

Association of Applied Geochemists Student Support Initiative: Geochemistry of LCT Pegmatites in part of Northeastern Nasarawa state, Northcentral Nigeria

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INTRODUCTION

Pegmatites around the globe are known to host significant rare metals, such as Be, Nb, Ta, Sn, Cs, and Li. These metals are presently in high demand due to their exceptional characteristics, such as high boiling and melting points, resistance to corrosion, ductility, alloys well, superconductivity, low coefficient of thermal expansion, and a high coefficient of capacitance (capacity to store and release an electrical charge) (Selway *et al.* 2005). They are very significant in the electronics industry for the manufacture of capacitors, which are found in cell phones, video cameras, and laptop computers. Hence, the need for continuing to explore for potential hosts of these rare metals globally cannot be overemphasized. The geology of Nigeria is of interest as it has considerable potential to host rare metal mineralization in its pegmatites.

The pegmatites are in the northeastern Nasarawa, where north-central basement complex is part of the unmetamorphosed rocks of acid and basic dykes of late- to post-tectonic Pan-African rocks (600 ± 150 Ma; Grant 1970; Matheis & Caen-Vachette 1983; Obiara & Ukaegbu 2009). The pegmatites are reported in a broad belt extending from the Ago – Iwoye area in the southwest to Jos, northcentral basement Nigeria (Fig. 1) (Jacobson & Webb 1946; Wright 1970; Matheis 1987; Kuster 1990). They are also reported in Zuru-Gusau, northwest (Garba 2003; Okunlola & King 2003) and the Obudu area of southeastern Nigeria (Ekwueme & Matheis 1995). Presently, rare metal recoveries of these pegmatites in the study area are partially known only around Wamba areas, but not known in other parts of the study area. Furthermore, artisanal mining of rare metals, dominantly cassiterite and subordinated columbite-tantalite, has been ongoing for decades around Wamba (Kuster 1990). The pegmatites of the southwest and part of Wamba are dated from 580-530 Ma by the Rb/Sr method (Matheis 1987).

Most of the studies in the Nasarawa north-central basement were concentrated in the western part around the Keffi area. Onyeagocha (1984) and Obiara & Ukaegbu (2009) described the basement rocks around the boundary between the basement and sediments as migmatitic banded gneisses and granitic rocks of calc-alkaline and peraluminous compositions, but fail to account for the pegmatite mineralization

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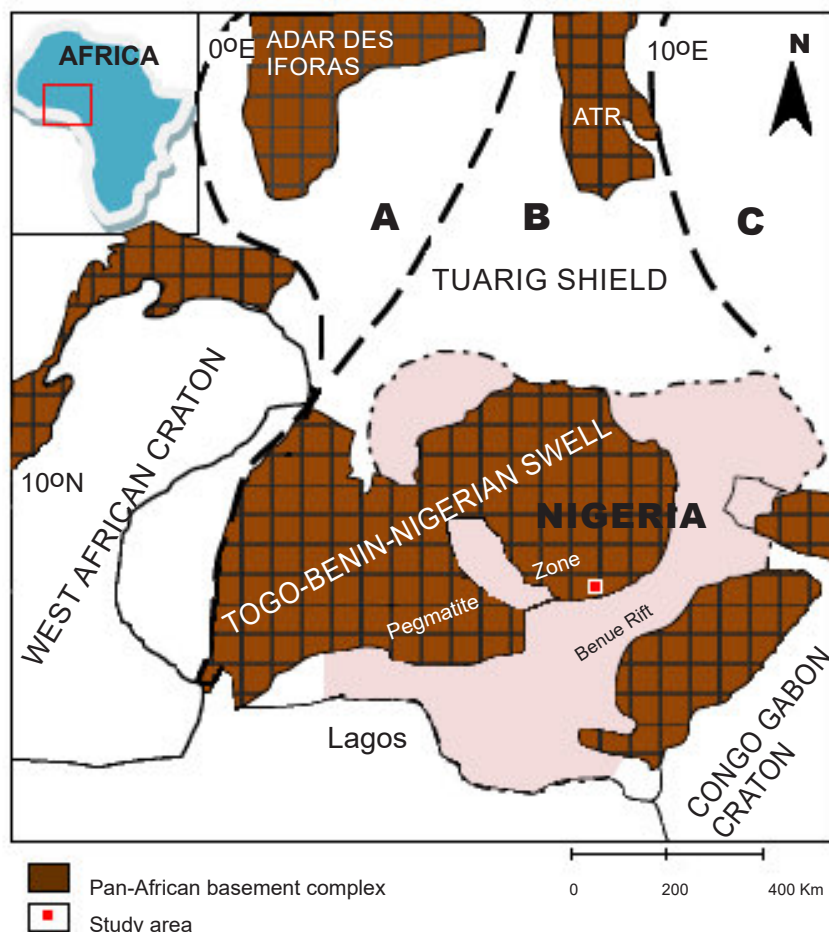


Figure 1. Location of the Precambrian basement complex of Nigeria in relation to the West African and Congo cratons and southern Tuareg Shield. (A) represents the western Tuareg Shield (Pharusian belt); (B) central Tuareg Shield (Hoggar-Air segment); (C) eastern Tuareg Shield (East-Saharan Craton). Modified after Obiara & Ukaegbu 2009.

