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Geological and Geochemical Characterisation of Pegmatites around Olode, Southwestern Nigeria

Razak O. Jimoh[1*] and Akinade S. Olatunji[2]
[1]*Department of Chemical and Geological Sciences, Al-Hikmah University, P. M. B. 1601, Ilorin, Nigeria*
E-mail: rojgems@yahoo.com
[2]*Department of Geology, University of Ibadan, Ibadan, Nigeria*
E-mail: akinadeshadrach@yahoo.com
** Corresponding author*

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Abstract

Olode is prolific in terms of pegmatites, occurring in different ways as large intrusive bodies, as veins and dykes, discordantly intruding the host rocks of mica schist, gneiss and granite. This study is aimed at the geological and geochemical characterisation of pegmatites around Olode. Field investigation was undertaken to determine the occurrences and relationships of the pegmatites with the host rocks. Fresh pegmatite samples were studied petrographically and geochemically. Two main lithologically and chronologically different groups of pegmatites were distinguishable in the study area. These were the tourmaline pegmatites associated with the Older Granite rocks and the NE-SW trending beryl-bearing pegmatites typically occurring as dykes, hosted by the mica schist. Results of the geochemical analysis showed variations in the chemical compositions of the two varieties of pegmatites, reflecting their mineralogical differences, but with common peraluminous provenance. The discrimination plots of Cs and Rb versus K/Rb have classified most of the beryl-bearing pegmatites as mineralised, with mean K/Rb ratio of 85, and the tourmaline pegmatites as barren. The Olode pegmatites have emanated from a common source, a higly mineralised magma, and their differences in chemical composition and occurrences have resulted from fractional crystallisation of the parent magma and varied evolutionary trends.

Keywords: Olode, Pegmatites, Beryl-bearing, Tourmaline, Mineralised.

Introduction

Pegmatites being hosts to many metallic and non-metallic minerals have attracted remarkable interests the world over, and particularly in Nigeria, where they are widely spread within the Nigerian Basement Complex rocks. A belt of mineralised pegmatites which extends from Ago-Iwoye in the southwest to Bauchi in the northeast, a distance of more than 400 kilometres have been reported (Akintola and Adekeye 2008). Similar rare-metal pegmatites occurrences have also been reported in the Obudu and Oban massifs of southeastern Nigeria (Figure 1) and are believed also to continue into the northeastern part of Brazil (Garba 2003).

In Nigeria, Pan African intrusive suites which comprise mainly granites, granodiorites and tonalites are intruded by pegmatite and aplites in numerous forms (Okunlola and Udoudo 2005). These pegmatites are believed to belong to the early Precambrian pegmatites, which together with the granite are 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). Precambrian pegmatites (625 Ma) of Nigeria occur mostly as dyke-like intrusions which vary from few centimetres to metres in width (Okunlola and Akintola 2007).

Olode pegmatites which are part of the late Pan-African rare metals granitic pegmatites (Wright 1970) occur in various forms including; as large intrusive bodies, as veins and dykes, intruding discordantly into the older rocks. The average ages of the Pan-African granites and the associated pegmatites in southwestern Nigeria are between 620 and 580 Ma (Dada et al. 1993). Olode and environs; the study area is located in southwestern Nigeria and consists of areas between latitudes 7° 8’ to 7° 14’ and longitudes 3° 54’ to 4° 0’. In most parts of the area, mining of gem minerals like beryl, metallic minerals such as tantalite and columbite and industrial or non-metallic minerals like feldspars and quartz is very active. The purpose of this paper is to categorize the pegmatites of Olode and environs in terms of their geology, mineralogy and geochemistry and also further generate additional information on their mineralisation potentials.

Research Methods

Geological mapping of Olode and environs was undertaken to ascertain the occurrences and relationships of pegmatites with country rocks and associated geological structures. Fresh whole rock samples of the different pegmatites were collected for both petrographic study and geochemical analysis. Eleven pegmatite samples made up of seven beryl-bearing and four tourmaline pegmatites were analysed for their major and trace elements compositions using Inductively Coupled Plasma-Mass spectrometry (ICP-MS) at the Bureau Veritas Mineral Laboratories, Vancouver, Canada. The results of the various analyses were subjected to statistical analysis and interpreted using standard geochemical plots to ascertain trends, patterns and associations. Appropriate geochemical and computer software were used for data evaluation.

Geological settings

Olode area is underlain by crystalline rocks collectively referred to as the southwestern Nigerian Basement Complex. 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). Different ages have been ascribed to the Nigerian Basement Complex rocks using different radiometric dating. Grant (1970) observed that the majority of the radiometric ages obtained fall in the range of 600 Ma, which corresponds to the Pan-African thermo-tectonic event. The Nigerian Basement Complex occupies about half the landmass of the country (Black 1980) and it is a polycyclic terrain which suffered its most pronounced deformation and mobilization during the Pan-African age (600 Ma) (Figure 1).

