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Geological Processes of Lithium Mineralization in Pegmatites Around Madubi, North-Central Nigeria

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Abstract: *The study investigates the geological processes of lithium mineralization in pegmatites around Madubi, North-Central Nigeria. The size of the total area mapped is 33km² and falls within latitude 8°57'0.18"N to 9°0'24.26"N and longitude 7°49'35.08"E to 7°52'21.58"E. Geological field mapping and geochemical analyses were employed to evaluate the lithological units, structural framework and mineralogical characteristics controlling lithium enrichment. The study area, which lies within the Nigerian Basement Complex, is underlain by schist, medium-to coarse-grained granites and pegmatites that intrude the older lithologies. Geochemical analysis, including X-ray fluorescence (XRF) and flame photometry, indicates that the pegmatites are highly siliceous (SiO_2 averaging 70 –75wt.%), rich in alkalis (Na_2O + K_2O > 8wt.%), and depleted in mafic components (Fe_2O_3, MgO, TiO_2). Lithium oxide (Li_2O) concentrations range from 0.11 to 0.67wt.%, with the highest enrichment in samples TJ2a–TJ2f. These values suggest moderate lithium mineralization potential, consistent with lithium–cesium–tantalum (LCT)-type pegmatites derived from fractionated granitic melts. The pegmatite bodies show distinct internal zoning and are structurally controlled by fractures trending mainly NNW - SSE and NNE - SSW. Generally, the Madubi pegmatites are products of residual granitic magmatism and show promising lithium enrichment, although the analysis of the rock samples taken at the surface shows a relatively low in Li_2O concentration. However, sampling at deeper depths may give a higher Li_2O concentration.*

Keywords: *Madubi, Pegmatites, Geochemistry, Mineralization, Lithium, Petrography*

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1.0 Introduction

Pegmatites are igneous rocks that have very large crystals with sizes usually >1cm to sometimes >1m. There are some rare instances when you will find crystals that have a length as long as several meters (London, 2008). The key to the importance of these rocks is that they are likely to contain minerals that are rich in lithium, such as spodumene ($LiAlSi_2O_6$), petalite $LiAlSi_4O_{10}$ and lepidolite ($K(Li,Al)_3(Al,Si,Rb)_4O_{10}(F,OH)_2$). They are particularly widespread in the lithium-caesium-tantalum (LCT) pegmatites (Bradley et al., 2017). Spodumene is very important due to the quantity of lithium and prevalence it has in pegmatitic bodies (Kesler et al., 2012). (Černý, 1991; Černý & Ercit, 2005)

The formation of pegmatites is linked to the late stages of cooling of the magmatic body, where residual melts that are rich in volatiles and incompatible elements separate from the parent granitic magma and crystallize to give rise to pegmatitic bodies (Jahns & Burnham, 1969; London, 2008). As the magma undergoes cooling, early-formed minerals such as quartz, feldspar and mica crystallize first, leaving a residual melt enriched in incompatible elements such as lithium, cesium, rubidium,

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tantalum, etc. This enriched melt is then injected into voids and fractures in the surrounding rocks, where it cools and crystallizes to form pegmatites characterized by their large crystals (London, D., & Cerny, P., 2008). Therefore, lithium mineralization can be hosted in pegmatites globally, of which Nigeria is not left out. (Černý, 1991; Černý & Ercit, 2005)

Nigeria is one of the few African countries that have uncovered substantial high-grade lithium deposits. This has attracted the attention of investors, explorers, and miners interested in tapping into this sought-after "white gold". With the rapid growth in the electric vehicle sector, Nigeria has emerged as a key focus for lithium exploration, with a growing emphasis on discovering and extracting these valuable deposits and developing processing facilities and battery manufacturing infrastructure. Although the first discovery was made in 2018, the geological characteristics and mechanisms responsible for lithium mineralization in Nigeria's Pan-African pegmatites have not been comprehensively unraveled. This research gap presents a challenge amidst the urge to exploit these resources. It is important that more research be conducted not only to determine the extent to which lithium is actually present, but to ensure that the mining is done in a sustainable and well-thought-out manner.

