Acta Geochim (2020) 39(3):337–354
https://doi.org/10.1007/s11631-019-00365-7

ORIGINAL ARTICLE

Geochemical characteristics and origin of the Neoproterozoic high-K calc-alkaline granitoids in the northern part of Mandara hills, northeastern Nigeria

Musa B. Girei[1,2] · **Tavershima Najime**[3] · **Paul O. Ogunleye**[4]

Received: 2 February 2019 / Revised: 24 June 2019 / Accepted: 12 July 2019 / Published online: 24 July 2019

Abstract The high-K calc-alkaline granitoids in the northern part of the Mandara Hills are part of the well-exposed post-collisional plutons in northeastern Nigeria. The calc-alkaline rock association consists of quartz monzodiorite, hornblende biotite granite, biotite granites and aplite which intruded the older basement consisting mainly of low-lying migmatitic gneisses and amphibolites during the Neoproterozoic Pan-African Orogeny. Petrological and geochemical studies have revealed the presence of hornblende, iron oxide, and metaluminous to slightly peraluminous characteristics in the granitoids which is typical of I-type granite. The granitoids are also depleted in some high field strength elements (e.g. Nb and Ta) as well as Ti. Plots of Mg# versus SiO_2 indicate that the granite was derived from partial melting of crustal sources. Lithospheric delamination at the waning stage of the Pan-African Orogeny possibly triggered upwelling of hot mafic magma from the mantle which underplated the lower crust. This, in turn, caused partial melting and magma generation at the lower to middle-crustal level. However, the peculiar geochemical characteristics of the quartz monzodiorite especially the enrichment in compatible elements such as MgO, Cr, and Ni, as well as LILE element (e.g. K, Ce, Cs, Ba, and Sr), signify that the rock formed from an enriched upper mantle source. The emplacement of high-K granites in the Madara Hill, therefore, marked an important episode of crustal reworking during the Neoproterozoic. However, further isotopic work is needed to confirm this model.

Keywords Calc-alkaline · I-type granitoids · Pan-African · Mandara hills · Nigeria

1 Introduction

Orogenic belts typically contain large batholiths of granitoids plutonism covering several kilometers. The emplacement of the granitoids can be linked to collisional or subduction geodynamic process (e.g. Moyen et al. 2016). High-K calc-alkaline granitoids are especially prevalent in post-Archean orogenic belts (Roberts and Clemens 1993; Liégeois et al. 1998; Neves et al. 2000; Bonin 2004). Despite recent advances in modeling magmatic processes and identification of source materials through trace element geochemistry, isotope systematic, and experimental petrology, the origin of high-K calc-alkaline I-type granitoids are still conjectural (e.g. Roberts and Clemens 1993; Liégeois et al. 1998; Clemens 2012; Castro 2004; Brown 2013). Most of the uncertainties lie in the determination of the sources of granitoids (e.g. Castro 2004, 2014). This is more so as granitoids source constraints, based on whole rocks trace element patterns, radiogenic isotopes of lithophile elements (e.g. Rb–Sr and Sm–Nd), and Pb–Pb isotope, often provide somewhat ambiguous information (e.g. Moyen et al. 2016). Chappell and White (1974) coined the term I-type to describe granitoids derived from igneous protoliths, which contain a

✉ Paul O. Ogunleye
ogunleyepo@gmail.com

[1] State Key Laboratory of Geological Processes and Mineral Resources, Faculty of Earth Resources, China University of Geosciences, Wuhan 430074, China

[2] Department of Geology, Faculty of Earth and Environmental Sciences, Bayero University, Kano, Nigeria

[3] Department of Geology, Ahmadu Bello University, Zaria, Nigeria

[4] Centre for Energy Research and Training, Ahmadu Bello University, P. M. B. 1014, Zaria, Nigeria

moderate amount of Al_2O_3 and Na_2O. In general, the melting of igneous and metaigneous source rocks has remained the most accepted model for the genesis of I-type granitoids (e.g. Clemens et al. 2011). However, the determination of the most suitable igneous and metaigneous protoliths of such granitoids has been fraught with many uncertainties (e.g. Clemens et al. 2011; Castro 2004, 2014). According to Roberts and Clemens (1993) and Liégeois et al. (1998), about 30–45% of the known granitoids show high-K calc-alkaline affinity. It is therefore imperative to unravel the origin and condition of formation of such granitoids which have remained conjectural and inconclusive. In this study, we examined the geochemical features and attempted to determine the origin of the Pan-African high-K calc-alkaline I-type granitoids from the northern part of the Mandara Hills, northeastern Nigeria in the light of new sets of geochemical data. Although isotope geochemistry remains the most robust tool of constraining magma source, major and trace geochemistry can also provide an important constraint on the magma source of granite (e.g. Frost et al. 2016).

2 Regional geology

The Nigerian Pan-African Basement Complex is part of the Neoproterozoic Trans-Saharan orogenic belt which extends from the Hoggar Massif of Algeria into Nigeria (Fig. 1). This Neoproterozoic (Pan-African) belt is believed to have formed by the amalgamation of allochthonous terranes between the West African Craton, Congo Craton and Pharusian belt of the Tuareg Shield between 700 and 580 Ma (Ajibade and Wright 1989; Caby 1989; Ferré and Caby 2007). To the north of the Nigerian Pan-African Province lies the Hoggar Province and to the south lies the Borborema Province. All the three provinces share similar lithological units and have experienced contemporaneous thermotectonic event during Neoproterozoic (Caby 1989; Dada 2008). Based on field evidences (e.g. Dada et al. 1995; Oyawoye 1972; McCurry 1976; Rahaman 1976; Fitches et al. 1985; Ajibade et al. 1987); structural studies (Black et al. 1994; Ferré et al. 1996); metallogeny (Woakes et al. 1987) and remote sensing studies (Ananaba and Ajakaiye 1987), the Nigerian Pan-African Basement Complex has been divided into two contrasting terranes namely the western and the eastern terranes (e.g. Ferre´ et al. 1997). The western terrain corresponds to an area west of Jos Plateau and composed of Archaean tonalites–trondhjemite–granodiorites suites which are largely overlain by the N–S trending supracrustal metasediments (e.g. McCurry 1976; Turner 1983). The metasediments are loosely divided into “Older Metasediments” and “Younger Metasediments” (McCurry 1971). The so-called Older Metasediments generally occur as minor high-grade metasedimentary units of amphibolite facies metamorphic grade that is believed to have been formed at about 2.5 Ga (McCurry 1971). They vary in composition and include high-grade schist, arkosic quartzite, and highly metamorphosed calc-silicate rocks that occur as relics in gneisses and migmatites (McCurry 1971; Oyawoye 1972; Danbatta 2008). The “Younger Metasediments” on the other hand, are low-grade metasedimentary and metavolcanic rocks that depict greenschist facies metamorphic grade (Turner 1983; Fitches et al. 1985; Ferré et al. 2002) and are composed mainly of psamatic schist, pelitic and semipelitic schist, metasandstone, metaconglomerate, quartzite, marble, mafic to ultramafic rocks, acid to intermediate volcanic rocks, calc-silicate rocks and occasionally, banded iron formation (Turner 1983; Danbatta 2008). By contrast, the eastern terrane which corresponds to an area east of Jos Plateau is composed of high-grade metamorphic rocks comprising gneisses, migmatites, and metapelites (Ajibade et al. 1987; Ferré et al. 1996, 2002). Metamorphism in this region has reached upper amphibolite and granulite facies condition in places (e.g. Ferré and Caby 2007). Both the western and the eastern terranes are intruded by Neoproterozoic granitoids generally dubbed as Older Granites to distinguish them from the Mesozoic anorogenic alkaline granitoids otherwise known as “Younger Granites”. In addition, the eastern terrane has also experienced a relative instability during the Mesozoic and Tertiary which culminated in the development of deep sedimentary basins, intense volcanism and intervening basement swells where erosion has given considerable surface relief (Abaa and Najime 2006; Lar et al. 2013).

3 Geological setting and petrography

The Mandara hills form part of the geologically unexplored Hawal Massif in northeastern Nigeria (Fig. 1). The Massif is bordered in the north by the Cretaceous Chad Basin and to the west by the Gongola arm of the Benue Trough. To the east, the Massif extends into Cameroon. The area is underlain by low-lying migmatitic gneisses, amphibolites, quartz monzodiorites, granites, aplites, and pegmatites (Fig. 2). The migmatitic gneiss outcrops commonly at the margins of the hilly granites where sharp contact relationship is more common than gradational. The rock is believed to have been partially migmatized by the intrusion of sialic magma resulting in distinct felsic and mafic bands of few millimeters to tens of centimeters (Baba et al. 2006). The amphibolite occurs as small pockets and lenses within the migmatitic gneiss in the southeastern part of the study area, especially near Atagara village. Ekwueme (2003) reported the occurrence of amphibolite as lenses within the

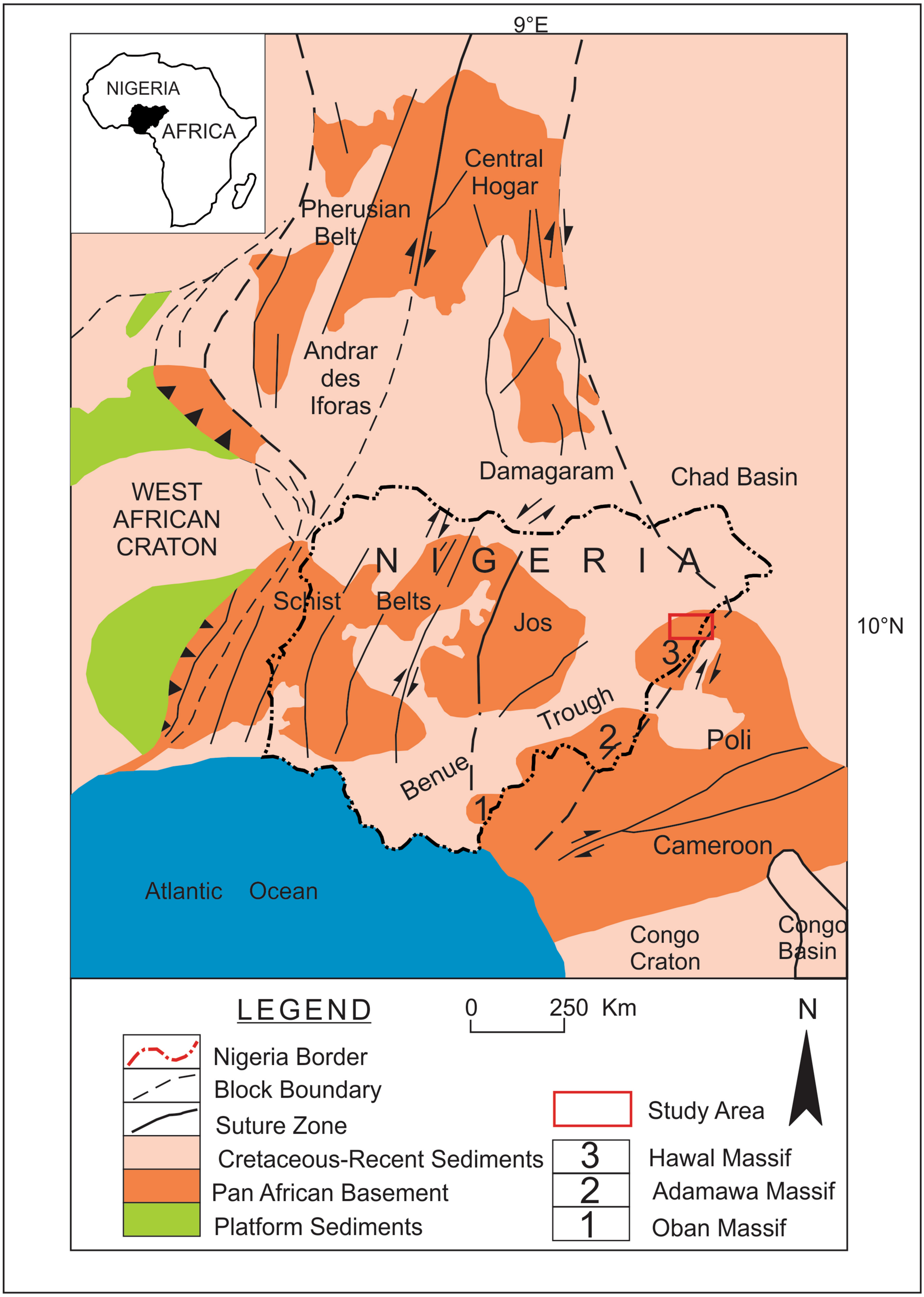

Fig. 1 Geological sketch map of the Hoggar-Air-Nigeria Province showing the location of Hawal Massif (adapted from Haruna et al. 2013)

