70      |
| M2             |      | 43.80     | 15.01     | 12.61     | 0.166   | 8.54    | 8.32    | 3.40    | 1.87    | 2.727   | 0.74     | 1.5      | 98.68     | 5.50      | 3.05      | 1.80      |
| G1             |      | 49.69     | 14.90     | 9.83      | 0.142   | 8.10    | 7.07    | 3.34    | 1.70    | 1.659   | 0.47     | 1.33     | 98.81     | 9.03      | 4.26      | 2.11      |
| G2             |      | 64.21     | 14.74     | 5.60      | 0.087   | 2.37    | 3.91    | 3.29    | 3.54    | 1.124   | 0.43     | 0.96     | 100.3     | 13.11     | 3.48      | 3.77      |
| S1             |      | 44.97     | 12.41     | 11.51     | 0.166   | 12.85   | 9.43    | 3.13    | 1.62    | 2.213   | 0.59     | 0.03     | 98.92     | 5.61      | 4.26      | 1.32      |
| S2             |      | 44.77     | 12.48     | 11.34     | 0.165   | 12.74   | 9.39    | 2.96    | 1.50    | 2.194   | 0.57     | 0.47     | 98.58     | 5.69      | 4.28      | 1.33      |
| S3             |      | 45.75     | 16.00     | 11.92     | 0.161   | 6.34    | 8.16    | 3.58    | 2.21    | 2.849   | 0.70     | 0.99     | 98.66     | 6.62      | 2.86      | 1.96      |
| K1             |      | 46.99     | 13.99     | 11.36     | 0.630   | 8.36    | 9.47    | 3.74    | 1.53    | 2.176   | 0.60     | 0.52     | 98.95     | 6.43      | 4.35      | 1.48      |
| K2             |      | 50.06     | 14.23     | 10.83     | 0.149   | 7.16    | 8.9     | 3.50    | 1.22    | 2.158   | 0.37     | < 0.01   | 98.57     | 6.59      | 4.12      | 1.60      |
| K3             |      | 48.02     | 18.07     | 10.42     | 0.164   | 3.30    | 7.74    | 5.28    | 2.80    | 2.516   | 0.84     | 0.12     | 99.27     | 7.18      | 3.08      | 2.33      |
| K4             |      | 47.49     | 14.17     | 11.35     | 0.167   | 7.81    | 9.29    | 3.82    | 1.58    | 2.211   | 0.64     | 0.20     | 98.74     | 6.41      | 4.20      | 1.53      |
| K5             |      | 47.05     | 13.87     | 11.28     | 0.160   | 8.17    | 9.36    | 3.55    | 1.59    | 2.17    | 0.64     | 0.67     | 98.52     | 6.39      | 4.31      | 1.48      |
| S4             |      | 45.26     | 13.52     | 11.34     | 0.162   | 10.71   | 9.47    | 3.28    | 1.70    | 2.397   | 0.62     | 0.32     | 98.78     | 5.64      | 3.95      | 1.43      |
| S5             |      | 44.77     | 12.82     | 11.40     | 0.166   | 11.50   | 9.58    | 2.83    | 1.65    | 2.318   | 0.61     | 1.08     | 98.73     | 5.53      | 4.13      | 1.34      |
| S6             |      | 46.27     | 13.02     | 11.25     | 0.163   | 11.24   | 9.21    | 3.51    | 1.69    | 2.262   | 0.69     | 0.23     | 99.35     | 5.76      | 4.07      | 1.41      |

Table 3. Major element compositions (in weight percentage) of volcanic rocks from the Jos Plateau Volcanic Province.
reflection of the variations in Al₂O₃ contents of the basalts since TiO₂ contents remain relatively constant. Similarly, their CaO/TiO₂ and Al₂O₃/CaO ratios vary from 2.6 to 4.3 and 1.34–1.60 respectively. Such narrow difference in these ratios is expected from a low degree of magmatic differentiation of the same parent material by partial melting process (Figures 3 and 4).

Similarly, the rocks present subtle variations in incompatible element ratios Ba/Sr and Zr/Y (0.73–0.90 and 8.77–9.35, respectively); all supportive of their subjection to low degree of magmatic differentiation and/or similar source.

5.1 Silica versus major oxides correlation plots

In the SiO₂ versus MgO wt% plot, the southern volcanoes overwhelmingly display higher MgO contents as opposed to the lower values for the northern group of volcanoes (Figure 5c). It is expected that the Kassa volcanoes (K1–5) which are more differentiated (by their higher SiO₂ contents) than the others to present lower MgO contents but instead display similar MgO contents. This scenario is true of their Fe₂O₃ contents. However, there is a weak negative correlation between Fe₂O₃, MgO, TiO₂ and MnO versus silica indicating a progressive decrease of these oxides with differentiation (Miango-Southern group-Kassa) corresponding to compositional variations related to the removal of different proportions of olivine/pyroxenes from the melt as it becomes more felsic (Figure 6a–d).

