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Geochemical Characterization and Rare-Metals (Ta-Nb) Mineralization Potentials of Pegmatites Around Lokoja, Central Nigeria

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ABSTRACT

Five pegmatite dykes in suburbs of Lokoja area, central Nigeria are studied using field, petrographical and geochemical data to characterize and determine the rare-metals (Ta-Nb) mineralization attributes. The pegmatites which occur as near-vertical, large veins and dykes are hosted by migmatitic biotite gneiss. The pegmatites consist of quartz, feldspar, muscovite with rare biotite, occasional beryl and some minor/accessory apatite and zircon. Composite whole-rock samples were analysed for major, trace and rare earth elements using X-Ray Fluorescence Spectrometer (XRF) and Inductively Coupled Plasma Mass Spectrometer (ICP-MS). The results reveal the pegmatites are considerably siliceous with SiO_2 values of 69.00% to 74.60%. Al_2O_3 values are relatively moderate (14.80% to 19.60%). Na_2O and K_2O abundances are low with ranges of 2.32% – 5.93%, 1.22% – 11.00% respectively. MgO abundances are generally low (0.03 – 0.07%). Fe_20_3 values are also low; ranging from 0.31% to 1.16%. Alumina Saturation Index (A/CNK) computation with values ranging from 1.40 to 3.06 indicates the pegmatites are peraluminous. Trace and rare-earth elements results show Bakunba location pegmatite is mineralised (Nb: 571.86ppm, Ta: 180ppm) and compare favourably with other mineralised pegmatites in Nigeria; while Ganaja-2 location (Nb: 100.37ppm, Ta: 26.6ppm) are moderately mineralised. Nb-Ta values of Shagari location (33.14ppm; 2.7ppm), Ganaja-1 location (12.6ppm; 3.6ppm) and Crusher location (0.91ppm; 0.2ppm) show they are barren. Various variation plot diagrams, such as Kb/Rb vs Cs, K/Rb vs Rb, also show mineralization status of these pegmatite bodies as compared with some local and foreign pegmatites. Plots of Zr vs SiO_2, Rb vs Y+Nb and Rb vs Sr indicate the pegmatites are magmatic, from within plate granites and in crustal thickness of more than 30 km during the time of emplacement.

1. Introduction

Pegmatites occur throughout the Basement Complex of Nigeria. There are numerous studies on these pegmatites. Earlier study of Pegmatites in Nigeria includes the work of Jacobson and Webb (1946) which identified that the pegmatites are of the complex category and also that the rare-metals pegmatites of Nigeria are confined to a 400 km long NW-SW trending belt stretching from Wamba area in central Nigeria to Ibadan area southwest Nigeria. This point of view was refuted by the work of Garba (2003) and Okunlola (2005) as well as the occurrences in the Southeastern part of Nigeria, notably around Obudu hill (Ekwueme, 2004). The Nigerian pegmatites evolved during the time span of 600+530Ma, (Matheis and Caen-Vachette, 1983), which indicates formation (Orogeny) during the periods of Pan African magmatism.

Ta – Nb (± Sn) mineralized pegmatites are hosted by rocks of the Pan – African basement complex. Many areas have been reported by Jacobson and Webb (1946), Matheis and Caen-Vachette (1983), Kuster (1990), Garba (2003), Okunlola and Jimba (2006), Okunlola and Akintola (2008), Okunlola and Ocan (2009) and Elueze and Aromolaran (2014) from central, northwest, southwest and southeast Nigeria. Matheis (1987), Matheis et al. (1982), Kuster (1990), Garba (2003) and Okunlola (2005) classified the metallogeny of rare metal Ta-Nb pegmatites of Nigeria. Okunlola (2005) outlined seven broad fields namely Oke Ogun, Ibadan-Osogbo, ljero-Aramoko, Kabba-Isanlu, Keffi-Nasarawa, Share-Lema Ndeji, and Kushaka-Birnin Gwari (Fig. 1).