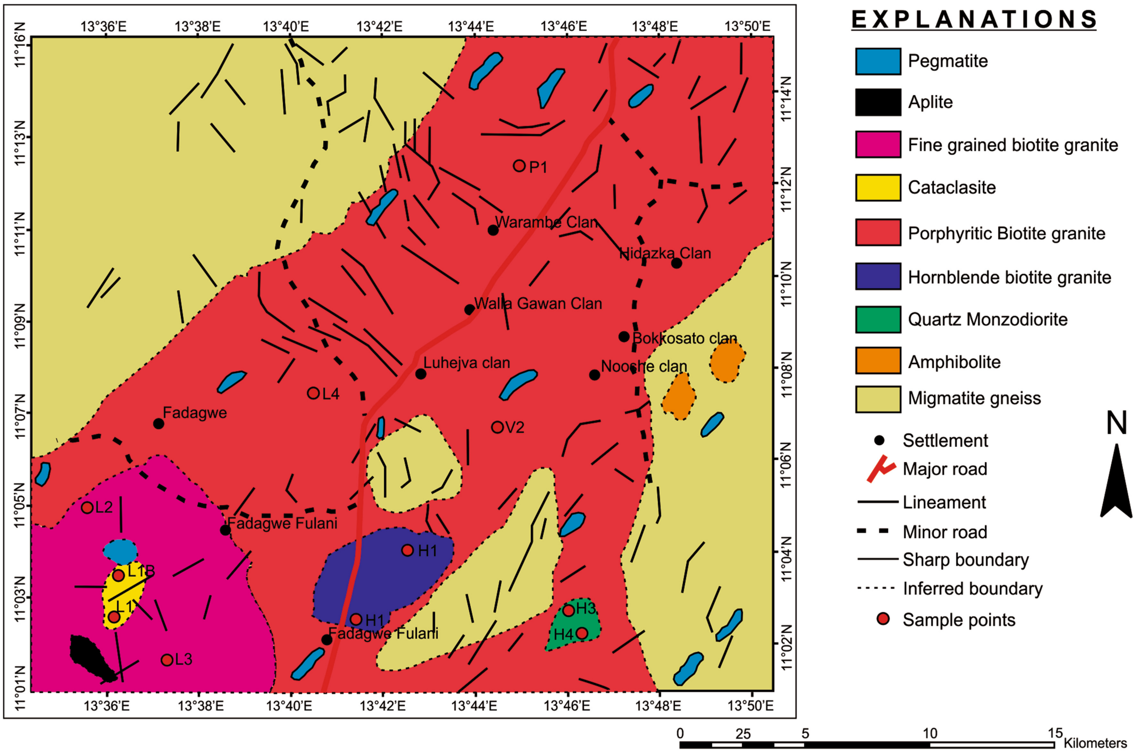

Fig. 2 Geological map of the study area

gneisses of Oban Massif in southeastern Nigeria. The occurrence of small bodies of amphibolites interleaved with gneisses has also been reported in central Nigeria (Dada 1999) and in parts of Borborema Province, northeastern Brazil (Carlos et al. 2014).

The granitoids constitute part of the Neoproterozoic (ca. 600–580 Ma) suites that are well exposed in eastern Nigeria (Ferré et al. 2002; Goodenough et al. 2014). They vary in composition from quartz monzodiorite to granite sensu stricto (Fig. 3). The occurrence of quartz monzodiorite is restricted to the southeastern part of the study area near Hambagda village. The rock is generally melanocratic, medium-grained, highly weathered and poorly exposed. Petrographic studies indicate that the rock is made up of plagioclase (30%), quartz (11%), and microcline (20%). Ferromagnesian minerals are biotite (15%), pyroxene (6%), and hornblende (14%) while garnet and iron oxide are the only accessory minerals observed in the rock. Plagioclase is slightly calcic based on its moderate extinction angle (30°–40°). The mineral occurs as subhedral to euhedral crystals characterized by Carlsbad twinning. Quartz is typically anhedral and colorless with high relief. Microcline ranges from 2 to 3 mm in size and exhibits cross-hatched twining. Biotite occurs as brown, subhedral crystal with high relief while hornblende occurs as anhedral crystal up to 3 mm in size. The latter mineral is pleochroic from light green to leaf green and exhibits a two-directional set of cleavages at angles of 56° and 124°.

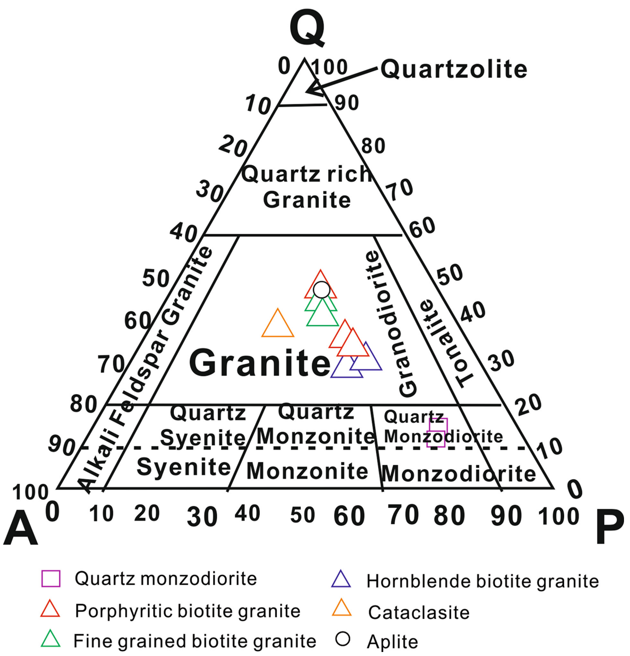

Fig. 3 Modal composition of the granitoids plotted on the QAP diagram of Streckeisen (1976)

By contrast, the granite varies in texture and composition and consists of biotite granite, hornblende biotite granite, and tectonized granite (cataclasite). Biotite granite is the most dominant of the granitoids in the area. On the basis of texture, two different varieties namely: porphyritic and fine-grained biotite granites have been distinguished. Mineralogically, the biotite granite is made up of quartz (32%), microcline (27%), plagioclase (21%), and biotite (19%). Apatite, zircon and iron oxide are the common accessory minerals in this granite. The proportion of these minerals varies slightly with the coarse-grained variant of the rock containing more biotite and plagioclase. The plagioclase crystals in the biotite granite are largely sodic based on their low extinction angle (15°–20°) while biotite occurs as subhedral crystal occasionally poikilitic and characterized by inclusion of apatite.

Hornblende biotite granite is restricted to the south–western part of the area, especially near Hambagda village where sharp contact relationship between the rock and porphyritic biotite granite has been recorded (Fig. 4a). Mineralogically, the rock is made up of quartz (30%), plagioclase (24%), microcline (25%), hornblende (11%) and biotite (9%) while apatite and iron oxide constitute the bulk of the accessory minerals. Quartz is characteristically anhedral, colorless and has high relief (Fig. 5a–f). Plagioclase occurs as subhedral crystal with low relief and albite twinning. Hornblende is the major ferromagnesian mineral in the rock; it occurs as anhedral crystals and is pleochroic from light green to leaf green while biotite occurs as subhedral crystals with moderate relief. Minor rocks are pegmatite and aplite. Pegmatite constitutes the bulk of the minor rocks. On the basis of field relation and mode of occurrence, two types of pegmatite have been mapped. The first category of pegmatite occurs as large, zoned, oval-shaped bodies trending in E–W direction. This pegmatite occurs mainly in the northern part of Liga hills forming a morphological unit rising about 50 m above the surrounding plain. A small occurrence of the pegmatite has been recorded in the western part of the hills. The second category of pegmatite occurs as dikes. They strike mainly in the NE–SW direction concordant with the major structural trend of the area. The pegmatites in the study area have been characterized on the basis of field occurrences and geochemical data (Girei et al. 2017). Aplite occurs as small lensoid dikes trending roughly in NNW–SSE. The fresh outcrop is leucocratic (pink), and where weathered, it

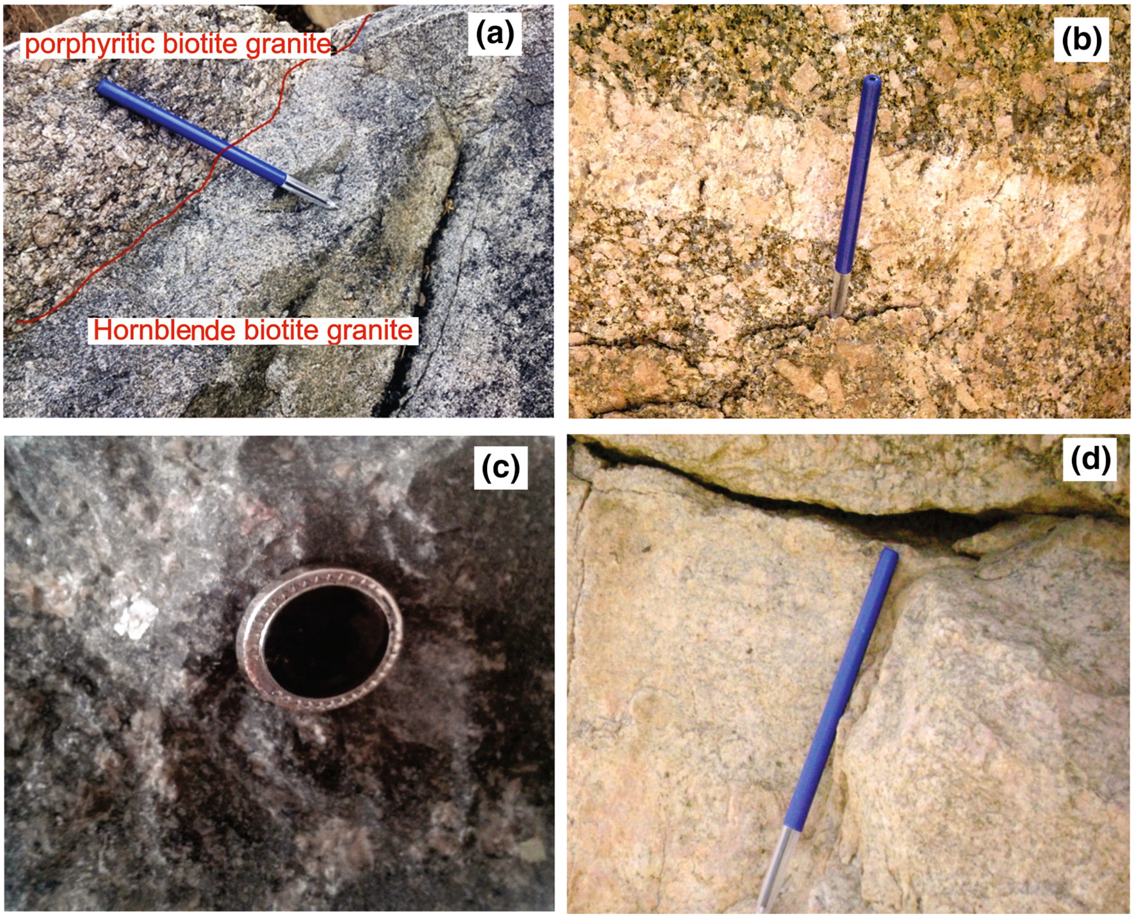

Fig. 4 Field photographs showing: **a** sharp contact between hornblende biotite granite and porphyritic biotite granite; **b** porphyritic biotite granite with aplitic dikes; **c** hand specimen of tectonised granites (cataclasite); and **d** fine-grained biotite granites