The Kassa volcanoes in the northern group and those of the southern group exhibit higher CaO contents compared to lower CaO values at Miango (M1&M2) and also of the northern group. The observed high CaO content suggest the

| Analyte symbol unit | Ba ppm | Sr ppm | Y ppm | Sc ppm | Zr ppm | Be ppm | V ppm | Ba/Sr | Zr/Y |
|---------------------|--------|--------|-------|--------|--------|--------|-------|-------|------|
| M1                  | 619    | 840    | 25    | 19     | 234    | 2      | 161   | 0.74  | 9.36 |
| M2                  | 865    | 799    | 26    | 19     | 239    | 2      | 153   | 1.08  | 9.19 |
| G1                  | 518    | 637    | 18    | 15     | 205    | 2      | 122   | 0.81  | 11.39|
| G2                  | 1215   | 723    | 26    | 12     | 328    | 3      | 121   | 1.68  | 12.62|
| S1                  | 530    | 654    | 22    | 23     | 193    | 2      | 185   | 0.81  | 8.77 |
| S2                  | 554    | 646    | 21    | 22     | 190    | 2      | 178   | 0.86  | 9.05 |
| S3                  | 794    | 1098   | 24    | 15     | 228    | 2      | 174   | 0.72  | 12.00|
| K1                  | 571    | 782    | 25    | 18     | 177    | 2      | 161   | 0.73  | 7.08 |
| K2                  | 551    | 460    | 43    | 20     | 155    | 2      | 171   | 1.20  | 3.06 |
| K3                  | 820    | 983    | 26    | 7      | 258    | 3      | 155   | 0.83  | 9.92 |
| K4                  | 672    | 758    | 38    | 19     | 176    | 2      | 164   | 0.39  | 4.63 |
| K5                  | 523    | 1095   | 24    | 18     | 177    | 2      | 157   | 0.48  | 7.36 |
| S4                  | 569    | 748    | 23    | 21     | 212    | 2      | 178   | 0.76  | 9.22 |
| S5                  | 585    | 697    | 23    | 23     | 204    | 2      | 180   | 0.84  | 8.84 |
| S6                  | 688    | 766    | 23    | 20     | 215    | 2      | 172   | 0.90  | 9.35 |

Table 4.
Trace elements compositions (in ppm) of the basaltic rocks from the Jos Plateau Volcanic Province.
recrystallization of clinopyroxenes in the early stages of crystallization. In general, there is a positive correlation depicting a progressive increase of CaO with differentiation from Miango to the southern group to Kassa (Figure 5a-f). This increase is not visible at the level of one volcano but several of them put together. The high Fe₂O₃, MgO and CaO could be as a result of the bulk crystallization of olivine, pyroxene and plagioclase during the early stages of differentiation. The progressive increase in the contents of Al₂O₃ corresponds with the increase in the alkaline metals content (Na₂O + K₂O) suggesting the crystallization of plagioclase with increased degree of differentiation. The alkaline oxides (Na₂O + K₂O) are correspondingly highest in the most differentiated rocks (K1–5) (Figure 6d). In a silica versus total alkali diagram (Figure 7), the rocks fall within the alkaline field and are therefore classified as predominantly alkaline basalts. Only a few rocks fall in the
sub-alkaline field which could be of tholeiitic character (high silica and Fe contents). Furthermore, in a log \((\text{Zr}/\text{TiO}_2)\) versus \(\text{SiO}_2\) diagram (Figure 8), the bulk of the rocks fall in the alkaline field reaffirming their alkaline nature (Figure 9).

In respect to their Mg#, it varies very narrowly within the individual volcano signifying a subtle degree of differentiation (partial melting) and thus reflecting a low degree of magmatic differentiation and the consequent subtle compositional variations observed. However, for the entire volcanoes put together, the Mg# vary significantly from 27 to 56 suggesting formation of the rocks by fractional crystallization at larger scale. The southern volcanoes (S1–6) have the highest Mg# relative to those of the northern group (K1–5 and M1 & M2) (Figure 10a–d). When the rocks are plotted in Mg# versus \(\text{Fe}_2\text{O}_3\) diagram (Figure 10b), a positive correlation is obtained indicating a progressive decrease in \(\text{Fe}_2\text{O}_3\) with increasing degree of magmatic differentiation. The relatively similar Ba/Sr. and Zr/Y ratios for these rocks but with progressive decrease in Mg# lends credence to their derivation from

Figure 5.