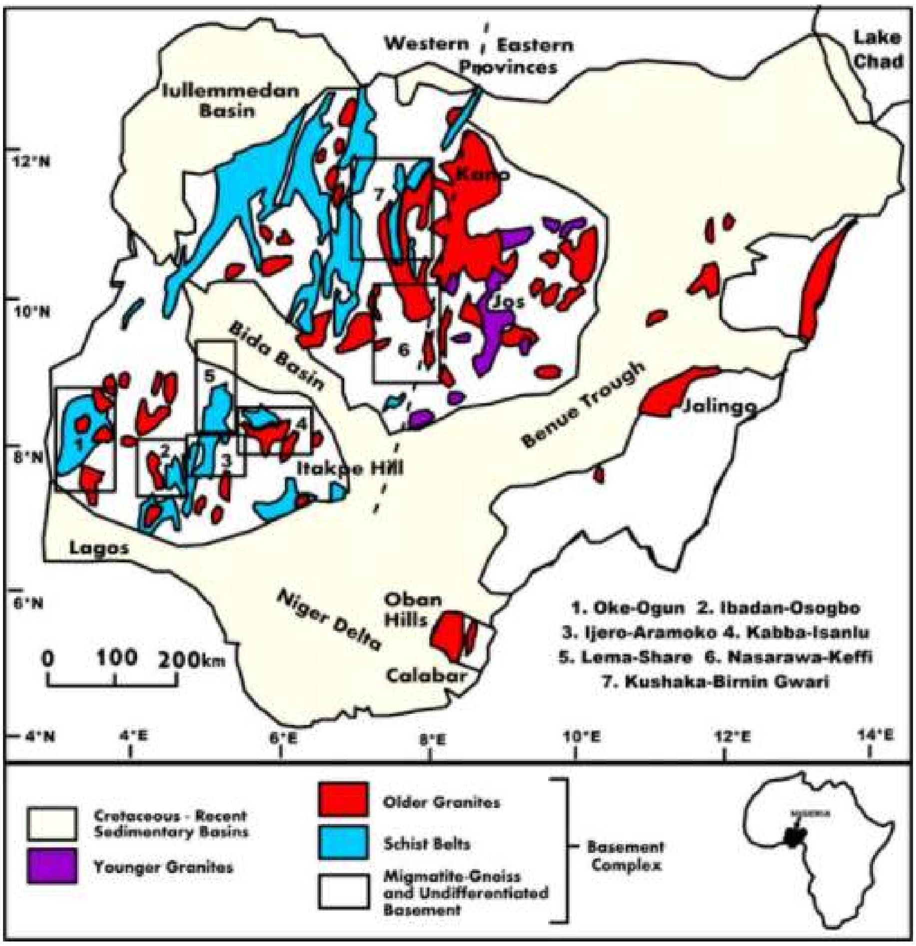

Fig. 1. Ta-Nb mineralized pegmatite fields of Nigeria (after Okunlola, 2005)

Omada, et al. (2015), in his study of pegmatite bodies in the present study area, noted that the mineralogy and composition of the pegmatite bodies are indicative of post tectonic anorogenic acidic igneous protolith which underwent alkali metasomatism involving selective enrichment of trace elements and REE, fractionation and rock-fluid interactions

Lokoja and environs are part of Nigerian Topography *'LOKOJA'* sheet 247 located in central Nigeria within longitude 06°35'00"-06°45'00" and latitude 07°43'00"-07°55'00". The coordinates of the sample locations (Fig. 2) in named suburbs of Lokoja which are accessible by the Benin-Lokoja-Abuja Expressway, Lokoja-Jakura and Lokoja-Ganaja-Ajaokuta highways are;

1. Bakunba, N 07°53' 50.5" E 06° 41' 06.7" Elevation: 140 m
2. Crusher, N 07° 49' 57.7" E 06° 39' 12.4" Elevation: 100 m
3. Shagari, N 07° 50' 08.1" E 06° 39' 47.2" Elevation: 113 m
4. Ganaja 1, N 07° 42' 46.3" E 06° 43' 52.0" Elevation: 102 m
5. Ganaja 2, N 07° 43' 30.1" E 06°44' 05.5 Elevation: 110m

2. Regional Geological Setting

The Nigeria Basement Complex forms part of the Pan-African mobile belt which lies between the West- African and Northwest of Congo Craton. It is believed that the Pan-African belt evolved by plate tectonic activity which involved collision between the passive continental margin of West African Craton and the active continental margin of the Tuareg shield about 600 Ma ago (Black et al., 1979; Ajibade et al., 1987).

The collision led to the reactivation of the internal region of the belt especially at the plate margin. The Basement Complex is one of the major litho-petrological components that make up the geology of Nigeria. It is believed to have been affected by, at least, three major tectonic cycles of deformation, metamorphism and remobilization corresponding to the Liberian (2700 Ma), the Eburnean (2000 Ma) and the Pan- African cycles (600 Ma).

These cycles were characterized by intense deformation and isoclinal folding accompanied by regional metamorphism which was followed by extensive migmatization. The Pan-African deformation was accompanied by a regional metamorphism, migmatization, extensive gneissification which produced syntectonic granite and homogenous gneisses (Abaa, 1983). Late tectonic emplacement of granites and granodiorites and associated contact metamorphism accompanied the end stages of this last deformation. The end of the orogeny was marked by faulting and fracturing (Olayinka, 1992).

Four major petro-lithological units are distinguishable in the basement complex of Nigeria, namely; (1) The Migmatite – Gneiss Complex (Rahaman, 1988; Dada, 2006), (2) The Schist Belt (Metasedimentary and Metavolcanic rocks (Grant, 1978; Olade and Elueze, 1979; Rahaman, 1981; Holt, 1982; Egbuniwe, 1982; Turner, 1983), (3) The Older Granites (Pan African granitoids) (Falconer, 1911; Rahaman, 1981; Rahaman, 1988; Dada, 2006) and (4) Undeformed minor felsic and mafic intrusives (Grant, 1970; Matheis and Caen-Vachette, 1983; Dada, 2006). The main basement lithologies in the Lokoja area include the porphyritic granite, granodiorite and migmatitic biotite gneiss which host the pegmatite bodies.

