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ORIGINAL PAPER

Petrogenesis and tectonomagmatic updates on the origin of the igneous rocks in the lower Benue rift, southeastern Nigeria

Anthony Chukwu[1] · Smart C. Obiora[2]

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Abstract
This work presents updates on the tectonomagmatic origin of igneous rocks in the lower Benue rift based on recent available geochemical data. The igneous rocks occur as volcanic and plutonic rock series. The rock types are basalts and basaltic sills, pyroclastic rocks (tuffs and lapilli tuff), trachytes, trachybasalts, gabbros (stocks), dolerite sills, and dioritic rocks (stocks). The rocks were emplaced within folded sedimentary sequence of shales, subordinate sandstones, and siltstone and carbonate rocks of Asu-River and Eze-Aku Group. Most of the rocks are moderately to highly altered, with the pyroclastic rocks showing higher effects of alteration (LOI 3 to 22 %). Incompatible and immobile elements and less altered rocks with LOI < 3% show that the rocks were derived from mantle enriched source and possibly HIMU signatures. The high ratios of $(La/Yb)_N$ 4.40 to 31.55 in the basic rocks and 23.59 to 135.35 in the trachytic rocks show alkaline affinity with sparse tholeiites and garnets in the source region. The rocks were formed by plume uprising in a within-plate setting of intra-continental rift system similar to the South Atlantic Ocean rocks and East African rift. The magnesium number (Mg#) and differences of the spidergrams and rare earth patterns indicate that the rocks are cogenetic, and source is heterogeneous. The depletion of K, P, Th, and Rb and formation of calcites and sericites in the rocks show mobilization probably by interaction with calcareous host rocks in prevailing conditions.

Keywords Volcanic and sub-volcanic rocks · Alteration · Immobile elements · Enriched mantle · Within-plate · Lower Benue rift

Introduction

The igneous activities in the lower Benue rift (LBR) have been reported in parts by notable authors such as Burke et al. (1972), Ojoh (1990), Obiora (1994), Obiora and Umeji (1995), Maluski et al. (1995), Coulon et al. (1996), Obiora and Charan (2011), and Chukwu and Obiora (2014, 2018). However, their relative distributions and comprehensive geochemical relationships of the rock suites have remained vague. The occurrences of the magmatic rocks in the entire Benue rift are tied to its formation and evolution. The Jurassic–Cretaceous Benue rift is a Y-shaped intracontinental structure that stretches from northeastern part of Nigeria to southwest (Niger delta area) (Fig. 1) and filled with continental and marine sediments (up to 6500 m thick). The southwestern parts of the Benue rift constitute the lower Benue rift (LBR) (Fig. 2). The Benue rift is part of the massive West and Central African Rift system; its origin is genetically related to crustal stretching of the African plate during to the opening of the equatorial and South Atlantic Ocean during the Jurassic–Early Cretaceous times (140 Ma) (Fitton 1980; Popoff 1990; Fairhead and Binks 1991; Maluski et al. 1995; Coulon et al. 1996; Nwajide 2013). Regionally, the magmatic province of the Benue rift constitutes a spatial link with the alkaline and paralkaline province of the Jos Plateau to the north (the younger granites of Nigeria) and the younger alkaline volcanic Cameroon hot line to the south (Fig. 1) (Maluski et al. 1995; Burke 2001). Burke (2001) established that the three provinces were produced by an existed stationary plume located at latitude 7° N and longitude 11.5° E which he referred to as "plume 711 theory," during the rotation of Gondwana continent from the north 213 Ma to the south 30 Ma (Cameroon hot line). Although the alkaline and the Cameroon hot line

Responsible Editor: Abdullah M. Al-Amri

✉ Anthony Chukwu
achukwu1@gmail.com; tonaro4u@yahoo.com

Smart C. Obiora
smartobiora@gmail.com; smart.obiora@unn.edu.ng

[1] Department of Geology, Ebonyi State University, Abakaliki, Nigeria

[2] Department of Geology, University of Nigeria, Nsukka, Nsukka, Nigeria

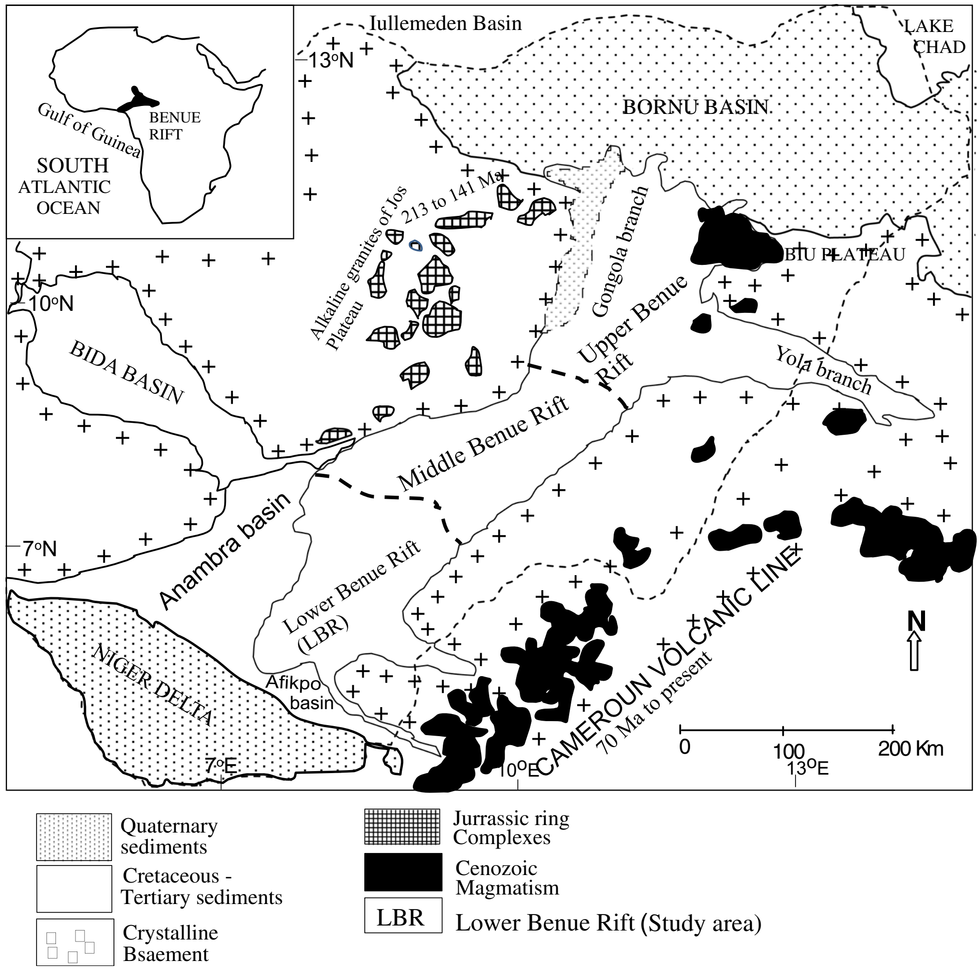

Fig. 1 Geological map of Benue Rift showing its relationship with the alkaline rocks of the Jos plateau and Cameroon hot line

showed age migrations to support the plume 711 theory of Burke (2001), the rocks of the Benue rift have not shown a clear age migration based on available data.

Maluski et al. (1995) and Coulon et al. (1996) accounted for two major magmatic districts within the southern Benue rift based on the ages of the rocks (1) the Early Cretaceous core of the Abakaliki anticlinorium (2) the Upper Cretaceous Anambra and Afikpo basins (Fig. 1). They reported that the magmatic rocks in the Abakaliki anticlinorium which represents the LBR occur in five areas, which include the Gboko, Katyo, Wanakum Hills, Abakaliki, and Okigwe areas. However, Obiora and Charan (2010) grouped the magmatic rocks in the LBR into four major districts: the southwest of Gboko, Ejekwe-Wanikande, Abakaliki, and Okigwe-Ishiagu districts. The igneous rocks of the Abakaliki anticlinorium magmatic districts are mostly alkaline and peralkaline intermediate to basic rocks with few peralkaline rhyolitic dykes around Gboko area. The rock types are phonotephrites, tephriphonolites, phonolites and trachytes, volcaniclastic rocks, basalts, camptonites, nepheline syenite, gabbro, and dolerites (Okezie 1957; Obiora 1994; Obiora and Umeji 1995; Maluski et al. 1995; Coulon et al. 1996; Obiora and Charan 2010, 2011; Chukwu and Obiora 2014, 2018). In the Anambra and Afikpo basins, the igneous rocks occur mostly as tholeiites in the form of doleritic sills in the Turonian shales and Sandstones around Makurdi and Afikpo areas (Baudin 1991; Maluski et al. 1995; Coulon et al. 1996), although, presently, no igneous activities has been mapped in the Anambra basin but there is the possibility that they occurred underneath.