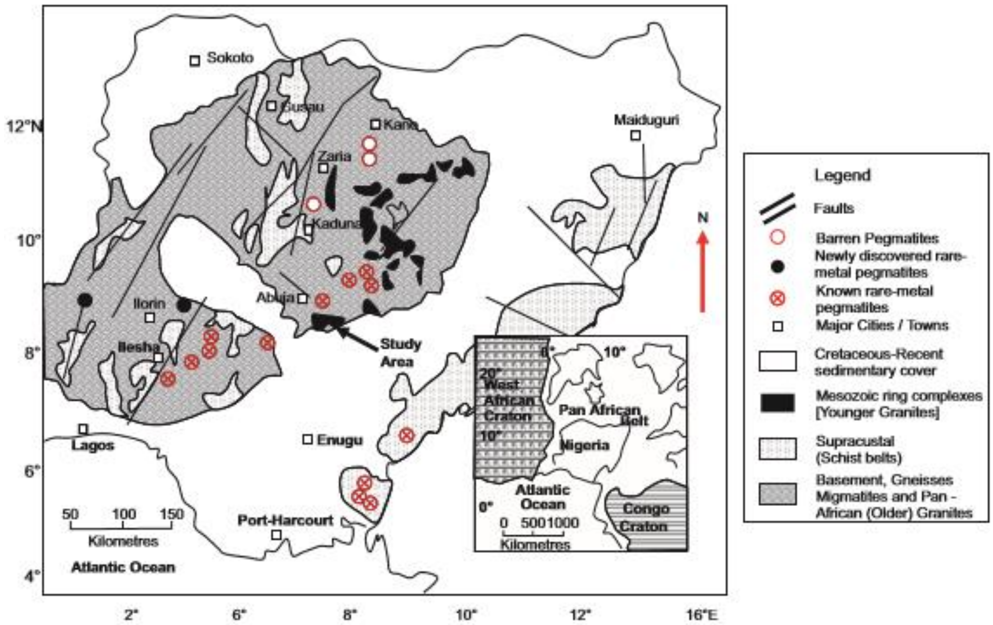

Figure 1: Geological map of Nigeria showing locations of rare-metal and barren pegmatites (Garba 2003).

Within the Basement Complex of Nigeria, four major petro-lithological units are distinguishable (Obaje 2009), namely;

1. The Migmatite – Gneiss Complex (MGC);
2. The Schist Belts (Metasedimentary and Metavolcanic rocks);
3. The Older Granites (Pan African granitoids); and
4. Undeformed Acid and Basic Dykes.

The Migmatite-Gneiss Complex represents the oldest recognizable rocks (Grant 1969) and it is the most widespread, making up about 60% of the surface area of the Nigerian Basement Complex (Rahaman and Ocan 1978). It has a heterogeneous assemblage comprising migmatites, gneisses and a series of basic and ultrabasic metamorphosed rocks. Petrographic evidence indicates that the Pan-African reworking led to re-crystallisation of many of the constituent minerals of rocks of the Migmatite-Gneiss Complex by partial melting with majority of the rock types displaying medium to upper amphibolites facies metamorphism. The imprint of the Pan-African event did not only structurally overprint and re-set many geochronological clocks in the older rocks, but also gave rise to granite gneisses, migmatites and other similar lithological units. The Migmatite-Gneiss Complex has ages ranging from Pan-African to Eburnean.

The Schist Belts which comprise low grade, metasediments-dominated belts, trending North-South are best developed in the western half of Nigeria, west of 8°E longitude. They are considered to be Upper Proterozoic supracrustal assemblages of low to medium grade meta-sedimentary rocks with subordinate mafic and ultramafic rocks which have been in-folded into the migmatite-gneiss complex rocks (Turner 1983). The lithological variations of the schist belts include quartzites, amphibolites, pelitic and mica-schists, calc-silicate rocks, marbles, phyllites, meta-conglomerate iron formations and subordinate meta-igneous rocks (Elueze 1992). Olade and Elueze (1979) reported that the schist belt is a fault controlled rift-like structure, but Turner (1983), while agreeing with the fault-controlled theory linked the origin to structural and lithological associations, suggesting that they are of different ages of sediment deposition. The geochronology of the schist belts remains problematic although the ages of the intrusive cross-cutting Older Granites provide a lower limit of 750 Ma.

The Older Granites rocks occur intricately associated with the Migmatite-Gneiss Complex and the Schist Belts into which they generally intruded and they comprise mainly granites and granodiorite, with subordinate pegmatite and aplites. Affiliated rocks include charnockites, syenites, tonalites, adamellites, quartz monzonites and gabbro, plus extrusive and hypabyssal bodies. Geochronological data from previous works (Rb-Sr whole-rock and U-Pb zircon) of Pan-African granitoids intruding the reactivated Archean to Lower Proterozoic crust of central and southwestern Nigeria showed that intrusive magmatic activity in these areas lasted from at least 630 to 530 Ma (Dada et al. 1993). 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 reported so far in southwestern Nigeria. Results of the rock ages showed that pegmatites' emplacement in the southwestern Nigeria occurred mainly after the peak of the Pan-African orogenic event. The end of the Pan-African tectonic event is marked by a conjugate fracture system of the strike-slip faults. Fault directions have consistent trend and sense of displacement; i.e. a NE-SW trending system having a dextral sense of movement and a NW-SE trending system a sinistral sense (Ball 1980). Both sets crosscut all the main Pan-African structures, including older N-S trending shear zones (mylonites) and late orogenic granites (Ball 1980, Kuster 1990). Gold and rare metal mineralizations are closely associated with the fractures in the Pan-African belt (Kuster 1990, Garba 2003).

The Undeformed acid and basic dykes are late to post-tectonic Pan-African, cross-cutting the Migmatite-Gneiss Complex, the Schist Belts and the Older Granites. These include the felsic dykes that are associated with Pan African granitoids on the terrain such as the muscovite, tourmaline- and beryl-bearing pegmatites (Dada 2006) and the basic dykes that are generally regarded as the youngest units in the Nigerian basement such as dolerite and the less common basaltic and lamprophyric dykes.