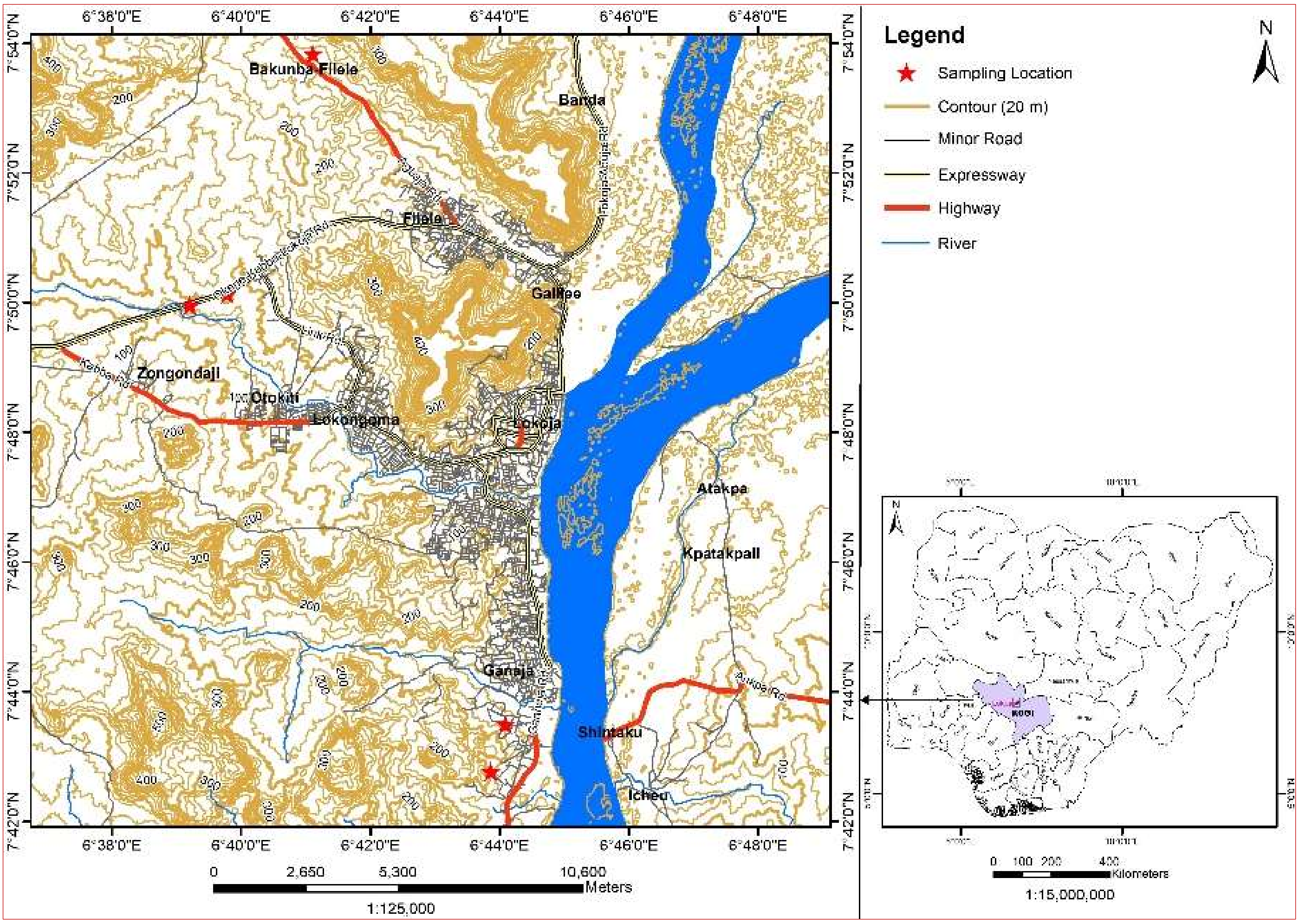

Fig. 2. Location map of the study area

3. Materials and Method

A detailed intensive field mapping exercise was carried out on a scale of 1:25,000 map. Fresh whole-rock samples were obtained for thin sections and geochemical analyses. Thin section was prepared in the Laboratory of Department of Geology, University of Benin, Benin City. Samples were pulverized to rock pulp using Agate mortar mill at the Laboratory of Department of Geology, University of Ibadan, Ibadan and sent to ACME Laboratory, Vancouver, Canada for analyses for major elements using X-Ray Fluorescence Spectrometry, trace elements using four-acid digestion Inductively Coupled Mass spectrometry.

