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Mineralogy and Geochemistry of Beryl-Bearing Prgmatite Dykes from Gbayo, Southwestern Nigeria

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Abstract

The Gbayo granitic beryl-bearing pegmatites occur as discontinuous dykes, intruding into the host rock of mica schist. This study was aimed at appraising the geochemistry and mineralization potentials of the pegmatites. Systematic geological mapping to ascertain the relationships between the pegmatites and their host rocks was undertaken. Fresh pegmatite samples were collected for both petrographic and geochemical studies. Analytical results showed high SiO_2 (64.88 to 81.94%) and Al_2O_3 (11.54 to 19.11%,), and fair concentrations of Na_2O (av. 4.10%) and K_2O (av. 3.58%). The relatively high aluminum and alkaline compositions have promoted beryl crystallization from the pegmatitic melt. Incompatible elements are fairly concentrated in most of the analyzed samples, except for Rb which has the highest and greatest variability, with values ranging from 30.10 to 1,528.40ppm which could be indicative of the high degree of melts fractionation, resulting from long travel distance of pegmatite-forming melts. The K/Rb ratios for most of the analyzed beryl-bearing pegmatite samples are less than 100, with a mean value of 75.11, which is indicative of mineralization. Elevated Be values (>142ppm) were observed for some samples, indicating some levels of beryl mineralization. The dominance of Fe chromophore in the pegmatites accounts for the manifestations of aquamarine.

Keywords: *Gbayo, Pegmatites, Beryl-bearing, Mineralisations, Aquamarine.*

1. Introduction

Granitic pegmatites form an intrinsic and genetically important part of granitic intrusions in most orogenic belts (Cerny et al., 2012a), and as such have their mineralogy similar to those of the granites, consisting mainly of quartz, feldspar, and muscovite. They are characterized by anomalous enrichment in incompatible lithophile elements such as Rb, Cs, Li, Be, and Sn and are often associated with Nb-Ta-Sn-W mineralizations (Linnen et al., 2012). These occasional enrichments in the unusual trace elements will also result in the crystallization of equally unusual and rare minerals such as beryl, tourmaline, etc. This distinctiveness has made the study of pegmatites a subject of interest to many authors all over the world, particularly in Nigeria. Beryl, the most common beryllium-bearing mineral in the earth's crust, occurs in granite pegmatites and may form at different stages of pegmatite consolidation and crystallization, by auto-metasomatic processes, and during hydrothermal events (Cerny 2002; Wang et al. 2009).

Pegmatites within the Precambrian Basement Complex rocks of Nigeria have been categorized in terms of rare elements (e.g. Nb, Ta, Li, W, Sn, Be, B, Cs, Rb) mineralization as mineralized and non-mineralized (Adetunji et al, 2016). Matheis and Caen-Vachette (1983), while working on the pegmatites of the Pan-African reactivation zone, covering areas of Egbe, Ijero, and Wamba, distinguished them as barren and mineralized. In the Nasarawa area of Central Nigeria, Akintola and Adekeye (2008) also categorized the pegmatites in the area into two; the simple, barren quartz-feldspar and the complex rare-metal pegmatites. Jimoh and Olatunji (2020), in classifying the Olode groups of pegmatites as mineralized and barren, suggested the same parental source for the two varieties but believed that the differences, particularly in their mineralization potentials, might have resulted from their varied degree of fractionation and evolutionary trends. The Nigerian pegmatites were formed during the time of 562–534 Ma, indicating emplacement related to the end of the Pan-African magmatic activity, and have been sources of cassiterite and columbite–tantalite production (Garba 2003). They occur mostly as dyke-like intrusions, which vary from a few meters to several kilometers in length and a few centimeters to meters in width (Okunlola and Akintola 2007).

Mining activities have been going on in various parts of Gbayo, (Latitudes 7^0 11' to 7^0 14' and Longitudes 3^0 55' to 3^0 58' 30) for some time now, taking out various quality grades of beryl, including top facet grades from the beryl-bearing pegmatite dykes. Several tons of high-grade gem beryls, particularly aquamarine are being exploited from

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the different mines in the area. Metallic minerals such as columbite-tantalite and some rock-forming minerals which are valuable like feldspar are also included in the mineral resources that are being mined for economic purposes in the area. The mineralogy and geochemistry of the Gbayo beryl-bearing pegmatite dykes were studied to appraise their nature of mineralization.

2. Research Methods

A geological mapping exercise was undertaken in Gbayo and the surrounding area to unravel the geology of the area. Representative fresh samples of beryl-bearing pegmatites were collected from various mines for both petrographical and geochemical studies. Ten of the samples were each cut into slides, from which the mineralogical contents were determined with the aid of the petrological microscope using transmitted polarized light. Due to the coarse-grained nature of pegmatites' mineral contents, large enough samples were taken to characterize the whole rock geochemistry. Ten such samples were individually pulverized and subjected to major, trace, and rare elements analysis, using the technique of Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) after fusion with $LiBO_2$, at the ACME Analytical Laboratories Ltd, Vancouver, Canada. The detection limits for major elements range from 0.002 to 0.04%, and 0.02 to 1ppm for trace elements. For the elemental determinations, 0.2gm each of powdered samples and 1.5gm LiBO2 flux were mixed in a graphite crucible and subsequently heated to 1050^0C for 15 min. The molten samples were then dissolved in 5% HNO3. The sample solution was typically introduced into the ICP plasma as an aerosol, it is completely dissolved and the elements in the aerosol are converted first into gaseous atoms and then ionized towards the end of the plasma. They are then brought into the mass spectrometer via the interface cones. The interface region in the ICP-MS transmits the ions traveling in the argon sample stream at atmospheric pressure into the low-pressure region of the mass spectrometer. Once the ions enter the mass spectrometer, they are separated by their mass-to-charge ratio. They are then detected by a suitable detector which translates the number of ions striking the detector into an electrical signal that can be measured and related to the number of atoms of that element in the sample via the use of calibration standards.

3. Geological Setting

Gbayo and the surrounding areas are underlain by crystalline rocks of the southwestern Nigerian Basement Complex. The crystalline rocks in Nigeria are divided into three main groups; the Basement Complex (Pan-African and Older (Precambrian), > 600 Ma), Younger Granites (Jurassic, 200 – 145 Ma), and Tertiary to Recent volcanic (Fig. 1). The Basement Complex of Nigeria, of which the Southwestern Nigeria Basement Complex is part, forms a part of the African crystalline shield, which occurs within the Pan-African mobile belt that lies between the West African and Congo Cratons, and south of the Tuareg Shield (Black, 1980). It has a complex geologic history, resulting from different episodes of rock formation spanning the Achaean to Lower Proterozoic. Within the Basement Complex, Obaje (2009) distinguished four petro-lithological units; the Migmatite-Gneiss Complex, the Schist Belts, the Older Granites, and the Undeformed Acid and Basic Dykes.