(a–f) Plots of \(\text{SiO}_2\) versus major oxides of the volcanic rocks of the Jos Plateau Volcanic Province.
the same magma reservoir by differentiation. It appears that the rocks with the highest Mg# (samples S1–6) present compositions that are close to that of the parent materials since the magma did not suffer high degree of differentiation giving rise to a variety of rocks. The subtle variation of Mg# and the incompatible

Figure 6.
(a–d) Plots of SiO$_2$ versus major oxides of the volcanic rocks of the Jos Plateau Volcanic Province.

Figure 7.
Silica versus Total Alkali diagram [21] of the volcanic rocks of the Jos Plateau (Alk = alkaline and Subalk = subalkaline).
Figure 8. 
Plot of Log (Zr/TiO$_2$) ratio versus SiO$_2$ [12] of the volcanic rocks of Jos Plateau Volcanic province (Sub-AB = subalkaline basalts, AB = alkaline basalts).

Figure 9. 
SiO$_2$ versus Na$_2$O + K$_2$O classification diagram of basalts of the Jos Plateau volcanoes [13].
element ratios highlighted above are supportive of the derivation of these basalts by partial melting process of a magma from the same source.

5.2 Tectonic environment of emplacement

The geochemical data plotted in the ternary diagram of Ti/100-Zr-Y*3 [12] show clearly that they were majorly emplaced within the continental crust (Figures 11 and 12). This fact distinct these basalts from those of the Island arc and the Mid Oceanic Ridge.

5.3 Incompatible elements spidergraph

The incompatible elements when plotted in a spidergraph normalized to Chondrites in comparison with OIB (Figure 13) display a relatively similar pattern with slight enrichment in their incompatible elements. These characteristic features are typical of most alkali basaltic suites derived from a deeper mantle source akin to that of the OIB [12, 14, 16–19].

5.4 Ar\(^{40}\)-Ar\(^{39}\) dating

A sample by sample result is presented in Table 5. The Ar/Ar ages span between 1.3 and 2.5 Ma, confirm the earlier K-Ar ages of 2.1 and 1.9 ± 0.31 Ma reported by [1] on dolerites on the Jos Plateau. The short interval in the radiometric ages suggests volcanic eruptions occurred at discrete times, separated by short periods of non-activity at a mean age average of 0.55 Ma (CN3 = 2.500 ± 0.318 Ma and CN5 = 1.970 ± 0.173 Ma). This long period must have been dominated by profound erosion. The considerable long-time difference from the oldest to the youngest eruption suggests that there was relatively steady magma source overtime.
5.5 Hydrogeochemistry of the Pidong Crater Lake

Comparative hydrogeochemical parameters of previous study [7] and this present study is presented in Table 5. It shows clearly that pH and alkalinity have decreased overtime from 9.35 to ≥7.0 and from 335 to 145 mg/l, respectively as well
as increase in the concentrations of Cl from 2.5 to 5.6 mg/l; SO$_4$ from <0.33 to 1.05 mg/l (Table 5).

5.5.1 Major element concentration/distribution

In general, the major element concentrations in the Pidong Lake decrease in the order Mg > Ca > K > Na (Table 5). The highest concentrations of Mg (30 to ≤40 mg/l), Ca (21–25 mg/l), K (15 mg/l) Na (8–11 mg/l) are observed during the dry season (January–April) while lowest concentrations of Mg (16–25 mg/l), Ca (10–15 mg/l), K (4–7 mg/l) in the rainy season (August–October). The intermittent change of color of the Lake from clear blue to brown has been attributed to the increase in Fe concentrations into the Lake.

5.5.2 Rare earth element (REEs) concentrations

Figure 14 presents the REE patterns from the Crater Lake normalized to Chondrites. The REE concentrations are impoverished relative to Chondrite values (<1 × Chondrite). There are significant variations in the LREE (0.03–0.18 × Chondrite for La) relative to HREE (Gd-Lu). An important characteristic of the spectra is the similarities between the LREE patterns indicating similar source. The slight enrichment in LREE must have been influenced by fluid percolation through the host crustal materials (host granite basement) rich in these elements.