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potential. Other workers on pegmatites mostly around the Keffi area, NW of Akwanga include Adekeye & Akintola (2007, 2008) and Akintola & Adekeye (2008) who suggested that these pegmatites were structurally controlled and have a high potential for rare metals. Okunlola & King (2003) revealed the occurrence of Ta-Sn-Li-Be mineralization in vertical and lateral pegmatites around the Keffi area. Jacobson & Webb (1946), Kuster (1990), and Akintola & Adekeye (2008) thought that the rare metal pegmatites in part of Wamba, Nigeria, are genetically related to the Pan African granitoids, based on field observations and available data; however, earlier age differences from isotopic data from Matheis and Caen-Vachette (1983) proved otherwise that led Matheis (1987) to suggest that the pegmatites in southwest Nigeria resulted from reactivation of tectonic trends in addition to partial melting and external volatiles.

Most of these investigators of pegmatites in Nigeria attributed their formation to the model of extended fractional crystallization of fertile parent granites (cf. Crouse & Černý 1972; Stilling *et al.* 2006) even when such granite bodies are unknown. However, recent work by Goodenough *et al.* (2014) and Melcher *et al.* (2015), which considered the age differences (more than 100 Ma difference) between the pegmatites in Sarkin Pawa north-central Nigeria and Pan African granitoids, concluded that they are not genetically related, suggesting a pegmatite conundrum. Apart from the generalized classification of the pegmatites in north-central basement as Wamba-Nasarawa field of the 'Older Tin-field' by Jacobson & Webb (1946), literature accounts of pegmatitic rocks in part of the northeastern Nasarawa area are rare. Secondly, data on whole-rock geochemistry of the pegmatites in Nigeria is very rare. This work used detailed field studies, mineralogical and bulk rock chemistry to characterize the pegmatites in the northeastern Nasarawa region.

REGIONAL GEOLOGICAL SETTING

The Nigerian basement complex is situated between the West African and Congo cratons and south of the Tuareg Shield (Fig. 1). The Pan-African trans-Saharan mobile belt evolved through plate collision of the active margin of the Pharusian belt (Taureg shield) and the passive plate of the continental margin of the West African craton approximately 600 Ma (Burke & Dewey 1972; Black *et al.* 1979). McCurry & Wright (1977) reported that the subduction and the collision at the eastern margin of the West African craton led to extensive melting of rocks and emplacement of calc-alkaline granitoids and basaltic intrusions.

Rocks of the Nigerian Basement Complex are believed to have undergone a series of orogenic cycles that are characterized by deformation, metamorphism, remobilization and reactivation. These correspond to the Liberian (2650 ± 150 Ma), Eburnean (2000 ± 50 Ma), Kibaran (1100 ± 200 Ma) and Pan-African (600 ± 150 Ma) cycles. The basement complex of Nigeria consists of migmatite-gneiss complex (biotite and biotite-hornblende gneisses, quartzites, quartz schist and small lenses of calc-silicate rocks), slightly migmatized to unmigmatized paraschists and metagneous rocks (pelitic schists, quartzites, amphibolites, talcose rocks metaconglomerates, marbles, banded iron-formations, and calc-silicate rocks) and older granites (granodiorites, granites, and potassic syenites).

Migmatite-gneiss complex represents the oldest basement rocks of the Nigerian Basement complex and common in most parts of the Nigerian Basement complex. They exhibit a great variation in composition, which is a result of the different protoliths and pressure-temperature conditions under which they were formed (Obiora 2005; Obiora and Ukeagbu 2009). The components of the migmatite-gneiss include the leucosome, mesosome, and paleosome. The schist belt represents the younger meta-sediments with occasional metagneous units. The schist trends mostly N-S and appears to have been restricted to the western half of the Nigerian Basement, although meta-sediments have been mapped around the Nigerian Oban massif (southeastern basement complex). The Pan-African granite suites intruded the migmatite-gneiss and the schist complex. Other rocks of the Pan-African granites include porphyritic/porphyroblastic muscovites-granites, aplites, tonalities, diorites, syenites, and charnokites (Obiora 2005), with calc-alkaline and peraluminous to metaluminous compositions. These granitic rocks are

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often slightly foliated, with gradational contacts, which may not be magmatic. Jones & Hockey (1964) identified three phases of the Pan-African granite suites based on field relationships, mineralogy, and textures: 1) early phase comprising gabbroic rock, dolerites, granodiorites, and quartz diorites; 2) main phase made up of coarse porphyritic hornblende granite, syenites, and coarse porphyritic biotite granite; 3) late phase made up of homogenous granite, pegmatite, and aplite dykes. However, Dada & Respaut (1989) using field and geochemical evidences believed that the dolerites and pegmatites were unmetamorphosed rocks of the Basement complex since they cross-cut the Pan-African rocks, representing the youngest rocks of the Basement complex. The Jurassic Younger granites of the Jos area intruded the basement complex. In contrast to the older granites, it has sharp contacts with the basement rocks, which shows that it is magmatic, occurring as ring dykes and is alkaline in nature. These Jurassic Younger granites serve as a major source of tin and other rare metal mineralization within the basement, especially around the Jos Plateau of Nigeria.