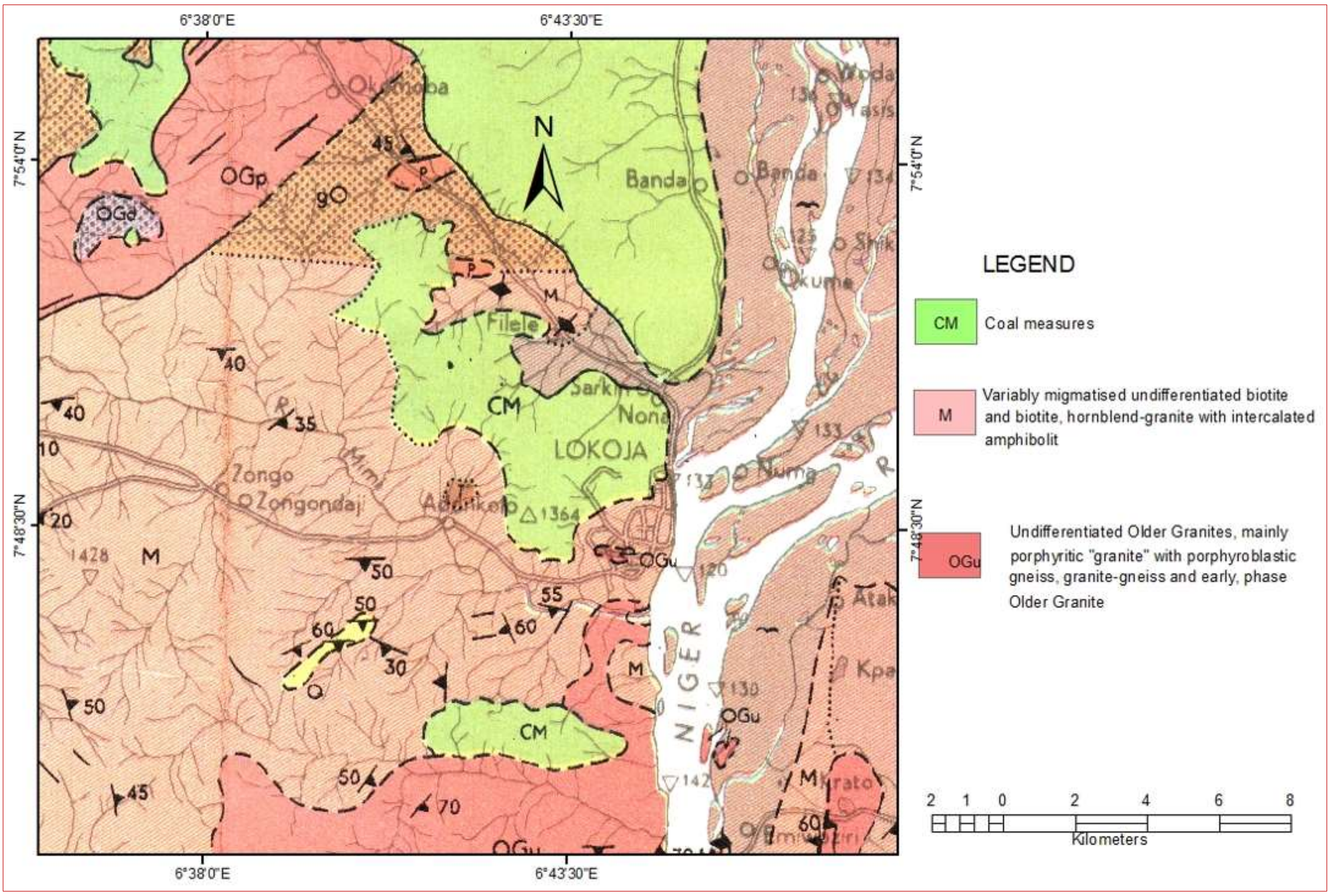

Fig. 3. Geological map of the study area

4. Results and Discussion

4.1 Minerology

Field observation (Figs. 4 - 6) show the pegmatite are composed of quartz, microcline, plagioclase feldspar, muscovite (or biotite). Petrographic study of the thin section shows the predominant minerals are Quartz, Microcline, Muscovite, Plagioclase, Biotite, and Opaque minerals (magnetite, ilmenite) and accessory apatite, zircon, topaz and beryl. Quartz appear in the thin section as colourless and clear with low relief in plane-polarized light showing first-order interference colours of grey and white; Microcline show the characteristic cross-hatched (grid) twinning or pericline twinning and is often graphically inter-grown with quartz; Plagioclase shows with its distinct lamellar twinning; Biotite occur in some samples (Shagari and Ganaja-1) as lath-shaped brown crystals showing perfect cleavage in one direction and strongly pleochroic which undergo extinction from light brown to dark brown; Muscovite also occur in some samples and differ from biotite with its lack of colour.

Fig. 4. Bakunba Pegmatite exposure showing abandoned water-filled artisanal mining pit worked for gemstones in the foreground

4.2. Whole rock geochemistry of the pegmatites

The values obtained from analyses for the major elements and trace elements are presented in Tables 1 and 2, values from other researchers are included in tables for the comparison.

4.2.1. Major elements

The bulk composition shows that the pegmatites are highly siliceous. SiO_2 values range from 69.00% to 74.60% with Bakunba pegmatites having values 74.60% which compare favourably with Ijero pegmatite value of 74.30% (Matheis et al., 1982) and Itakpe barren pegmatite 70.59% (Okunlola and Somorin, 2006) but less than those of Ofiki (Southwest Nigeria) pegmatite (53.15%) (Elueze et al., 2014), Cap de Creus (Spain) pegmatite (46.62%) (Alfonso et al., 2003).

Ganaja-2 pegmatite has SiO_2 values of 70.70% with the Crusher and Ganaja-1 being 69.50% and 69.00% respectively. Al_2O_3 abundances range from 15.20% to 19.60% with Bakunba pegmatite having the low value of 15.20% and Shagari pegmatite having a higher value (19.60%).

Fig. 5. Large Pegmatite dyke exposed at a massive road-cut at Shagari

Fig. 6. Pegmatite dyke exposed at Ganaja-2

Shagari, Bakunba and Ganaja-2 pegmatites have NaO_2 values of 5.93%, 5.82% and 5.21% which also compare fairly well with 5.0% value of Ijero pegmatite.

K_2O values are relatively high for Crusher and Ganaja-1 pegmatites (11.20%, 11.00%) but moderate for Shagari (5.57%), Ganaja-2 (4.37%), and low for Bakunba pegmatite (1.22%) (Figs. 7 and 8).

MgO abundances are generally low (0.03 – 0.07%) except for Shagari pegmatite with a value of 0.34%. Fe_20_3 values are also low; ranging from 0.31% to 1.16%.