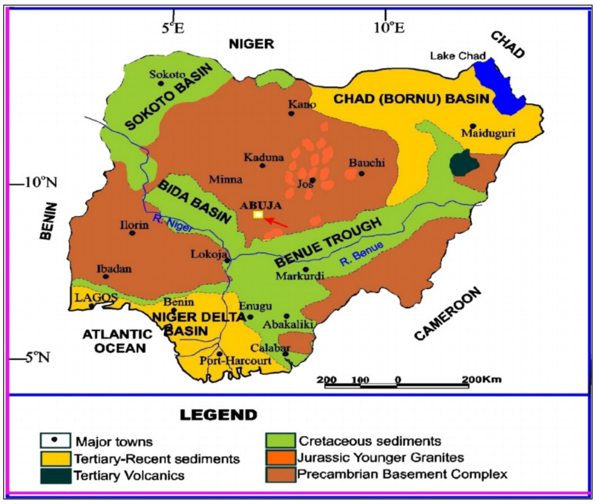


Figure 1. Generalized geological map of Nigeria showing the three lithological units (After Obaje, 2009).

The Migmatite-Gneiss Complex has a heterogeneous assemblage, comprising migmatites, orthogneisses, paragneisses, and a series of basic and ultrabasic metamorphosed rocks. Petrographic evidence indicates that the Pan-African reworking led to the re-crystallization of many of the constituent minerals of rocks of the Migmatite-Gneiss Complex by partial melting with the majority of the rock types displaying medium to upper amphibolites facies metamorphism. The rocks of the Schist Belts are best developed in the western half of Nigeria, west of 8^0E longitude, and are Upper Proterozoic supracrustal assemblages of low to medium-grade metasediments-dominated belts (Annor et al., 1996). They generally trend North-South and have been in-folded into the Migmatite-Gneiss-Quartzite Complex. Lithologically, the Schist Belts consist of quartzites, amphibolites, pelitic and mica-schists, calc-silicate rocks, marbles, phyllites, meta-conglomerate iron formations, and subordinate meta-igneous rocks (Elueze, 1992). The Older Granites, otherwise known as the Pan-African Granitoids are believed to have been emplaced during the Pan-African orogeny and occur intricately with the Migmatite-Gneiss Complex and the Schist Belts into which they are generally intruded (Harper et al., 1973). The Pan-African intrusive suite comprises mainly granites and granodiorite, with subordinate pegmatite and aplites. Affiliated rocks include charnockites, syenites, tonalites, adamellites, quartz monzonites, and gabbro. The Undeformed acid and basic dykes often observed to crosscut the rocks of the Migmatite-Gneiss Complex, the Schist Belts and the Older Granites are late to post-tectonic Pan-African. They include the felsic dykes, such as the muscovite, tourmaline- and beryl-bearing pegmatites, and the basic dykes such as dolerite dykes which are believed to belong to the terminal stage of the Pan-African orogenic event in Nigeria (Olarewaju, 1999).

4. Field Relationships

Although rocks are poorly exposed in major parts of Gbayo, field observations have shown that the geology of the area is dominated by mica schist, pegmatite, and aplite, with the schist being the oldest and the host to the other rock types in the area (Fig. 2). The mica schist generally served as the host rock to the beryl-bearing pegmatites in virtually all the mining excavations in the area (Fig. 3). The poor exposure of the host mica schist in the area could have resulted from its high susceptibility to weathering. Over three-quarters of the map, area is underlain by the Precambrian pegmatites, ranging from huge intrusive bodies to small pockets of pegmatitic intrusions intermittently observed in the area.

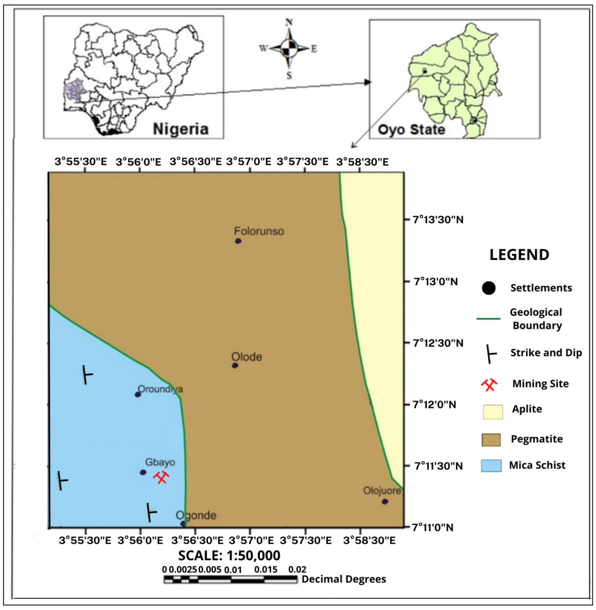


Figure 2. Geological map of Gbayo, the study area.

Figure 3. Photograph shows beryl-bearing pegmatite generally hosted by the micaceous schist in Picnine mines, Gbayo.

Latitude 07^0 11' 25.6" N, Longitude 003^0 55' 39.2" E

The central portion of the map area is predominantly underlain by pegmatites that have intruded the older mica-schist discordantly, making pegmatites the most prominent visible rock type in the area. In most instances they occur as low-lying intrusive bodies, while in many others they are found as flat-lying veins and dikes, either crosscutting each other or with quartz veins. These pegmatites belong to the early Precambrian pegmatites, classified by Rahaman (1988) as members of the Older Granite suite, believed to have been emplaced during the Pan-African orogeny (Harper et al, 1973). Megascopically, pegmatite is deficient in muscovite but mainly contains orthoclase feldspar and quartz with schorl and garnet crystals as accessory minerals. Bordering the Pan-African pegmatites to the northeast of the map area is aplite, which is similar in composition to the pegmatite but with finer grain sizes. Just like the pegmatites the aplites also bear some euhedral crystals of schorl and garnet disseminated within the matrix.

In all the mining excavations observed in the study area, pegmatites occur as dykes of varying widths, trending NE-SW and intruding into the host mica schist. These pegmatite dykes are lithologically and chronologically different from the Precambrian pegmatites in the central portion of the map area. They are the NE-SW trending beryl-bearing pegmatite dykes, which are highly rich in muscovite, and have been described by Dada (2006) as members of the felsic dykes, belonging to the Un-deformed acid and basic dykes. They are believed to be late to post-tectonic Pan African, whose ages range between 580 and 535 Ma using Rb-Sr studies on whole rocks (Matheis and Caen-Vachette, 1983; Dada, 2006). Adetunji et al. (2016) recently obtained U-Pb zircon age of 709 +27/-19 Ma established for the Ede pegmatites to represent the oldest Pan African magmatic event so far reported in southwestern Nigeria. Ball (1980) believed that a conjugate fracture system of the strike-slip faults that is believed to have marked the end of the Pan-African tectonic event probably controlled the emplacement of the NE-SW trending beryl-bearing pegmatite.