Generally, three periods of magmatic activities have been identified within the Jurassic–Cretaceous Benue rift (Umeji and Caen-Vachette 1983; Maluski et al. 1995; Coulon et al. 1996). The first is the 147–106 Ma magmatic periods which is Late Jurassic to Albian age and mostly concentrated in the northern Benue but sporadically found also in the southern Benue within the core of the Abakaliki anticlinorium, represented by rhyolitic dome around Gboko area and altered volcaniclastic rocks in Abakaliki areas. This first magmatism (147–106 Ma) pre-dates the opening of the equatorial Atlantic and is believed to have created the zones of weakness which initiated the opening of the oceanic equatorial domain (Maluski et al. 1995). The second is the 97–81 Ma magmatic periods; Cenomanian to Santonian was restricted to the

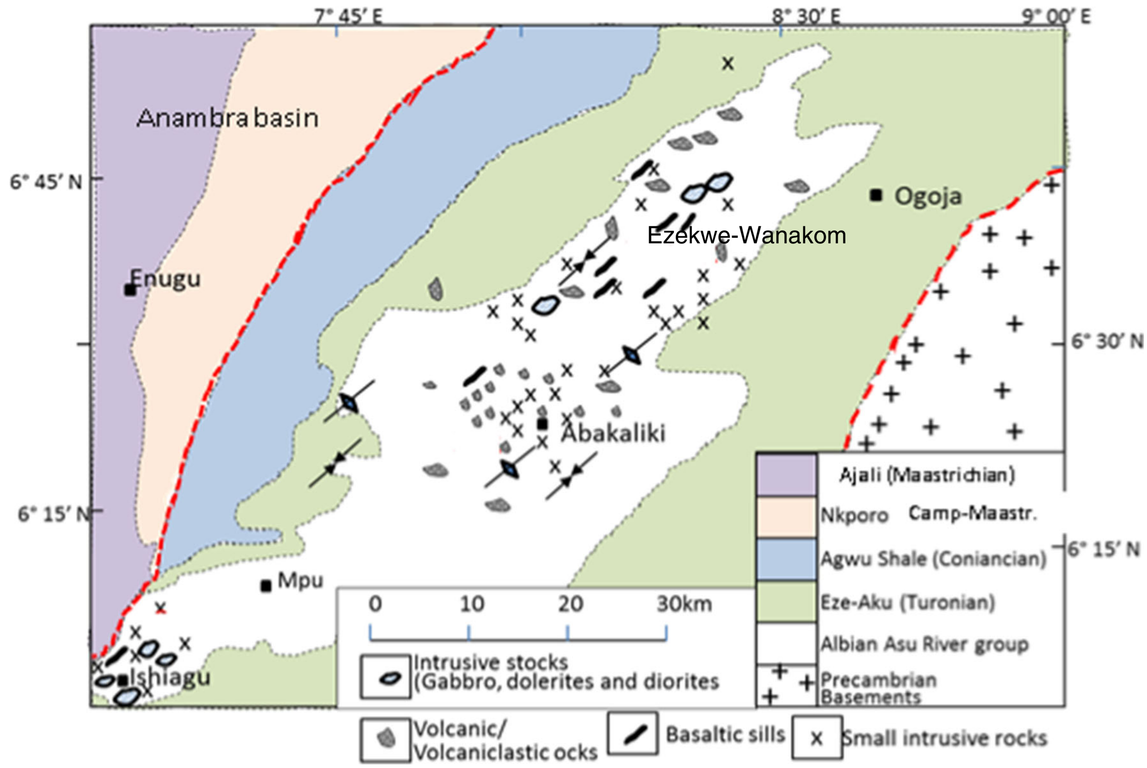

Fig. 2 Geological map of the of the pre-Santonian lower Benue rift showing the distribution of the igneous rocks in the area

southern Benue rift (Gboko, Wanakom Hills and Okigwe-Ishiagu axis). This second period postdates the break-up of the South American and African continents which started in this region about 105–100 Ma (Mascle et al. 1986; Nurnberg and Muller 1991; Coulon et al. 1996). The third magmatic period (68–49 Ma; Late Maastrictian to Eocene) is also restricted to the southern Benue. The rocks in this group are subvolcanic rocks, composed of alkaline rocks around Katyo area and mostly tholeiites around Otukpo (60 Ma), Afikpo (55 Ma), and Markurdi (49 Ma) (Maluski et al. 1995; Coulon et al. 1996). The periods of these magmatism compared with the alkaline rocks of Jos province and Cameroon line lead to the proposition of the "plume 711" theory of Burke (2001) in relation to the basin evolution and African continent.

This present work presents an integrated geochemical study of the igneous rocks of the lower Benue rift (LBR) to update the tectonomagmatic origin of the igneous rocks in the lower Benue rift based on recent available geochemical data and comparing them with other rocks of similar tectonic origin.

Location and nature of the magmatic rocks in the lower Benue rift

The mapped igneous bodies in lower Benue rift (LBR) are over 145 in number; they occur as volcanic and subvolcanic rocks and show great diversity from gabbros, basalts, dolerites, diorites, trachybasalts, trachytes, and basaltic volcaniclastic rocks (pyroclastic rocks). The igneous rocks in the lower Benue rift (LBR) can be grouped arbitrary into three geographic locations (the northeastern lower Benue rift, the central lower Benue rift and southwestern lower Benue rift) which correspond to the magmatic districts of Maluski et al. (1995). However, considering their regional field occurrences and geochemical signatures couple with regional scale in which magmatism can occur, the rocks are grouped into two: the volcanic series and the plutonic series. The volcanic series include alkali basalts, basalt and basaltic sills, trachybasalts, trachytes, and basaltic volcaniclastic rocks (pyroclastic rocks) while the plutonic series composes of the gabbros, dolerites, doleritic sills, and diorites. The igneous rocks in the LBR are predominantly oval shaped in northeastern–southwest orientation emplaced in a folded sedimentary sequence of Albian to Turonian in age, locally known as the Asu-River and Eze-Aku groups, respectively (Fig. 2). The sedimentary rocks consist of mainly calcareous shales, intercalated with siltstones, sandstones, and intermittently interbedded with limestones and mudrocks.

Generally, the plutonic series are widely distributed in the LBR compared with the volcanic series. The volcanic series (mostly pyroclastic rocks) predominate around Abakaliki areas at the central LBR. Basaltic sills, trachytes, trachybasalts, and small bodies of volcaniclastic deposits are also located around Wanakom Hills and Ezekwe area in NE parts. The basalts constitute small dome shaped about 280 m in diameter, 150 m wide and 3 m high while the basaltic sills are exposed mostly along stream channels in NE direction and mostly along fracture zones of the host rocks. The basalts are grayish to blackish, fine grained, and porphyritic with olivine phenocrysts seen megascopically. The trachytes, trachybasalts, and the volcaniclastic rocks occur mostly as small deposits in the Turonian Formations. The pyroclastic rocks occur as small conical hills around otherwise flat and swampy terrain. They range from 4 to 1 km long, 30 to 550 m wide, and about 10 to 120 m high. Notable outcrops can be found at Sharon quarry, Juju hills, Old ministry of works to new layout, Onyikwa and Mile-50 all around Abakaliki town. The rocks are composed of mostly welded tuffs and few agglomerates that are highly altered with formation of secondary minerals as amygdules. The tuffs are composed of lithic fragments and glass shards of basaltic rocks. Xenolites of angular metamorphosed rock fragments (2–5 cm) are also common both in the tuffs and agglomerates. The pyroclastic rocks are characterized by structures such as laminations, graded beddings and poorly sorted beds well discussed in Chukwu and Obiora (2018). In locations at the boundary between Albian shales and Turonian sediments, the pyroclastic deposits overlie unconformably on the Albian shales flanked by the Turonian (Eze-Aku Formation) (see Fig. 1). This shows that the pyroclastic rocks may be similar in space and time with the eroded Cenomanian Odukpani Formation (see Fig. 1) and directly overlies the Albian shales. Baudin (1991) had also reported camptonites, nepheline syenites, and phonolites around the Wanakom areas while Le Bas et al. (1986) accounted for phonotephrites, tephriphonolites, phonolites, and alkali-trachytes in the Turanian shales around Katyo areas of northern LBR. The plutonic series occur as stocks and sills within the Asu-River shales mostly around Ishiagu–Okigwe axis southern parts of LBR although sporadically emplaced dioritic rocks also occurred around Oriuzo–Umuaghara axis, Mkpumakwaokuku, and Oferekpe area around Abakaliki districts (geochemical data not available). The stocks are gabbroic and dioritic in composition while the sills are doleritic. The stocks are about 150–700 m in length, 10–400 m wide and height of about 5–50 m while the sills are about 180–400 m length, 40–250 m wide, and 10–45 m high trending in NE-SW orientation. Among the plutonic series, the dolerites and diorites are more in number and widely distributed. They are medium–coarse grained and porphyritic and have sharp contacts with the host rocks (shales and mudrocks), and evidence of baking on the host rocks are mild which also supports that the intrusive rocks are post Albian while the volcanic rocks especially around Abakaliki areas and the Wanakom Hills and Ezekwe areas are said to be among the earliest magmatic events in the LBR (Maluski et al. 1995; Coulon et al. 1996).