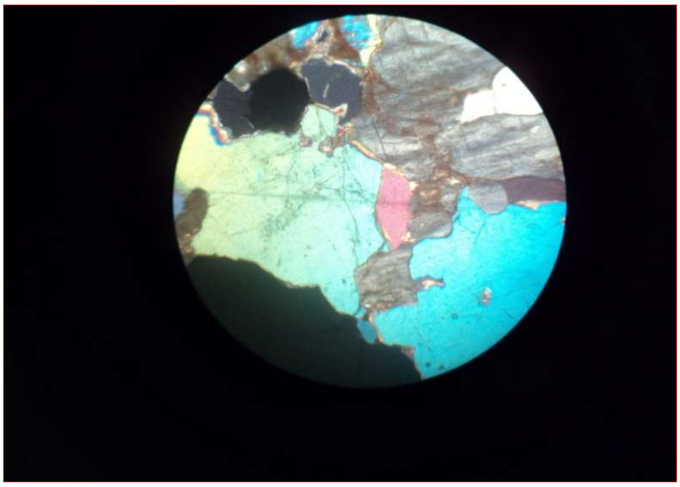

Fig. 7. Photomicrograph of Ganaja-1 pegmatite (xpl; x40; op: opaque mineral; qz: quartz; mc: microcline)

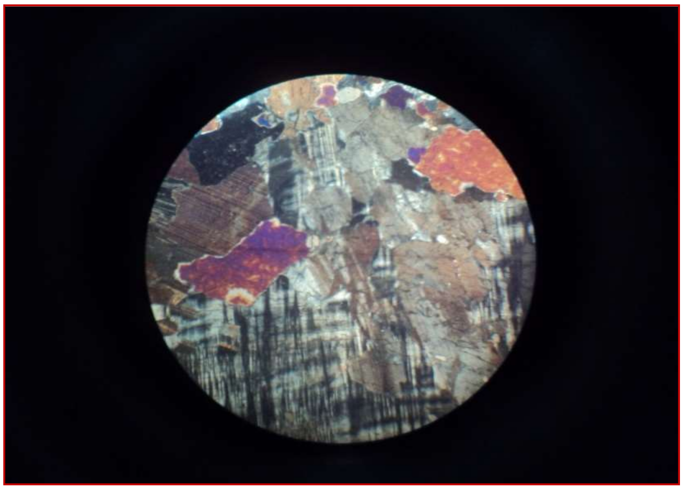

Fig. 8. Photomicrograph of Shagari pegmatite (xpl; x40; mc: microcline; qz: quartz)

The Alumina Saturation Index defined by molecular ratio $Al_2O_3/(CaO+Na_2O+K_2O)$ [A/CNK] is used to classify rocks into metaluminous (A/CNK<1); peraluminous (A/CNK > 1); or peralkaline (A<NK). The computation of A/CNK for the pegmatites yielded the following values: Bakunba 3.06; Crusher 1.40; Shagari 2.04; Ganaja-1 1.42 and Ganaja-2 2.06. These values show that all the pegmatites are peraluminous with Bakunba pegmatite body being highly peraluminous.

4.2.2. Trace elements

The major elements analysis shows that the pegmatites are highly siliceous. SiO_2 values range from 69.00% to 74.60% with Bakunba pegmatites having values 74.60% which compare favourably with Ijero pegmatite value of 74.30% (Matheis et al., 1982) but less than those of Ofiki (Southwest Nigeria) pegmatite (53.15%) (Elueze et al., 2014), Cap de Creus (Spain) pegmatite (46.62%) (Alfonso et al., 2003). Ganaja-2 pegmatite has SiO_2 values of 70.70% with the Crusher and Ganaja-1 being 69.50% and 69.00% respectively.

Table 1. Major Element composition of the Pegmatite (1-5) and others for comparison (A-E)

Major element (%)	1 Bakunba	2 Crusher	3 Shagari	4 Ganaja1	5 Ganaja2	A Itakpe	B Wamba	C Ijero	D Ofiki	E Creus
SiO_2	74.60	69.50	69.10	69.00	70.70	70.59	---	76.2	53.15	46.62
Al_2O_3	15.20	16.60	19.60	16.60	16.90	14.90	---	14.3	29.34	36.83
Na_2O	5.82	2.39	5.93	2.32	5.21	3.50	0.97	5.0	0.26	0.82
K_2O	1.22	11.20	5.57	11.00	4.37	5.89	---	1.4	10.31	9.49
MgO	0.07	0.03	0.34	0.03	0.07	0.09	---	0.19	0.01	0.21
Fe_2O_3	1.02	0.31	1.23	0.60	0.54	1.11	1.84	0.81	1.15	1.34
TiO_2	0.01	<0.01	0.14	0.01	0.04	0.03	---	0.03	0.08	0.20
CaO	0.81	0.09	1.55	0.20	1.84	1.25	---	0.36	0.02	0.05
MnO	0.11	<0.01	0..02	<0.01	<0.01	---	---	0.09	1.0	0.01
P_2O_5	0.032	0.012	0.039	0.003	0.009	0.02	---	0.14	0.012	0.11

1-5: Present study; 1 Bakunba, 2 Crusher, 3 Shagari, 4 Ganaja-1, 5 Ganaja-2
A: Itakpe, Central Nigeria [n = 11] (Okunlola and Somorin, 2006)
B: Wamba, Central Nigeria [n = 51] (Kuster, 1990)
C: Ijero, Southwest, Nigeria [n = 5] (Matheis et al., 1982)
D: Ofiki, Southwest Nigeria [n = 10] (Elueze et al., 2014)
E: Cap de Creus, Spain [n = 4] (Alfonso et al., 2003)

Table 2. Trace Element composition of the Pegmatite (1-5) and others for comparison (A-E)