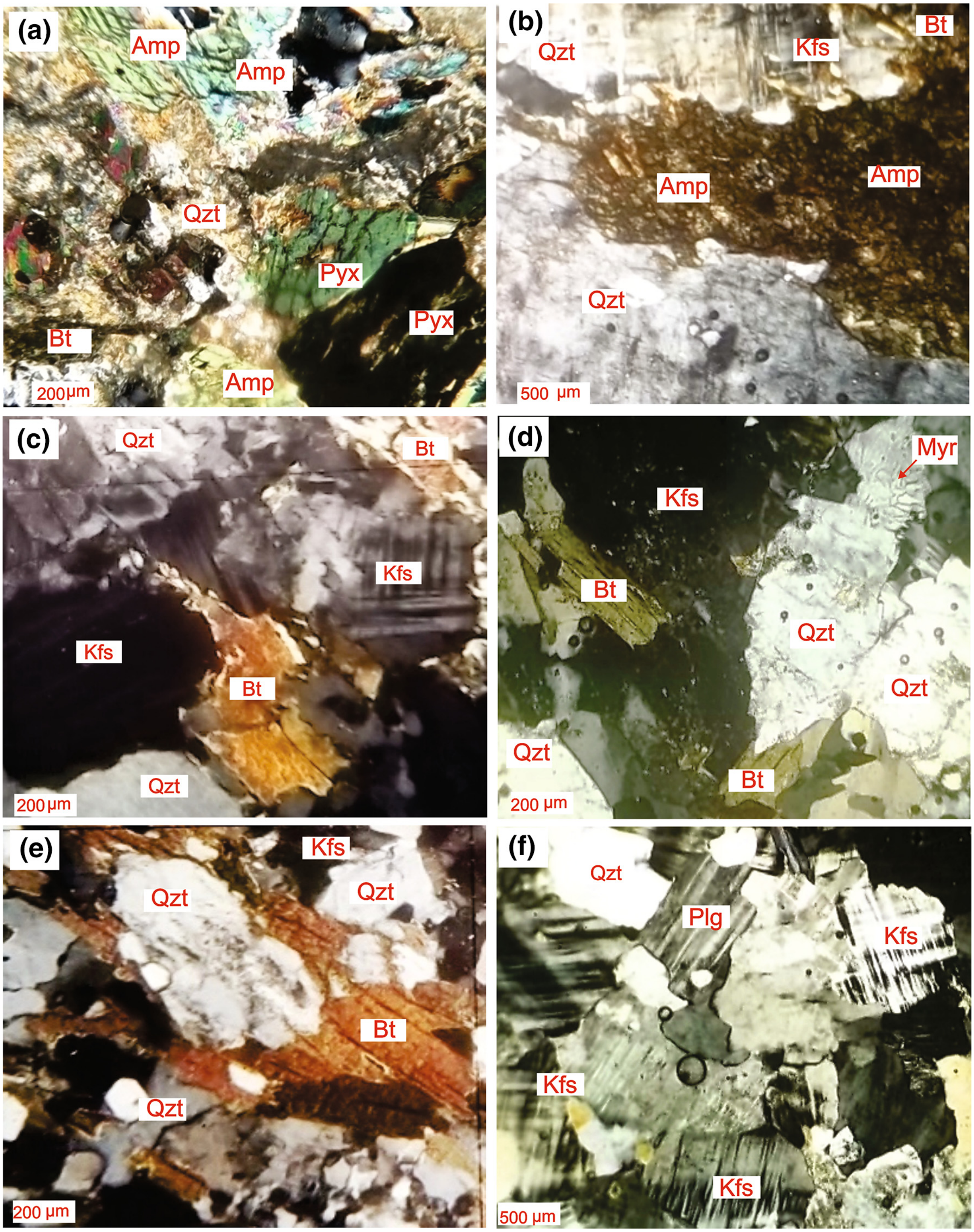

Fig. 5 Photomicrograph of **a** quartz monzodiorite; **b** hornblende biotite granite; **c** porphyritic biotite granite; **d** tectonised granites (cataclasite); **e** fine grained biotite granites; **f** aplite. Note: all photomicrographs were taken under cross-polarized light. Pyx = pyroxene, Kfs = K-feldspars; Amp = amphiboles, Qtz = quartz; Plg = plagioclase

is reddish brown. Microcline, quartz, and plagioclase form the essential minerals while biotite, apatite, and iron oxide are the accessory minerals in the rock (Fig. 5f).

4 Sample handling and analysis

Fresh representative samples of mappable lithologic units were pulverized to fusible fineness in a tungsten carbide mill at the Department of Geology, Ahmadu Bello

Table 1 Major elements composition and calculated CIPW norm of granitoids from the northern part of Mandara Hills, northeastern Nigeria

Major oxide (in wt%)	Quartz monzodiorite		Hornblende biotite granite		Porphyritic biotite granite			Cataclasite		Fine grained biotite granite		Aplite
Samples	H4	H3	H2	H1	L4	V2	P1	L1	L1B	L3	L2	L9
SiO_2	55.86	56.12	68.85	67.44	74.13	69.88	72.67	75.87	74.86	76.20	77.47	77.57
TiO_2	1.57	1.61	0.43	0.46	0.30	0.46	0.39	0.25	0.37	0.19	0.03	0.07
Al_2O_3	15.20	14.58	14.23	14.11	12.83	13.70	12.72	11.02	11.68	11.79	11.25	11.47
Fe_2O_3	5.46	5.52	2.77	2.64	1.66	2.87	1.27	2.34	2.45	0.86	0.74	0.67
FeO	4.11	4.83	2.50	2.43	1.49	2.59	1.86	2.11	2.16	0.72	0.66	0.53
MnO	0.14	0.12	0.04	0.05	0.05	0.05	0.03	0.03	0.02	0.01	0.01	0.01
MgO	4.69	4.80	0.80	0.94	0.28	0.71	0.36	0.08	0.10	0.05	0.03	0.02
CaO	4.99	5.62	2.34	2.12	1.02	2.11	1.72	0.74	1.11	0.73	0.73	0.56
Na_2O	2.89	2.82	3.88	3.77	3.62	3.61	3.55	2.97	3.02	3.49	3.52	3.44
K_2O	2.79	2.25	3.63	4.06	4.19	3.85	3.93	3.88	4.14	4.02	3.94	3.88
P_2O_5	0.26	0.31	0.16	0.13	0.13	0.16	0.07	0.02	0.03	0.01	0.01	0.01
LOI	0.92	0.27	0.33	0.85	0.29	0.21	0.94	0.36	0.28	1.11	0.83	0.86
Total	99.88	99.85	99.96	99.00	99.99	100.20	99.51	99.67	100.22	99.18	99.22	99.09
Normative composition												
Q	10.21	11.62	25.87	23.68	34.36	28.24	32.34	41.38	38.38	38.76	40.14	41.36
C	0.00	0.00	0.05	0.00	0.80	0.14	0.00	0.64	0.28	0.39	0.00	0.62
Or	16.49	13.30	21.45	23.99	24.76	22.75	23.23	22.93	24.47	23.76	23.28	22.93
Ab	24.45	23.86	32.83	31.90	30.63	30.55	30.04	25.13	25.55	29.53	29.79	29.11
An	20.26	20.48	10.56	9.59	4.21	9.42	7.17	3.54	5.31	3.56	3.26	2.71
Di	2.19	4.24	0.00	0.07	0.00	0.00	0.77	0.00	0.00	0.00	0.26	0.00
Hy	13.86	14.28	3.66	3.92	1.66	3.49	2.28	1.78	1.62	0.44	0.51	0.37
Mt	7.92	8.08	4.02	3.83	2.41	4.16	1.84	3.39	3.55	1.25	1.07	0.97
Il	2.98	3.06	0.82	0.87	0.57	0.87	0.74	0.48	0.70	0.36	0.06	0.13
Ap	0.62	0.73	0.38	0.31	0.31	0.38	0.17	0.05	0.07	0.02	0.02	0.02
Sum	98.98	99.65	99.64	98.16	99.71	100.00	98.57	99.31	99.94	98.07	98.39	98.23

University, Zaria, Nigeria. The pulverized samples were thereafter shipped to the ACME analytical laboratory, Vancouver, Canada for major oxides and trace elements analysis. Major oxides were analyzed using inductively coupled plasma atomic emission spectrophotometry (ICP–AES). Analytical precisions vary from 0.1 to 0.04% for the major oxides. Inductively Coupled Plasma Mass Spectrometry (ICP–MS) was used to analyze for the trace element composition of the rock samples. The sample preparation procedure involves the fusion of 0.2 g of each pulverized rock sample with 1.5 g of $LiBO_2$, followed by the dissolution of the mixture in 10 mL of trioxonitrate (V) acid (HNO_3) prior to the analysis. The rare earth elements (REE) were also analyzed using conventional ICP–MS analytical techniques. For the determination of REE, about 0.25 g of each pulverized rock sample was dissolved in a mixture of 5 mL of perchloric acid ($HClO_4$) and trioxonitrate (V) acid (HNO_3) and 15 mL of hydrofluoric acid (HF) prior to the analysis. Analytical precisions for trace elements vary from 0.1 to 0.4 ppm and for rare earth elements, the precisions vary from 0.01 to 0.4 ppm.

5 Major oxides and trace elements geochemistry

The chemical compositions of the rocks from the study area are presented in Tables 1 and 2. Silica (SiO_2) contents range from 55.86 to 77.56 wt% in the granitoids with the lowest content of SiO_2 (56.12–55.86 wt%.) recorded in the quartz monzodiorite while the highest content (77.56 wt%) is recorded in the aplite. The quartz monzodiorite and granite define the regular trend of liquid from 55 to 77 wt% SiO_2 similar to some high-K calc-alkaline suites from central Hoggar as reported by Acef et al. (2003). Expectedly, the quartz monzodiorite has a high content of MgO, CaO, and Fe_2O_3 relative to the granite. The value of MgO in the quartz monzodiorite is comparable to the value reported by Neves et al. (2000) in the quartz diorite from

Table 2 Trace elements composition of granitoids from the northern part of Mandara Hills Northeastern Nigeria