Mineralogical compositions of the rocks

The basalts and basaltic sill consist mainly of basic plagioclase, glass, and olivine which have mostly altered to iddingsite and clinopyroxene (augites). Other alteration products are calcite and epidote from breakdown of pyroclase. Gabbros and dolerites possess sub-ophitic to ophitic texture in which clinopyroxene is enclose by plagioclase mostly oligoclase and labradorite (Fig. 3). Other minerals are altered olivine less than 5% and nepheline. Apatites and magnetites occur as accessory. Alteration products are calcites, analcine, thuringite (chlorites), serpentinized olivine, tremolite, and epidote. Pyrite and hematite occur as opaque. The diorites are characterized by randomly oriented plagioclase in similar sub-ophitic texture with plagioclase (sodic andesine) enclosing pyroxenes and hornblende (Fig. 3). Biotite replaces hornblende in some of the diorites. Diorites from the southern LBR have quartz minerals (less than 2%) in intersertal position with other minerals. Trachytes are composed of lath shaped plagioclase and K-feldspars, closely parked exhibiting flow structures. Altered mafic mineral augite is in intersertal position. The feldspars are highly sericitized while other plagioclase albertized. Volcaniclastic rocks/pyroclastic rocks consist of altered plagioclase and irregular glass shards as phenocryst and altered pyroxene and laths of plagioclase as groundmass in vitric components. The pyroclastics are scoriaceous in some locations while quartz, calcites, and zeolites occur as amygdules and vein fillings. Pyrites and magnetites constitute the opaques in the pyroclastic rocks.

Geochemistry

Analytical procedures

A total of seventy-eight relatively fresh samples from the lower Benue rift were analyzed for major oxides and trace elements. Samples from the northern part of LBR were analyzed at the National Geophysical Research Institute, Hyderabad, India, by the XRF for major elements and ICP-MS for trace elements while the samples from the other parts of the LBR were analyzed at the Activation Laboratories (ACTLABS), Ancaster, Ontario, Canada, also by ICP-MS methods (see Chukwu and Obiora 2014 and http://www.actlabs.com for details).

Results

The major oxides and trace elements including REE of the volcanic and plutonic series were presented in the table in Online Resource 1. The loss on ignition (LOI) of many of the samples is moderately to very high. The higher values of

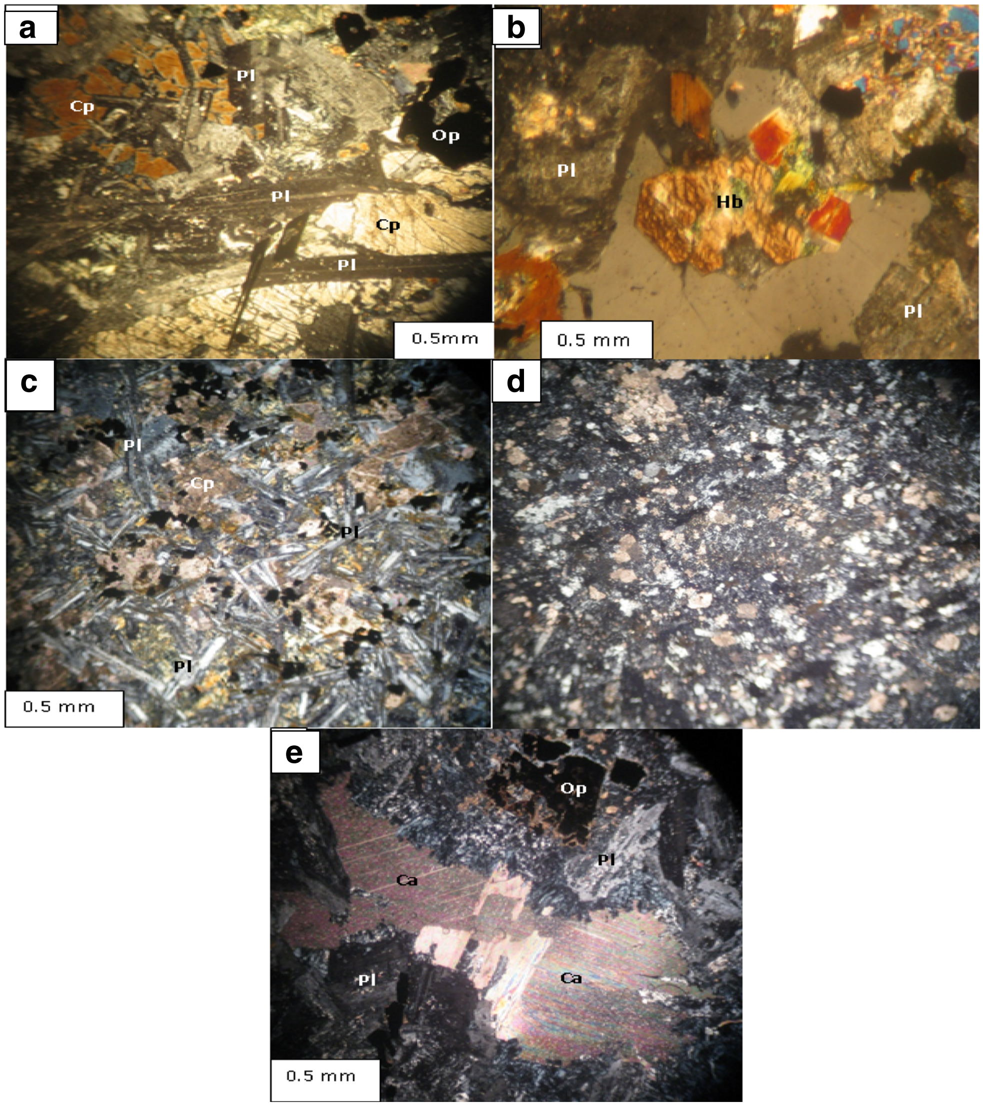

Fig. 3 Photomicrographs of the lower Benue Rift rocks (**a**) gabbros showing long plagioclase partially enclosed by clinopyroxene. **b** Diorites showing basal section of hornblende in altered ferromagnesian minerals. **c** doleritic textures. **d** Pyroclastic rocks showing altered pyroxene in groundmass of glassy components. **e** Alteration products, calcites replacing pyroxenes in the rocks

LOI (4–22%) are predominant in more than 85% of the volcanic and plutonic rocks in the LBR except few basalts and dolerite diorites rock samples which supports their alterations nature in the field. Consequently, the data were re-calculated on volatile-free basis. Due to the alteration effects on the rocks in the LBR, change in the bulk rock chemistry may occur as a result of mobility of some elements. To test for the reliability of the of the elements, concentration of selected major oxides and trace elements was plotted in Harker diagrams and shown in Figs. 4 and 5, respectively. Generally, the concentration of high field strength elements (HFSE) (Zr, Y, Hf, Nb, Ti, and Ta), and Th and major oxides (CaO and Fe_2O_3t) and REEs seems to have maintained their original composition in the melts while the composition of major elements (Si, Na, Al) and the trace elements Ni, Cr, and Sr seems to have been compromised and may not be reliable for the petrogenetic and tectonomagmatic interpretations of the rocks.

Major and trace elements

The lower Benue rift (LBR) rocks show diverse values of SiO_2 which range from 31.41 to 65.48 (wt%) in volcanic series and from the pyroclastic rocks to the trachybasalts while SiO_2 values ranging from 39.71 to 61.47 (wt%) in the plutonic series with the diorites showing the highest values which generally corresponds to ultrabasic to intermediates in composition in the LBR. The variations in SiO_2 could be attributed to mobilization of elements during alteration; however, critical observations (Fig. 4) and the immobile elements characteristics suggest that some of the elements are as a result fractional differentiation. The plots of the major oxides versus MgO (Fig. 4) show increase in TiO_2, Fe_2O_3t, and CaO with MgO for all the rocks in the LBR; P_2O_5, Na_2O, and Al_2O_3 show partly decrease in the rocks of the LBR with dominantly no clear trend.