METHODOLOGY

The study was carried out by intensive field studies involving visitation of outcrops and collection of rock samples for further laboratory studies. Nineteen representative samples of large pegmatite bodies (more than 3 kg) were collected. The samples were selected from traverses across the ridges of the pegmatites according to field grouping in key locations. The samples were crushed to a minimal grain size of less than 5 mm to achieve homogeneity and powdered to 200 mesh using a tungsten mill at the Department of Geology, University of Nigeria, Nsukka. The samples were analyzed at Genalysis (Intertek) Laboratory Services Pty Ltd, Maddington, Australia. The major oxides were determined using X-Ray Fluorescence (XRF) spectrometry, whereas the trace elements and rare earth elements were determined by lithium metaborate fusion Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Loss on ignition (LOI) was determined by robotic thermogravimetric analyzer (TGA). Lower detection limits for the major oxides are: 0.01 wt. %, 20 ppm for B, 5 ppm for Li, 2 ppm for Sn, 0.5 ppm for Rb, 0.1 ppm for Cs, 10 ppm and 0.1 ppm for Nb and Ta, respectively.

LOCAL GEOLOGY AND PETROGRAPHY

The basement rocks of the northeastern Nasarawa area consist of largely migmatitic gneisses, granitic gneisses, and sparse amphibolites (Fig. 2). The grade of metamorphism ranges from greenschist to amphibolite facies across the region. These basement rocks are discordantly intruded by the pegmatites. The migmatitic gneiss shows coarse-grained, mesocratic and gneissose foliations with NNE-SSW directions. The foliation planes dip ranges from about 15° - 60° in SE direction. There are obvious banding (folia) and alignments of biotite and conspicuous alternation of leucocratic and melanocratic components within the gneisses. The locally developed leucosome is composed mainly of quartz, microcline, and plagioclase, whereas the melanosome is composed of mainly biotite and minor hornblende, with other minor constituents including cordierite and sillimanite. There is also evidence of undifferentiated older meta-sediment (paleosome) in the migmatitic gneisses. The migmatitic gneisses also possess quartzo-feldspathic veins ranging from 0.5 – 5 cm, mostly concordant with a few cross-cutting the foliation trends. Ptygmatic folds of the quartzo-feldspathic

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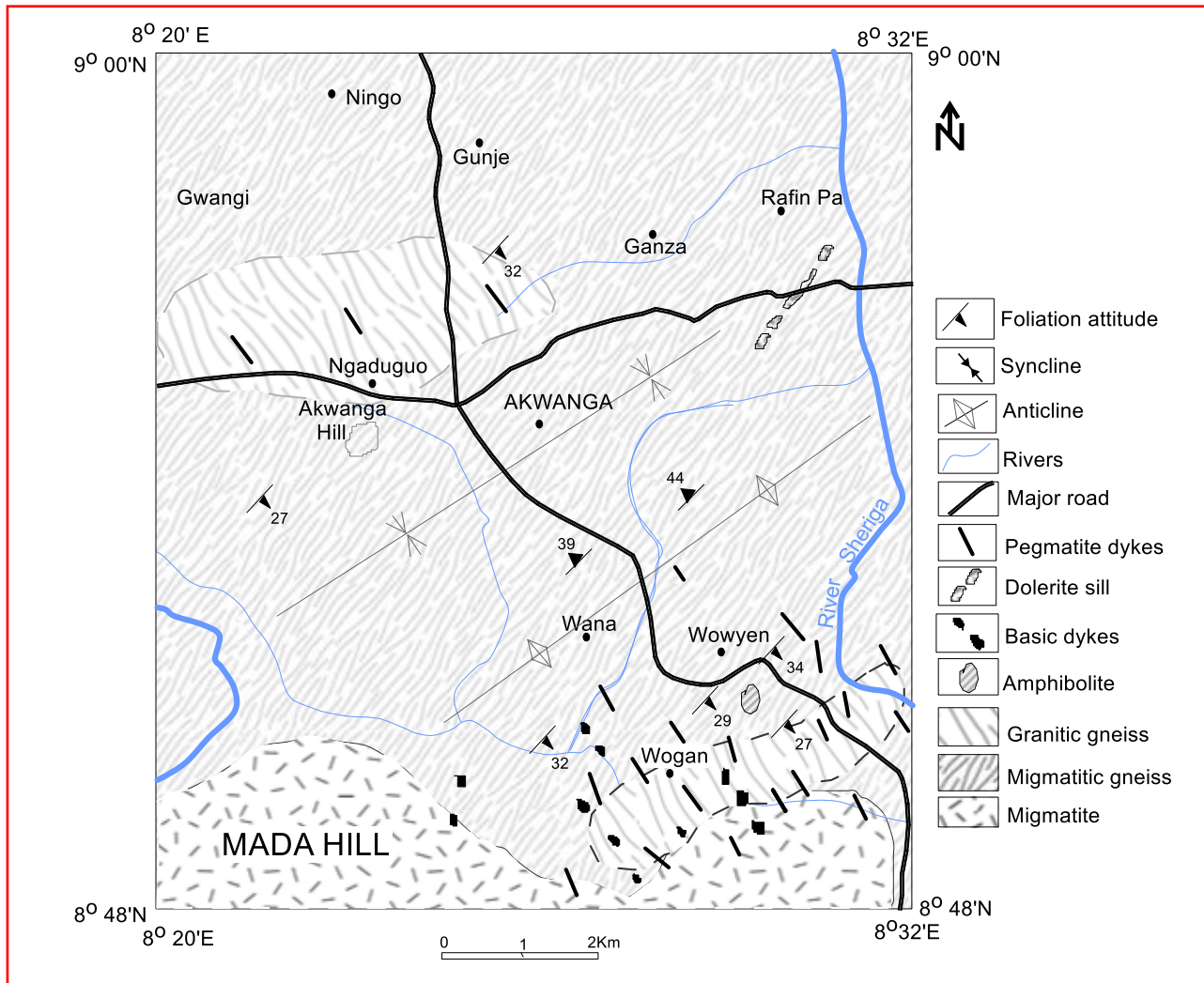