5. Petrography

The mineralogy of the beryl-bearing pegmatite dyke is simple, consisting of quartz, feldspar, and muscovite with beryl and occasional metallic oxides, including columbite-tantalite ($(Fe, Mn)(NB, Ta)_2O_6$), and rarely cassiterite (SnO_2). The petrographic study of the beryl-bearing pegmatite samples reveals they contain plagioclase feldspar (30-35%), orthoclase feldspar (15-20%), microcline (5-10%), quartz (15-20%), muscovite (10-15%), and other accessory minerals which may include beryl and columbite-tantalite (Fig. 4 and 5). As shown in the photomicrographs, most of the quartz crystals display granophyric textures, owing to their intergrowth with alkali feldspar, even though their outlines are visible due to their slightly different reliefs. The polysynthetic twinning in plagioclase distinguishes it from tartan or cross-hatched twinning, which is diagnostic of microcline, particularly under crossed polar. However, most of the feldspar crystals are microperthitic in nature (Fig. 5a and 5b), as both the plagioclase and alkali feldspars have intergrown together. No twinning is visible in the field of alkali feldspar. It is therefore most appropriate to name these minerals orthoclase-microperthite.

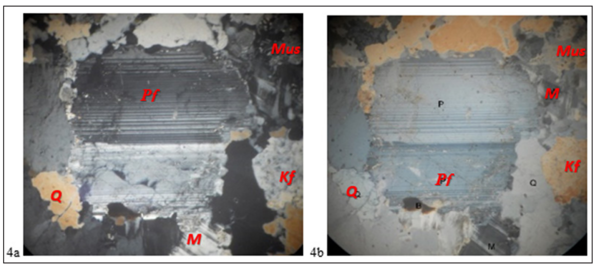
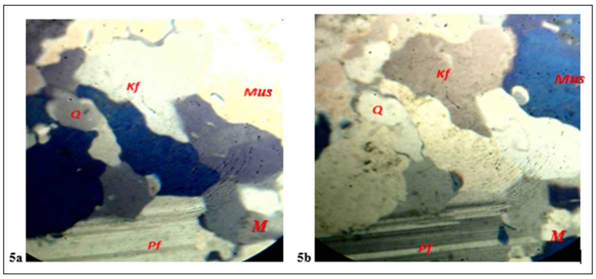


Figure 4. Figures 4a&b. Photomicrographs of the beryl-bearing pegmatite sample from Picnine mines in Gbayo; in transmitted light, Pf =Plagioclase feldspar, Kf = Potassium feldspar, Q = quartz, Mus = Muscovite, M = Microcline (X40).



Figures 5a and **b**. Photomicrographs of the beryl-bearing pegmatite sample from Otoki mines in Gbayo; (4a) under plane-polarized light (ppl) & (4b) under crossed polars (xpl), Pf =Plagioclase feldspar, Kf = Potassium feldspar, Q = quartz, Mus = Muscovite, M = Microcline (X40).

Interesting economic mineralization, consisting of huge gem potentials of beryl, particularly aquamarine accompanied by metallic minerals such as columbite-tantalite and cassiterite, is prevalent within the beryl-pegmatite dykes. Where visible, these pegmatite dykes often bear crystals of blue, colorless, and occasionally yellow beryl, occurring either within quartz-muscovite assemblages along the contacts between these pegmatites and the host mica schist, or in miarolitic cavities within the pegmatites (Fig. 6). Columnar pale blue beryl crystals with simple morphology commonly occur in blocky pegmatite units, in close association with quartz, microcline, and muscovite, where they reach several centimeters to meters in length. In most gem-mineral deposits of southwestern Nigeria, tourmaline and beryl which are usually associated with other gem minerals alongside other rock-forming minerals such as feldspars, quartz, and muscovite, occur in miarolitic cavities within granitic pegmatites, and along the contacts which these pegmatites make with their host rocks (Jimoh, 2018). Beryl mostly occurs as euhedral to subhedral crystals of aquamarine ($Be_3Al_2Si_6O_{18}$) (Fig. 7) and goshenite ($Be_3Al_2SiO_6$) of varied diameters embedded in the beryl-bearing granitic pegmatite dykes crosscutting the micaceous schist in the area. Several tons of gem-quality aquamarine crystals have been exploited from the different mines in the area (Jimoh, 2018). Although most of the beryl crystals are fractured and opaque, a lot of clear and transparent crystals were also found, and have been cut into good-quality pieces of jewelry. Other economic minerals usually found associated with the beryl crystals which are also being exploited include metallic minerals such as columbite-tantalite and cassiterite, and rock-forming minerals like feldspar and quartz.

Figures 6. Photograph shows a miarolitic cavity within the NE-SW beryl-bearing pegmatite form which crystals of beryl have been evacuated.

Figures 7. Photograph shows a miarolitic cavity within the NE-SW beryl-bearing pegmatite form which crystals of beryl have been evacuated.

6. Geochemistry

6.1. Major elements

The chemical compositions of the analyzed samples of the Gbayo beryl-bearing pegmatite dykes, which are the direct reflections of their modal compositions, have major oxides constituting more than 99% of their entire chemical compositions (Table 1). Results from the geochemical analysis show high enrichments in SiO_2 and Al_2O_3, fair enrichments of the alkali metal oxides, Na_2O and K_2O, but depletion in the remaining major oxides. While SiO_2 values ranged from 64.88% to 81.94%, with a mean value of 75.05% and a standard deviation of ±5.81, the Al_2O_3 values ranged from 11.54% to 19.11%, with an average value of 14.97% and a standard deviation of ±2.44 (Table 2). The alkali metal oxides, Na_2O and K_2O are fairly enriched in most of the sampled pegmatites with their mean values of 4.10% and 3.58% respectively, which could be due to the high feldspar content of the pegmatites. The relatively high aluminum and alkaline compositions might have promoted beryl crystallization from the pegmatitic melt. London and Evensen (2002) observed that high aluminum and alkaline compositions are the main conditions required for beryl crystallization, especially in pegmatites. The aluminum saturation indices (ASI) for the sampled pegmatites are greater than one (A/CNK > 1 and A/NK > 1, where A = Al_2O_3, CNK= $CaO+Na_2O+K_2O$ and NK = Na_2O+K_2O), indicating that all the investigated rocks are per-aluminous. Their provenances are therefore believed to be peraluminous and belong to the Lithium - Cesium - Tantalum (LCT) family pegmatites, as Cerny (1982) found pegmatites of the LCT family to be of mild to extremely per-aluminous parent granitic compositions. The highly siliceous and per-aluminous compositions provided the silicic and acidic environments necessary for beryl formation (Jimoh, 2018). Beryllium saturation levels in melts are mostly affected by temperature but also decrease with increasing alumina and silica activity (London and Evensen, 2002), which explains the empirical association of beryl with silica-rich peraluminous magmas. Most beryl occurrences, particularly economic beryl deposits, are in pegmatites derived from peraluminous magmas (Groat et al, 2005). Turpin et al. (1990) pointed out that peraluminous granites are generally considered to be generated through the partial melting of upper crustal rocks, especially during continent-continent collision events.

Table 1. Representative pegmatite compositions from Gbayo.