Trace Element (ppm)	1 Bakunba	2 Crusher	3 Shagari	4 Ganaja1	5 Ganaja2	A Itakpe	B Wamba	C Ijero	D Ofiki	E Creus
Rb	110.4	362.3	197.5	402.9	153.0	115.6	3150	241	9888.4	1479
Cs	9.8	2.2	2.3	2.9	2.1	1.3	116	---	5681.7	100
Ba	22	236	327	882	176	136	---	514	20	410
Sr	18	45	94	229	138	544	---	16	13	21
Ga	58.29	24.78	25.92	28.09	34.67	18.88	---	---	89.30	---
Be	179	<1	5	2	13	4	---	22	28	---
Sn	21.0	0.8	3.1	0.8	2.0	1.2	745	22	102.7	231
Nb	571.86	0.91	33.14	12.60	100.37	1.36	238	74	209.3	358
Ta	180.0	0.2	2.7	3.6	26.6	4.6	53	---	174.0	---
W	16.1	<0.1	0.3	0.6	4.1	0.65	---	---	365	102
Y	13.1	0.4	12.4	9.2	85.2	2.6	---	52	1.9	10
Zn	8.6	1.8	15.1	3.8	7.6	15.3	171	---	210.0	97
Zr	2.5	0.2	3.3	4.1	57.3	14.0	---	203	4.1	10
Hf	0.20	<0.02	0.28	0.34	3.65	0.46	---	---	0.33	---
Li	54.1	1.3	22.1	1.8	20.0	11.7	510	96	---	---
Th	18.2	0.2	55.5	4.7	23.9	1.93	---	---	0.59	---
U	46.7	0.2	5.9	5.5	62.4	0.56	---	---	0.1	---
Sc	25.1	0.3	7.0	0.2	1.8	0.75	---	---	---	---
Ti	70	30	790	60	250	---	485	---	---	---
Tl	0.43	2.05	1.19	1.84	0.75	---	---	---	25.2	---
K/Rb	91.74	256.63	234.13	226.65	237.10	380.00	---	49.68	8.89	54.71
K/Cs	1033	42262	20104	31488	17275	31657	---	---	15.47	809.19
K/Ba	460	394	141	104	206	369	---	23	4396	736
Ta/W	11.18	----	9.00	6.00	6.49	7.07	---	---	0.48	197.36
Th/U	0.390	1.000	9.407	0.855	0.383	3.447	---	---	5.9	---
Na/K	4.263	0.190	0.951	0.188	1.065	0.49	---	3.098	0.022	0.075
K	10128	92976	46239	91316	36277	50223	---	11974	87911	80919
Na	43176	17730	43992	17211	38651	25965	7196	37093	1929	6083

1-5: Present study; 1 Bakunba, 2 Crusher, 3 Shagari, 4 Ganaja-1, 5 Ganaja-2
A: Itakpe, Central Nigeria [n = 11] (Okunlola and Somorin, 2006)
B: Wamba, Central Nigeria [n = 51] (Kuster, 1990)
C: Ijero, Southwest, Nigeria [n = 5] (Matheis et al., 1982)
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Al_2O_3 abundances range from 15.20% to 19.60% with Bakunba pegmatite having the low value of 15.20% and Shagari pegmatite having a higher value (19.60%).

Shagari, Bakunba and Ganaja-2 pegmatites have NaO_2 values of 5.93%, 5.82% and 5.21% which also compare fairly well with 5.0% value of Ijero pegmatite.

K_2O values are relatively high for Crusher and Ganaja-1 pegmatites (11.20%, 11.00%) but moderate for Shagari (5.57%), Ganaja-2 (4.37%), and low for Bakunba pegmatite (1.22%).

MgO abundances are generally low (0.03 – 0.07%) except for Shagari pegmatite with a value of 0.34%. $Fe_2 0_3$ values are also low; ranging from 0.31% to 1.16%.

The Alumina Saturation Index which is defined by molecular ratio Al_2O_3/ ($CaO+Na_2O+K_2O$) [A/CNK] is used to classify rocks into metaluminous (A/CNK < 1); peraluminous (A/CNK > 1); or peralkaline (A<NK). The computation of A/CNK for the pegmatites yielded the following values: Bakunba 3.06; Crusher 1.40; Shagari 2.04; Ganaja-1 1.42 and Ganaja-2 2.06. These values show that all pegmatites are peraluminous with Bakunba pegmatite body being highly peraluminous.

4.2.3. Rare-earth elements

Rare-earth elements abundances for pegmatites have varying ranges. Values of La for Shagari pegmatite is high (59ppm) relative to others; Bakunba (6ppm), Ganaja-1 and 2 (2ppm each) and Crusher (1ppm). Ce abundances followed a similar pattern of Shagari (140ppm) while Bakunba (13ppm), Ganaja-1 (6ppm), Ganaja-2 (3ppm) and Crusher (2ppm). Values of Nd are also following the same trend with Shagari having the relatively high values of 58ppm; Bakunba (5ppm), Ganaja-2 (2ppm), Ganaja-1 (1.0ppm) and Crusher (0.5ppm). (Table 3).

Table 3. Rare-earth element composition of the pegmatite normalized against chondrite values (c.v.) of McDonough et al. (1995)

Rare- Earth Element (ppm)	c.v.	A Bakunba	B Crusher	C Shagari	D Ganaja-1	E Ganaja-2
La	0.237	23.63	3.8	249.37	6.75	6.75
Ce	0.612	21.42	2.55	229.31	10.29	4.26
Pr	0.0928	17.24	1.08	190.73	3.23	3.23
Nd	0.457	11.38	1.09	126.26	2.19	4.16
Sm	0.148	17.57	0.68	111.49	3.38	14.86
Eu	0.0563	3.55	3.55	15.99	7.10	7.10
Gd	0.199	8.54	1.00	53.27	5.03	27.64
Tb	0.0361	11.08	2.77	44.32	5.54	44.32
Dy	0.246	12.20	0.41	20.73	7.72	60.57
Ho	0.0546	9.16	1.83	9.16	7.33	69.60
Er	0.160	9.38	0.63	7.50	8.13	81.88
Tm	0.0247	20.24	4.05	8.10	12.15	105.26
Yb	0.161	24.84	0.62	6.21	11.80	106.83
Lu	0.0246	28.45	4.07	4.07	16.26	121.95

Chondrite normalised diagram show elevated values of light rare-earth elements (LREE) of La, Ce, Pr, Nd and Sm for Shagari, Ganaja-1and Ganaja-2 but lower for Bakunba and Crusher. All the pegmatite bodies display a very clear negative Eu anomaly that is consistent and comparable to granite chondrite diagram; including those Jurassic Younger granites (Okunlola and Somorin, 2006).