Figure 2. Geological map of the study area showing the locations of the pegmatites and the host rocks

veins and pinch and swell structures with lit per lit ejections are common especially around the Wowyen and Agbanju hills. Strike-slip faults, dextral and sinistral dislocation of veins and veinlets abound. The migmatite-gneisses are cross cut by basic dykes, basaltic and rhyolitic porphyries, and thin pegmatite dykes, although some occur as sills. Some of the biotite gneisses are porphyroblastic in compositions with phenocrysts of plagioclase forming augen structures. The plagioclase crystals occur as oligoclase in the leucosome and andesine-labradorites in the melanocratic components and are characterized mostly by albite polysynthetic twinning with few showing Carlsbad-albite combine twinning. Microcline is colourless, subhedral to euhedral with distinct cross-hatch twinning.

Granitic pegmatites are widely distributed within the granitic gneisses and migmatitic gneisses in the study area and less common in other rock types in the area. The pegmatites occur as discrete dykes down the base of Mada Hill and abound around the hills in Wamba areas, although some occur as lenses at the surface. Pegmatites occur as tabular bodies, numbering more than thirty-five in the study area. The major trend of the pegmatites is NNW-SSE, although some are also oriented NE-SW and rarely E-W. The thickness of the tabular and massive dykes ranges from 4 to 30 m; the length of the dykes ranges from 20 m to more than 700 m with discontinuity between the dykes. The pegmatites generally show sharp contacts with the host rocks and roof pendants of the granitic gneiss are observed close to the peripheral regions of the pegmatites, especially around the Wogan area. The pegmatites in the study area are grouped into simple and complex pegmatites, based on their field characteristics and mineralogy. The simple pegmatites (biotite-microcline-quartz pegmatites) occurred mostly towards the northern part of the map. The pegmatites show extremely coarse, euhedral grains of quartz, biotite, microcline, albite, muscovite, sparse garnet, and magnetite. The quartz is colourless whereas the feldspars are pinkish and blocky. The biotites are mostly primary and some are replaced by secondary muscovites. Biotite is brownish and pleochroic from pale brown to deep brown and exhibits parallel extinction. Albite is colourless with thin albite polysynthetic twinning. Microcline is colourless with its unique cross-hatch twinning. Small graphic to granophyric intergrowths occur as well as myrmekite that were observed petrographically.

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The complex pegmatites (albite-muscovite pegmatites) are dominant towards the southern and eastern parts of the mapped area (Fig. 2) around the Wogan-Wowyen-Wamba pegmatite field. There is no clear zoning in these pegmatites, although careful observations can trace large crystals up to 15 cm of quartz, muscovite-cleavelandite and locally black tourmalinized irregular core zones, whereas coarse to aplitic quartz-muscovite and minor biotite wall zones can be observed. These pegmatites have potential for Sn, Nb, and rare Ta mineralization in contrast to the earlier notion of Matheis (1987) who disputed the potential of columbite around the Nasarawa pegmatites. The pegmatites are categorized by colourless to smoky quartz, light - pinkish albite, and minor microcline, and large books of colourless to brownish muscovites. Black tourmaline patches also occur as accessory and garnet are sporadically distributed in the pegmatites. Mirolitic textures were observed in few locations of the pegmatites and graphic textures of quartz and albite are common than the simple pegmatites.

From the mineralogical studies, extremely coarse-grained and euhedral quartz, albite and muscovite are the major mineral constituents of the pegmatites. Biotite also occurs in less than 5 % of the mode. Quartz is characterized by colourless with undulating extinction in some of the samples. Albite shows albite twinning with anorthite composition of An₇₋₁₃. Graphic to granophyric, and myrmekitic textures (intergrowth of albite and quartz) are also common. Albitisation is the product of selective sodic metasomatic replacements in the pegmatites where some of the slides in modal analysis recorded almost 65 – 80 % albite (cleavelandites) in place of microcline and other K-feldspars, which occur as patchy replacements in most of the slides. Other accessory minerals are fractured almandine-garnet, black tourmalines (schorl), and tiny dark patchy minerals possibly cassiterite-columbite-tantalite, which are mostly associated with the albitisation. The muscovites are primary with no obvious deformation showing that the pegmatites are post-tectonic within the region.

RESULTS

The granitic pegmatites have moderate to very high SiO₂ contents (63.88 – 78.81 wt %). The concentrations of TiO₂, MgO, CaO, MnO, and P₂O₅ are generally less than 1 wt.%. Na₂O concentrations predominate over K₂O consistent with albitization in the pegmatites across the study areas. Al₂O₃ concentrations are moderate to high (13 – 21 wt.%) across the pegmatite samples. The A/CNK of the pegmatites in the study area reflects strongly peraluminous (A/CNK = 1.45 – 2.14) compositions, with the complex pegmatites having the highest values. On the alkaline-silica variation diagram, the simple and rare metal pegmatites plot predominantly in the granite field, except two rock samples of the complex pegmatite and one sample of the simple pegmatite which plot in the syenite field (Fig. 3).