Trace element (ppm)	Quartz monzodiorite		Hornblende biotite granite		Porphyritic biotite granite			Cataclasite		Fine grained biotite granite		Aplite
	H4	H3	H2	H1	L4	V2	P1	L1	L1B	L3	L2	L9
Rb	81.20	79.70	126.70	136.10	144.10	145.00	174.00	176.90	186.10	308.20	261.10	163.10
Sr	459.90	465.00	364.00	351.10	212.00	334.00	224.00	76.00	82.00	65.00	57.00	14.00
Ba	629.70	618.00	1464.00	1442.00	439.00	1001.00	668.00	525.00	586.20	50.00	32.00	21.00
U	1.20	1.00	2.80	2.60	4.40	2.50	1.700	4.20	4.00	54.60	6.00	2.80
Th	8.10	7.30	19.00	16.20	35.10	23.90	15.00	30.10	28.10	342.60	30.70	31.20
Ta	0.80	0.80	1.00	1.00	2.50	0.60	3.50	3.10	1.80	3.20	0.70	0.50
Nb	12.10	10.60	8.80	8.70	21.60	5.70	45.30	43.30	16.30	33.70	2.40	3.20
Cs	3.50	3.90	5.30	6.10	9.20	6.10	6.40	7.10	1.00	11.10	13.20	17.60
Ga	19.00	18.40	21.10	23.10	19.10	23.60	21.40	22.00	20.90	19.30	17.50	19.90
Zr	33.10	31.20	195.70	198.20	62.50	81.20	81.00	220.70	232.70	592.30	25.10	41.70
Hf	1.40	1.00	5.50	6.30	2.50	2.50	7.30	8.20	2.50	17.50	0.80	1.60
Sn	1.90	2.00	1.60	2.10	2.60	3.30	0.60	6.30	7.20	1.30	0.30	0.50
Ni	154.00	153.80	0.90	0.80	0.50	3.20	1.00	0.40	0.50	0.10	0.10	0.40
Cr	440.30	442.00	11.00	9.90	6.00	9.00	3.00	3.00	3.10	3.00	1.00	3.10
Pb	8.00	8.00	20.30	21.50	27.10	25.20	25.90	37.20	39.00	41.10	26.80	25.70
Co	58.10	59.90	66.00	63.20	56.40	59.70	58.20	73.90	71.20	47.20	64.10	60.70
V	163.00	173.00	38.00	37.00	17.00	39.00	15.00	1.00	1.30	7.00	7.00	1.00
Y	21.68	22.90	14.90	14.70	26.50	37.30	6.10	59.20	54.40	28.60	6.90	5.60
Mg#	60.10	64.00	36.30	35.20	32.80	36.00	6.30	6.80	25.10	15.70	12.90	9.80
La	40.90	42.00	56.30	57.60	47.00	66.50	30.60	120.20	118.90	34.00	10.30	23.00
Ce	92.20	93.20	113.50	112.90	94.50	144.50	60.50	250.10	246.10	47.10	9.60	22.90
Pr	11.10	11.30	12.40	12.00	10.70	18.10	6.80	29.10	28.90	5.90	1.70	6.30
Nd	45.00	45.70	42.20	42.70	38.20	63.30	23.00	104.40	101.60	20.20	5.10	20.10
Sm	8.40	8.00	7.30	7.10	6.90	14.20	4.10	19.40	19.10	4.00	0.90	3.30
Eu	1.60	1.50	1.10	1.10	0.80	1.50	0.80	1.20	1.10	0.30	0.30	0.40
Gd	5.50	5.30	4.60	4.50	4.50	10.20	1.90	15.50	15.00	3.40	0.50	2.50
Tb	0.90	0.90	0.60	0.60	1.10	1.50	0.30	2.20	2.40	0.70	0.10	0.30
Dy	4.90	4.80	3.30	3.20	5.10	8.00	1.20	12.70	12.90	4.90	0.80	1.40
Ho	0.90	0.90	0.60	0.60	1.00	1.30	0.20	2.20	2.20	1.10	0.20	0.20
Er	2.10	2.30	1.40	1.40	2.30	3.50	0.50	5.40	5.40	3.20	0.50	0.50
Tm	0.30	0.30	0.20	0.20	0.40	0.60	0.10	0.90	1.00	0.60	0.10	0.10
Yb	2.10	2.30	1.90	1.90	2.20	3.30	0.40	5.30	5.10	4.80	0.70	0.70
Lu	0.20	0.20	0.20	0.20	0.30	0.40	0.10	0.80	0.80	1.00	0.10	0.10
Eu/Eu*	0.70	0.70	0.60	0.60	0.40	0.40	0.90	0.20	0.20	0.30	1.40	0.40
(La/Yb)N	15.10	14.00	19.80	20.70	14.20	13.40	51.00	15.10	15.50	4.70	9.80	21.90
(La/Sm)N	3.00	3.20	4.70	5.00	4.20	2.90	4.60	3.80	3.80	5.20	7.00	4.30
(Ce/Yb)N	13.00	11.90	15.20	15.40	10.90	11.10	38.50	12.00	12.30	2.50	3.50	8.30
(Eu/Yb)N	2.50	2.10	1.70	1.70	1.00	1.30	5.70	0.70	0.60	0.20	1.20	1.60
$\sum$ REE	215.80	218.40	245.60	246.00	215.00	336.90	130.50	569.40	560.40	131.20	30.90	81.80

Caruaru-Arcoverde batholiths in Borborema province, northeastern Brazil. The major oxides composition of the granitoids plotted on Harker diagram using SiO_2 as an index of differentiation shows that TiO_2, Al_2O_3, FeOt, MnO, MgO, CaO, and P_2O_5 behave as compatible components (Fig. 6). Each of these oxides decreases as SiO_2 increases and generally defined consistent linear trends. According to Hassanen et al. (1996) such linear trends can be attributed to either hybridization or fractionation. Potash (K_2O) shows somewhat opposite behavior, increasing with increase in SiO_2 but at SiO_2 value of about 75 wt%, it begins to decrease while soda (Na_2O) shows scatter trend.

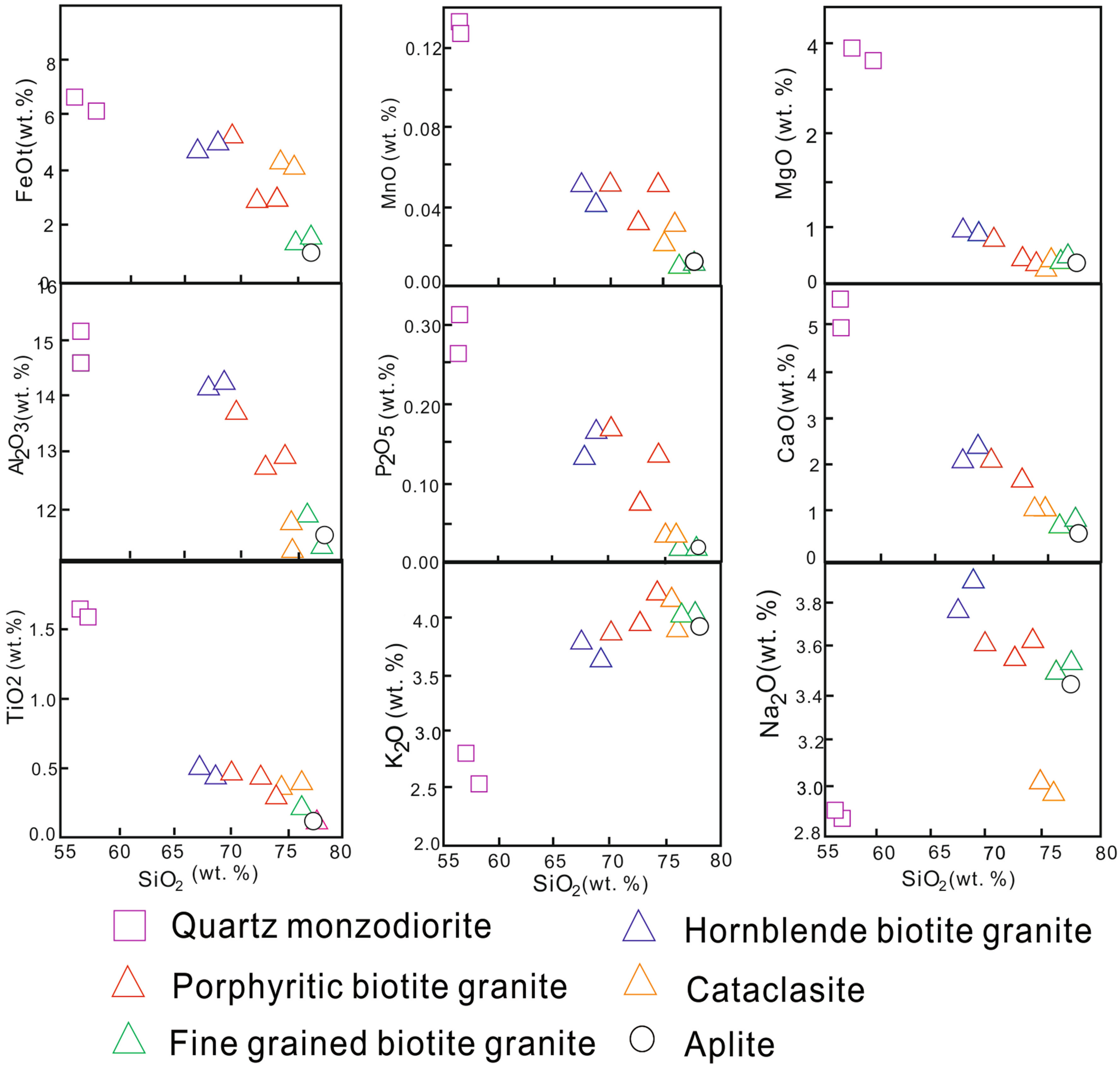

Fig. 6 Harker plot of some major elements against SiO_2

The granitoids are metaluminous to weakly peraluminous (Fig. 7a) similar to the high-K calc-alkaline granite in Fomopéa plutonic complex, Cameroon (Kwékam et al. 2010) but a slight compositional gap exists between the quartz monzodiorite and the granites. They are calc-alkalic to calcic in compositions according to the classification of Frost et al. (2001) (Fig. 7b). By contrast, the high-K calc-alkaline granites from the central Hoggar batholith are alkali-calcic to calc-alkalic in composition, whereas those from Fomopéa plutonic complex are decidedly alkali-calcic (Fig. 5b). On the diagram of Peccerillo and Taylor (1976) all the rocks plot in the field of high potassium calc-alkaline granites (Fig. 7c) whereas in the A/CNK versus SiO_2 discrimination diagram (after Chappell and White 1974), the rocks plot within the field defined for I-type granitoids (Fig. 7d). The quartz monzodiorite has a relatively high content of compatible trace elements (Cr 440–442 ppm and Ni 153–154 ppm) compare to the granites. The LILEs (K, Rb, Sr, Ba, and Cs) show significant variation in the granitoids. Rubidium (Rb) is fairly enriched in all the granites (126–308 pm) but relatively depleted in quartz monzodiorite (79.7–81.2 ppm) compared to the mean crustal average of 90 ppm. Barium (Ba) and strontium (Sr) which are strongly compatible in granitic systems, show a large variation (32–1464 ppm and 57–364 ppm respectively), in the granites. Strontium (Sr) decreases most probably as it replaced Ca in plagioclase and K in K-feldspars while Ba also replaced K in K-feldspars during crystallization. Large variation of these lithophile elements in the granites suggests that fractional crystallization was probably responsible for their evolution. It is worthy of note that the incompatible elements (e.g. Rb and Ba) content in the investigated granites is similar to the value obtained from some high-K calc-alkaline granite of

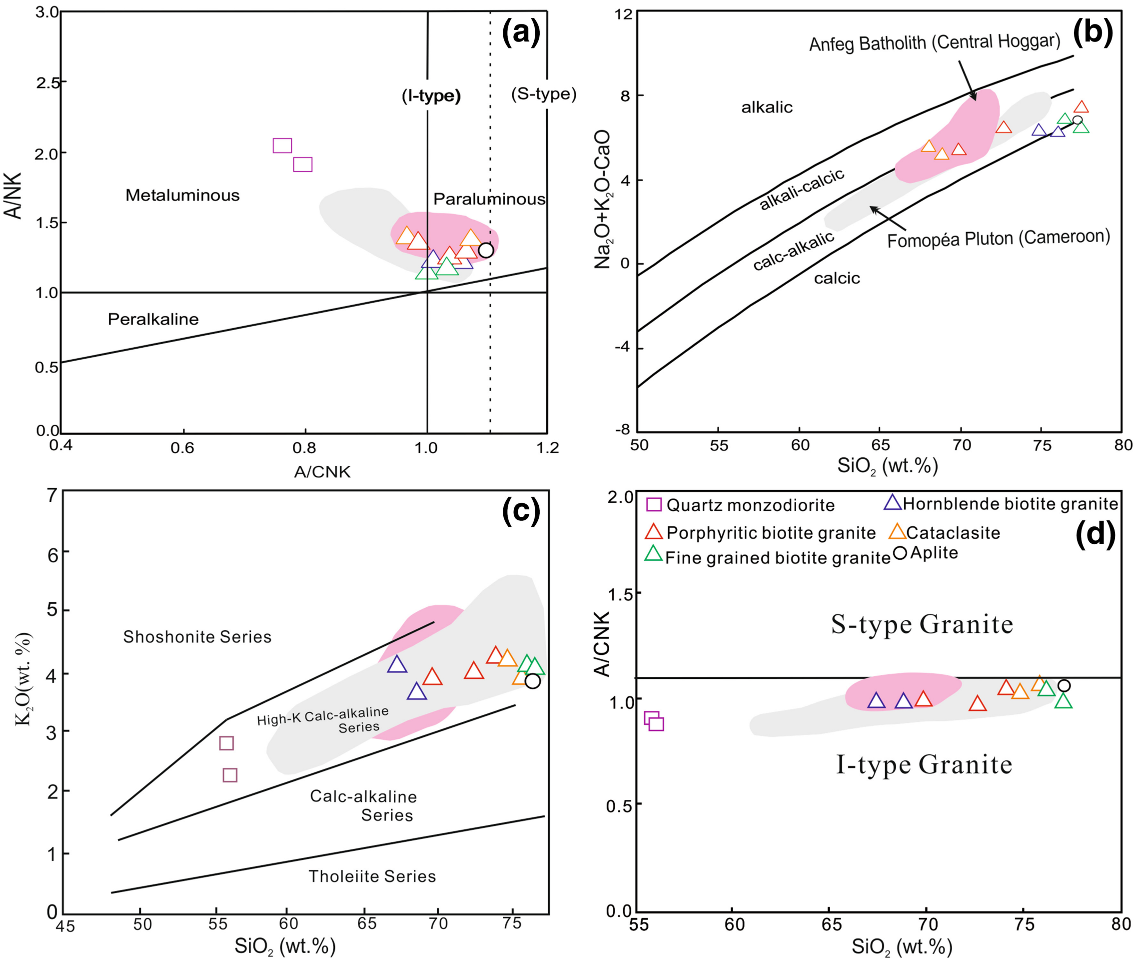

Fig. 7 **a** A/NK versus A/CNK plot discriminating the rocks into metaluminous to weakly peraluminous composition (after Shand 1943); **b** SiO_2 versus ($Na_2O + K_2O–CaO$) after Frost et al. (2001); **c** K_2O versus SiO_2 distinguish the rock into high-K-calc-alkaline and calc-alkaline composition (after Peccerillo and Taylor 1976), **d** A/CNK versus SiO_2 (after Chappell and White 1974) discriminating the rocks into the field of I-type granitoid. Published data of granites from central Hoggar batholiths, Algeria (Acef et al. 2003) and Fomopéa plutonic complex, Cameroon (Kwékam et al. (2010) are also plotted for comparison