Field relationships and petrography of Olode pegmatites

The geology of Olode and environs is dominated by mica and quartz schist, granite gneiss, granite, pegmatite and aplites (Figure 2). Mica schist which is considered the oldest rock type in the area is not exposed anywhere on the surface except in mining excavations where it is observed to serve as hosts to pegmatitic veins and dykes. The high susceptibility of this rock to weathering is believed to be responsible for the poor exposures. Apart from various intrusive bodies of pegmatites which dotted the outcropping rock types, the northwestern and central portions of the area are predominantly underlain by pegmatitic outcrops of various shapes and sizes.

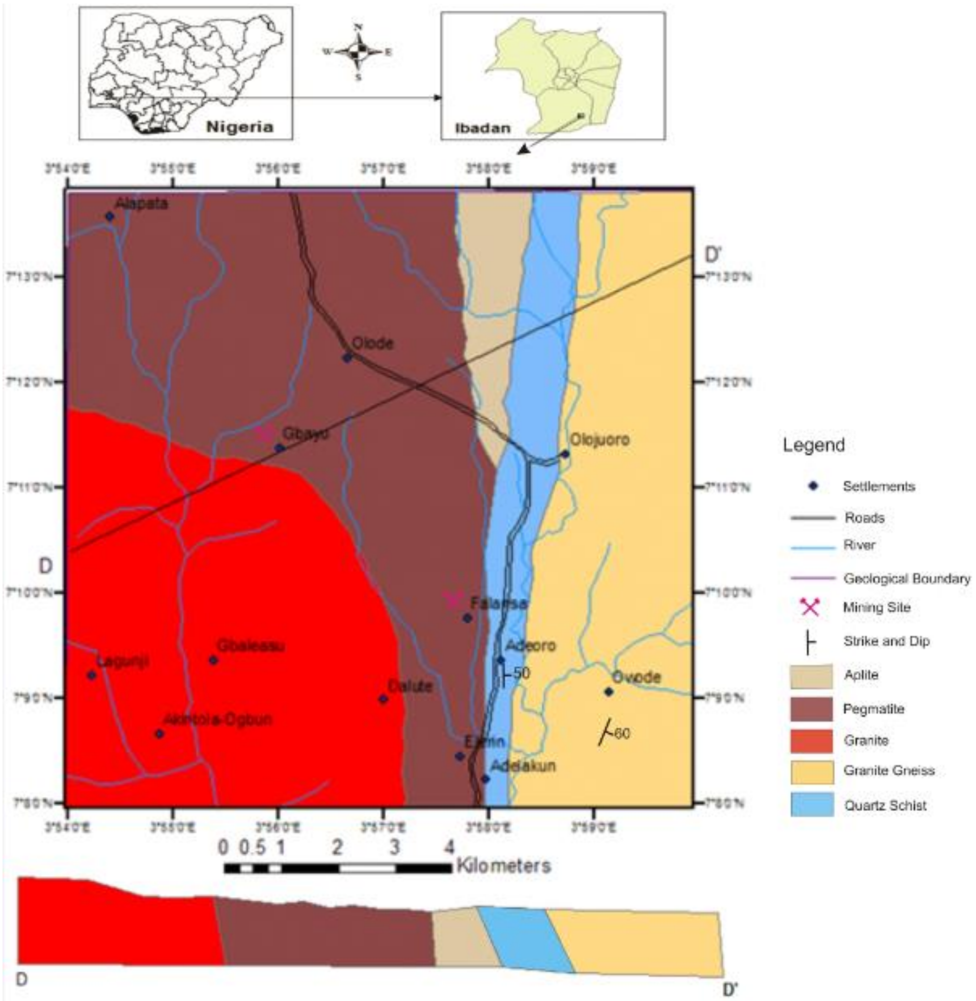

Figure 2: Geological map of Olode and environs (Jimoh 2018).

Two lithologically and chronologically different groups of pegmatites are distinguishable in the study area. These are the massive quartz-microcline tourmaline pegmatites and the NE-SW trending beryl-bearing pegmatites, which are dyke-like intrusions. The tourmaline pegmatites contain abundant euhedral crystals of black tourmaline (schorl) and occur as massive intrusive bodies, and are more conspicuous in the granite to the southwestern part of the area where they are commonly and spatially associated, suggesting similar age and origin for both rocks. Unlike the more prominent tourmaline pegmatites, the NE-SW (036°) trending beryl-bearing pegmatites, which vary in widths between a few centimetres to about 2 m, were observed to be distanced from granite, their presumed parent rock and are usually occurring as veins and dykes, discordantly intruding the host mica schist, virtually in all the mining excavations in the area, revealing sharp contacts between them.

The tourmaline pegmatites mainly consist of quartz and feldspar, largely microcline, and also contain abundant euhedral crystals of schorl, and sometimes also possess a few crystals of garnet and zircon as accessory minerals, but very deficient in muscovite. The modal analysis showed microcline (35-45%), quartz (20-30%), plagioclase feldspar (15-20%) and minor amounts of schorl and garnet (Figure 3). Perthitic microcline crystals with cross-hatched twinning characteristic of microcline were observed in thin section, while the plagioclase feldspar is recognized by its polysynthetic twinning. The beryl-bearing pegmatites are very rich in muscovite and also contain quartz and feldspar, as major minerals. The average modal composition revealed plagioclase feldspar (30-35%), muscovite (20-25%), quartz (10-15%), orthoclase feldspar (10-15%) and other accessory minerals like beryl (Figure 4) as the mineral components. The quartz is easily recognized in thin section by its clear and unaltered non-cleaved white or grey interference colours under cross polarized light, while the muscovite exhibit similar interference colours due to their preferred orientation in the rock, but a few had mottled appearance.