The localization of lithium-bearing pegmatites is primarily controlled by structural factors, with their formation being influenced by the surrounding geological framework and the lithium content of these pegmatites is significantly influenced by metasomatic processes. Within these pegmatites, lithium-bearing minerals tend to occur in unique forms. Medium to large-sized crystals of spodumene and lepidolite are either scattered or clustered in felted masses, creating economically viable deposits. In subsurface exposures, mineralized pegmatite bodies appear as continuous sheets or tabular zones, several meters thick, containing coarse spodumene and lepidolite. Pegmatites can be categorized based on various factors and these include the depth of consolidation or emplacement, the type of mineralization in relation to igneous processes, and the metamorphic environment in which they are commonly found (Ginsburg et al., 1979; Cerny,1982a). Furthermore, pegmatites are also classified based on their major and accessory minerals, geochemical and rare-metal constituents. Tanko et al. (2015) classified the pegmatites in Keffi based on the environment of their emplacement. The objectives of the study are to map and classify the pegmatites and other rock types in Madubi, understand the field relations of the lithological units in the study area and conduct an X-ray fluorescence (XRF) and flame photometry analysis on representative rock samples from the study to determine their percentage lithium content. (Černý, 1991; Černý & Ercit, 2005)

This paper examines whether they are most likely to be associated with the ones found around Keffi and Akwanga or the pegmatite belt of North-Central Nigeria. (Dada, 2006; Obaje, 2009) The broader Nigerian igneous framework also includes alkaline complexes, as documented by Abaa (1983), illustrating the diversity of igneous provinces within the Nigerian geological setting. Studies of Nigerian pegmatites in other basement regions have also demonstrated their geochemical and economic significance (Ekwueme & Matheis, 1995).

2.0 Materials and Methods

Geological field mapping of the study area was done using field instruments, namely; a compass clinometer, global positioning system (GPS), a digital camera, masking tape, a geological hammer, markers, sample bags, a field notebook, ruler and a pencil.

The compass clinometer, GPS and topo map aided in traversing to identify outcrop exposures of the lithological units in the study area. The strike and dip of lithological units and structural features were determined using compass clinometers.

In the field, physical parameters such as textures, colours and the mode of occurrence of the outcrop exposures in the study area were observed to provide a proper description. The photographs of outcrop exposures and other interesting features were taken using a digital camera. Sampling was carried out systematically, that is, across the pegmatites to observe the internal crystallization. The taking of rock samples was done using a sledgehammer, sample bags, markers and masking tape. Each sample was assigned a unique sample identification number, labelled with permanent markers and securely packaged in sample bags. Detailed field information, including sample identification, GPS coordinates, lithology, structural observations and field descriptions, was recorded in the field notebook for each sample location. The samples were selected for geochemical analysis, out of which 26 samples were subjected to X-ray fluorescence analysis at the Geology Laboratory of Gombe State University, Nigeria, while 22 samples were subjected to flame photometry analysis for lithium at the Biochemistry Laboratory of the same university.

GCDkit was employed to generate geochemical and petrogenetic plots from the geochemical results obtained from the XRF and flame photometry analyses. This was useful to understand and interpret the geochemical evolution and fractionation characteristics of the pegmatites and the host rocks.

Georient was used to produce rose diagrams of the trends of quartz veins, fractures on pegmatites and host rocks. The resulting plots were used to determine the dominant structural trends controlling pegmatite emplacement and regional deformation within the study area.

The integration of field observations, measurements of structural trends and geochemical analysis provided a comprehensive dataset for interpreting the geology, structural evolution, petrogenesis and mineralisation potential of the pegmatites in the study area.