Sample	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10
Major Oxides (wt%)										
SiO_2	80.50	81.94	74.89	75.88	65.00	74.71	76.27	64.88	78.38	78.05
Al_2O_3	12.49	11.54	14.72	14.72	19.01	15.27	14.29	19.11	13.88	14.22
Fe_2O_3	0.62	0.79	0.64	0.41	0.32	0.65	0.43	0.40	1.08	1.12
MgO	0.08	0.10	0.06	0.02	0.01	0.05	0.02	0.01	0.10	0.10
CaO	0.17	0.17	1.10	0.45	0.04	1.10	0.54	0.04	0.11	0.09
Na_2O	2.78	1.86	6.51	5.43	2.68	6.60	5.40	2.74	0.92	0.87
K_2O	2.08	2.21	0.44	1.88	12.62	0.42	1.78	12.50	3.44	3.58
TiO_2	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.03
P_2O_5	0.02	0.03	0.04	0.39	0.19	0.04	0.46	0.19	0.06	0.05
MnO	0.02	0.02	0.73	0.07	0.01	0.70	0.08	0.01	0.03	0.03
Cr_2O_3	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
LOI	1.2	1.3	0.4	0.7	0.1	0.4	0.7	0.1	1.9	1.8
Sum	99.99	99.94	99.97	99.99	99.99	99.98	99.99	99.99	99.93	99.92
A/NK	2.57	2.84	2.18	2.01	1.24	2.18	1.99	1.25	3.18	3.20
A/CNK	2.48	2.72	1.88	1.90	1.24	1.88	1.85	1.25	3.11	3.12
Trace Elements (ppm)										
Ba	20	28	67	17	50	66	15	51	24	26
Be	31	174	33	32	5	32	32	6	142	170
Co	0.5	0.5	0.7	0.1	0.3	0.6	0.3	0.3	0.3	0.5
Cs	13.1	6.5	1.1	4.7	30.8	1	4.5	30.3	22.8	24.3
Ga	23.0	22.1	16.7	18	12.7	16.4	15.9	12.6	37.9	38
Hf	0.4	0.5	2.5	1.6	0.1	3.1	1.4	0.1	1.2	7.4
Nb	38.0	54.9	8.3	17.1	0.4	6.6	14.5	0.4	98.6	85.9
Rb	232.4	213.1	31.9	224.8	1528.4	30.1	197.3	1523.3	661.1	628.8
Sn	10	9	4	3	0.5	3	2	0.5	29	31
Sr	20.4	18.2	177.3	27.3	42	171.1	26.9	41.1	8.9	9.1
Ta	19.3	25.7	5.5	4.8	0.2	3.1	4	0.2	23.5	20.1
Th	2.2	1	4.8	2.6	0.1	3.1	2.3	0.1	1.2	0.6
U	0.7	0.7	2.2	4.9	0.2	2	5.7	0.1	1	2.1
V	*4*	12	4	4	4	4	4	4	4	15
W	0.6	1.3	0.3	0.3	0.3	0.3	0.3	0.3	2.2	1.8
Zr	4.9	4.8	24.7	17.4	1.3	26.6	15	0.7	12	70.1
K	17267	18345	3652	15606	104759	3486	14776	103763	28555	29718
K/Rb	74.3	86.1	114.5	69.4	68.5	112.8	74.9	68.1	43.2	47.3
Nb/Ta	1.97	2.14	1.51	3.56	2.00	2.13	3.63	2.00	4.19	4.27
Ta/Nb	0.51	0.47	0.66	0.28	0.5	0.47	0.27	0.5	0.24	0.23
Y	0.6	1.3	3.7	0.6	0.1	3.1	0.8	0.1	1.9	1.9
La	0.4	1.5	1.7	1	0.4	0.9	0.7	0.3	1.2	2.6
Ce	1.3	2.1	2.5	1	0.2	2	0.9	0.1	2	2.2
Pr	0.11	0.32	0.26	0.07	0.01	0.2	0.06	0.01	0.28	0.23
Nd	0.7	1	1	0.2	0.2	0.8	0.2	0.3	0.8	0.8
Sm	0.13	0.34	0.32	0.06	0.03	0.29	0.06	0.03	0.3	0.32
Eu	0.01	0.07	0.11	0.01	0.01	0.09	0.02	0.01	0.04	0.05
Gd	0.17	0.33	0.37	0.08	0.03	0.37	0.09	0.03	0.31	0.28
Tb	0.01	0.05	0.09	0.02	0.01	0.08	0.02	0.01	0.06	0.06
Dy	0.08	0.29	0.52	0.07	0.03	0.41	0.14	0.03	0.29	0.35
Ho	0.01	0.05	0.1	0.01	0.01	0.07	0.01	0.01	0.04	0.06
Er	0.02	0.14	0.3	0.04	0.02	0.21	0.05	0.02	0.14	0.14
Tm	0.01	0.02	0.04	0.01	0.01	0.03	0.01	0.01	0.02	0.03
Yb	0.03	0.12	0.32	0.03	0.03	0.22	0.06	0.03	0.11	0.19
Lu	0.01	0.02	0.04	0.01	0.01	0.03	0.01	0.01	0.01	0.03

Table 2. Statistical summary of major oxide compositions of Gbayo beryl-bearing pegmatites.

Major Oxides	Range	Mean ± S.D	Standard Deviation (S.D)
SiO_2	64.88 - 81.94	75.05	± 5.81
Al_2O_3	11.54 - 19.11	14.97	± 2.44
Fe_2O_3	0.32 - 1.12	0.65	± 0.28
MgO	0.01 - 0.10	0.05	± 0.04
CaO	0.04 - 1.10	0.38	± 0.41
Na_2O	0.87 - 6.60	3.58	± 2.21
K_2O	0.42 - 12.62	4.10	± 4.58
TiO_2	0.01 - 0.03	0.02	± 0.01
P_2O_5	0.02 - 0.46	0.15	± 0.16
MnO	0.01 - 0.73	0.17	± 0.29

It is therefore believed that the Gbayo beryl-bearing pegmatite dykes from the study area have resulted from the partial melting of un-depleted upper to middle crustal materials. Matheis (1987) argued that rare-metal pegmatites of Nigeria are products of high-grade metamorphic conditions, which were emplaced along a deep-seated continental lineament and enhanced by high crustal heat flow and the addition of fluid phases. He reinstated that the host rock contributed significantly to the individual characteristics of each pegmatite occurrence, as demonstrated by the marked differences between the pegmatite fields of southwest and central Nigeria. The fluids precipitating the beryl-bearing pegmatites are probably a mixture of expelled magmatic and hydrothermal melts from some plutons and mobilized metamorphic fluids from the surrounding metasedimentary rocks of the host mica schist.