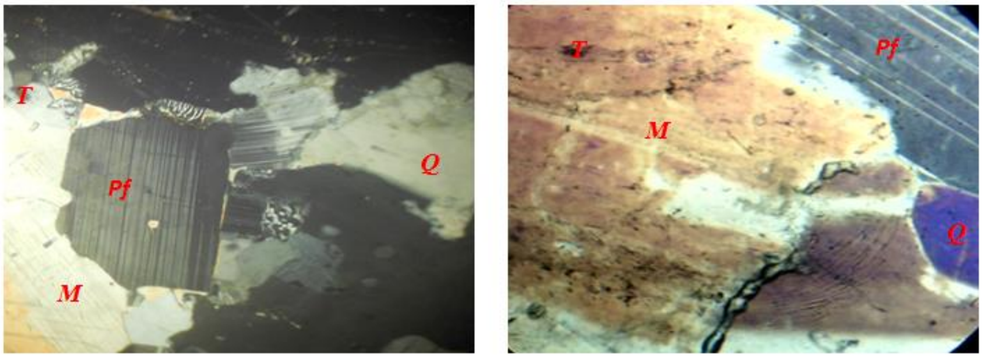

Figure 3: Photomicrographs of samples of tourmaline pegmatite from Olode study area under cross polarized light. Pf = Plagioclase feldspar, M = Microcline feldspar, Q = quartz (X40).

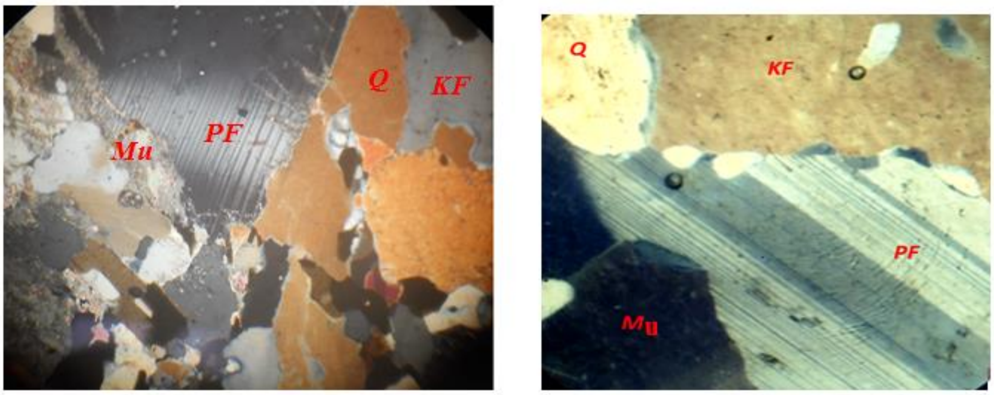

Figure 4: Photomicrographs of samples of the beryl-bearing pegmatite from Concord mines in Falansa under cross polarized light. PF = Plagioclase feldspar, KF = K-feldspar, Mu =Muscovite, Q = quartz (X40).

Furthermore, the beryl-bearing pegmatites bear different varieties of euhedral to subhedral crystals of gem quality beryl, which occur mostly as aquamarine, goshenite, and very rarely heliodor. These beryl crystals mostly occur as veins in close associations with quartz, feldspar and muscovite, particularly lining the contacts between the pegmatites and the host schist in cavities. Mineralisation appears to be particularly well developed in the areas of intersection of the veins. Although most of the beryl crystals are fractured and opaque, a few flawless and transparent crystals have been found especially from gem pockets known as miarolitic cavities.

The NE-SW trending beryl-bearing pegmatites are classified as felsic dykes, members of the Undeformed acid and basic dykes, and are believed to be late to post-tectonic Pan African, whose age varies from 580 and 535 Ma (Dada 2006). It is believed that a conjugate fracture system of the strike-slip faults believed by Ball (1980) to have marked the end of the Pan-African tectonic event probably controlled the emplacement of the NE-SW trending beryl-bearing pegmatite. They are therefore believed to be younger than the tourmaline pegmatites which are Pan African in age. The general trend of most dykes observed in the Basement Complex is between NE-SW and ENE-WSW (Rahaman 1973).

Results and Discussion

Results of the geochemical analyses of the two varieties of pegmatites showed variations in their chemical compositions, reflecting their mineralogical and lithological differences. Both groups exhibited high and moderate enrichments in SiO_2 and Al_2O_3, respectively, resulting from their high contents in quartz and aluminosilicates such as the feldspars. These high siliceous and per-aluminous compositions provide the silicic and acidic environments necessary for tourmaline and beryl crystallisation (Jimoh 2018). The beryl-bearing pegmatites are however slightly more enriched in SiO_2 than the tourmaline pegmatites with average values of 74.27% and 67.22%, respectively, but low in Al_2O_3 with mean values of 14.49% and 15.63%, respectively (Table 1). The tourmaline pegmatites are more enriched in Fe_2O_3 and most of the other basic major oxides than the beryl-bearing pegmatites. Highly differentiated pegmatites contain phases such as zircon, rutile and monazite that act as sinks for these elements (Speer 1982). The mean values of Fe_2O_3, MgO, CaO, TiO_2, and P_2O_3 in the tourmaline pegmatites are 4.62%, 1.72%, 1.86%, 0.38%, and 0.26%, while in the beryl-bearing pegmatites they are 0.90%, 0.35%, 0.31%, 0.05%, and 0.11%, respectively.

The presence of schorl, an iron-rich tourmaline, grossular, a Ca-rich garnet and zircon in the tourmaline pegmatites is responsible for the relatively higher contents of these oxides. Tourmaline's structure is known to have the capacity to accommodate major and trace elements of widely varying ionic charge and radius (Olatunji and Jimoh 2017).