3.0 Results and Discussion

3.1 Results

3.1.1 Geology of the Study Area

The study area is typical of the basement complex of North-Central Nigeria and falls within the pegmatite belt of the country. The lithological units observed from hand specimens, field occurrence indicate four lithological units, namely schist, coarse-grained granite, medium-grained granites and pegmatites. From the field studies and other geological processes that have taken place in the study area, it can be established that the schist is the oldest rock, followed by the granites, then the pegmatites and quartz veins are the youngest. The pegmatites and the quartz veins, being the last to form, must have intruded into the schist and the granites (older rocks). Within the pegmatites in the study area, the crystals of minerals, particularly quartz, are bigger towards the center. The minerals have enough time to form from the residual fluid during the crystallization process. The common structural features identified are fractures and joints with quartz veins. The fractures are generally aligned in NE-SW and NW-SE directions, suggesting a conjugate fracture system and can be attributed to regional tectonic processes, which aided mineralization in the study area. The quartz veins are structurally controlled based on the fact that they came to be as a result of the flow of hydrothermal fluid through the fractures, which later Fcrystallized to form the quartz veins. (Oyawoye, 1972; Rahaman, 1988; Dada, 2006; Obaje, 2009).

3.1.2 Geochemical Characteristics of the Pegmatites

The X-ray fluorescence results presented in Table 3a and 3bs show that the pegmatites are characterized by relatively high SiO_2 concentrations, ranging from 63.8 to 72.1 wt.%, with an average of 69.22 wt.%. The relatively high silica content reflects the felsic and highly evolved nature of the pegmatitic rocks. Na_2O and K_2O concentrations average 2.46 and 9.06 wt.%, respectively, giving an average total alkali content of approximately 11.52 wt.%. This alkali nrichment is characteristic of evolved felsic rocks and is consistent with the presence of abundant feldspar and mica within the pegmatites.

Al_2O_3 concentrations range from 12.3 to 17.6 wt.%, with an average of 13.69 wt.%, whereas P_2O_5 averages 1.81 wt.%. The concentrations of the mafic-related oxides are generally low, with average MgO, TiO_2, MnO, and Fe_2O_3 contents of 0.10, 0.05, 0.18, and 2.25 wt.%, respectively. The low abundance of MgO and TiO_2, together with the relatively low Fe_2O_3 concentration, indicates that the pegmatites are strongly felsic and depleted in mafic components.

In comparison, the schist and granite samples show relatively lower SiO_2 contents, averaging 62.40 wt.%, but higher concentrations of MgO (0.75 wt.%), CaO (4.11 wt.%), TiO_2 (1.05 wt.%), and Fe_2O_3 (7.46 wt.%). These compositional differences distinguish the pegmatites from their host rocks and indicate a progressive felsic differentiation associated with pegmatite formation.