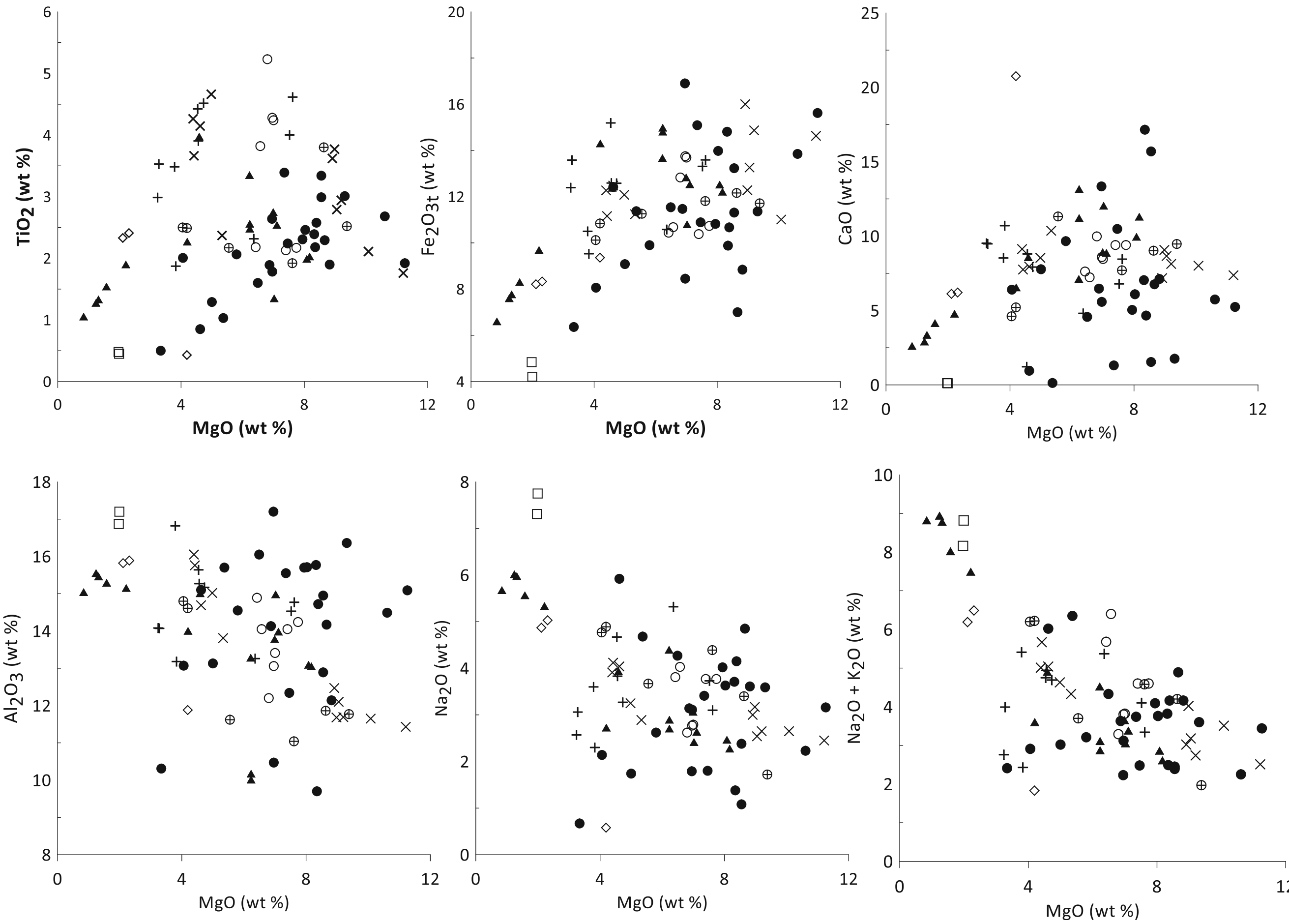

Fig. 4 Harker diagrams for selected major oxides of the lower Benue rift rocks. Shaded triangle = diorites, x sign = dolerites, cross = gabbro, unshaded rectangle = trachytes, unshaded rhombus = trachybasalt, unshaded circle = basalts, shaded circles = pyroclastic rocks, crossed circles = basaltic sill

But total alkali shows relatively decease in the rocks (both the volcanic series and the plutonic series). In general, the volcanic and plutonic rock series in the LBR show overlapping magmatic origins as observed from the rock types in the LBR (Figs. 4 and 5). The rocks also show originating most probably from a common primary magma source that is heterogeneous in composition. The Magnesium number (Mg#) for the LBR rocks given by 100Mg/Mg^{2+} + Fe^{2+} ranges from 31.41 to 72.68 in the volcanic rock series and 18.60 to 61.99 in the plutonic series. The basaltic volcaniclastic rocks around Abakaliki areas have the highest Mg# while the diorites around Ishiagu area, south of the LBR have the lowest (Online Resource 1). This shows that the rocks have undergone some degrees of fractional crystallization from primary melts although rocks from the central LBR seems to be more related to primary magma which represent the older part of the lower Benue rift. The relatively low Mg# value in the C-LBR could result from loss of MgO during olivine breakdown to iddingsite mineral as alteration progresses.

Trace elements

The HFSE elements (Y, Nb, Hf, Ta, Rb) and Th show increase with increasing Zr (Fig. 5). The trends are almost linear with Hf showing constant increment at about 45° for all the rocks in the LBR, with the evolved rocks (diorites) from Ishiagu areas having higher enrichment. Ba and Sr show increase with Zr but with more scatter. Ni, Cr, and Co show more scatter and different trends throughout the rocks in the LBR suggesting that the elements might have been slightly compromised. There are also overlapping relationship between the volcanic and plutonic rock series in Figs. 4 and 5 indicating cogenetic similar to the major elements oxides.

On the basis of the immobile elements, Zr/Ti versus Nb/Y variation diagram of Winchester and Floyd (1977) with fields as modified by Pearce (1996; Fig. 6), the rock samples of the LBR fall predominantly within the field of the alkaline basalts while the more evolved samples (mostly from the southern LBR) plot within the trachyandesite field. Most of the pyroclastic rocks from the Wanakom and Ejekwe areas (northern part), five pyroclastic rocks from the Abakaliki area (central

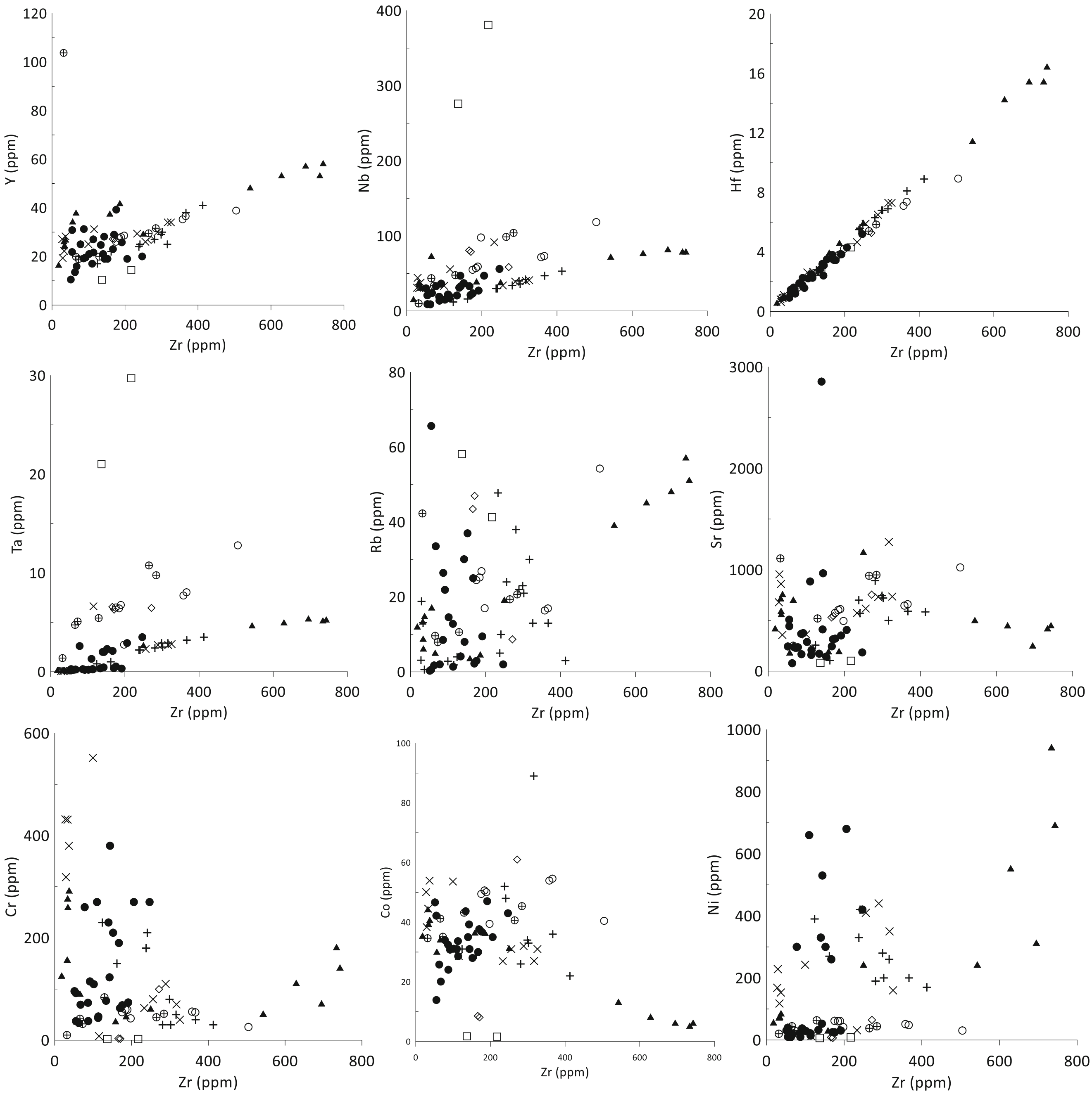

Fig. 5 Harker diagrams for selected trace elements in the lower Benue rift rocks. Symbols same as Fig. 4

part), and two gabbros from the Ishiagu area (southern part) plot in the subalkaline fields (tholeiites). The predominant alkaline and sporadic tholeiites are concordant with the observations of Coulon et al. (1996) (Fig. 6) in the upper Benue rift.