The calculated Aluminium Saturation Indices (ASI) for the sampled pegmatite varieties are greater than one (Table 1) (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 pegmatites are per-aluminous and therefore implied a relationship to S-type granites (Cerny et al. 2012). The plot of A/CNK versus A/NK (Figure 5) confirmed the peraluminous nature of the investigated pegmatites and therefore assumed to belong to the Lithium-Cesium-Tantalum (LCT) family pegmatites (Cerny 1982). Zen (1988) noted that such peraluminous rocks can be derived from sub-aluminous magma by factional crystallisation, or by partial melting of peraluminous source rocks. Turpin et al. (1990) also pointed out that peraluminous granites are generally considered to be generated through partial melting of upper crustal rocks, especially during continent-continent collision events.

Table 1: Representative pegmatite compositions from Olode and environs

Sample	R001	R002	R003	R004	R005	R006	R007	R008	R009	R010	r01
Major oxides (%)											
SiO_2	70.42	75.83	66.95	80.50	76.47	61.39	70.29	76.25	70.10	69.14	71.38
Al_2O_3	15.87	13.86	15.76	12.49	13.58	15.90	16.02	13.53	16.10	13.59	17.26
Fe_2O_3	0.08	1.85	3.73	0.62	1.79	6.66	0.09	1.81	0.08	4.36	3.74
MgO	0.02	0.77	1.04	0.08	0.76	3.56	0.03	0.76	0.03	1.52	0.74
CaO	0.14	0.53	2.18	0.17	0.54	2.36	0.15	0.53	0.14	2.56	0.33
Na_2O	3.36	2.91	3.18	2.78	2.88	3.68	3.49	2.87	3.39	3.11	3.83
K_2O	9.00	2.64	5.25	2.08	2.55	4.00	9.10	2.60	8.99	4.09	1.13
TiO_2	0.01	0.14	0.31	0.02	0.13	0.66	0.01	0.14	0.01	0.45	0.11
P_2O_5	0.16	0.10	0.49	0.02	0.10	0.39	0.17	0.09	0.16	0.09	0.06
MnO	0.01	0.05	0.14	0.02	0.05	0.19	0.01	0.05	0.01	0.07	0.05
A/NK	1.28	2.50	1.87	2.57	2.50	2.07	1.27	2.47	1.30	1.89	3.49
A/CNK	1.28	2.28	1.49	2.48	2.27	1.58	1.26	2.26	1.28	1.39	3.27
Trace elements (ppm)											
Ba	173	114	414	20	107	549	188	122	167	597	30
Be	6	36	7	31	39	28	5	32	10	2	6
Co	0.1	4.4	6.2	0.5	3.7	20.0	0.1	4.6	0.1	10.5	0.8
Cs	40.3	58.3	14.6	13.1	61.6	220.5	39.6	60.1	40.2	1.2	3.4
Ga	13.7	25.6	28.2	23.0	23.6	22.6	13.3	23.6	12.3	22.0	27.9
Hf	0.3	2.2	6.6	0.4	1.3	5.7	0.2	1.0	0.1	7.1	0.6
Nb	4.8	42.3	16.3	38.0	40.9	34.8	3.2	40.6	3.0	23.7	11.2
Rb	672.9	367.8	277.4	232.4	347.7	618.3	657.8	364.4	648.0	129.4	62.7
Sn	0.5	12	4	10	11	7	0.5	12	0.5	4	12
Sr	71.4	83.3	102.8	20.4	79.5	301.6	79.3	77.8	78.7	116.9	5.6
Ta	1.3	20.2	1.3	19.3	17.9	7.7	1.3	18.4	0.9	1.1	1.2
Th	0.3	5.4	17.0	2.2	4.5	17.7	0.2	2.3	0.6	32.1	15.4
U	0.7	2.9	5.9	0.7	1.3	4.4	0.7	1.4	0.7	6.7	8.7
V	*4*	21	31	***4***	21	86	***4***	23	***4***	55	4
Zr	3.4	41.0	175.0	4.9	36.7	166.6	4.9	26.6	2.0	199.6	13.1
Cu	2.8	11.3	14.4	2.5	9.2	46.5	0.9	10.5	1.0	20.7	NA
Pb	23.4	3.2	11.8	2.7	3.3	7.1	22.0	3.5	20.6	4.7	NA
Zn	2	41	37	3	39	197	1	42	2	58	NA
Ni	0.3	15.4	3.6	0.8	15.0	78.0	0.3	16.2	0.4	6.2	NA
Bi	0.7	27.8	1.1	73.0	38.1	48.2	1.0	30.9	1.0	0.1	NA
K	74713	21916	43583	17267	21169	33206	75544	21584	74630	33953	9380
K/Rb	111.0	59.6	157.1	74.3	60.9	53.7	114.8	59.2	115.2	262.4	149.6
Y	0.1	4.5	35.2	0.6	5.6	32.0	0.2	5.2	0.2	51.5	17.5
La	0.4	10.3	36.8	0.4	10.7	46.7	0.5	5.3	0.4	74.6	15.3
Ce	0.8	19.1	74.0	1.3	19.4	98.2	0.7	11.0	0.9	147.3	38.6
Pr	0.08	2.17	7.76	0.11	2.19	11.02	0.03	1.20	0.06	14.88	4.16
Nd	0.2	9.7	28.4	0.7	9.1	42.5	0.2	5.0	0.2	55.9	14.7
Sm	0.03	1.44	5.18	0.13	1.37	8.25	0.03	1.07	0.03	10.37	6.01
Eu	0.01	0.15	0.53	0.01	0.16	0.72	0.01	0.13	0.01	0.93	0.05
Gd	0.03	1.31	5.28	0.17	1.26	7.30	0.03	1.05	0.03	9.26	4.77
Tb	0.01	0.17	0.91	0.01	0.17	1.02	0.01	0.14	0.01	1.49	0.84
Dy	0.03	0.87	5.37	0.08	1.16	5.63	0.03	0.87	0.03	8.99	3.78
Ho	0.01	0.16	1.19	0.01	0.21	1.27	0.01	0.11	0.01	1.89	0.49
Er	0.02	0.50	3.90	0.02	0.51	3.46	0.02	0.43	0.02	5.74	1.13
Tm	0.01	0.09	0.56	0.01	0.05	0.51	0.01	0.06	0.01	0.81	0.2
Yb	0.03	0.46	3.92	0.03	0.43	3.32	0.03	0.47	0.03	5.72	1.47
Lu	0.01	0.06	0.58	0.01	0.05	0.52	0.01	0,07	0.01	0.89	0.17