The inter-oxide associations existing between the major oxides of the beryl-bearing pegmatites as expressed by Pearson correlation coefficients revealed some significant levels of positive and negative correlations (Table 3). SiO_2 exhibits strong negative correlations with Al_2O_3 (-0.99), an amphoteric oxide, and K_2O (-0.84), an alkali metal oxide, while it is positively correlated with the basic oxides; SiO_2-MgO (0.81), SiO_2-TiO_2 (0.69), SiO_2-Fe_2O_3 (0.62), significant in most cases. The weak correlation existing between SiO_2 and CaO (0.11) is an indication of magmatic origin for the beryl-bearing pegmatites (Frondel and Collette, 1957). The Harker plots of; SiO_2 versus MgO (Fig. 8A) yielded a well-defined positive trend, reflecting the positive correlation between the two oxides, while SiO_2 versus Al_2O_3 (Fig. 8B) shows a discernible negative trend, confirming an inverse correlation between the two oxides. This negative correlation between SiO_2 and Al_2O_3, coupled with the high enrichments of the pegmatite samples in SiO_2 in preference to Al_2O_3 are necessary conditions required for beryl crystallizations in pegmatites (London and Evensen, 2002).

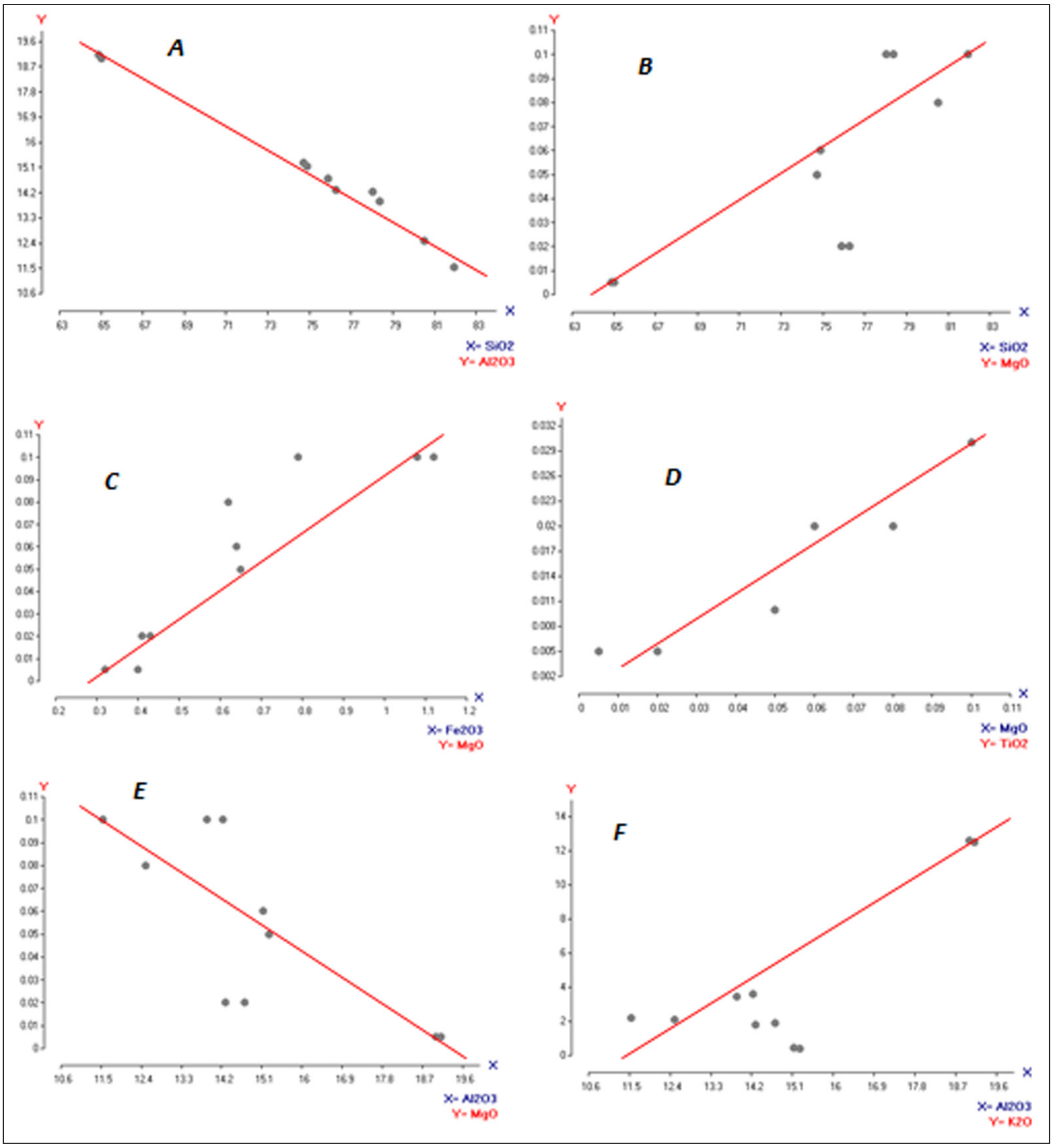
Table 3. Statistical correlation coefficients for major oxides of analyzed Gbayo beryl-pegmatite samples.

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
SiO_2	1									
Al_2O_3	-.99**	1								
Fe_2O_3	.62	-.55	1							
MgO	.81**	-.77**	.91**	1						
CaO	.11	-.09	-.13	-.09	1					
Na_2O	-.12	.11	-.54	-.48	.89**	1				
K_2O	-.84**	.82**	-.40	-.54	-.61	-.41	1			
TiO_2	.69*	-.67*	.91**	.97**	-.19	-.58	-.39	1		
P_2O_5	-.28	.26	-.61	-.71*	-.02	.35	.13	-.71*	1	
MnO	.01	.02	-.01	.01	.94**	.75*	-.47	-.06	-.29	1

***. Correlation is significant at the 0.01 level (2-tailed).*
**. Correlation is significant at the 0.05 level (2-tailed)*

Since aluminum is a major component that is usually immobile during most geological processes such as metamorphic and hydrothermal processes, variation diagrams of different element oxides plotted against Al_2O_3 may assist in defining the behavior of these oxides in geological materials. While Al_2O_3 is negatively correlated with most of the basic oxides, it is positively correlated with the alkali metal oxides, confirming the necessity for adequate concentrations of aluminum and alkaline for beryl crystallization in pegmatites (London and Evensen, 2002). The negative correlations between Al_2O_3 and most of the basic oxides are possible indications of cations substitutions within the respective mineral crystal lattices within the pegmatite. The higher the negative correlation coefficients, the greater the ease with which substitutions take place between the concerned cations. The Al elements show a general negative correlation to other elements that substitute for it (Jimoh, 2018). The binary plot of Al_2O_3 versus MgO (Fig. 8C) yielded a negative trend, while that of Al_2O_3 against K_2O (Fig. 8D) presented a positive trend.