The Rb contents in the complex pegmatite (277 – 1719 ppm) and simple pegmatite (126.5 ppm – 559.8 ppm) are high. In contrast, the concentrations of Ba and Sr in the pegmatites are below average crustal abundances of Wedepohl (1995). The values of Sr in some samples of the pegmatites are mostly below detection limit of 20 ppm and not greater than 230 ppm. Tin, Nb, and Ta values in the pegmatites are higher in the complex pegmatite with values up to 4466 ppm Sn, 106 ppm Nb, and 45 ppm Ta compared to average fertile pegmatitic leucogranite of Superior Province (Černý & Meintzer 1988; Selway *et al.* 2005). Tin, Nb, and Ta contents in simple pegmatites range from 4 – 35 ppm, 7 – 15 ppm, and 0.8 – 10.7 ppm, respectively. The pegmatites are also depleted in REEs and base metals, e.g., Ag, Cr, Co, Ni, Cu, Mo, Pb, and Zn. Cs, Ga, and B values are enriched in complex pegmatites. The highest values of Cs, Ga, and B are up to 56.5, 59, and 4205 ppm, respectively. Lithium concentrations range from 5.0 ppm in the simple pegmatites up to 161 ppm in the complex pegmatites. These variations in elemental values show that the degree of fractionation is proportional to rare element

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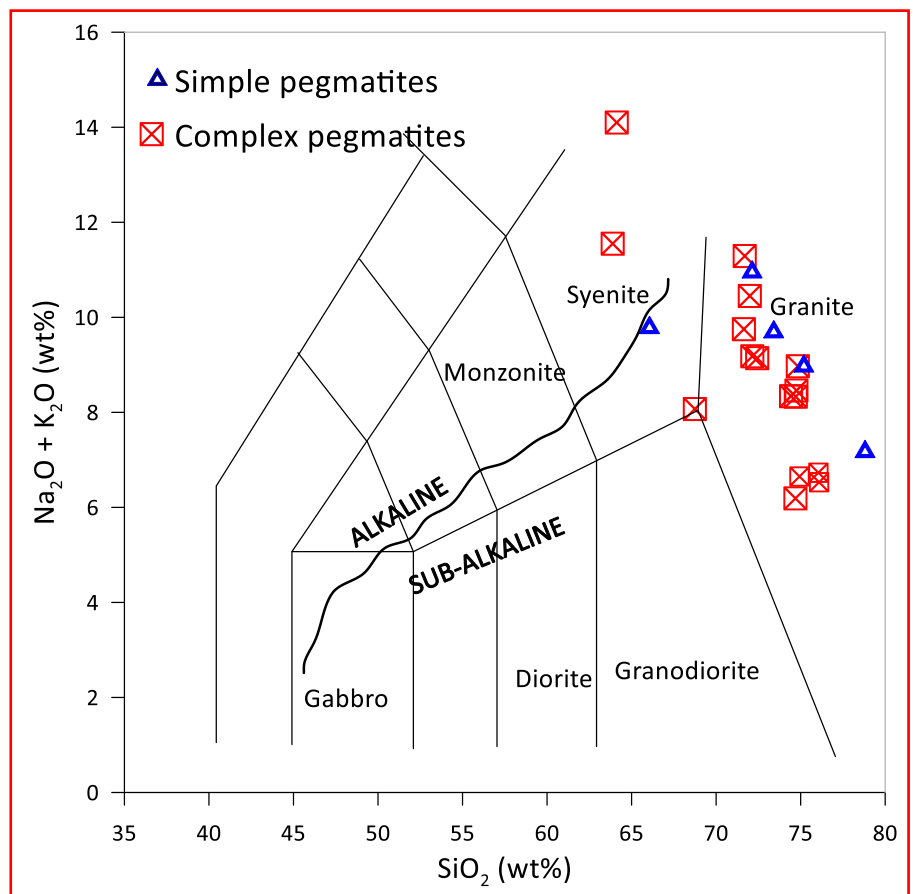


Figure 3. Nomenclature of the granitic pegmatites using alkaline-silica diagram.

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abundances (Li, Be, B, F, P, Ga, Rb, Cs, Y, Nb, Sn, and Ta) in fertile granites (Černý & Meintzer 1988), whereas Ti, Sr, Ba, and Zr decreases with fractionation.

DISCUSSION

The strongly peraluminous nature of the pegmatites from the study area is clearly observed on the Shand index diagram (Fig. 4a), $Al_2O_3/(Na_2O+K_2O)$ versus $Al_2O_3/(CaO+Na_2O+K_2O)$ of Maniar & Piccoli (1989). The complex pegmatites are most evolved and show higher peraluminosity than the simple pegmatites. These pegmatites are spatially associated with S – type granites. Samples of the pegmatites plot predominantly in the high-K calc-alkaline and shoshonite series field of Peccerillo & Taylor (1976) (Fig. 4b). On the SiO_2 vs Fe^* of Frost *et al.* (2001), the pegmatites fall in the ferroan field (Fig. 4c). The ferroan affinity of the rocks is consistent with the presence of magnetite both in the mode and norm of the pegmatites, in the absence of other Mg-rich ferromagnesian phases. In the MALI diagram of Frost *et al.* (2001), the pegmatites plot dominantly in the alkali and stretches into calcic-alkalic field (Fig. 4d).