R001, R002, R004, R005, R007, R008, R009: Beryl-bearing pegmatites, R003, R006, R010, r01: tourmaline pegmatites.

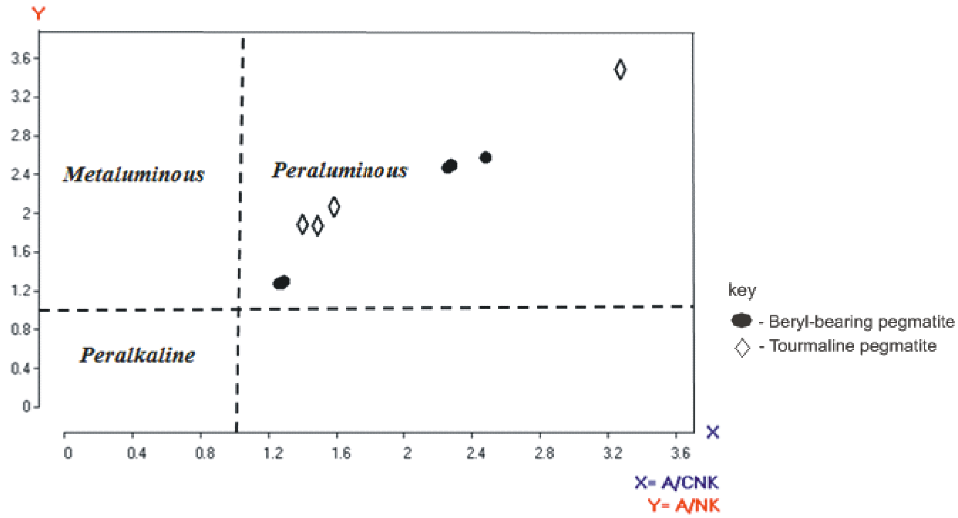

Figure 5: The plot of A/CNK versus A/NK (Maniar and Piccoli 1989).

There is therefore the possibility that the pegmatites from the study area were derived from the anatexis of un-depleted upper to middle crustal materials. 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 (Matheis 1987). Host rocks have therefore contributed significantly to the individual characteristics of each pegmatite occurrence, as demonstrated by the marked differences between the pegmatite fields of south-west and central Nigeria. The two varieties of pegmatites in the study area have possibly crystallised from fluid-rich melts resulting from factional crystallisation and partial melting of their respective country rocks. This therefore accounts for their lithological dissimilarities as the beryl-bearing pegmatites are hosted by mica schist, while the tourmaline pegmatites are associated with and hosted by the granites.

The two groups of pegmatites are generally enriched in the Large Ion Lithophile Elements (LILE), such as Ba, Cs, Rb and Sr, but depleted in the High Field Strength Elements (HFSE) such as Nb, Ta, Hf and Th, indicating that the pegmatites have indeed crystallised from granite related melt (Kleemann 1982, Plimer et al. 1991). The tourmaline pegmatites however, showed more enrichment in most of the LILE and the Rare Earth Elements, REE, but depletion in the HFSE, showing that they have crystallised from a less fractionated melt than the beryl-bearing pegmatites (Jimoh 2018). Variations in the trace elements and REE distributions in pegmatites are usually controlled by crystal-chemical and/or geochemical factors. Ba is highest in most of the tourmaline pegmatite samples with a mean value of 397.50 ppm but low in most of the beryl-bearing pegmatites samples with a mean value of 127.29 ppm. Mean values of Cs, Rb, Sr, Ga, Cu, Zn, Nb, Ta and Sn in the tourmaline pegmatite samples comprise 59.93, 271.95, 131.73, 25.18, 27.20, 97.33, 21.50, 2.83, and 6.75 ppm, while in the beryl-bearing pegmatites they are 44.74, 470.14, 70.06, 19.30, 5.46, 18.57, 24.68, 11.33 and 6.64 ppm respectively. R006, a tourmaline pegmatite sample has a highest singular Cs value of 220.50 ppm. The elements Zr, Hf, V and Co are also highest in the tourmaline pegmatites with mean values of 180.4, 4.4, 57.33 and 12.23 ppm, while their mean values in the beryl-bearing pegmatites are 17.07, 0.79, 11.57 and 1.93 ppm, respectively. The occurrences of tourmaline and zircon crystals in the tourmaline pegmatites have obvious influences on the concentrations of some of these elements. In addition to the major-element occupation of the sites, tourmaline, a major constituent of tourmaline pegmatites accommodates a range of trace elements. Zr^{4+} in zircon for instance is easily a victim of substitution by Hf^{4+} due to their similar coordination numbers, ionic radii and charges. The tourmaline pegmatites showed higher enrichments in the radioactive elements, U and Th, and REE over the beryl-bearing pegmatites. Zircon which is an observed constituent of the tourmaline pegmatites often contains traces of radioactive elements such as U and Th in its structure, which causes it to become metamict (Dissanayake et al. 2000). Madenbach (1976) has also reported that the sum of the concentrations of REE and Y in zircon can be as high as 25 wt%. The enriched REE, U and Th in tourmaline pegmatites may not be solely due to zircon, but some other expected associated radioactive minerals like uraninite, thorite and monazite which may contain significant concentrations of these elements. The mineral sources, particularly those rich in trace elements such as Zr, Hf, REE, U and Th, are associated with late stage magmatic events that brought about metal-rich solutions through igneous activity that included pegmatite emplacement. The origin of these mineral sources is closely related to the geologic and tectonic history of the tourmaline pegmatites.