Spider diagrams

The multi-element diagrams with primitive mantle-normalized are presented in Fig. 7 for the rocks of the lower Benue rift. Generally, the patterns show that the LBR rocks are generally enriched in the incompatible elements similar to ocean island basalts (OIB). The first patterns (Fig. 7a) which are the rocks from the volcanic series are characterized by depletion in Rb, K, Hf, and Zr across the rock types; the trachytes and samples of the tholeiitic pyroclastic rocks are depleted in P, Sr, and Ti. On the other hand, the rocks are enriched in Ta and Nb except the tholeiitic pyroclastic rocks from the northern part (Wanakom Hills and Ezekwe area) which are depleted in Ta showing non-convergent environment. The second pattern (Fig. 7b) which represents the plutonic rock series across the LBR is also depleted in Rb, K, Hf,

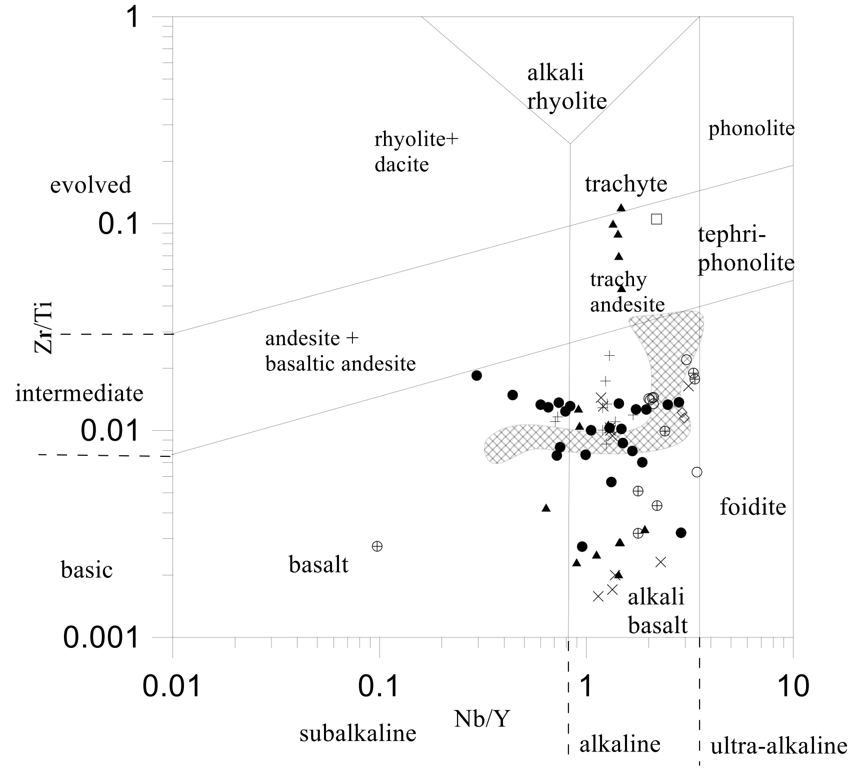

Fig. 6 Zr/Ti versus Nb/Y diagram of Winchester and Floyd (1977) with fields modified by Pearce (1996). Data for cross-hatched field are from upper Benue rift of Coulon et al. (1996). Symbols same as Fig. 4

and Zr and mild depletion in Sr. The rocks also indicated enrichment in Ta and Nb except the few tholeiitic diorite and dolerites from Wanakom Hills and Ezekwe area which are depleted in Ta. Generally, the volcanic and the plutonic series have similar elemental signatures which also show they are cogenetic. The variations in some elemental enrichment and depletions across the rock samples show that the common sources could be heterogeneous.

Considering the two patterns in Fig. 7 a and b, though they have similar elemental behavior, critical observation shows three salient groups: (1) The group that is enriched in Ta and mildly Nb which are mainly alkaline rocks (basaltic stocks, basaltic sills, basaltic pyroclastic rocks, gabbros, dolerites, diorites, trachybasalts, and trachytes) which is dominant in LBR, (2) those groups that are depleted in Ta which are mainly the basaltic pyroclastic rocks (tholeiitic in composition) from northern part, (3) those rocks that are depleted in Sr and Ti which are the diorites from Ishiagu areas (southern parts), trachytes, and two samples of the pyroclastic rocks from northern part. These groups indicate magma from similar origin but heterogeneous source. The differences could also be attributed to magma mixing of uprising melt.

REE patterns

The rare earth elements were normalized by chondrites values and presented in Fig. 8. The patterns for the volcanic and plutonic rock series in LBR generally show enrichment in the light REEs (LREE) relative to the heavy REEs (HREEs) which shows presence of garnet in OIB like basalts. The two patterns are generally similar with moderate to no Eu anomaly except the tholeiites which composes of the trachytes and pyroclastic rocks from the Wanakom Hills and Ezekwe areas which show mild negative anomalies. The similarities in the patterns of the rocks in the LBR also indicate that the rocks are cogenetic. This is supported by the reliability of the REEs in withstanding alterations. The mild negative Eu anomaly suggests partial basic plagioclase fractionation in the tholeiitic rocks.

The ratios of LREEs to HREEs of the volcanic rock series range from 4.84 to 15.69 in alkaline rocks and 3.61 to 8.41 in the tholeiitic rocks while in the plutonic rock series, it is 4.05–9.44 in alkaline and 4.16–4.24 in. Similarly, the $(La/Yb)_n$ ratios in the volcanic rock series range from 7.58 to 31.55 in the alkaline and 4.40 to 12.44 in the tholeiitic rock while in the plutonic rock series, it range from 5.44 to 19.91 in the alkaline and 4.83 to 5.13 in the tholeiites These generally show that the alkaline rocks in LBR are enriched in LREEs compared with HREEs.

Discussion

Alterations

The volcanic and plutonic rock series in the LBR were emplaced in mostly calcareous argillaceous sediments of

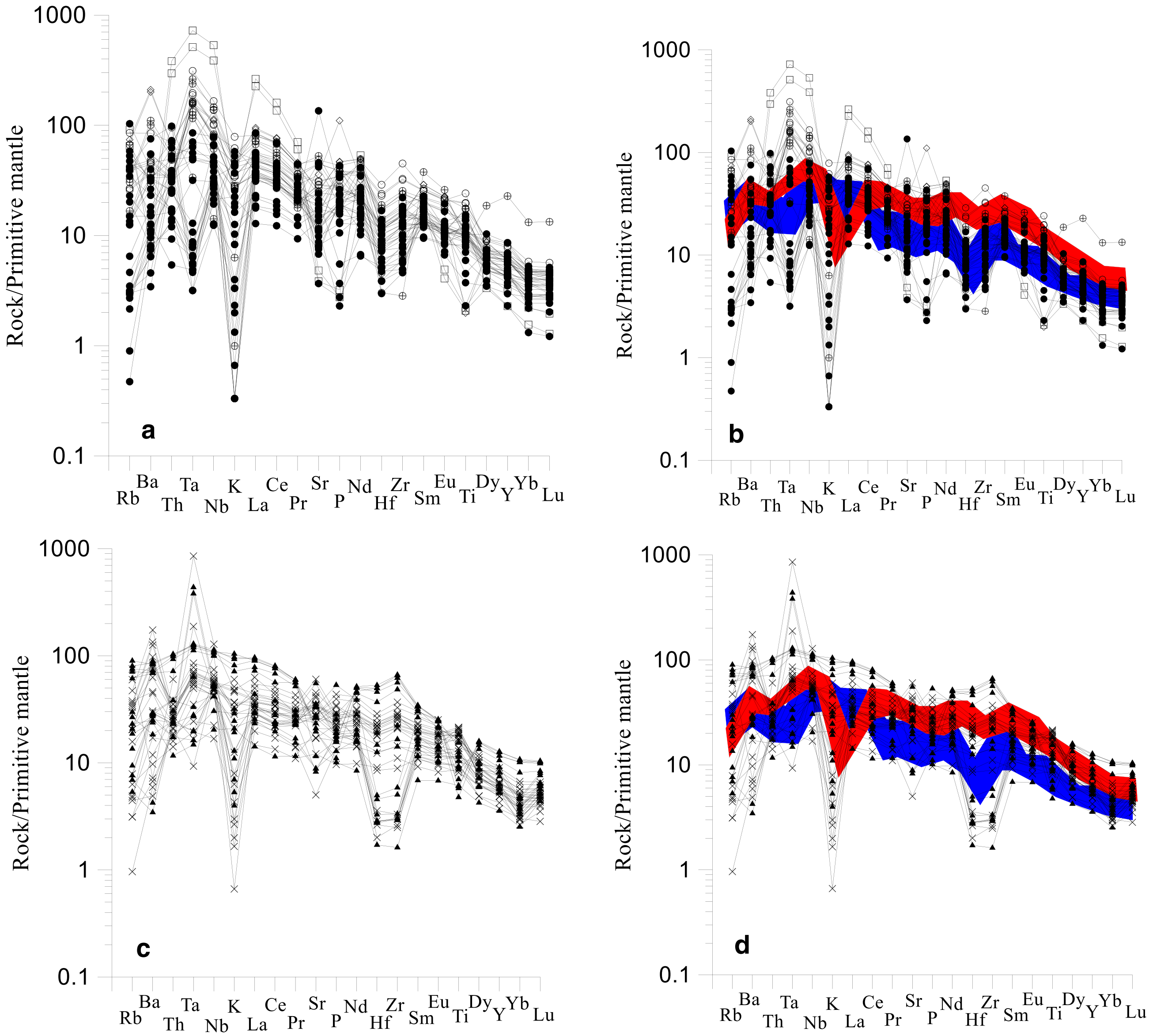

Fig. 7 Primitive mantle–normalized patterns of the lower Benue rift rocks, normalized values after Sun and Mc Donough (1989). **a**, **b** Volcanic series of LBR rocks. **c**, **d** Plutonic series of LBR rocks compared with St. Helena (red) and ascension rocks (blue). Symbols same as Fig. 4 above