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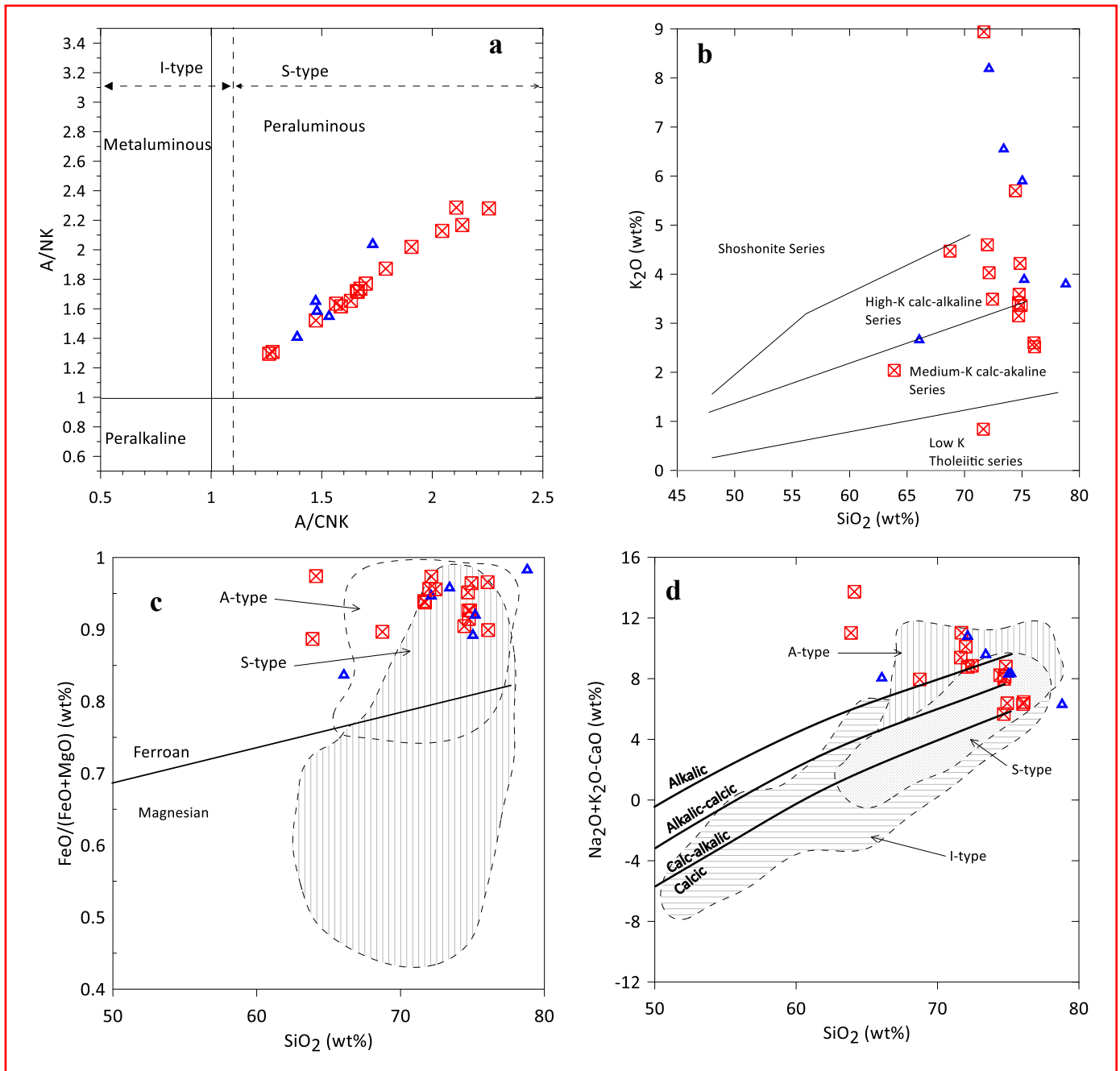


Figure 4. (a) Shand index plot for the pegmatites in Wogan area. $A/NK = Al_2O_3/(Na_2O+K_2O)$ and $A/CNK = Al_2O_3/(CaO+Na_2O+K_2O)$ after Maniar & Piccoli (1989). Binary plots for the granitic pegmatites in Wogan (b) K_2O versus SiO_2 of Peccerillo & Taylor (1976); (c) $FeO/(FeO + MgO)$ versus SiO_2 after Frost *et al.* (2001); (d) modified alkali-Lime Index (MALI) versus SiO_2 of Frost *et al.* (2001). Symbols are as in Figure 3.

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These geochemical properties are similar to the findings of Chukwu & Obiora (2021) and Goodenough *et al.* (2014) in pegmatites around the north-central basement complex of Nigeria. The peraluminous characteristic of the pegmatites in the study area are consistent with the observations of other rare metal and barren pegmatites in other parts of Nigeria, such as the southwestern Nigerian Oke-Asa and Igbeji pegmatites (Okunola & Oyedokun 2009); north-central Nigerian Sarkin Pawa-Minna pegmatites (Goodenough *et al.* 2014) and Angwan Doka pegmatites (Akoh *et al.* 2015), and southeastern Nigeria's Oban and Bamenda massif pegmatites (Ibe & Obiora 2019).