REE contents are generally more enriched in the tourmaline pegmatites than the beryl-bearing pegmatites (Table 1). Most of the analysed pegmatite samples, especially all the tourmaline pegmatites display light REE (LREE)-enriched and heavy REE (HREE)-depleted patterns, as shown from the chondrites normalized plot of the rare earth elements (REE) (Figure 6).

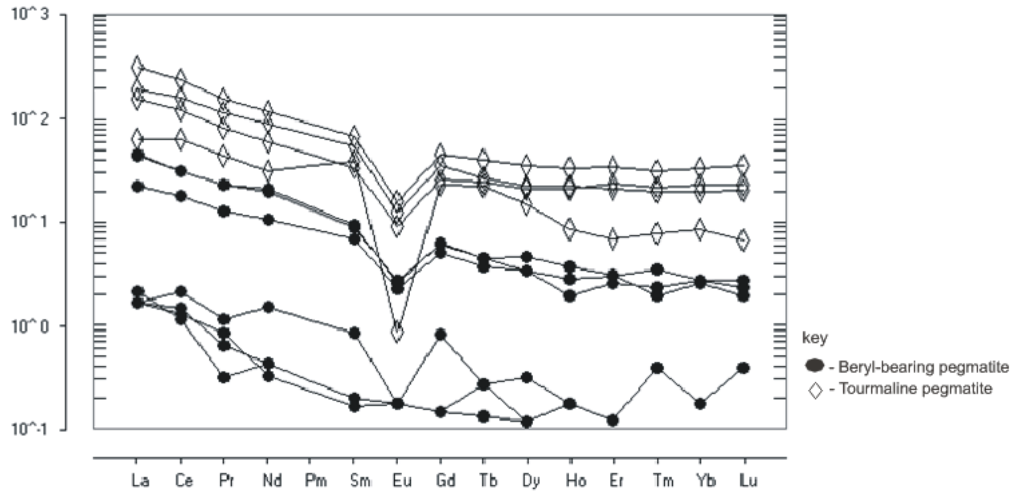

Figure 6: Chondrites-normalized REE patterns for the analysed pegmatites from Olode and environ.

Most REE patterns for the analysed Olode pegmatite samples generally exhibited fractionated asymmetric concave-upward shapes, with strong negative Eu anomalies, an indication for granite-related pegmatites. These have resulted from the high contents of zircon, garnet and the plagioclase feldspar in the pegmatites. Garnet will change REE patterns to LREE-enriched and HREE depleted, whereas plagioclase feldspar will enrich all REE, but deplete Eu (Davidson et al. 2013). The relative abundance of LREE as compared to HREE suggests that the study samples have originated and sourced from the upper continental crust material and not the mantle. The characteristically similar shapes presented by most of the analysed pegmatite samples indicate that they have crystallised from the same source and through the same geological process. Three of the beryl-bearing pegmatites however, show no visible Eu anomaly. The slight differences in shapes have resulted from compositional variations of the pegmatites which must have been due to varied evolutionary trends.

Some individual beryl-bearing pegmatite samples are observed to be markedly more enriched in some incompatible elements than the tourmaline pegmatites. Nb, Ta and Sn are highest in R002, a beryl-bearing pegmatite with values of 42.3, 20.2, and 12 ppm, respectively. Be and Rb are highest in R005 and R001, both beryl-bearing pegmatites with values of 39 and 672.9, respectively. These elemental concentrations, though not highly enriched, clearly indicate columbite-tantalite, cassiterite and beryl mineralisations in the beryl-bearing pegmatites. Their enrichments in some of these elements are believed to be due to the relative longer distances they have travelled from their presumed respective parental rocks. Classic models of fractionation and evolution of mineralisation in pegmatites suggest the farther a pegmatite forming melt travelled from its parental source, the more fractionated and enriched in incompatible elements such as Be, Li, Rb, Cs, Ta the resulting pegmatite will be (Cerny 1991). This explains why the beryl-bearing pegmatites appear to be more fractionated than the tourmaline pegmatites. Field observations showed that in almost all the mines visited, where gem quality beryl is being mined, the pegmatites which bear the beryl crystals are visibly hosted by mica schist, and are distanced from granites, their supposedly parental rocks, signifying that the magmatic fluids from which these pegmatites have crystallised must have travelled long and varying distances from their sources. The host mica schist must have also contributed immensely to the beryl and other mineralisations of the beryl-bearing pegmatites. The Olode beryls have crystallised from fluid-rich melts that have resulted from fractional crystallisation and partial melting. The fluids precipitating these minerals are probably a mixture of expelled magmatic fluids rich in water and some incompatible elements such as beryllium, rubidium and caesium, and mobilized metamorphic fluids from the surrounding meta-sedimentary rocks. Virtually in all the known gem mineral deposits in southwestern Nigeria, the pegmatite phases in which the gem mineral crystals are found, appear to be more abundant in areas that are underlain by the metasedimentary environments of the Schist Belt (Jimoh 2018). This clearly indicates that there were peculiar geochemical conditions suitable for gem minerals crystallisation and formation, especially beryls and tourmalines in these environments. Beryl represents a characteristic accessory mineral in the Olode granitic beryl-bearing pegmatites. Other minerals currently being mined from these pegmatites include tantalite-columbite, cassiterite, feldspar and quartz. Beryl commonly occurs together with Nb-Ta oxide minerals, mainly members of columbite group and secondary Nb-Ta oxide phases (Uher et al. (2007), Novak et al. (2000). Kinnaird (1984) did report primary mineralisation of tantalum, niobium, tin, beryllium and lithium hosted in quartz-feldspar- muscovite pegmatites elsewhere. Beryl crystals of various colours are found most commonly in granitic pegmatites and often associated with tin and tungsten ore bodies (London and Evensen 2002).