submarine environment (Albian to Turonian ages) and subsequently exposed to tropical climatic system. This results to the decomposition of ferromagnesian and basic plagioclase minerals, migration, and absorption of calciferous components from the carbonaceous sediments to form the secondary minerals such as calcites, zeolites, and chlorite which are common in the rocks. Furthermore, Obiora and Charan (2010) were of the opinion that the secondary minerals were formed through possible interactions of hydrothermal waters resulting from saline waters in parts of the lower Benue rift. However, considering the diversification effect of the alterations in the LBR rocks, saline water which most times were localized in the area may not have accounted for all the alterations; therefore, the host rock compositions and alternating tropical climate must have contributed immensely in breaking down minerals and introducing calcites to such an intensively altered rocks. High LOI concentration (> 4%) in the rocks especially in the volcanic rocks from the central parts of the lower Benue rift which range from, 5.01 to 22.07 wt% is also evidence of the alteration. However, it is important to note that not all the rocks with LOI > 2% could result from alteration considering the presence of sulfide minerals in LBR rocks such as pyrites which can influence the concentration of LOI in rocks (Hikov 2013; Chukwu and Obiora 2018). It is

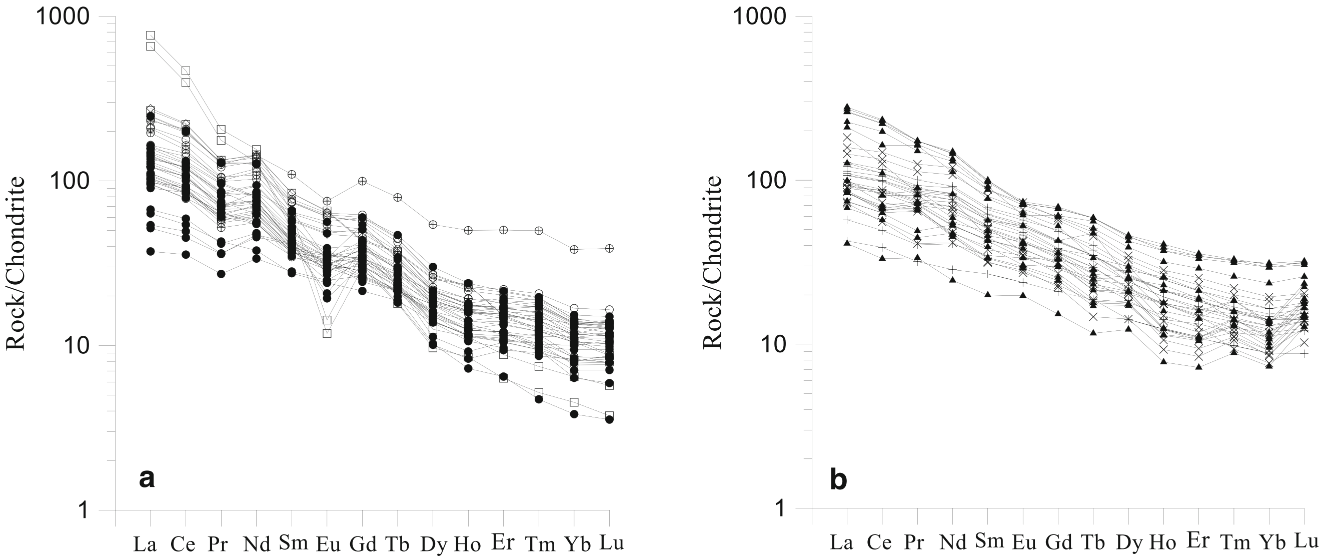

Fig. 8 Chondrite-normalized REE patterns of the lower Benue rift rocks, normalized values after Sun and Mc Donough (1989). Symbols same as Fig. 4 above

obvious from Fig. 5, which the LBR rocks show strong positive correlation between Zr, Hf, Nb, Ta, and Th (though immobile elements) while Rb and Ba show fairly good correlation. Conversely, Sr, Cr, Ni, and Co and major elements Si, Al, Na, K, and P show some degree of scatter which also suggest that their concentration could have been compromised by alteration, although some of the elements variation could result fractional crystallization. Sr could result from basic feldspar fractionation as seen in spidergrams (Fig. 7). This can also be seen in depletion of the mobile elements (Rb, K, and P) in the spidergrams. The excessive alterations of these rocks in LBR most probably resulted from diagenetic processes and chemical weathering in calcareous sediments which liberates carbonates in form of calcites.

Magma sources, fractional crystallization, and partial melting

The rocks of the lower Benue rift (LBR) are predominantly alkaline rocks as seen in Fig. 6, Zr/Ti versus Nb/Y variation diagram of Winchester and Floyd (1977) with fields as modified by Pearce (1996) with the tholeiites sparsely distributed and mostly in the pyroclastic rocks from the peripheral parts of the NE-LBR. As discussed earlier, the immobile incompatible elements (Zr, Ti, Ta, Y, Nb, and Hf) and REEs generally maintained uncompromising composition and their ratios can be reliably used to infer mantle conditions. The alkaline rocks in the LBR indicate enrichments in incompatible elements compared with the tholeiites as follows: in the volcanic

Table 1 Comparison of the rocks of the lower Benue rift with other mantle sources. Mantle data after Weaver (1991)

	This study								
	Volcanic series		Plutonic series		OIB			N-MORB	
	Alkaline Mean	Tholeiites Mean	Alkaline Mean	Tholeiites Mean	HIMU Mean	EMI Mean	EMII Mean	Depleted mantle Mean	Primordial mantle Mean
Zr/Nb	3.313564	6.224778	5.274538	9.062893	4.1	6.9	6.1	30	14.8
La/Nb	0.885546	1.704359	0.706991	0.66195	0.72	0.94	0.98	1.07	0.94
Ba/Nb	6.162604	9.897596	8.650373	4.77673	5.6	13.2	9.7	4.03	9
Rb/Nb	0.481248	1.022616	0.42149	0.194969	0.37	1.01	0.73	0.36	0.91
Th/Nb	0.090879	0.228519	0.068132	0.081132	0.09	0.112	0.134	0.07	0.117
Th/La	0.098172	0.106392	0.098325	0.207484	0.12	0.115	0.137	0.07	0.125
Ba/La	8.418968	5.871668	12.57193	12.69802	7.8	14.1	8.2	4	9.6

series, alkaline rocks have the ratios of $(La/Sm)_n$ 2.10–3.38 and $(La/Yb)_n$ 7.58–31.55 compared with the tholeiitic rocks $(La/Sm)_n$ 1.31 to 3.72 and $(La/Yb)_n$ 4.40 to 12.44 while in the plutonic series, alkaline rocks show ratios $(La/Sm)_n$ 1.71 to 4.1 and $(La/Yb)_n$ 5.33 to 19.91 compared with the tholeiitic rocks $(La/Sm)_n$ 1.59–1.66 and $(La/Yb)_n$ 4.83 to 5.13. On the other hand, the ratios of Zr/Nb and Y/Nb in the LBR rocks are lower in alkaline rocks compared with the tholeiitic rocks; in volcanic series, alkaline rocks has Zr/Nb of 0.66–5.61 and Y/Nb 0.03–0.56 compared with the tholeiites with Zr/Nb 6.34–7.98 and Y/Nb 0.94–2.27 while in the plutonic series, alkaline rocks have Zr/Nb 1.71–5.06 and Y/Nb 0.32–1.56 compared with the tholeiites with Zr/Nb 2.64–6.73 and Y/Nb 0.77–1.42. These ratios obviously indicate that the LBR rocks are not products of depleted MORB but intraplate magmatism derived from geochemically enriched mantle source regions (Table 1). High incompatible elements in spidergrams (Fig. 7) and LREEs compared with HREEs in LBR rocks which also reflected in $(La/Yb)_n$ ratios show garnet-bearing lherzolite source (Sayit and Goncuoglu 2009) since heavy rare earth elements exhibits high partitioning affinity into garnet. These can be attributed to magma generated within the upper mantle region (around the asthenosphere) since Wilson (1989) has shown that residual melt containing garnet are produced at depth of about 80 km. Coulon et al. (1996); Obiora and Charan (2010), and Chukwu and Obiora (2014) had reported similar compositions around the upper and lower Benue rifts. In Fig. 9, the volcanic and plutonic rocks of LBR show low, intermediate to high ratios of Y/Nb and Zr/Nb comparable with the South Atlantic Ocean islands basalts (SOIB) such as Vema, St Helena, Tristan, Ascension, Bouvet, Marion, Gough and Meteor rise (Le Roex et al. 2010).