5.5.3 Anion concentrations (SO$_4$, Cl, HCO$_3$, NO$_3$, F, Br, and PO$_4$)

The major anion concentrations from the lake vary in concentrations in the order of -HCO$_3$ > Cl > SO$_4$. The highest concentration of in the LREE range from <0.5 to 5.5 mg/l and 0.0675 to 0.0321 mg/l, respectively, and were observed during
| Period                      | pH   | Temperature (°C) | EC (μs/m) | Mg (mg/l) | Ca (mg/l) | Na (mg/l) | K (mg/l) | Zn (mg/l) | Fe (mg/l) | Cu (mg/l) | Al (mg/l) | SO₄ (mg/l) | Cl (mg/l) | Alkalinity (CaCO₃) (mg/l) | F (mg/l) |
|-----------------------------|------|------------------|-----------|-----------|-----------|-----------|----------|-----------|-----------|-----------|-----------|-----------|-----------|---------------------------|---------|
| Patterson (1986) report     | 9.35 | 28.5             | 410       | 36.4      | 13.65     | 12.8      | 25.8     | 0.065     | 0.27      | <0.004    | —         | <0.33     | 2.5        | 335                       | —       |
| Present study (2013–2015)   | 7.17 | 26.1             | 299       | 29.68     | 39.67     | 6.89      | 11.39    | 0.064     | 0.612     | 0.0039    | 0.456     | 1.03      | 5.67       | 141.5                      | 0.249   |

Table 5. Comparative hydrogeochemical data of 1986 and the present study.
the dry season (October–April). The concentrations of HCO$_3^-$, Cl and F could have been influenced by interacting percolating water and host rock chemistry. The increase in the concentrations of SO$_4^{2-}$, Cl$^-$ (<0.33–1.03 and 2.5–5.67 mg/l, respectively) as well as the decrease in Alkalinity and pH from 335 to 141.5 mg/l and 9.35 to ≈7.00, respectively. These variations in concentrations suggest a possible input of magmatic/fumaroles percolating upwards to shallow groundwater aquifers coming in contact with meteoric water. The oxygen and hydrogen isotope composition and plot of $\delta^{18}$O and $\delta^2$H relative to SMOW line shows that the Pidong Crater Lake is of meteoric origin.

6. Conclusion

i. This work presents and affirms the existence of relicts of past volcanic eruptions (dormant volcanoes) in Nigeria (Jos and Biu Plateaux).

ii. That these volcanic edifices were previous eruption sites suggest they are potential eruption sites. The proximity of these volcanic edifices to those of the Cameroon volcanic line, which has witnessed a series of volcanic activity, is worrisome.

iii. The mafic lavas in both the Jos and the Biu Plateaux volcanic provinces display geochemical compositions that are characteristic of alkaline basalts.

iv. Petrologically, the basaltic rocks display compositions varying from basalt proper to basanite-tephrite-hawaiite, emplaced within the host crustal rocks (Basement rocks).

v. The chain of volcanoes evolved from the same basalt parent magma by crystal fractionation each cluster derived by partial melting of the same residual parent magma.
vi. Recent $^{40}\text{Ar} / ^{39}\text{Ar}$ dating of basalts from overlapping volcanic cones from the Jos Plateau province (ranging from 2.5 to 1.34 Ma) confirms the Quaternary age (Pleistocene epoch) of emplacement for these volcanoes and the intermittency of eruptions inter and intra the volcanic line in the provinces.

vii. That these volcanic edifices were previous eruption sites suggest they are potential eruption sites. The proximity of these volcanic edifices to those of the Cameroon volcanic line, which has witnessed a series of volcanic activity, is worrisome. The volcanic eruption of Mount Vesuvius in Italy in the year 2004 known to have been dormant since 24 AD is a clarion call. Furthermore, the recent volcanic eruption in Iceland April 15, 2010 after 200 years of silence should increase the worry. All these information calls for further comprehensive work on these dormant volcanoes for risk assessment.

viii. The minor intermittent fumarolic activities observed within the Pidong Crater Lake marked by the change in the water color from the normal bluish to brown-red color, (due to Fe-input) call for more comprehensive investigation of the volcano and further strengthen the idea of the possibility of the volcano roaring back to life.

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Conflict of interest

We declare that there are no “conflict of interest.”

Notes thanks other declarations

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Appendices and nomenclatures

Alk alkali basalt
ASL above sea level
Ma million ($10^6$) years
MORB mid-ocean ridge basalt
NASRDA National Space Research and Development Agency
OIB ocean island basalt
ppb parts per billion ($1/10^9$)
Is a Volcanic Eruption Possible in Nigeria?
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ppm parts per million \((1/10^6)\)
SMOW standard mean ocean water
ICP-OES inductively coupled plasma optical emission spectrometry
\(\delta\) stable isotope ratio expressed relative to a standard

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