Zing-Monkin area, Adamawa Massif south of the study area as reported by Haruna et al. (2013). In addition, the content of U and Th in the fine-grained biotite granite of the study area is comparable to the value in the U-rich fined grained granite of Zing-Monkin area. Specifically, the concentration of U and Th is 54.6 and 343 ppm respectively in the fine-grained granite. These values are significantly higher than the values reported by Haruna et al. (2011, 2013) in the fine-grained granites of Zing-Monkin area. However, this feature could be attributed to the presence of high concentration of zircons in the rocks.

On trace element spider diagram normalized to primitive mantle value of Sun and McDonough (1989), both the quartz monzodiorite and granites are somewhat depleted in some high field strength elements (e.g. Nb and Ta) as well as Ti but are rather enriched in U, K and Pb similar to the high-K granites from central Hoggar batholiths, Algeria, and Fomopéa plutonic complex, Cameroon (Kwékam et al. 2010; Acef et al. 2003, Fig. 8a). This distinct chemical characteristic is referred to as the “arc-like signature” and is typical of crustal rocks (Niu and O’hara 2009). Furthermore, the rare earth distribution pattern of the granite and quartz monzodiorite are characterized by moderate LREE enrichment, HREE depletion and moderate to strong negative Eu (Fig. 8b). However, the value of Eu anomaly in the quartz monzodiorite is much less than it is in the granites but similar to the Eu anomaly recorded in the diorite from Fomopéa plutonic complex, Cameroon (Kwékam et al. 2010). Also worthy of note is the strong correlation between the Eu anomaly and Sr content of all the rocks; the highly fractionated granites which are characterized by strong Eu anomaly have very low Sr content whereas the quartz monzodiorite which is characterized by weak Eu anomaly have high Sr content.

On the Rb versus (Y + Nb) and Nb versus Y tectonic discrimination diagrams (after Pearce et al. 1984), the

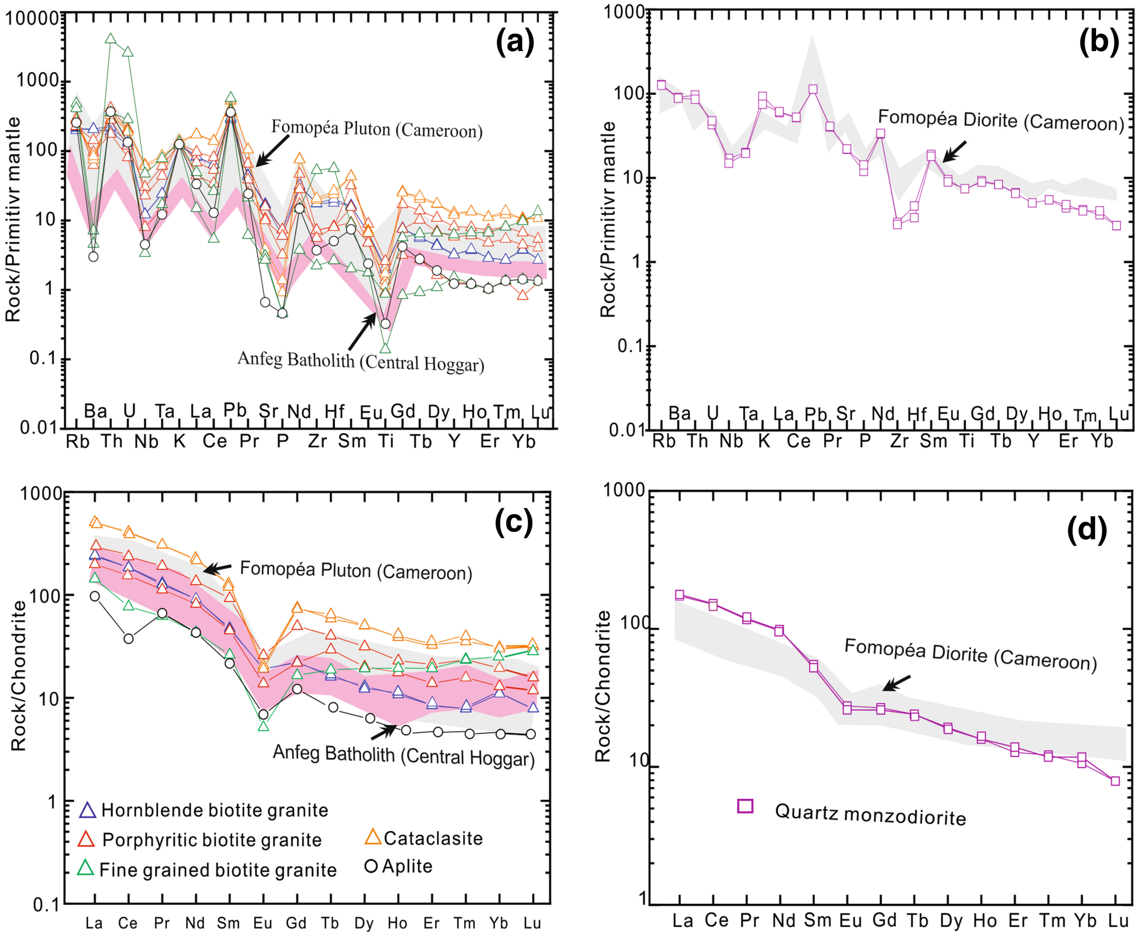

Fig. 8 Primitive mantle normalized multi-element diagram (after Sun and McDonough 1989) for (a) granites (b) quartz monzodiorite, and Chondrite-normalized REE diagram (after Nakamura 1974) for (c) granites and (d) for quartz monzodiorite. Published data of granites from central Hoggar batholiths, Algeria (Acef et al. 2003) and granites and diorite from Fomopéa plutonic complex, Cameroon (Kwékam et al. (2010) are also plotted for comparison

Mandara Hills granitoids plot in a volcanic arc, syn-collisional and within plate granites fields (Fig. 9) typical of post-collisional granites (Pearce 1996; Song et al. 2015). It has been noted that the Rb vs (Y + Nb) and Nb vs Y tectonic discrimination schemes are invalid for certain granite suites such as the highly fractionated Pan-African granitoids in the Arabian-Nubian Shield (e.g. Farahat et al. 2011). This is because incompatible trace elements distribution in such granites has been significantly modified by late-stage accessory minerals precipitation and/or fractionation (Robinson et al. 2017). Geological input is therefore required in constraining the tectonic setting of granites (e.g. Robinson et al. 2017). The high-K calc-alkaline granites of the Mandara Hills do not show any evidence of tectonic deformation which further confirms that they were most likely emplaced in the post-collisional geotectonic setting. By contrasts, syn-collisional granites in Nigeria are generally foliated because their emplacement was related to the D1 and D2 deformations which are interpreted as collision-related nappe (Ferré et al. 2002; Goodenough et al. 2014).

6 Discussion

6.1 Petrogenesis

Field relationship, petrography, and geochemical characteristics are the basic criteria utilized in establishing the petrogenesis of the granitoids of the northern part of Mandara Hills. Based on field relationship, the granitoids intruded the older Basement Complex rocks. Geochemical and mineralogical attributes such as relatively high Na_2O content, low CIPW normative corundum (in most cases less than 1%), and presence of hornblende and iron oxide suggest that the granitoids are typical calc-alkaline, I-type

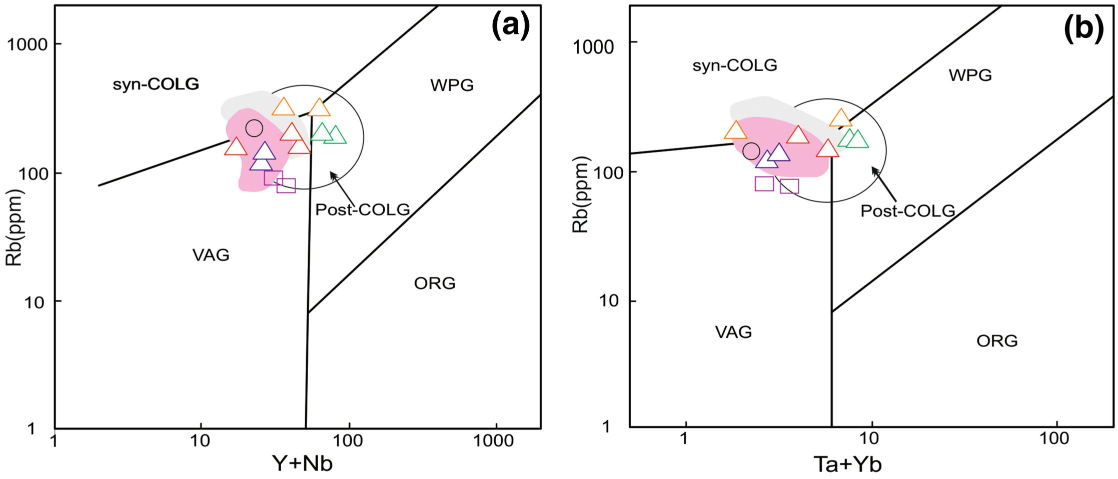

Fig. 9 Rb versus Y + Nb and Nb versus Y tectonic discrimination diagrams after Pearce et al. (1984). Published data of granites from central Hoggar batholiths, Algeria (Acef et al. 2003) and Fomopéa plutonic complex, Cameroon (Kwékam et al. (2010) are also plotted for comparison

metaluminous to slightly peraluminous granites (Fig. 7b). The quartz monzodiorite and the granites share many geochemical characteristics in common, for instance, the quartz monzodiorite has a higher content of Sr and weaker Eu anomaly compared to the granites which probably suggest that the rocks are related via fractionation of plagioclase because plagioclase is the only mineral that can significantly fractionate Eu from the other rare earth elements in a granitic system (Niu and O'hara 2009). However, the small volume of quartz monzodiorite in the study area and the absence of cumulate phase argue against this possibility. Apart from that, the quartz mozodiorite is geochemically more enriched in Ba relative to the granites. If granite and the diorite are related via fractional crystallization, Ba which is an incompatible element would be more enriched in the granites than the diorite (Neves and Mariano 1997). Similarly, previous geochemical studies carried out on the granitoids from western Nigeria (e.g. Goodenough et al. 2014) and eastern Nigeria (e.g. Dada et al. 1995; Ferré et al. 1998) ruled out direct fractional crystallization of more mafic monzodioritic magma for the formation of some Pan-African metaluminous granitoids. Also, the conspicuous absence of mafic enclave and the small volume of quartz monzodiorite in Mandara Hills ruled out the possibility of magma mixing in the formation of Mandara Hills granitoids. Rather, the granitoids in northeastern Nigeria were generally considered to have originated from mixed melts derived from Archean meta-igneous source and mantle-derived magmas (e.g. Dada et al. 1995; Dada 1998; Ferré et al. 1998; Goodenough et al. 2014).