High Nb/La ratio (> 1) indicates OIB-like source from asthenospheric mantle for basaltic magma while the lower ratio (< 0.5) indicates source from a lithospheric mantle (Abdel-Fattah et al. 2004). The ratios of Nb/La, in the LBR rocks which is greater than/equal to one suggest common source of the rocks, i.e., asthenospheric mantle. These ratios and REEs pattern (Fig. 8) indicate ocean island basalt of asthenospheric mantle source. The average ratios Ba/Nb, Zr/Nb, Rb/Nb, and Th/Nb (Table 1) of the predominant alkaline rocks and sparse tholeiites of the LBR are as follows: in volcanic rock series, alkaline are 6.16, 3.31, 0.48, and 0.09 respectively, while in tholeiitic rocks are 9.89, 6.22, 1.02, and 0.22 respectively; in plutonic series, alkaline rocks are 8.65, 5.27, 0.42, and 0.068 respectively while tholeiitic rocks are 4.77, 9.06, 0.19, and 0.081 respectively. These show that most of alkaline rocks are comparable with HIMU reservoir and enriched mantle source while the tholeiites are mostly enriched mantle (EMI and EMII) source (Weaver 1991) (Table 1). The LBR rocks which are predominantly composed of alkaline rocks are generated by plume activities (Fig. 10) in

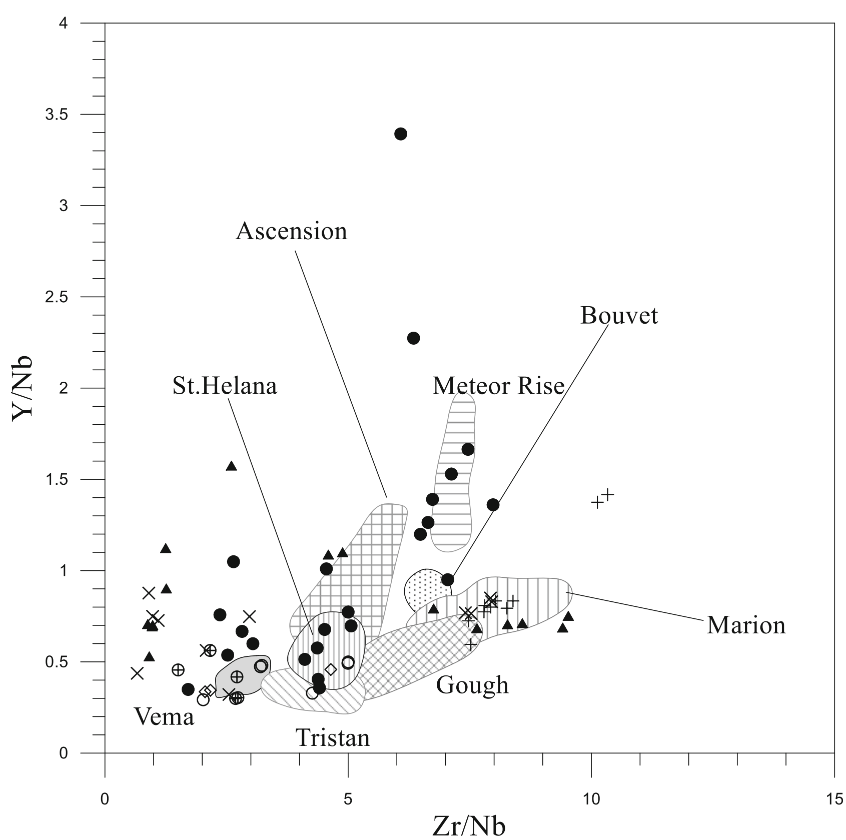

Fig. 9 Comparing the ratios of the rocks of the lower Benue rift with the rocks of the south Atlantic ocean. Data for Southern Atlantic Ocean basalts are from Le Roex et al. (2010). Symbols same as Fig. 4

similar plume that produced the alkaline rocks of St Helena basalts (HIMU reservoir), while the tholeiitic rocks are generated similar to the Ascension Island in mid-oceanic ridge by their close relationship in space and time.

The log-log diagram of Zr/Y against Nb/Y (Fitton et al. 1997) (Fig. 10) indicates that the rock suits in the LBR are products of plume related. Rocks which plot below the ΔNb line are said to be derived from shallow depleted source (DM) or from subduction related or plume melts contaminated by continental crust/sub-continental lithosphere. The LBR rocks fall just above the ΔNb line in the area of the mantle plume and trends along the recycled components (REC) around the OIB source. This also attests to the heterogeneous nature of the LBR rocks made up of recycled subducted ocean crust (HIMU), lower continental crust (CC) (EMI), and upper CC or marine sediment (EMII) (Zindler and Hart 1986) as shown by upwards trend along the N/Y axis (Fig. 10). Unlike the N-MORB sources of rocks from the upper parts of the Benue rift as shown by Coulon et al. (1996) and Maluski et al. (1995), this work has indicated that the rocks of the lower Benue rift result from within plate plumes. The plume source of the LBR rocks as shown in this work also aligned with the existence of a common plume "plume 911" of Burke (2001), which relates to the formation of the alkaline rocks of Jos Plateau, Nigeria, the Benue Rift rocks, and the hot Cameroon line magmatism during the rotation of the super continent Gondwana land from the north 213 Ma to the south 30 Ma.

The depletion of the mobile large ion lithophile elements (LILE) such as Ba, K, Rb, and Sr (Fig. 7) especially in rocks with LOI < 3 cannot be attributed to the effect of alteration rather they reflect processes of crystallization of individual minerals and source characteristics. Green (1980) has shown that Rb can easily replace K in amphiboles in melts that are basaltic in composition. Hence, the depletion of Rb and K in the LBR rocks depicts availability of amphiboles (hornblende) in the source. Furthermore, the depletion of K is related to the formation of leucites in the initial stage of differentiation of the melt but easily substituted by analcite which is very unstable especially in such tropical weathering activities. The depletion of P, Sr and Ti (Fig. 7) in the LBR rocks indicates substantial fractionation/accumulation of apatite plagioclase and titano-magnetite respectively in basalts. The partial enrichment in Sr (Fig. 7b) indicates that plagioclase is availability in the melt; Ta and Hf depletion reflect removal of zircon, ilmenite, and sphene from the melt. The three multi-element patterns of the LBR rocks indicate that they are genetically related and result through partial melting and fractional crystallization. The minor elemental behaviors in multi-element patterns also show probably mixed melts from heterogeneous sources. The linear trend along the ΔNb direction (Fig. 10) also supports partial melting of enriched garnet mantle source (Fitton et al. 1997; Revillon et al. 2000; Escuder Viruete et al. 2007). The generation of the alkaline and tholeiitic rocks in the LBR is depended mainly on variable degrees of partial melting as a

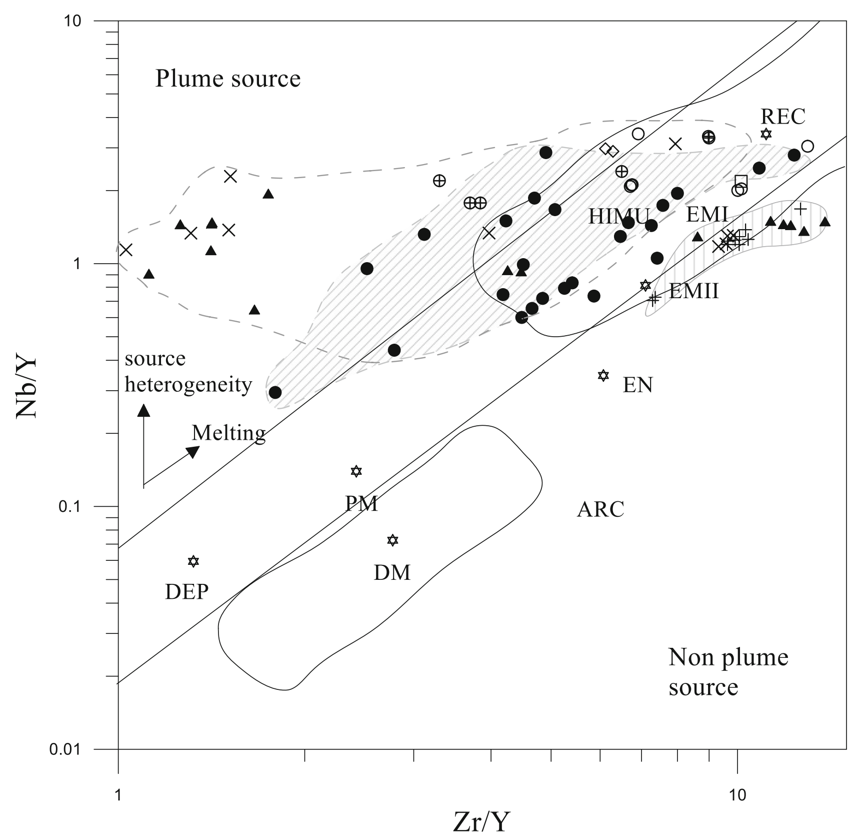

Fig. 10 Nb/Y versus Zr/Y log-log diagram after Fitton et al. (1997) for discrimination of plume and non-plume of the lower Benue rocks. The rocks plots within the tramlines defined by the Icelandic mantle plume lavas. Primitive mantle (PM), depleted mantle (DM), enriched components (EN), and recycled components (REC). Symbols same as Fig. 4