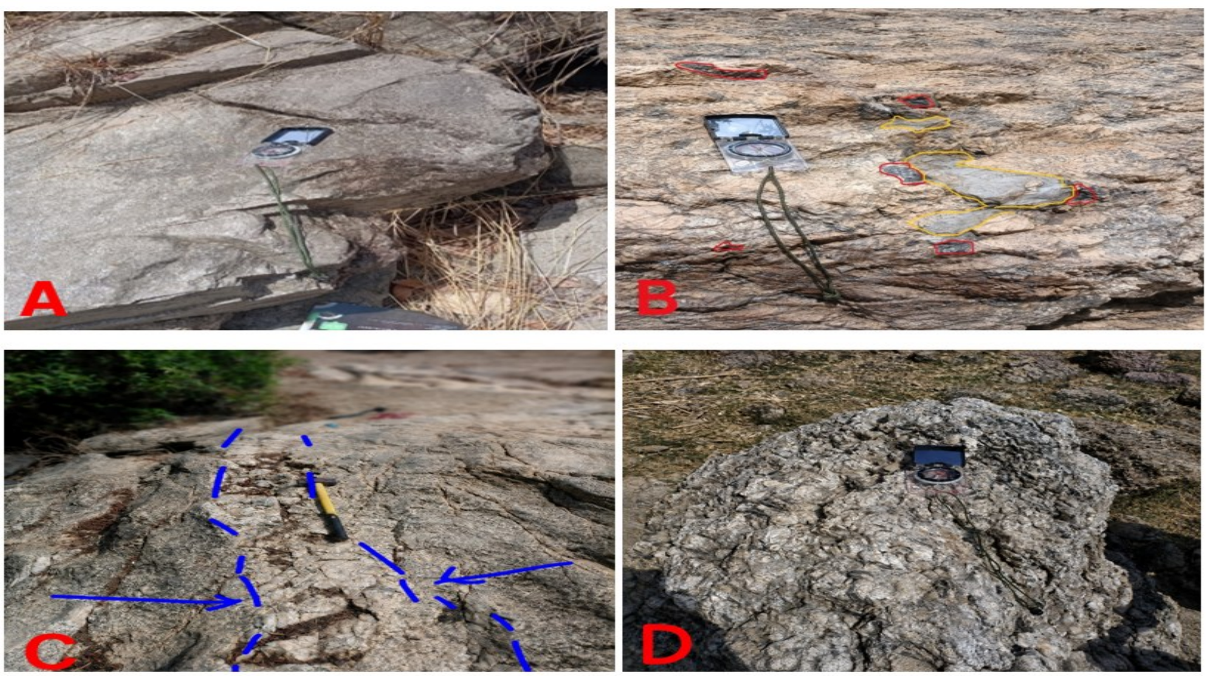

Fig. 1: Exposures of Schist and pegmatries: A is an exposure of schist at Dogon Giya 132°SE/20°SW, intruded by the Dogon Giya pegmatite, B is a section of pegmatite at Dogon Giya. Large crystals of quartz (marked in yellow) are seen towards the center. The large crystals of minerals form over a longer period during the crystallization process. Also, black tourmaline (in red) is one of the minerals that can be identified from field observation, C is an exposure of Madubi pegmatite showing zonation, where the wall zones are similar in terms of texture and color. The center (core) of the pegmatite is coarser compared with other sections of the pegmatites. This clearly indicates zonation during the crystallization process,

where cooling and formation of crystals took place inwardly from the sides of the pegmatites. (Černý, 1991), D is a rough-textured pegmatite at Madubi with large crystals of quartz and pegmatites, typical of most pegmatites in North-Central, Nigeria.

Table 1: Measured trends of fractures of pegmatites in the study area

082°	342°	114°	024°	082°	024°	114°	354°	022°	018°
262°	128°	082°	354°	042°	342°	342°	082°	018°	094°
042°	024°	082°	022°	024°	024°	024°	114°	350°	024°
354°	042°	018°	354°	114°	342°	342°	114°	354°	022°
022°	082°	350°	062°	022°	082°	354°	342°	022°	024°
024°	042°	062°	082°	354°	022°	342°	342°	354°	018°
082°	080°	082°	018°	342°	024°	342°	354°	354°	342°

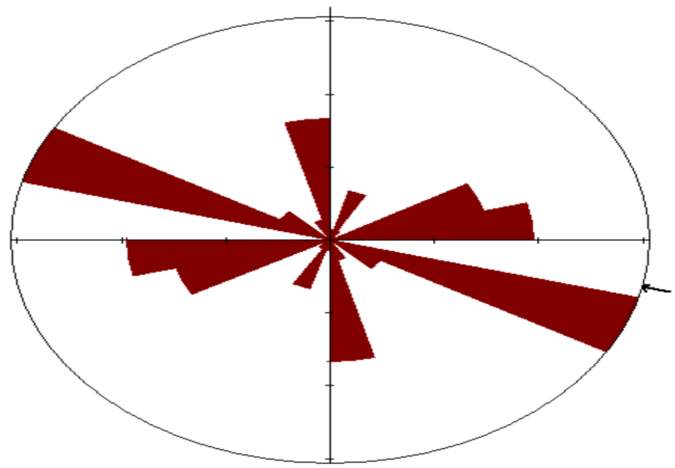

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Fig. 1: Rose diagram of fractures showing the E–W and NNW–SSE trends dominant in pegmatites.