Significant positive correlations were established among most of the basic oxide pairs; Fe_2O_3-MgO (0.91), Fe_2O_3-TiO_2 (0.62), MgO-TiO_2 (0.97), and CaO-MnO (.94). The degree of positive correlation is indicative of the level of affinity among the cations in the respective pair. The binary plots of Fe_2O_3 against MgO (Fig. 8E) and that of Fe_2O_3 versus TiO_2 (Fig. 8F) all yielded visible positive trends, indicating positive correlations between the respective basic oxides. The high positive correlations among the basic oxides might probably be due to the petrogenetic influence of the dominant host mica schist on the pegmatites. The Gbayo beryl-bearing pegmatite dykes are believed to have crystallized from fluid-rich melts resulting from fractional crystallization and partial melting of their metamorphic rock. The rare metal pegmatites of Nigeria are products of high-grade metamorphic conditions (Matheis, 1987), whereby the host rocks to the individual pegmatites contributed immensely to their occurrences, through partial melting.



Figures 8A-F. Binary plots of; **A)** SiO_2 versus Al_2O_3, **B)** SiO_2 against MgO, **C)** Fe_2O_3 versus MgO, **D)** Fe_2O_3 against TiO_2, **E)** Al_2O_3 versus MgO, and **F)** Al_2O_3 against K_2O

6. Trace elements

Trace element contents of the Gbayo beryl-bearing pegmatite dykes vary over several orders of magnitude across the analyzed samples with their median values generally varying between 0.30ppm (W) and 228.60ppm (Rb) (Table 4). Incompatible elements are fairly enriched in most of the samples, except for Rb which shows high enrichment. The highest concentration and greatest variability in compositions were observed for Rb, with values ranging from 30.10ppm to 1,528.40ppm, a mean and standard deviation values of 533.52, and ±571.04 ppm respectively. These observed variations in the pegmatites' composition, coupled with the high enrichment, particularly in Rb could be indicative of a high degree of melts fractionation and evolution, resulting from the long traveling distance of the pegmatite forming melt from its parental source (Cerny, 1992). This indicates weak mineralization of the pegmatites. Although Rb is not known to form any ore mineral of its own, it is a common constituent of cesium and lithium ore minerals such as lepidolite ($K(Li, Al)_3(Al, Si, Rb)_4O_{10}(F, OH)_2$), pollucite ($(Cs, Na)_2Al_2Si_4O_{12}.2H_2O$), tourmaline ($Na(Mg, Fe)_3Al_6(BO_3)_3(Si_6O_{18}(OH)_4$ and beryl ($Be_3Al_2(SiO_3)_6$ (Jimoh, 2018). Rb, being a trace element may not be observed in some of the chemical formulae of these minerals, it is however a common substituting element.

Table 4. Summary of some trace element compositions of studied Gbayo beryl-bearing pegmatites (ppm)

Elements	*Range*	*Mean ± S.D*	*Median*
Ba	15.00 – 67.00	36.40 ± 20.13	27.00
Be	5.00 – 174.00	65.70 ± 67.79	32.00
Co	0.10 – 0.70	0.41 ± 0.18	0.40
Cs	1.00 – 30.80	13.91 ± 12.02	9.80
Ga	12.60 – 38.00	21.33 ± 9.39	17.35
Hf	0.05 – 7.40	1.82 ± 2.21	1.30
Nb	0.40 – 98.60	32.47 ± 35.95	15.80
Rb	30.10 – 1528.40	533.52 ± 571.04	228.60
Sn	0.50 – 31.00	9.20 ± 11.43	3.50
Sr	8.90 – 177.30	54.23 ± 64.23	27.10
Ta	0.20 – 25.70	10.64 ± 10.20	5.15
Th	0.10 – 4.80	1.80 ± 1.49	1.70
U	0.10 – 5.70	1.96 ± 1.93	1.50
V	4.00 – 15.00	5.90 ± 4.07	4.00
W	0.30 – 2.20	0.77 ± 0.73	0.30
Zr	0.70 – 70.10	17.75 ± 20.55	13.50

Trace elements like Be, Sr, Ba, Nb, Ga, Zr, Cs, Ta, and Sn are fairly distributed in most of the analyzed pegmatite samples with mean values of; 65.70ppm, 54.23ppm, 36.40ppm, 32.47ppm, 21.33ppm, 17.75ppm, 13.91ppm, 10.64ppm and 9.20ppm respectively. Be, Nb, Ta and Sn however show consistent enrichments in some pegmatite samples, indicating possible association with beryl, tantalite-columbite, and tin mineralization in the pegmatites. It is noteworthy that where mineralization is present in a pegmatite, there are usually elevated levels within the analyzed pegmatite samples of elements related to such mineralization. Consequently, samples R02, R09, and R10 which contain relatively high quantities of Be; 174ppm, 142ppm, and 170ppm respectively, indicate some level of beryl mineralization, and so are most likely to contain aquamarine or any other beryl minerals within their parent pegmatites. These values, although not exceptional, are significant and could be considered encouraging. Beryllium is a relatively rare element in the Earth's crust, ranking 47th most abundant. It averages approximately 3 ppm in the upper crust, which is elevated compared to 60 ppb inferred in the primitive mantle (Grew 2002). It can thus be inferred that some of the Gbayo pegmatite dykes are highly mineralized in terms of beryl, particularly aquamarine and goshenite mined from the area. Beryl mineral types that occur within the Gbayo beryl-bearing pegmatite dykes include aquamarine, goshenite, and very rarely heliodor ($Be_3Al_2Si_6O_{18}$). The relatively high Fe_2O_3 mean value of 0.65% in the analyzed pegmatite samples is possibly responsible for these occurrences. The chromophores for many beryl minerals include Cr ± V in green emerald, Mn in pink morganite, Fe^{3+} in yellow heliodor, and Fe^{2+} in blue aquamarine (Vianna et al. 2002a, b; Mihalynuk and Lett 2003), although Figueiredo et al. (2008) noted variable Fe^{3+}/Fe^{2+} in aquamarine. The depletion of the element, V and oxides; Cr_2O_3 and MnO in the analyzed pegmatite samples, with the elements getting below their detection limits of the LA-ICP-MS technique in some, are responsible for the non-occurrences of emerald and morganite in the Gbayo beryl-bearing pegmatite dykes. Cr, V, and Mn generally do not occur in sufficient concentrations in granitic rocks, and the geological conditions needed to bring Be into contact with Cr and/or V are typically absurd. The only dominant beryl chromophore within Gbayo beryl-bearing pegmatites is Fe, which accounts for the manifestations of aquamarine, goshenite, and rarely heliodor beryl types in the pegmatites of the area.

The geochemical data presented indicated that Be enrichment tends to coincide with enrichments in Ta, Nb, Sn, and Zr (Table 1). The primary mineralization of Ta, Nb, Sn, Be and Li is usually hosted in quartz-feldspar-muscovite pegmatites (Kinnaird, 1984). The Be is best enriched in magma through the process of fractional crystallization whereby the element behaves incompatibly, and so is not taken up in crystallizing rock mineral phases, and is thereby enriched in the residual melt fraction. Many high-field strength elements such as Ta and Nb, as well as halogens (Cl and F) and other small ions are also typically enriched in residual melts, and play a role in depressing the solidus (London et al., 1996) such that Be enrichments continue to take place, even at low temperatures with low percentages of remaining melt. In the same vein, beryl mineralization in Gbayo beryl-bearing pegmatites is generally associated with elevated Ta, Nb, Sn, and Zr contents, indicating tantalite-columbite, cassiterite, and zircon mineralization, and thus can serve as an exploration guide for these minerals. Beus (1966) established that ≥ 20ppm Ta concentrations are characteristic of columbo-tantalite pegmatites. It is also apparent to note that the target commodity deposit types in the area include beryl, tantalite-columbite, and cassiterite.