The near perfect fit of the graph of the pairs of Bakunba/ Crusher and Shagari/Ganaja-1 are probably a proof of the same source magma. However, pairs (Crusher and Bakunba, Shagari and Ganaja-1) could be the same pegmatite dykes exposed at different locations. The Fig. 9 is Chondrite Normalized spider-web diagram of the Pegmatite bodies from the values in Table 3.

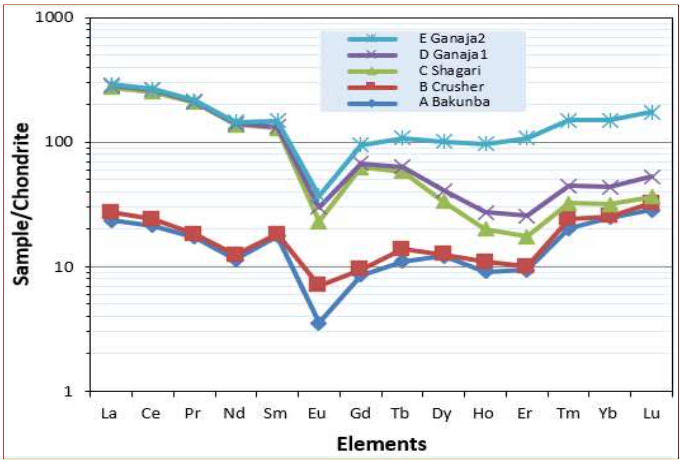

Fig. 9. Chondrite normalised spider-web diagram of the pegmatites

4.3. Geochemical characterization of the Pegmatites

Geochemical characterization of pegmatite is essentially the determination of the degree of chemical fractionation and the fertility (rare-metal mineralization potentials) of the pegmatite. Trace elements commonly used for geochemical characterization are: - Large-ion Lithophile elements (LILE): Rb, Cs, Sr, K, Ba, Pb and High Field Strength elements: Ta, Nb, Ti, Sc, Y, Th, U, Zr, Hf, Pb and Rare-Earth elements – La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu. Extreme fractionation of lithophile elements such as Rb and Cs is a common geochemical feature of granitic pegmatites, especially the rare-metal bearing types (Garba, 2003). The geochemical characterization of the pegmatites has been determined by using various geochemical ratios and variation plot diagrams.

4.3.1. Degree of chemical fractionation in relation with rare metal specialization.

The plot of K/Rb versus Cs after Trueman and Cerny (1982) determine the degree of chemical fractionation in relation with rare metal specialization (Fig. 10). Low K/Rb and high Cs values indicate higher Ta mineralization. The plot has fields from the 'barren' to other fields of varying fractionation which is in turn indicative of their rare-metal mineralization potentials. Bakunba pegmatite fall within the Be zone while Wamba (Kuster, 1990), Ofiki (Elueze et al., 2014), and Creus (Alfonso et al., 2003) plot in the Li, Cs, Be Ta mineralized pegmatites zone. Crusher and Shagari pegmatites plot in the 'barren' zone as the barren Itakpe (Okunlola and Somorin, 2006) pegmatite.

4.3.2. Degree of albitization against chemical fractionation and mineralization potentials

The Na/K ratio which determine the degree of albitization is plotted against Rb, an alkali element (Fig. 11). The plot of K/Rb versus Rb of Straurov et al. (1966) show the mineralized or barren nature of the pegmatite based of the degree of fractionation (Fig. 12). The plot separates the pegmatites into 'barren' and 'mineralized' fields. Bakunba pegmatite falls within the mineralized zone like the mineralized Wamba and Creus pegmatites. Crusher, Shagari, Ganaja-1 and Ganaja-2 pegmatites all plot in barren field like Itakpe barren pegmatite.

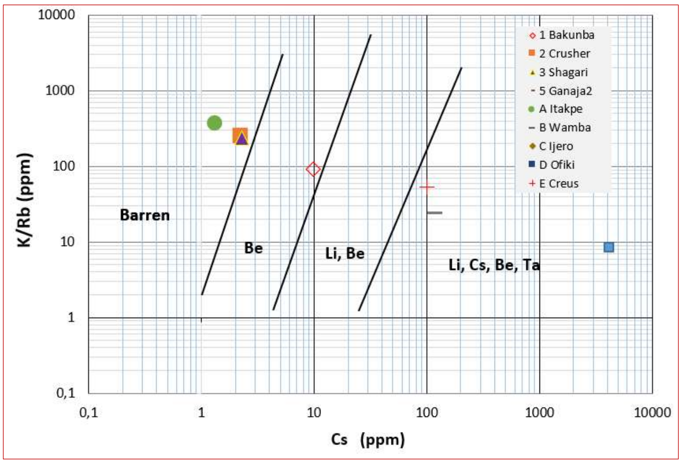

Fig 10. Plot of K/Rb vs Cs (modified after Trueman and Cerny, 1982)