Table 2: Trends of fractures on schist

188	264	188	188
188	264	188	264
264	188	274	274

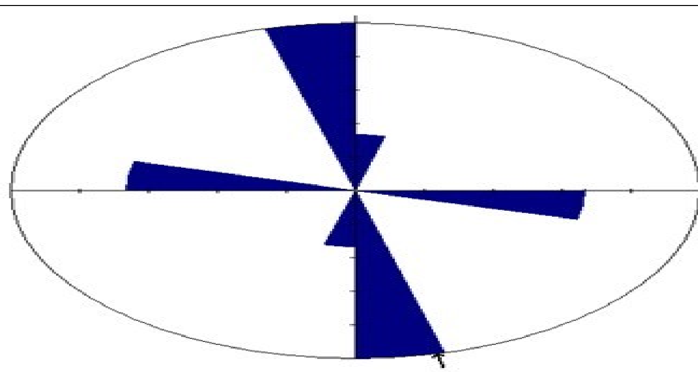

Fig. 2: Rose diagram of fractures on schist showing N-S dominant trend

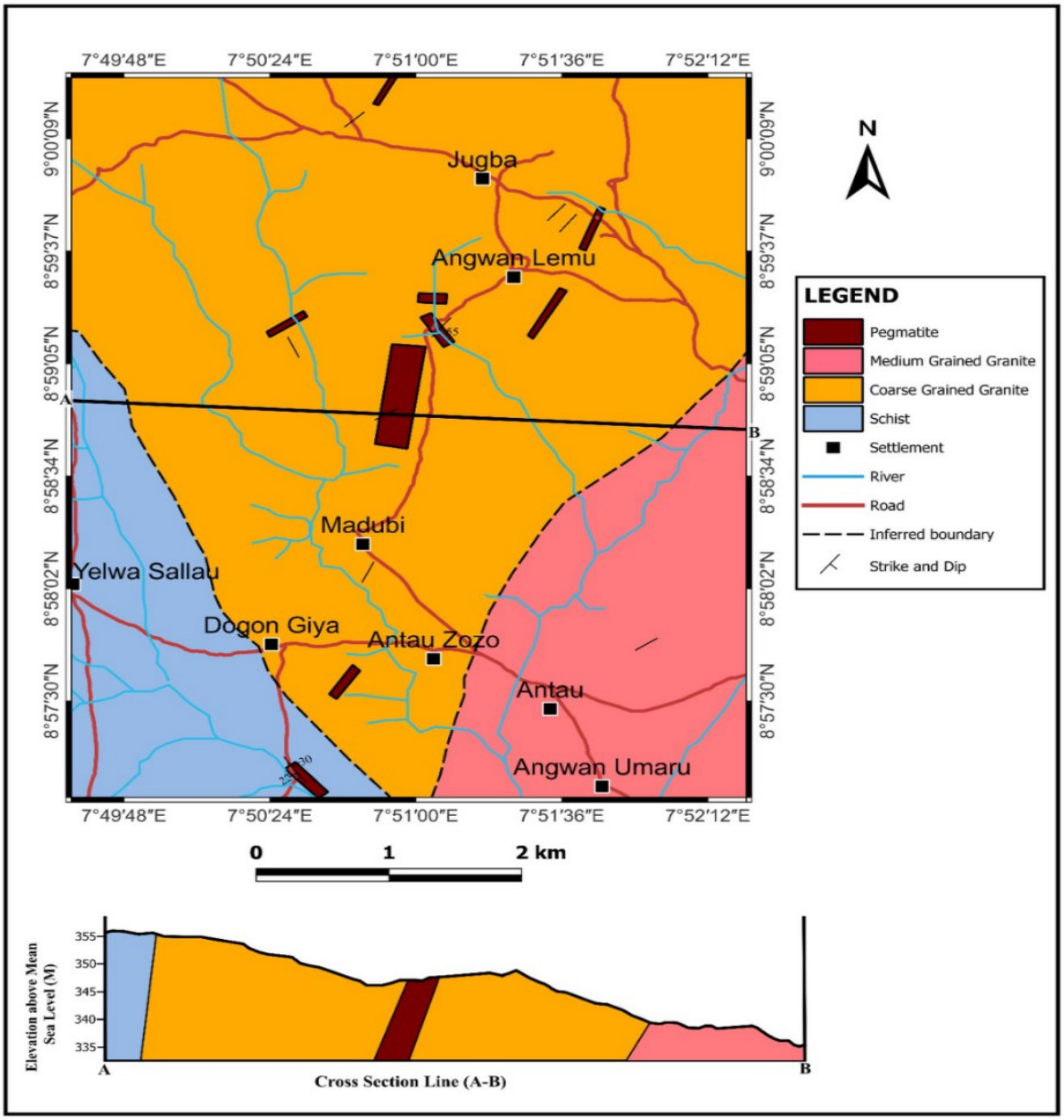

Fig. 3: Geological Map of the Study Area

Table 3a. Concentrations of major oxides in pegmatites and host rocks

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O
TJ1a	1.70	ND	12.30	65.60	1.56	17.00
TJ1b	2.24	0.091	17.60	66.30	1.32	9.52
TJ2a	1.78	0.064	14.60	67.50	1.53	10.40
TJ2b	2.32	ND	12.60	65.50	1.64	15.90

TJ2c	2.22	ND	12.40	65.00	1.62	17.20
TJ2d	3.49	ND	13.80	71.10	2.06	5.29
TJ2e	2.75	ND	12.90	71.30	1.72	6.80
TJ2f	2.83	0.108	13.00	69.40	1.76	7.79
TJ3	3.54	ND	16.20	71.00	1.71	2.67
TJ4	4.55	ND	14.70	72.10	3.16	2.88
TJ5	1.90	ND	12.50	64.80	2.25	16.70
TJ7	0.287	ND	4.36	89.90	1.36	2.33
TJ8	1.43	0.044	15.40	68.70	1.88	8.41
TJ10	0.640	ND	16.80	63.80	1.56	8.67
TJ11a	1.73	ND	16.60	66.80	1.88	8.65
TJ11b	2.24	ND	12.90	67.10	1.74	14.00
TJ12a	2.20	ND	12.60	70.90	2.02	7.67
TJ12b	3.33	ND	13.90	70.50	1.77	7.58
TJ12c	2.44	ND	12.80	67.10	1.72	12.60
TJ13a	3.18	ND	14.70	68.30	1.97	7.06
TJ13b	3.44	0.051	14.40	71.30	1.82	4.22
TJ13c	3.79	0.237	14.20	68.80	1.71	5.88