Based on the known mineralogy and geochemistry of the investigated Gbayo beryl-bearing pegmatites, the pegmatites can be classified as beryl-columbite pegmatites, as defined by Cerny (1991). Beryl represents the most abundant Be phase in the earth's lithosphere. It is the first of the truly exotic, rare-element minerals to crystallize in the evolutionary sequence of LCT rare-element pegmatites. It is a characteristic phase in the relatively less fractionated granitic pegmatites of the beryl-columbite subtype, lacking Li and Cs minerals, but commonly occurs with Nb-Ta oxide minerals, especially with members of the columbite group, e.g columbite-tantalite (Cerny, 2000). Such pegmatite populations are usually closely connected with their parental granitic rocks; the pegmatite dykes are usually situated within the granites or in adjacent metamorphic rocks, near parent granite. In the case of the Gbayo pegmatites, they occur as pegmatite dykes situated within the metamorphic rocks of mica schist, adjacent to their parent granitic rocks.

Very strong positive correlations exist between some trace element pairs; Be-Ta (0.87), Be-Nb (0.89), Be-Sn (0.81), Nb-Ta (0.89), Nb-Sn (0.96) and Sn-Ta (0.77) (Table 5). These are demonstrated by the correlation plots of the element pairs (Fig. 9A - F). The high positive correlations between these elements reflect their associations in the formation of rare metal ores from the pegmatitic melts.

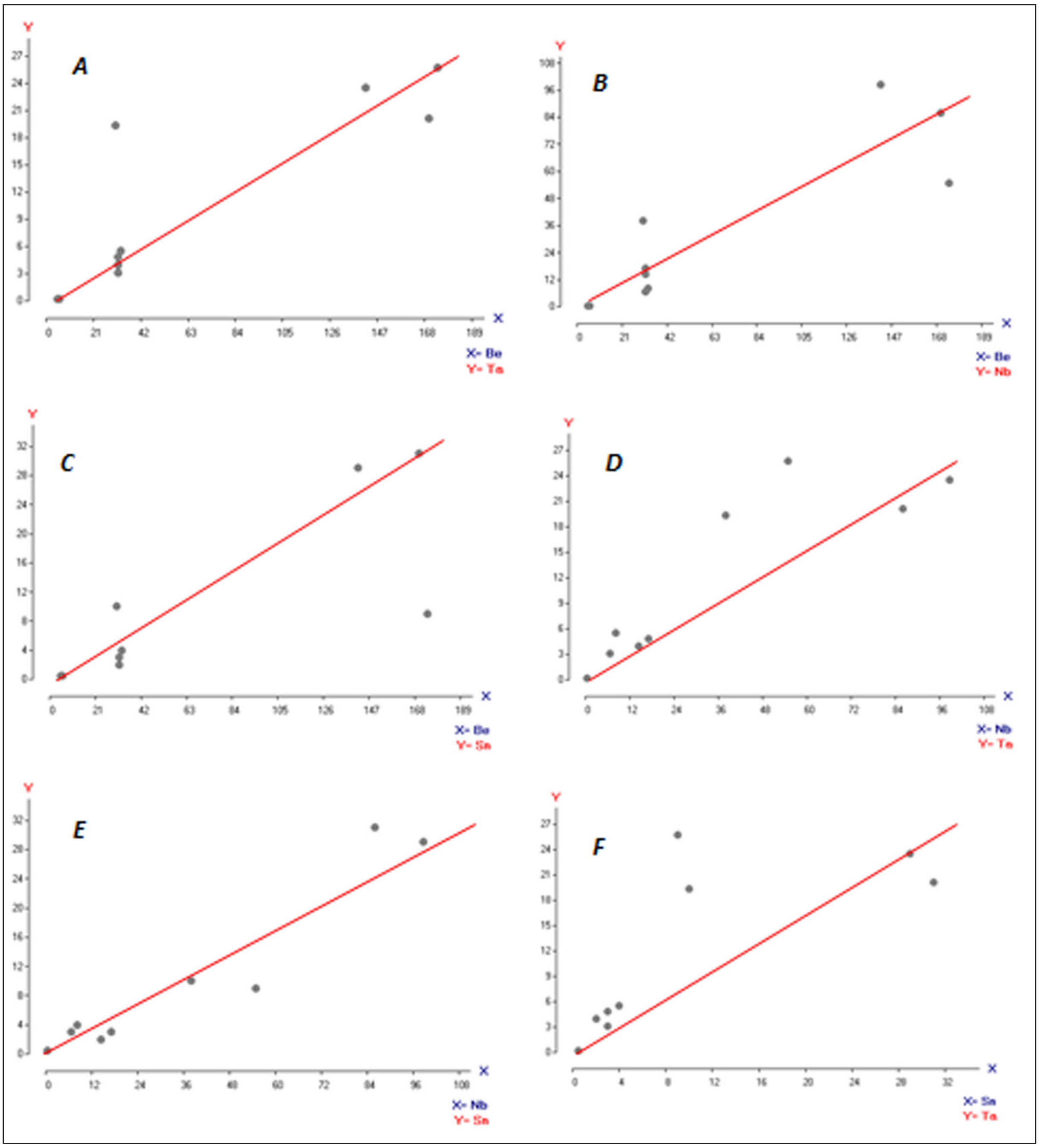
Table 5. Statistical correlation coefficients for trace elements of analyzed Gbayo beryl-pegmatite samples.

	Ba	Be	Co	Cs	Ga	Hf	Nb	Rb	Sn	Sr	Ta	Th	U	V	W	Zr
Ba		1														
Be		-.38	1													
Co		.55	.18	1												
Cs		-.03	.06	-.35	1											
Ga		-.45	$.82^{**}$	.08	.23	1										
Hf		.02	.45	.36	-.06	.56	1									
Nb		-.52	$.89^{**}$	.03	.22	$.97^{**}$	.41	1								
Rb		.15	-.18	-.42	$.93^{**}$	-.12	-.24	-.11	1							
Sn		-.39	$.81^{**}$	.10	.31	$.99^{**}$	.58	$.96^{**}$	-.03	1						
Sr		$.85^{**}$	-.40	$.64^{*}$	-.52	-.42	.13	-.51	-.36	-.41	1					
Ta		-.51	$.87^{**}$	.21	.02	$.81^{**}$	.20	$.89^{**}$	-.28	$.77^{**}$	-.47	1				
Th		.28	-.28	.46	$-.84^{**}$	-.21	.12	-.29	$-.80^{**}$	-.26	$.73^{*}$	-.19	1			
U		-.40	-.14	-.31	-.59	-.10	.24	-.15	-.53	-.16	.02	-.26	.47	1		
V		-.25	$.81^{**}$	.26	.13	.55	.63	.58	-.04	.57	-.33	.60	-.36	-.12	1	
W	-.41	$.90^{**}$	.04	.31	$.94^{**}$	.37	$.98^{**}$	.01	$.94^{**}$	-.48	$.85^{**}$	-.37	-.26	.59	1	
Zr	-.02	.45	.33	-.06	.56	$.99^{**}$	.42	-.24	.59	.10	.20	.12	.27	.63	.38	1