The pegmatites in this study area show variable trace element and REEs patterns and are strongly fractionated, especially in the complex pegmatites. They are enriched in Cs, Tl, Rb, B, Sn, K, Nb, Ta, Pb, U, and Li, but show typically depletions in Ba, Th, and Ti, as well as, REEs (Fig. 5a). These pegmatites generally show low concentrations of REE (Fig. 5b) with some of the values below detection limit. Though the pegmatites have minor higher LREE relative to the HREE [(La/Yb)_n = 1.23 – 25.3] with the simple pegmatites showing higher values, LREE and HREE concentrations are generally very low (Fig. 5b), because the REEs in pegmatites are easily partitioned into the accessory phases (Christiansen *et al.* 1993). Furthermore, the Eu concentrations in these pegmatites are very low, with most less than detection limit (< 0.1 ppm), except few samples of the simple pegmatites. Concentrations of Ho, Tm, and Lu in the pegmatites are also below

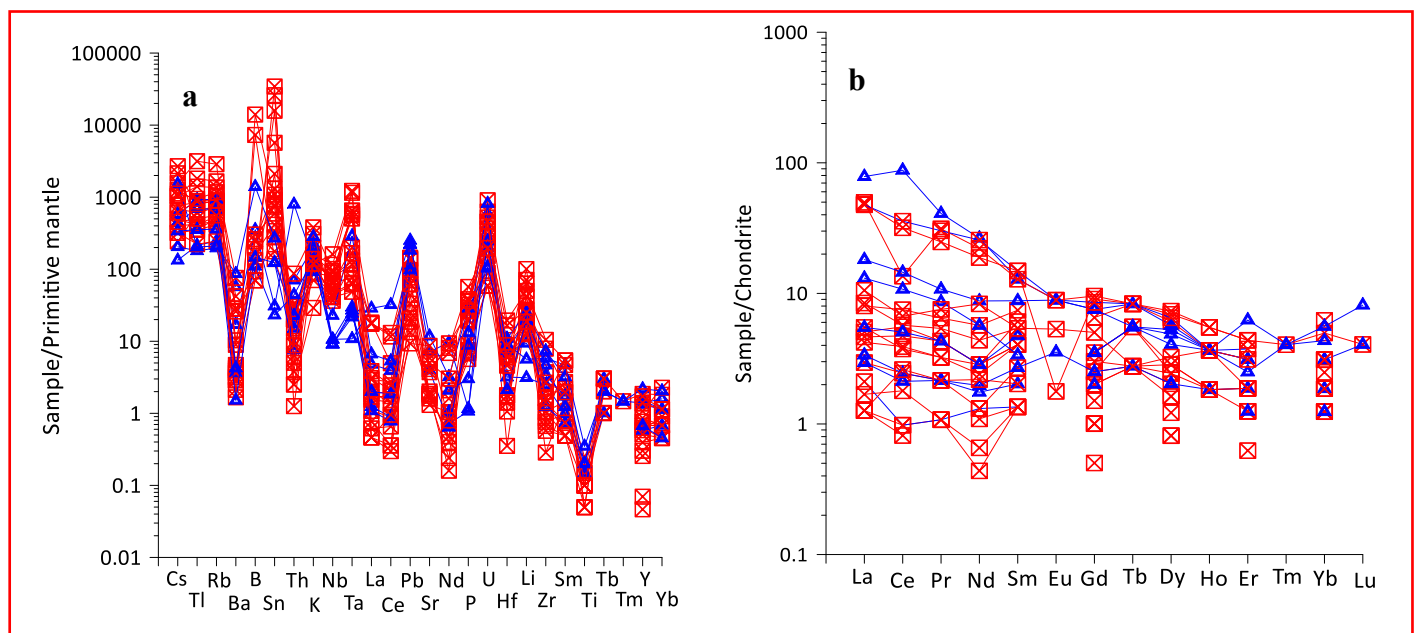
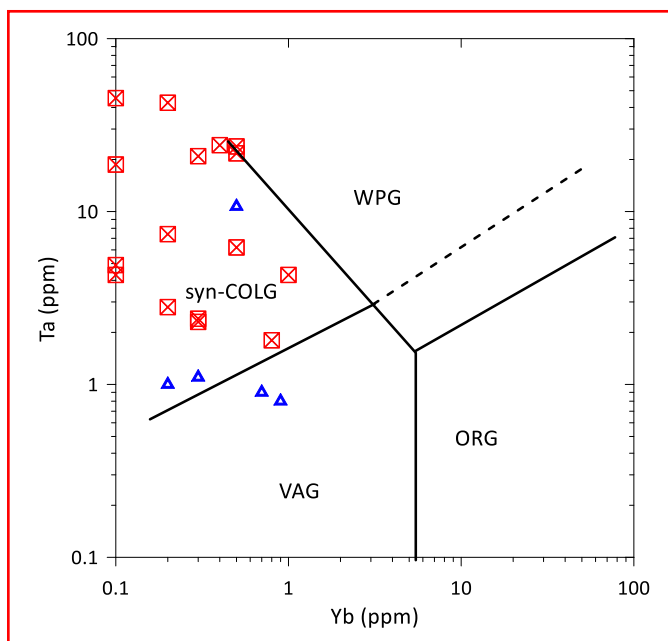


Figure 5. (a) Primitive mantle-normalized multi-element diagrams for the granitic pegmatites. Normalizing factors from McDonough and Sun (1995). (b) Chondrite-normalized rare earth elements diagrams for the granitic pegmatites. Normalizing factors from McDonough and Sun (1995). Symbols are as in Figure 3.



detection limits of 0.1 ppm and the pegmatites are mildly depleted in Nd and Er. The different patterns of the REE in these samples probably reflect the crystallization of accessory phases, as well as garnet. The Eu anomalies in the pegmatites can be explained by restite feldspar, fractional crystallization of feldspars, and melt-fluid interaction (including albitisation) in the last stage of magma solidification (Abdelfadil *et al.* 2016; Chukwu & Obiora 2014, 2018). Considering the diagram of Pearce *et al.* (1984) (Fig. 6) the pegmatites fall in the field of syn-COLG which further supports that S-type granite originating from collision setting.