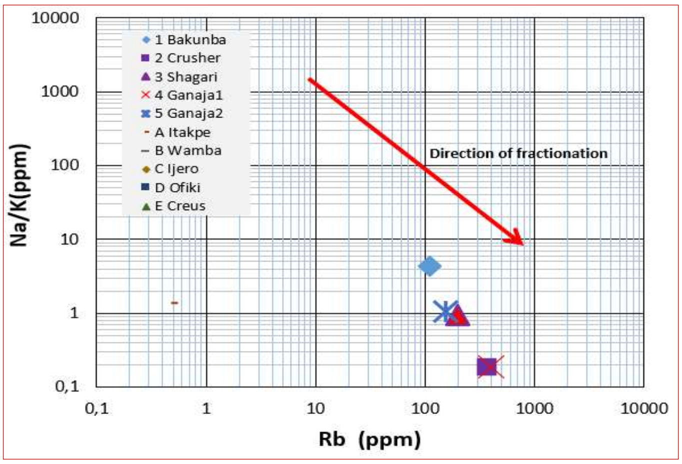

Fig. 11. Plot of Na/K vs Rb

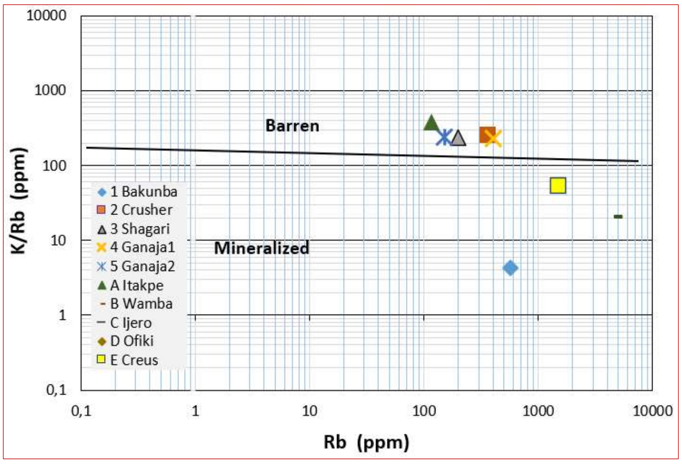

Fig 12. Plot of K/Rb vs Rb (modified after Straurov et al., 1966)

4.3.3. Tectonic environment of emplacement of pegmatite

The tectonic environment of emplacement of pegmatite is discriminated using the Rb versus Y+Nb Plot of Pearce et al. (1984) (Fig. 13). All the studied pegmatite bodies and those for comparison plot in the data field of Within Plate Granite (WPG). The Precambrian pegmatite bodies occur mainly as dykes and veins suggesting they are emplaced in pre-existing fractures (fracture healing). If these intrusions and/or emplacement are syn- or post-orogeny cannot be determined by this plot. The Rb versus Sr plot of Condie (1976) discriminate the Crustal Thickness during time of emplacement of the pegmatites (Fig. 14). The studied pegmatite bodies all plot in >30km field.

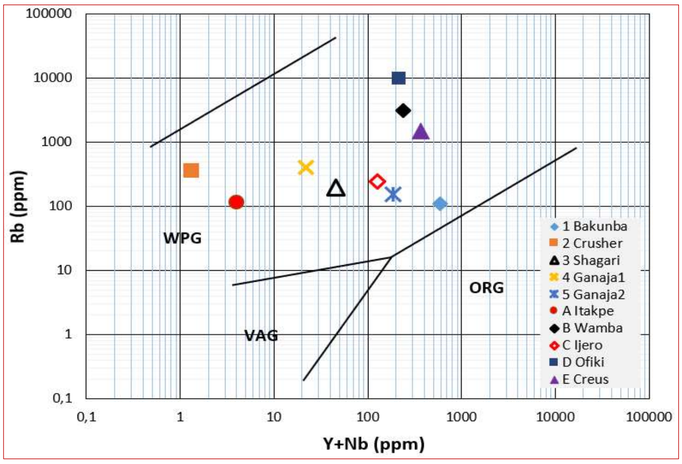

Fig. 13. Plot of Rb vs Y+Nb (modified after Pearce et al., 1984) WPG=Within Plate Granite; ORG=Ocean Ridge Granite; VAG=Volcanic Arc Granite

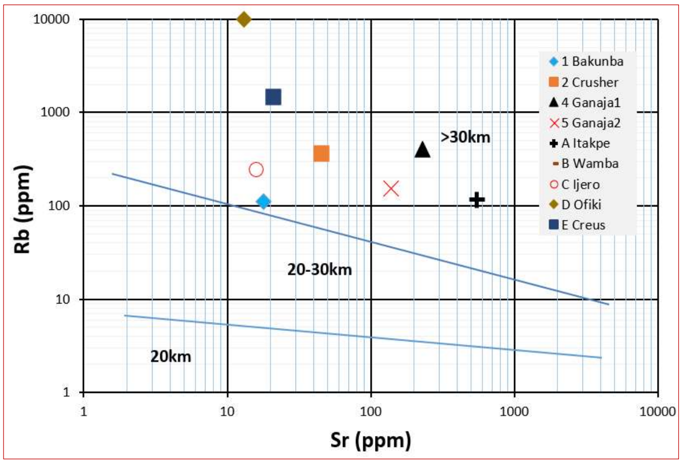

Fig 14: Plot of Rb vs Sr (modified after Condie et al., 1976)

5. Conclusion

The pegmatite dykes are moderately rare-metals mineralized, some are barren. They are siliceous and emplaced within plate at depth of over 30km.

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