6.2 Origin

6.2.1 *Quartz monzodiorite*

The quartz monzodiorite is the least evolved of the rocks of the northern part of Mandara Hills with low SiO_2 and relatively high MgO and compatible trace element (e.g. Cr, Ni) content. It has been established that quartz monzodiorite can be derived through anatexis of mafic rocks from the lower crust or via partial melting of enriched mantle material (Jung et al. 2009; Li et al. 2016). The high mg# ($>$ 60) of the quartz monzodiorite of the northern part of Mandara Hills preclude an origin via anatexis of mafic rocks from the lower crust as mg# content in melt from the lower crustal source is usually less than 60. According to Defant and Drummond (1990), Castillo (2012) and Li et al. (2016), partial melting of the delaminated lower crust in an intra-continental setting with contribution from peridotite can result in the formation of high MgO dioritic rocks with characteristics typical of adakitic rocks. Although the quartz monzodiorite has moderately high (459.93–465.10 ppm) Sr content, it has higher value of Y ($>$ 20 ppm) and Yb $>$ 2 ppm than typical adakitic rocks, this rock could not have resulted from melting of lower crustal source rocks. The quartz monzodiorite is geochemically more enriched in some compatible element (e.g. Cr and Ni) when compared to average values obtained from the lower continental crust as reported by Rudnick and Gao (2003). The rock has high content of large ion lithophile elements (e.g. Sr $>$ 400 ppm and Ba $>$ 600 ppm), high mg# ($>$ 60) as well as high LREE but low HREE with weak Eu negative Eu anomaly (Fig. 8b) which are geochemical features typical of less differentiated sanukitoids (Fu et al. 2018; Sun et al. 2019). According to

Sun et al. (2019) such less differentiated sanukiods are usually derived from partial melting of the enriched mantle. Based on abundance of the compatible elements, high mg# and high K content, it is our opinion that the quartz monzodiorite from northern part of Mandara Hills originated from partial melting of enriched mantle in a post-collisional setting, similar to the rocks of western Yunnan, SW China (Huang et al. 2010). This is in agreement with the work of Dada et al. (1995) who proposed an enriched mantle origin for some diorite from Bauchi province, eastern Nigeria.

6.2.2 Granites

The granites from Mandara Hills exhibit petrological and geochemical features typical of high-K calc-alkaline I-type granites earlier proposed by Chappell and White (1974); Chappell et al. (2000); Roberts and Clemens (1993); Altherr et al. (2000); Nono et al. (2010). Considering the fact that I-type granites constitute the building block of the continental crust, their origin can shed more light on the geodynamic evolution of the continental crust especially from Archean to Phanerozoic (Arndt 2013). According to Altherr et al. (2000), the origin of high-K granitic magmas can be traced to two end member processes and tectonic settings. These are:

(i) continental arc settings similar to the Andes (e.g. Pitcher 1987) where parent mantle magma becomes enriched in incompatible elements as a consequence of contamination from crustal derived material (e.g. Hildreth and Moorbath 1988; Lurh 1992).

(ii) post-collisional settings where crustal thickening triggered decompression melting of the source rock (Roberts and Clemens 1993) or partial melting of newly formed, warm, mafic lower crustal amphibolites as a consequence of underplating by a mafic magma (Neves et al. 2000).

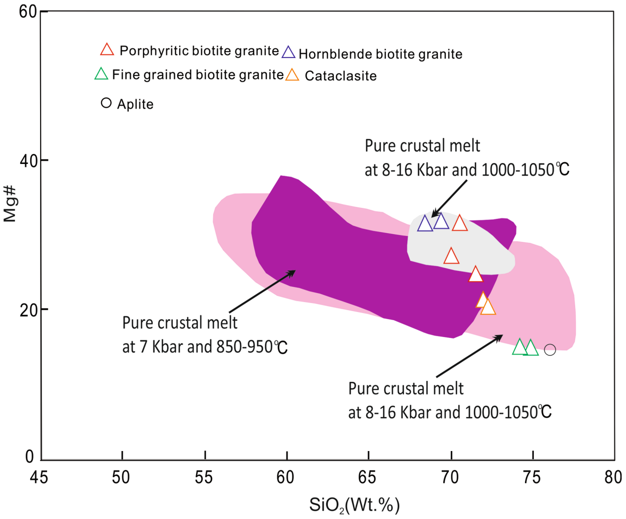

Fig. 10 Mg# versus SiO_2 plot for Mandara hill granites boundaries are from Liu et al. (2014)

The Mandara Hills granites have relatively high SiO_2 and low compatible elements such as MgO, Cr, and Ni content. This feature is the hallmark of granites derived from crustal sources. The granites are also characteristically depleted in Ba, Ti, Sr, P and to a limited degree Nb similar to high-K calc-alkaline granite of Fomopéa plutonic complex, Cameroon (Kwékam et al. 2010) as well as the high-K calc-alkaline granite batholith of the central Hoggar Massif, Algeria (Acef et al. 2003). According to Thompson et al. (1984) and Bambi et al. (2013), this geochemical feature is typical of calc-alkaline granites of crustal origin. This is consistent with the binary plots of Mg# versus SiO_2 which indicate largely crustal sources for the high-K I-type granites from the Mandara Hills (Fig. 10). However, the determination of the most suitable crustal source(s) for these granites is often fraught with a lot of uncertainties (e.g. Patiño Douce 1999; Altherr et al. 2000; Kazemi et al. 2019). In particular, the metaluminous nature of the Mandara Hills granite rules out an origin from partial melting of strongly peraluminous sedimentary source such as pelite. This chemical character is more consistent with metaluminous protolith derived from mafic lower crust. Nonetheless, the weakly peraluminous nature of the granite suites cannot be explained exclusively based on evolution via fractional crystallization dominated by fractionation of plagioclase. This is because fractionation of plagioclase is expected to decrease the concentration of Al_2O_3 in the melt which will, in turn, decrease the aluminum saturation index. According to Chappell et al. (2012), the metaluminous to weakly peraluminous chemistry of I-type granite is an inherent characteristic of their source.

Granitic melts generally retain a geochemical link with their sources regardless of the processes that prevailed at their origin (Chappell and White 1974; Chappell et al. 2000; Moyen et al. 2016). Significant information regarding melts produced from various crustal rocks (e.g. amphibolites, meta tonalite, metagraywacke, and metapelite) under different experimental conditions is usually represented on $CaO/[(MgO + FeO_{total})$ *vs* $Al_2O_3/(MgO + FeO_{total}$, molar ratio)] discrimination diagram (e.g. Patiño Douce 1999) for comparison with a natural system. The granites plot within the field of metatonalite and metagraywacke-derived magma thus suggesting that they formed by partial melting of metatonalitite and metagraywacke source rock (Fig. 11a). This is also corroborated by the normative albite-anorthite-orthoclase ternary diagram (Fig. 11b). Roberts and Clemens (1993)

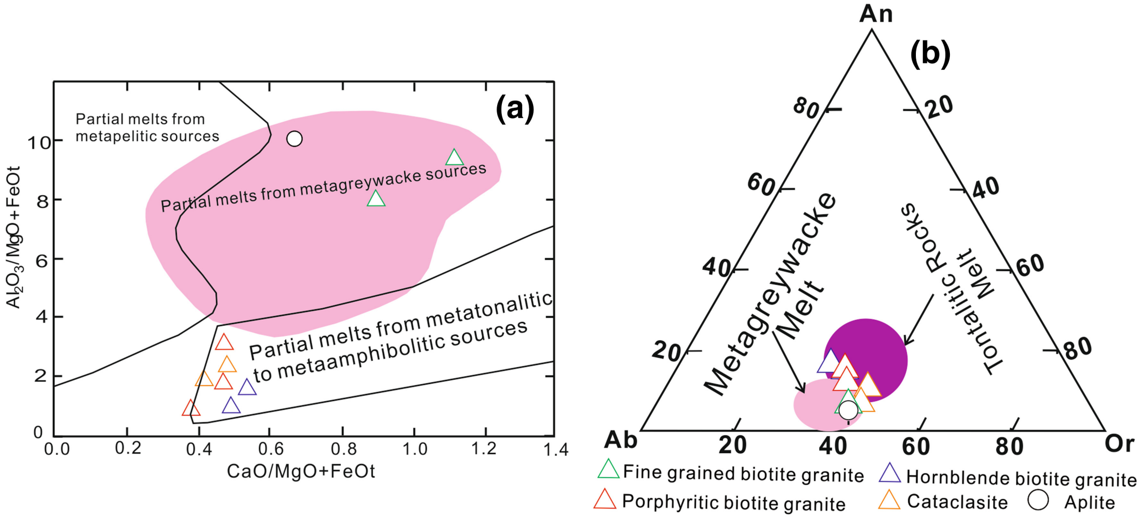

Fig. 11 **a** Molar CaO/(MgO + FeOt) versus Al_2O_3/(MgO + FeOt) for the granitoids adapted after Patiño Douce (1999), **b** normative albite-anorthite-Orthoclase ternary diagram showing the distribution of the granitoids in the meta tonalitic and metagraywacke adapted after Patino Douce and McCarthy (1998)

argued that the melting of calc-alkaline andesite and/basaltic andesite can give rise to high-K calc-alkaline granites. However, experimental studies carried out by Patiño Douce (1999) revealed that melt produced by melting of basaltic or calc-alkaline andesite cannot give rise to high-K calc-alkaline I-type granite, because the melt produced from such melting is generally poor in K_2O. This later author also argues that direct fusion of sodic meta tonalitic rocks (TTGS) alone cannot also produce high-K granite, especially in Archean terrane where partial melting typically occur at low pressure due to shallow crustal thickness (Watkins et al. 2007). In order to produce high-K granitic melt from a partial melt of TTGs, the partial melting has to take place at high temperature and pressure so that biotite would be unstable (Watkins et al. 2007) and the TTGs must have a relatively high K_2O content ($K_2O/Na_2O \approx 1$). Alternatively, partial melting of TTGs with contribution from metagraywacke (Patiño Douce 1999) or the mantle (e.g. Kazemi et al. 2019) could also give rise to high-K granitic melts. For the origin of high-K calc-alkaline I-type granite in Fomopéa plutonic complex, Cameroon; Kwékam et al. (2010) proposed a model involving partial melting of lower crust with limited contribution from the mantle. A similar model has been proposed for the origin of high-K calc-alkaline granite in central Hoggar, Algeria (Acef et al. 2003). This is in agreement with the extensive review of global Neoproterozoic crustal evolution carried out by Stern (2008) which indicates that the central Hoggar, Central African Fold Belt, as well as the Nigerian Shield, experienced significant metamorphism, crustal melting and/or reworking during Neoproterozoic (Ediacaran) period (Liégeois 2019).