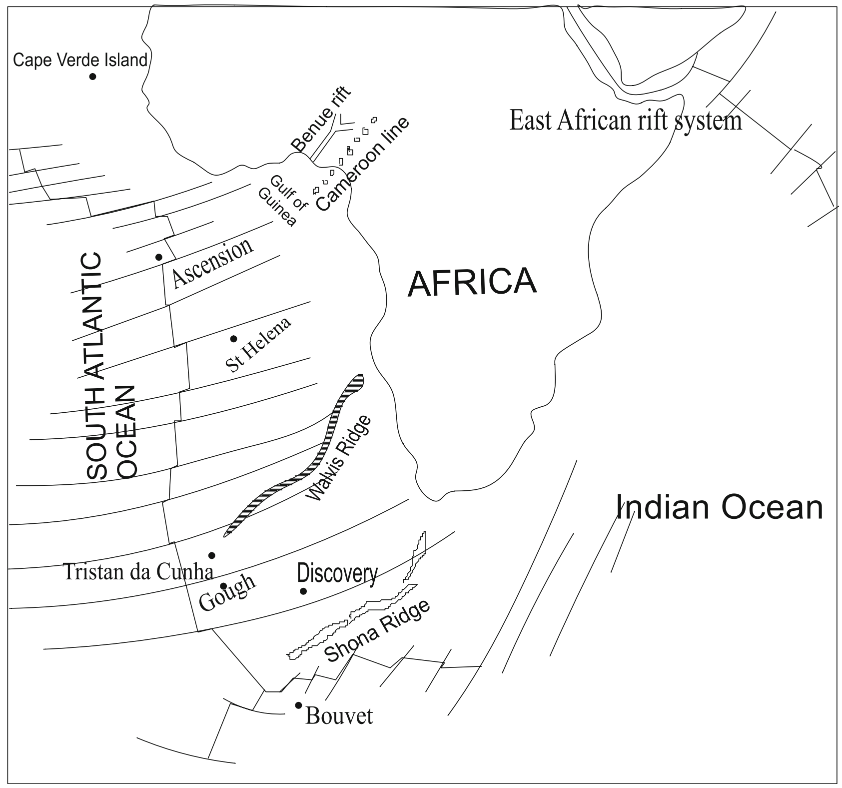

Fig. 11 The relationship between the rocks of the lower Benue rift and associated rocks of the south Atlantic ocean rocks

result of pressure changes similar to the younger rift system of the east African type in contrast to the work of Coulon et al. (1996) and Maluski et al. (1995) who opined that that only the alkaline rocks of the lower Benue rift were resulted by partial melting while the tholeiites by heat transfer. Furthermore, alkaline rocks are product of low degrees partial melting and high pressure unlike the tholeiitic rocks formed by high degrees partial melting and low pressures (Obiora and Charan 2011; Keppie et al. 1997). Hence, by plume model of Best and Christiansen (2001), the alkaline rocks are product of thick lithospheric plates similar to the St. Helena, Azores, Tristan da Cunha, Gough and Shona rocks south Atlantic Oceans (Figs. 9 and 11) while tholeiitic rocks are generated in thinner lithosphere away from the core of the Benue rift lithosphere comparable with the Mid-oceanic ridge axis such as Ascension, Grand Canary, and the Bouvet islands (Fig. 9). Chukwu and Obiora (2018) have discussed further on this in parts of the lower Benue rift.

The dominant alkaline affinity in the lower Benue rift is an indication of extension setting as oppose to andesitic magma which are common in subduction zones. The tectonic

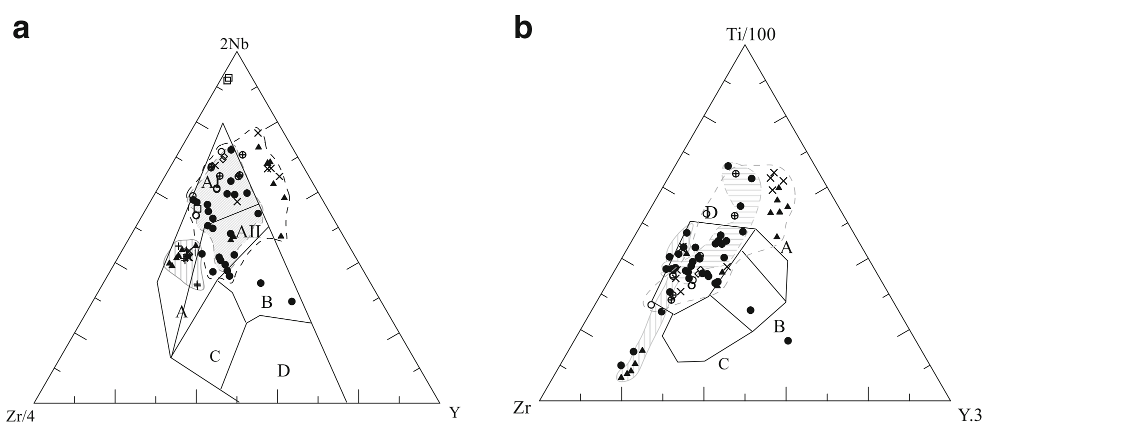

Fig. 12 **a** Plots of the lower Benue rocks in Zr-Nb-Y diagram of Meschede (1986). AI is within plate alkaline basalts, AII is within-plate alkaline basalts and within-plate tholeiites, B is E-type MORB, C is within-plate tholeiites and volcanic arc basalts, D is N-type MORB and volcanic arc basalts. **b** Zr–Ti–Y diagram of Pearce and Cann (1973). D is within plate basalts (OIB and continental basalts), A is island-arc tholeiites, C is calc-alkaline basalts, B is MORB, island-arc tholeiites, and calc-alkali basalts. Symbols same as Fig. 4

variation diagrams (Fig. 12a and b) clearly show that the rocks of the LBR are product of within plate alkaline basalt and within plate tholeiitic basalts, similar to the east Africa's rift system. The two magma types are well shown in the diagram of Meschede (1986), Zr–Nb–Y where the alkaline rocks plot in within-plate alkali basalts field while the tholeiitic rocks plot in the within-plate tholeiites fields (Fig. 8a). On the Zr–Ti–Y diagram of Pearce and Cann (1973), the rocks fall in the field of within-plate basalts (Fig. 8b). This study did not encounter subduction related rocks rather intraplate magmatism. The use of immobile elements in this work clearly indicates that the LBR rocks are products of within-plate (plume) intracontinental rifting-related environment, similar to the rocks of the south Atlantic ocean rocks (St. Helena, Azores, Tristan da Cunha, Iceland, and Ascension) and the East African rift system (see Fig. 11), which is in line with the views of Olade (1979), Hoque (1984), Obiora and Charan (2010, 2011), and Chukwu and Obiora (2014, 2018).

Conclusions

The study indicates that the igneous rocks in the lower Benue rift are regionally related and originate from primary magma by partial melting and fractional crystallization. Though the rocks are highly altered, incompatible elements and REEs still preserve the petrogenetic characteristics of the rocks. They are composed of intermediate, basic to ultrabasic rocks. The rocks are grouped as volcanic series and plutonic series with rock types showing wide diversity from gabbros, basalts, dolerites, diorites, tracybasalts, trachytes, and basaltic volcaniclastic rocks (pyroclastic rocks). They occur in folded sediments of Albian to Turonian ages. The plutonic series are mostly wide spread in the all the areas of the lower Benue rift. The field and geochemical analyses show evidences of alterations which is predominant in the volcaniclastic rocks around the central lower Benue rift (C-LBR). The less mobile elements coupled with the REEs show that the igneous rocks in the lower Benue rift are generally alkaline with sparse tholeiites. Further analysis of the HFSE ratios shows that the alkaline rocks are associated from HIMU mantle sources while the tholeiites are generated from EMI and EMII sources. The rocks of the LBR are regionally cogenetic and the source is heterogeneous. Nb/Y–Zr/Y variation diagrams show that the rocks are products of plume magmatism similar to the plume that generated the rocks of the south Atlantic oceans and the east African rift rocks. The age migrations and differences can be explained by the "911 plume" model of Burke (2001) which relates the activities of the opening of the rift, alkaline rocks of the Jos province, and the Cameroon line rocks. The rocks were formed in within-plate tectonic settings and consistent with the earlier work such as Coulon et al. (1996), Obiora and Charan (2010), and Chukwu and Obiora (2014, 2018).

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