Figure 6. Ta versus Yb diagram of Pearce *et al.* (1984). VAG: volcanic arc granites; syn-COLG: syn-collisional granites; WPG: within-plate granite; ORG: oceanic ridge granites. Symbols are as in Figure 3.

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POTENTIAL MINERALIZATION OF THE PEGMATITES

The elemental enrichments (Cs, Rb, Nb, Ta, B, and Li) in the spidergrams (Fig. 5a) are in accordance with the field observations that show that the complex pegmatites contain Sn-Nb-Ta oxides and B-bearing minerals (e.g., tourmaline) compared to the simple pegmatites. The presence of muscovite in the complex pegmatites may explain the enrichment in Li, Rb, and Cs. These elemental enrichments and depletions are consistent with recognized data (Černý *et al.* 2012) as evidence for rare-metal pegmatites of the LCT (Li-Cs-Ta) family. Rare metal pegmatites in high-grade metamorphic terranes with similar whole-rock geochemical patterns are also known from other areas of collision and post-collisional magmatism, such as the Lewisian Gneiss Complex of northwest Scotland (Shaw *et al.* 2016) and Altai mountains of China (Zhu *et al.* 2006). In Nigerian Pan-African orogenic belts, there is a scarcity of whole-rock geochemical data on rare metal pegmatites, but the few data available (Okunlola & Oyedokun 2009; Goodenough *et al.* 2014) also show similar geochemical signatures as this present study.

Degree of geochemical fractionation in pegmatites can lead to elemental concentrations for further exploration for rare metals. Strongly peraluminous values ($A/CNK > 1.2$) are used to evaluate the degree of fractionation in fertile granite (Selway *et al.* 2005). A/CNK of the complex pegmatites that are extremely peraluminous (1.5 – 2.1) indicate that the pegmatites are highly fractionated and have abundant Al-rich minerals, such as garnet and muscovite. Rare element contents in fertile granites/pegmatites increase with increasing fractionation of Li, Be, B, F, P, Ga, Rb, Cs, Y, Nb, Sn, and Ta and decrease in Ti, Sr, Ba and Zr (Černý & Meintzer 1988). Certain trace-element ratios are good indicators of fractionation in fertile granites/pegmatites, such as K/Rb, K/Cs, Mg/Li, Al/Ga, and Nb/Ta. These ratios are expected to be significantly lower than average upper continental crust of Taylor & McLennan (1985) (see also Wedepohl 1995), and are comparable to bulk trace element ratios of Černý (1989) in fertile granite/pegmatites (cf. Selway *et al.* 2005). The average ratios of K/Rb, K/Cs, Mg/Li, Al/Ga, and Nb/Ta in the complex pegmatites are 64.5, 2872, 24.8, 2015, and 8.76 respectively while their average ratios in the simple pegmatites are 196, 4190, 20.5, 4009, and 5.81, respectively. This shows that the complex pegmatites are strongly fractionated and have strong potential for rare metals relative to the simple pegmatites (Table 1). High ratios of Na/K (2.55 average) in the complex pegmatites also indicate considerable albitisation in the pegmatites. These ratios are also within the range obtained in muscovites for rare metal pegmatites in other parts of the Nigerian Basement Complex (Černý 1989; Okunlola & King 2003; Okunlola & Oyedokun 2009; Akintola *et al.* 2012; Chukwu & Obiora 2021).

Table 1. Selected trace elements ratios in the Wogan pegmatites compared with fertile granites

	Complex pegmatite		Simple pegmatite		UCC mean	Fertile Granites
	Range	Mean	Range	Mean		
K/Rb	40.4-107.6	64.5	149.4-331.6	196.0	252.0	42-270
K/Cs	299.7-6869	2871	687.9-7336	4191	7630	1600-15400
Mg/Li	5.97-51.4	24.8	11.7-25.6	20.5	--	1.7-50
Al/Ga	1596-2160	2015	3686-4584	4010	--	1180-3100
Nb/Ta	1.36-15.4	8.76	1.40-8.75	5.81	11.4	--

*Fertile peg. ratios data from Černý (1989)

*UCC represents average upper continental crust after Taylor and McLennan (1985)

CONCLUSIONS

This research shows that the pegmatites in the migmatitic to gneissic basement complex in areas of northeastern Nasarawa are predominantly complex rare-metal pegmatites. The complex pegmatites are highly peraluminous, relatively low K/Rb and Al/Ga ratios, highly enriched in Sn and B, and relatively enriched in Rb, Li, Cs, B, Be, Nb, and Ta compared to the simple pegmatites. The rare-metal pegmatites are dominated by albitic feldspar, muscovite, and quartz. Almandine garnets, tourmaline (schorl), and Sn-Nb-Ta minerals also occur as accessories. The mineralogy and whole rock chemistry of the pegmatites suggest a highly peraluminous source probably a metapelitic to associated metasedimentary protolith that was enriched in incompatible

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LILE and HFSE. Complex pegmatites are highly fractionated compared to the simple pegmatites; these similarities in the chemical characteristics show that the complex pegmatites and the simple pegmatites are generated contemporaneously, the differences in composition arose from magmatic fractionation, possibly related to spatially associated S-type granites.

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