In continental crust environment, the first episode of intracrustal partial melting often leads to increase in the concentration of SiO_2, K_2O, and Na_2O in the melt while the content of mafic oxides such as FeO and MgO as well as CaO would increase in the residuum of such melting reaction (Johannes and Holtz 1996). Fractionation of the melts and solids often leads to the formation of tonalite trondhjemite and granodiorite (TTG) as well as mafic granulites (e.g. Wyllie et al. 1996). The tonalite thus formed is a suitable parent rock for a generation of granitic melt (Johannes and Holtz 1996). The rock is later metamorphosed to form metatonalite trondjemite and granodiorite (TTGs) suite which is abundant in the deep crust (e.g. Castro 2004). Distinctive metasediments such as metagraywacke could be transported to the deep crust during a continental collision (Patino Douce and McCarthy 1998) or as a result of relamination (Hacker et al. 2011, 2015; Kelemen and Behn 2016). According to Patino Douce and McCarthy (1998), in the absence of H_2O infiltration, TTGs as well as more-mafic metasediments such as metagraywacke, remain unmolten even at a temperature as high as 900 °C. However, in a post-collisional setting; underplating of the lower crust by hot mafic magma usually takes place due to thinning of the continental lithospheric mantle occasioned by convection from the deep mantle or its delamination owing to crustal thickening (Küster and Harms 1998; Patino Douce and McCarthy 1998; Annen et al. 2006). This would lead to extensive melting of most quartzofeldspathic lithologies (e.g. meta-tonalite trondhjemite and granodiorite (TTG) at relatively higher pressure (e.g. Xiao and Clemens 2007). In our opinion, the Mandara Hills granites probably formed from partial melting of TTGs with contributions from metagraywacke

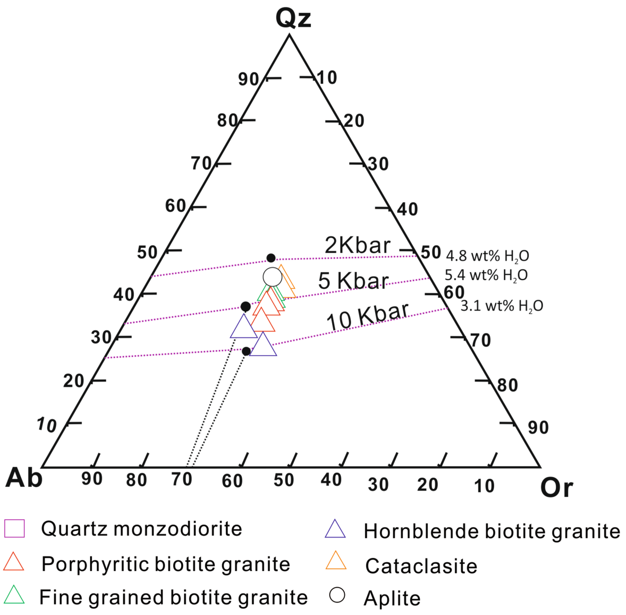

Fig. 12 Quartz—an albite-orthoclase ternary diagram showing the normative compositions and field of the pressure of all the granites (after Johannes and Holtz 1996; and Bartoli et al. 2016)

(Fig. 9) at lower to mid-crustal level (5–10 Kbars, see Fig. 12) leaving amphibole and ilmenite as the residual phases. The residual amphibole and ilmenite account for the depletion of some high field strength elements especially Nb and Ta as well as Ti in the melt (Mo et al. 2008; Niu and O'hara 2009; Niu et al. 2013).

At the waning stage of Pan-African orogeny (post-collisional period), delamination of the continental lithospheric mantle most probably took place following crustal thickening (e.g. Dada 1998; Black and Liégeois 1993; Acef et al. 2003; Bute et al. 2019). Although there is no available incontrovertible evidence of post-collisional gravitational collapse of the orogen yet probably due to paucity of geophysical data on the eastern Nigerian terrane, the Mandara Hills plutons, like most post-collisional plutons in the Trans-Saharan Belt, are associated with N–S crustal trending shear zones indicating that such shear zones played an active role during the emplacement of the plutons (Ferré et al. 2002). Transtensional movement along such lithospheric-scale shear zones may have resulted in planar lithospheric mantle delamination as in most part of Trans-Saharan Belt (e.g. Black and Liégeois 1993; Liégeois 2019) including eastern Nigerian terrane (e.g. Bute et al. 2019). This was accompanied by upwelling of hot mafic melt from the mantle. The mafic melt underplated the lower crust and provided the heat that ultimately caused partial melting of meta tonalite–trondhjemite and granodiorite suite and metagraywacke in the deep crust with limited mantle contribution as documented in some high-K granites from northern highlands, Scotland (Castro 2004). The resultant metaluminous to weakly peraluminous high-K melt formed magma chamber in middle crust and was subsequently emplaced in the upper continental crust. The calc-alkaline nature of the rocks indicates an evolution in a thick crust. The formation of post-collisional high-K granites in Mandara Hills, therefore, marked an important episode of intracrustal differentiation in the Neoproterozoic. From the foregoing, we posit that unless there is new evidence to prove otherwise, the Nigerian Basement may not have experienced significant crustal growth during the Proterozoic.

7 Conclusions

The Neoproterozoic calc-alkaline granitoids in the northern part of the Mandara Hills, northeast Nigeria share many petrological and geochemical features with those from central Hoggar Massif, Algeria, and central African Fault Belt, Cameroon. The chemical composition of the granite is similar to that of granitic melt produced by experimental partial melting of diverse crustal sources (metatonalite ± trondhjemite, granodiorite and metagraywacke) at a fairly high temperature and pressure. Partial melting probably took place in a post-collisional setting following planar lithospheric mantle delamination at the terminal stage of Pan-African orogeny. However, considering that lithospheric mantle delamination usually facilitates crust-mantle interaction; we do not rule out the possibility of "cryptic" contribution of mantle-derived melt in the genesis of Mandara Hills granites. Such cryptic mantle melt contribution could in part explain the high-K characteristics of the granites. On the other hand, the quartz monzodiorite show geochemical features (low SiO_2, but high Mg#, Cr, Ni, Sr, and Ba) similar to less differentiated sanukitoids indicating that the rock originated from partial melting of an enriched mantle source.

Acknowledgements We thank Professor Saidu Baba of the Department of Geology, University of Maiduguri, Nigeria for his assistance during the field mapping. The manuscript benefitted immensely from editorial handling by Chief-editor, Chongqing Liu and constructive criticism by five anonymous reviewers.

References

Abaa SI, Najime T (2006) Mineralization in Precambrian rocks of central Nigeria: implication for the Oban-Obudu-Mandara-Gwoza Complex of eastern Nigeria. Glob J Geol Sci 4(2):121–128

Acef K, Liégeois JP, Ouabadi A, Latouche L (2003) The Anfeg post-collisional Pan-African high-K calc-alkaline batholith (Central Hoggar, Algeria), result of the Latea microcontinent metacratonisation. J Afr Earth Sci 37:295–311

Ajibade AC, Wright JB (1989) The Togo-Benin-Nigeria Shield: evidence of crustal aggregation in the Pan-African belt. Tectonophysics 165:125–129

Ajibade AC, Woakes M, Rahaman MA (1987) Proterozoic crustal development in the Pan-African regime of Nigeria. In: Kroner A (ed) Proterozoic lithospheric evolution. AGU, Washington, p 430

Altherr FF, Holl A, Hegner E, Langer C, Kreuzer H (2000) High-potassium, calc-alkaline I-type plutonism in the European variscides: northern Vosges (France) and northern Schwarzwald (Germany). Lithos 50:51–73

Ananaba SE, Ajakaiye DE (1987) Evidence of tectonic control of mineralization in Nigeria from lineament density analysis: a landsat study. Int J Remote Sens 8:1445–1452

Annen C, Blundy JD, Sparks RSJ (2006) The genesis of intermediate and silicic magmas in deep crustal hot zones. J Petrol 47:505–539

Arndt NT (2013) Formation and evolution of the continental crust. Geochem Perspect 2(4):405–530

Baba S, Abba SI, Dada SS (2006) Preliminary petrogenetic study of some rocks from Gwoza area, NE Nigeria. Glob J Geol Sci 4(2):147–155

Bambi CKM, Frimmel HE, Zeh A, Suh CE (2013) Age and origin of Pan-African granites and associated U-Mo mineralization at Ekomedion, southwestern Cameroon. J Afr Earth Sci 88:15–37

Bartoli O, Acosta-Vigil A, Ferrero S, Cesare B (2016) Granitoid magmas preserved as melt inclusions in high-grade metamorphic rocks. Am Mineral 101:1543–1559

Black R, Liégeois JP (1993) Cratons, mobile belts, alkaline rocks and continental lithosphere mantle: the Pan-African testimony. J Geol Soc Lond 150:89–98

Black R, Latouche L, Liegeois JP, Caby R, Betrand JM (1994) Pan-African displacement terranes in Tuareg Shield (Central Sahara). J Geol 22:641–644

Bonin B (2004) Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting, mantle and crustal, sources? A review. Lithos 78:1–24

Brown M (2013) Granite: from genesis to emplacement. Geol Soc Am Bull 7(8):1079–1113

Bute SI, Yang XY, Cao LL, Deng J, Haruna IV, Girei MB, Abubakar U, Akhtar S (2019) Origin and tectonic implications of ferroan alkali-calcic granitoids from the Hawal Massif, east–eastern Nigeria terrane: clues from geochemistry and zircon U–Pb–Hf isotopes. Int Geol Rev. https://doi.org/10.1080/00206814.2019.1593250

Caby R (1989) Precambrian terranes of Benin-Nigeria and northeast Brazil and the Late Proterozoic South Atlantic fit. In: Dallmeyer RD (ed) Terranes in the Circum-Atlantic Palaeozoic orogens, vol 230. Geological Society of America Special Paper, Boulder, pp 145–158

Carlos EG, Umberto GC, Roberto FW, Miguel ASB, Richard A, Kei S (2014) Tracing Neoproterozoic subduction in the Borborema Province (NE-Brazil): clues from U–Pb geochronology and Sr-Nd-Hf-O isotopes on granitoids and migmatites. Lithos 202:167–189

Castillo PR (2012) Adakite petrogenesis. Lithos 134:304–316

Castro A (2004) The source of granites: inferences from the Lewisian complex. Scott J Geol 40:49–65

Castro A (2014) The off-crust origin of granite batholiths. Geosci Front 5:63–75

Chappell BW, White AJR (1974) Two contrasting granite types. Pac J Geol 8:173–174

Chappell BW, White AJR, Williams IS, Wyborn D, Wyborn LAI (2000) Lachlan fold belt granites revisited: high- and low-temperature granites and their implications. Aust J Earth Sci 47:123–138

Chappell BW, Bryant CJ, Wyborn D (2012) Peraluminous I-type granites. Lithos 153:142–153

Clemens JD (2012) Granitic magmatism, from source to emplacement: a personal view. Appl Earth Sci 121(3):107–136

Clemens JD, Stevens G, Farina F (2011) The enigmatic sources of I-type granites: the peritectic connexion. Lithos 126:174–181

Dada SS (1998) Crust-forming ages and Proterozoic crustal evolution in Nigeria: a reappraisal of current interpretations. Precambrian Res 87:65–74

Dada SS (1999) Pb–Pb and Sm-Nd isotope study of metaigneous rocks of Kaduna Region: implications for Archean crustal development in Northern Nigeria. Pure Appl Sci 6:7–16

Dada SS (2008) Proterozoic evolution of the Nigeria–Boborema province. Geol Soc Lond Spec Publ 294:121–136. https://doi.org/10.1144/SP294.7

Dada SS, Briqueu L, Harms U, Lancelot JR, Matheis G (1995) Charnockitic and monzonitic Pan-African series from north-central Nigeria: trace-element and Nd, Sr, Pb isotope constraints on their petrogenesis. Chem Geol 124:233–252

Danbatta UA (2008) A review of the evolution and tectonic framework of the schist belts of Western Nigeria, West Africa. Afr Geosci Rev 15(2):145–158

Defant MJ, Drummond MS (1990) Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature 347:662–665

Ekwueme BN (2003) The Precambrian geology and evolution of the Southeastern Nigerian basement complex. University of Calabar Press, Calabar, pp 1–57

Farahat ES, Zaki R, Hauzenberger C, Sami M (2011) Neoproterozoic calc-alkaline peraluminous granitoids of the Deleihimmi pluton, Central Eastern Desert, Egypt: implications for transition from late- to post-collisional tectonomagmatic evolution in the northern Arabian-Nubian Shield. Geol J 46:544–560

Ferré EC, Caby R (2007) Granulite facies metamorphism and charnockite plutonism: examples from the Neoproterozoic belt of northern Nigeria. Proc Geol Soc Lond Lond 118(1):47–54

Ferré EC, Deleris J, Bouchez JL, Lar AU, Peucat JJ (1996) The Pan-African reactivation of Eburnean and Archaean provinces in Nigeria: structural and isotopic data. J Geol Soc Lond 153:719–728

Ferré E, Gleizes MT, Djouadi MT, Bouchez JL, Ugodulunwa FXO (1997) Drainage and emplacement of magmas along an inclined transcurrent shear zone: petrophysical evidence from a granite-charnockite pluton (Rahama, Nigeria). In: Bouchez JL, Hutton DHW, Stephens WE (eds) Granite: from segregation of melt to emplacement fabrics. Petrology and structural geology. Kluwer Publishing Co, Dordrecht, pp 253–276

Ferré EC, Caby R, Peucat JJ, Capdevila R, Monie P (1998) Pan-African, post-collisional, ferro-potassic granite and quartz-monzonite plutons of Eastern Nigeria. Lithos 45:225–279

Ferré EC, Gleizes G, Caby R (2002) Obliquely convergent tectonics and granite emplacement in the Trans-Saharan belt of Eastern Nigeria: a synthesis. Precambrian Res 114:199–219