Based on their mineralogy and geochemical signatures, coupled with the presence of beryl and columbite-tantalite, and following the classification of Cerny et al. (2012), the investigated beryl-bearing pegmatites belong to the beryl type of the rare-elements LCT family of pegmatites. Beryl is the first of the truly striking, rare-element minerals to crystallise 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 (Cerny 2000). The mineralisation status of the investigated pegmatites is further confirmed by the discrimination and fractionation plots of Cs and Rb versus K/Rb (Figure 7) which also show that most of the beryl-bearing pegmatites are more mineralised than the tourmaline pegmatites. These plots show most of the beryl-bearing pegmatites to be mineralised, most of them belonging to the rare-elements pegmatites, while most of the tourmaline pegmatites are shown to be barren. The values of the K/Rb ratios of most of the analysed beryl-bearing pegmatites are less than 100 (Table 1), which is indicative of mineralisation (Tischendorf 1977). The mean K/Rb values of both the beryl-bearing and tourmaline pegmatites are 85.00 and 157.73, respectively. This clearly indicates that the beryl-bearing pegmatites are mineralised, though weakly so, while the tourmaline pegmatites mostly exhibit un-mineralised or barren status.

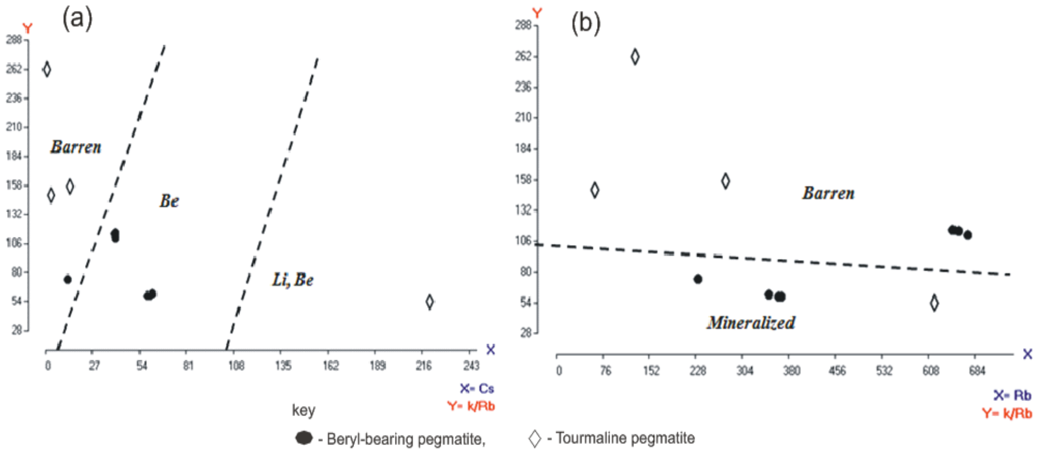

Figure 7: Discrimination diagrams showing the degree of fractionation and mineralisation of Olode pegmatites: (a) Cs vs K/Rb (Trueman and Cerny 1982), (b) Rb vs K/Rb (Stavrove et al. 1969).

The mineralised beryl-bearing pegmatites in Olode and environs, like in most pegmatite districts worldwide, occur along with many barren pegmatites most of which are highly tourmalinated, containing a lot of well developed schorl crystals. This therefore suggests that the two varieties of pegmatites have emanated from a common source, a higly mineralised magma and are believed to represent late-stage pneumatolytic fluids derived from acidic magma bodies. The slight chemical and mineralogical variations among the two groups of pegmatites must have resulted from fractional crystallisation of the parent magma.

Conclusion

The mineralised dyke-like NE-SW trending beryl-bearing pegmatites in Olode and environs, southwestern Nigeria like in most pegmatite districts worldwide occur alongside the barren massive tourmaline pegmatites, exhibiting slight differences both in mineralogical and chemical compositions, but with common peraluminous provenance. While the beryl-bearing pegmatites are hosted by the mica schist and distanced from granites, the tourmaline pegmatites are found hosted and associated with granite, the presumed parent rock, indicating that the tourmaline pegmatites are less fractionated than the beryl-bearing pegmatites. The Olode groups of pegmatites have originated from a common source as they have crystallised from fluid-rich melts resulting from fractional crystallisation (residual pegmatitic melt) and partial melting (anatectic pegmatitic melt), their differences both in occurrences and mineralogical/chemical compositions have resulted from fractional crystallisation and their varied evolutionary trends.

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