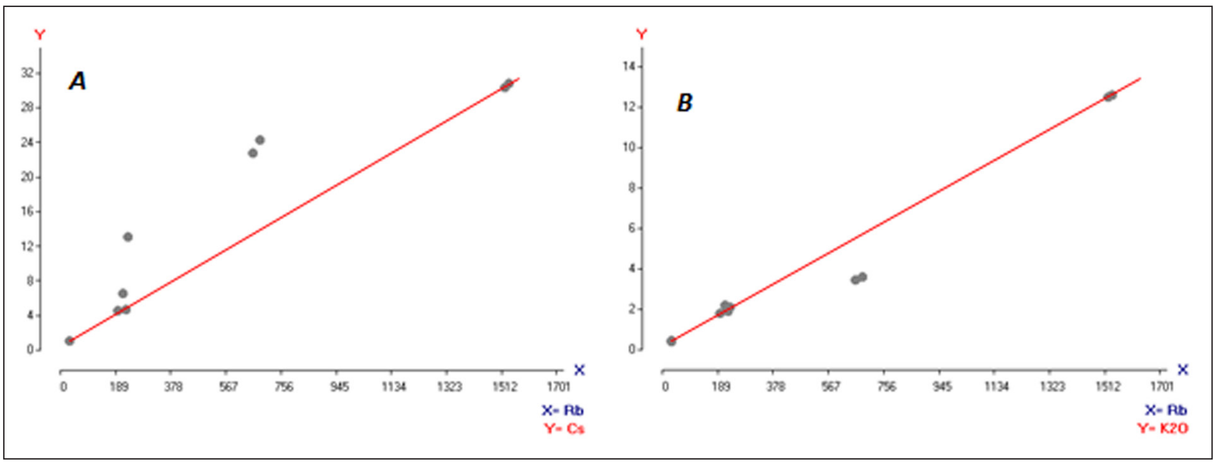
***. Correlation is significant at the 0.01 level (2-tailed).*
**. Correlation is significant at the 0.05 level (2-tailed).*

The binary plots of the individual pair of trace elements in the pegmatites highlight compositional variations, and mineralization trends, and suggest geochemical tools for future geochemical sampling procedures. Each plot exhibits well discernible positive trend, signifying positive correlations between the element pair. Rb, Cs, and K_2O show consistent enrichments in the analyzed pegmatite samples with their highest values of 1,528.4ppm, 30.8ppm, and 12.62% respectively. The highest values were observed in sample R05, while the lowest respective values of 30.1ppm, 1.0ppm, and 0.42% were observed in sample R06. Very strong positive correlations, therefore, exist among the three elements. The binary plots of Rb versus Cs and Rb against K_2O (Figures 10a and b) both display discernable positive trends, showing positive correlations between each element pair. The values of the K/Rb ratios for most of the analyzed beryl-bearing pegmatites are less than 100 (Table 1) with a mean value of 75.11, which is indicative of mineralization (Tischendorf 1977). This indicates that the Gbayo beryl-bearing pegmatites are mineralized to some extent. It is remarkable to note that both samples R03 and R06 with K/Rb ratios greater than 100 are also most depleted in Rb and Cs, making them the least fractionated and mineralized part of the analyzed beryl-bearing pegmatites. It follows therefore that the studied Gbayo beryl-bearing pegmatites have varied degrees of fractionations and mineralization, and this is believed to be dependent on the travel distance of the pegmatites from their various parent sources (Cerny, 1992).

The investigated pegmatite samples are fairly more enriched in the light rare earth elements (LREE) than the heavy rare earth elements (HREE) (Fig. 11), suggesting a lower crust source for the pegmatitic melts. Most of the samples exhibit chondrites-normalized REE patterns, which virtually display slight LREE-enriched and HREE-depleted patterns and generally exhibit fractionated asymmetric concave-upward shapes, with well-pronounced negative Europium (Eu) anomalies, an indication for granite-related pegmatite. The negative Eu anomaly suggests fractionation and indicates a late metasomatic effect (Taylor et al., 1986). Two of the samples however show no detectable Eu anomaly. A few of the samples also exhibit negative Ce anomaly, which according to Garba (2003) indicates oxidizing conditions during mineralization and interaction between melt-fluids and host rocks over great distances.



Figures 9A-F. Binary plots of; **A)** Be versus Ta, **B)** Be against Nb, **C)** Be versus Sn, **D)** Nb against Ta, **E)** Nb versus Sn and **F)** Sn against Ta



Figures 10A and **B.** Binary plots of; A) Rb versus Cs, B) Rb against K_2O.

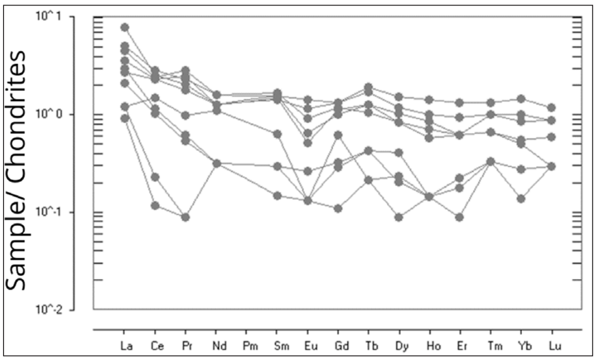


Figure 11. Chondrites-normalized REE patterns of the beryl-bearing pegmatite dyke samples from the Gbayo studied site, southwestern Nigeria. Chondrite values from Sun and McDonald (1989).

7. Conclusions

The studied Gbayo beryl-bearing pegmatite dykes comprise a simple mineralogy; feldspar, quartz, and muscovite, with beryl and occasionally some metallic oxides including tantalite-columbite and cassiterite, as accessory minerals. These pegmatite dykes have crystallized from fluid-rich melts resulting from fractional crystallization (residual pegmatitic melt) and partial melting (anatectic pegmatites). The fluids precipitating these minerals are probably a mixture of expelled magmatic fluids rich in water and some incompatible elements such as Be, Ta, and Nb, and mobilized metamorphic fluids from the surrounding meta-sedimentary rocks. Beryl represents a characteristic accessory mineral in the granitic pegmatites, and commonly occurs together with Nb–Ta oxide minerals, mainly members of the columbite group. Consequently, the mineral association, mineral chemistry, and petrologic features place these pegmatites within the beryl and beryl–columbite subtypes of the rare-element LCT family of pegmatites in the classification of Cerny and Ercit (2005).

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