Fitches WR, Ajibade AC, Egbuniwe IG, Holt RW, Wright JB (1985) Late Proterozoic schist belts and plutonism in NW Nigeria. Geol Soc Lond 142:319–337

Frost BR, Barnes CG, Collins WJ, Arculus RJ, Ellis DJ, Frost CD (2001) A geochemical classification for granitic rocks. J Petrol 42:2033–2048

Frost CD, Frost BR, Beard JS (2016) On silica-rich granitoids and their eruptive equivalents. Am Mineral 101:1268–1284. https://doi.org/10.2138/am-2016-5307

Fu J, Liu S, Cawood PA, Wang M, Hu F, Sun G, Gao L, Hu Y (2018) Neoarchean magmatic arc in the western Liaoning Province, northern North China Craton: geochemical and isotopic constraints from sanukitoids and associated granitoids. Lithos 322:296–311

Girei MB, Najime T, Elatikpo SM (2017) Chemistry of potassium feldspars and petrogenetic evolution of pegmatites from the northern part of Mandara Hills, northeastern Nigeria. Paper presented at 53rd annual international conference and exhibition of Nigerian mining and geosciences society (NMGS) abstract, vol 19, pp 16–17

Goodenough KM, Lusty PAJ, Roberts NMW, Key RM, Garba A (2014) Post-collisional Pan-African granitoids and rare-metal pegmatites in western Nigeria: age, petrogenesis and the pegmatite corundum. Lithos 200:22–34

Hacker BR, Kelemen PB, Behn MD (2011) Differentiation of the continental crust by relamination. Earth Planet Sci Lett 307:501–516

Hacker BR, Kelemen PB, Behn MD (2015) Continental lower crust. Annu Rev Earth Planet Sci 43:167–205

Haruna IV, Orazulike DM, Ofulume AB, Mamman YD (2011) Petrochemical and mineralogical constraints on the source and processes of uranium mineralisation in the granitoids of Zing-Monkin area, Adamawa Massif, NE Nigeria. Nat Resour Res 20(4):355–366

Haruna IV, Orazulike DM, Samaila NK (2013) Trace and rare earth elements petrochemical constraints on tectonogenetic evolution of the granitoids of Zing-Monkin area, Adamawa Massif, NE Nigeria. Res J Chem Sci 3(1):32–42

Hassanen MA, El-Nasir SA, Mohamed FH (1996) Geocheinistry and petrogenesis of Pan-African I-type granitoids at Gabal Igla Ahmar, Eastern Desert. Egypt J Afr Earth Sci 22(1):29–42

Hildreth W, Moorbath S (1988) Crustal contribution to arc magmatism in the Andes of Southern Chile. Contrib Mineral Petrol 98:455–489

Huang XL, Niu YL, Xu YG, Chen LL, Yang QJ (2010) Mineralogical and geochemical constraints on the petrogenesis of post-collisional potassic and ultrapotassic rocks from western Yunnan, SW China. J Petrol 51:1617–1654

Johannes W, Holtz F (1996) Petrogenesis and experimental petrology of granitic rocks. Springer, Berlin, p 366

Jung S, Masberg P, Mihm P, Hoernes H (2009) Partial melting of diverse crustal sources: constraints from Sr–Nd–O isotope compositions of quartz diorite-granodiorite leucogranite associations (Kaoko Belt, Namibia). Lithos 111:236–251

Kazemi K, Kananian A, Xiao Y, Sarjoughian F (2019) Petrogenesis of Middle-Eocene granitoids and their mafic microgranular enclaves in central Urmia-Dokhtar magmatic arc (Iran): evidence for interaction between felsic and mafic magmas. Geosci Front 10(2):705–723

Kelemen PB, Behn MD (2016) Formation of lower continental crust by relamination of buoyant arc lavas and plutons. Nat Geosci 9:197–205

Küster D, Harms U (1998) Post-collisional potassic granitoids from the southern and northwestern parts of the Late Neoproterozoic East African Orogen: a review. Lithos 45:177–195

Kwékam M, Liégeois JP, Njonfang E, Affaton P, Hartmann G, Tchoua F (2010) Nature, origin and significance of the Fomopéa Pan-African high-K calcalkaline plutonic complex in the Central African fold belt (Cameroon). J Afr Earth Sci 57:79–95. https://doi.org/10.1016/j.jafrearsci.2009.07.012

Lar UA, Lekmang IC, Shuaibu MT, Mahmud UM, Yakubu TA (2013) Volcanoes of Nigeria: a preliminary study. Acta Geol Sin (English Edition) 87:356–357

Li J, Niu Y, Hu Y, Chen S, Zhang Y, Duan M, Sun P (2016) Origin of the late early Cretaceous granodiorite and associated dioritic dikes in the Hongqilafu pluton, northwestern Tibetan Plateau: a case for crust-mantle interaction. Lithos 312:37–53

Liégeois JP (2019) A new synthetic geological map of the Tuareg Shield: an overview of its global structure and geological evolution. In: Bendaoud A, Hamimi Z, Hamoudi M, Djemai S, Zoheir B (eds) The geology of the Arab world—an overview. Springer Geology, Switzerland, pp 83–107

Liégeois JP, Navez J, Hertogen J, Black R (1998) Contrasting origin of post-collisional high-K calc-alkaline and shoshonitic versus alkaline and peralkaline granitoids: the use of sliding normalization. Lithos 45:1–28

Liu L, Qiu JS, Zhao JL, Yang ZL (2014) Geochronological, geochemical, and Sr–Nd–Hf isotopic characteristics of Cretaceous monzonitic plutons in western Zhejiang Province, Southeast China: new insights into the petrogenesis of intermediate rocks. Lithos 196:242–260. https://doi.org/10.1016/j.lithos.2014.03.010

Lurh JF (1992) Slab-derived fluids and partial melting in subduction zones: insights from two contrasting Mexican volcanoes (Colima and Ceboruco). J Volcanol Geotherm Res 54(2):1–18

McCurry P (1971) Pan-African orogeny in northern Nigeria. Geol Soc Am Bull 82:3251–3263

McCurry P (1976) The geology of Precambrian to lower Paleozoic rocks of northern Nigeria—a review. In: Kogbe CA (ed) Geology of Nigeria. Elizabethan Publication, Lagos, pp 15–36

Mo X, Niu Y, Dong G (2008) Contribution of syncollisional felsic magmatism to continental crust growth: a case study of the Paleogene Linzizong volcanic succession in southern Tibet. Chem Geol 250:49–67

Moyen JF, Laurent O, Chelle-Michou C, Couzini´e S, Vanderhaeghe O, Zeh A, Villaros A, Gardien V (2016) Collision vs. subduction-related magmatism: two contrasting ways of granite formation and implications for crustal growth. Lithos 277:154–177

Nakamura N (1974) Determination of REE, Ba, Fe, Mg, Na and K in Carbonaceous and ordinary chondrites. Geochem Acta 38:757–775

Neves SP, Mariano G (1997) High-K calc-alkalic plutons in NE Brazil: origin of the biotite diorite/quartz monzonite to granite association and implications for the evolution of the Borborema province. Int Geol Rev 39:621–638

Neves SP, Mariano G, Guimarães IP, da Saliva F, Melo SC (2000) Intralithospheric differentiation and crustal growth: evidence from the Borborema province, northeastern Brazil. Geology 28(6):519–522

Niu Y, O'Hara MJ (2009) MORB mantle hosts the missing Eu (Sr, Nb, Ta and Ti) in the continental crust: new perspectives on crustal growth, crust-mantle differentiation and chemical structure of oceanic upper mantle. Lithos 112:1–17

Niu Y, Zhao Z, Zhu DC (2013) Continental collision zones are primary sites for net continental crust growth: a testable hypothesis. Earth Sci Rev 127:96–110

Nono GDK, Nzenti JP, Suh CE, Ganno S (2010) Geochemistry of ferriferous, high-K Calc-alkaline granitoids from the Banefo-Mvoutsaha Massif (NE Bafoussam), Central Domain of the Pan-African Fold Belt, Cameroon. Open Geol J 4:15–28

Oyawoye MO (1972) The basement complex of Nigeria. In: Dessauvagie TF, Whiteman AJ (eds) African geology. Geology Department, University of Ibadan, Ibadan, pp 42–98

Patiño Douce AE (1999) What do experiments tell us about the relative contributions of crust and mantle to the origin of granitic magmas. In: Castro A, Fernandez C, Vigneresse JL (eds) Understanding granites: integrating new and classical techniques, vol 168. Geological Society of London Special Publication, London, pp 77–94

Patino Douce AE, McCarthy TC (1998) Melting of crustal rocks during continental collision and subduction. In: Hacker BR, Liou JG (eds) When continents collide: geodynamics and geochemistry of ultrahigh-pressure rocks. Petrology and structural geology. Kluwer, Dordrecht, pp 27–55

Pearce JA (1996) Sources and setting of granitic rocks. Episodes 19(4):120–125

Pearce JA, Harris NB, Tindle AG (1984) Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J Petrol 25:956–983

Peccerillo A, Taylor SR (1976) Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. Contrib Mineral Petrol 58:63–81

Pitcher WS (1987) Granites and yet more granites forty years on. Geol Rundsch 76:51–79

Rahaman MA (1976) Progressive polyphase metamorphism in pelitic schists around Aiyetoro, Oyo State, Nigeria. J Mineral Geol 13:33–44

Roberts M, Clemens JD (1993) Origin of high-potassium calc-alkaline I-type granitoids. Geology 21:825–828

Robinson F, Bonin B, Pease V, Anderson J (2017) A discussion on the tectonic implications of Ediacaran late-to post-orogenic A-type granite in the northeastern Arabian Shield, Saudi Arabia. Tectonics 36:582–600. https://doi.org/10.1002/2016TC004320

Rudnick RL, Gao S (2003) Composition of the continental crust. Treatise Geochem 3:1–64

Shand A (1943) Eruptive rocks: their genesis, composition, and classification. Wiley, Hoboken, pp 52–103

Song S, Wang M, Wang C, Niu Y (2015) Magmatism during continental collision, subduction, exhumation and mountain collapse in collisional orogenic belts and continental net growth: a perspective. Sci China Earth Sci 58(8):1284–1304

Stern RJ (2008) Neoproterozoic crustal growth: the solid Earth system during a critical episode of Earth history. Gondwana Res 14:33–50

Streckeisen A (1976) How should charnockitic rocks be named? Centenaire Societe´ Ge´ologique de Belgique, Ge´ologie des Domaines Cristallins, Lie‘ge pp 349–360

Sun SS, McDonough WF (1989) Chemical and isotopic systematics of ocean basalt: implications for mantle composition and processes. Geol Soc Spec Publ 42:323–345

Sun G, Liu S, Gao L, Hu Y, Guo R, Fu J, Wang M, Ma C, Hu F (2019) Neoarchean sanukitoids and associated rocks from the Tengzhou-Pingyi intrusive complex, North China Craton: insights into petrogenesis and crust–mantle interactions. Gondwana Res 68:50–68

Thompson RN, Morrison MA, Hendry GL, Parry SJ (1984) An assessment of the relative role of crust and mantle in magma genesis: an elemental approach. Philos Trans Royal Soc Lond 310:549–590

Turner DC (1983) Upper Proterozoic Schist Belts in the Nigerian sector of the Pan-African province of West-Africa. In: Kogbe CA (ed) Geology of Nigeria, 2nd edn. Rock View Publication Company, Jos, pp 93–109

Watkins JM, Clemens JD, Treloar PJ (2007) Archaean TTGs as sources of younger granitic magmas: melting of sodic metatonalites at 0.6–1.2 GPa. Contrib Mineral Petrol 154:91–110

Woakes M, Rahaman MA, Ajibade AC (1987) Some metallogenetic features of the Nigerian basement. J Afr Earth Sci 6:655–664

Wyllie PJ, Wolf MB, Van der Laan SR (1996) Conditions for formation of tonalites and trondhjemites: magmatic sources and products. In: Dewit MJ, Ashwal LD (eds) Tectonic evolution of greenstone belts. Oxford University Press, Oxford, pp 258–267

Xiao L, Clemens JD (2007) Origin of potassic (C-type) adakite magmas: experimental and field constraints. Lithos 95(3–4):399–414