Pegmatite mean	**2.46**	**0.099**	**13.69**	**69.22**	**1.81**	**9.06**
TJ6	2.96	0.063	13.30	70.20	1.37	7.59
TJ9	2.97	0.475	14.70	61.30	1.55	6.46
TJ14	2.32	1.720	12.60	57.80	1.49	5.30
TJ15	1.04	ND	9.97	60.30	1.21	9.48
Host-rock mean	**2.32**	**0.75**	**12.64**	**62.40**	**1.41**	**7.21**

Note. Values are mass %. ND = not detected.

Table 3b. Concentrations of accessory and ferromagnesian oxides in pegmatites and host rocks

Sample	CaO	TiO_2	MnO	Fe_2O_3	Rock type
TJ1a	0.551	ND	0.102	0.976	Pegmatite
TJ1b	0.489	ND	0.081	2.20	Pegmatite
TJ2a	0.653	ND	0.094	3.24	Pegmatite
TJ2b	0.897	ND	0.065	0.734	Pegmatite

TJ2c	0.589	ND	0.079	0.700	Pegmatite
TJ2d	1.630	ND	0.103	2.33	Pegmatite
TJ2e	1.380	ND	0.118	2.85	Pegmatite
TJ2f	1.500	ND	0.133	3.24	Pegmatite
TJ3	0.879	0.076	0.195	3.60	Pegmatite
TJ4	1.300	ND	0.118	0.980	Pegmatite
TJ5	0.348	ND	0.132	1.00	Pegmatite
TJ7	0.203	ND	0.166	1.27	Pegmatite
TJ8	1.180	ND	0.178	2.49	Pegmatite
TJ10	0.134	0.017	1.140	6.79	Pegmatite
TJ11a	0.985	ND	0.197	2.78	Pegmatite
TJ11b	0.518	ND	0.121	1.14	Pegmatite
TJ12a	1.540	ND	0.285	2.64	Pegmatite
TJ12b	1.670	ND	0.083	0.900	Pegmatite
TJ12c	0.854	ND	0.082	2.19	Pegmatite
TJ13a	1.420	ND	0.244	2.81	Pegmatite
TJ13b	1.930	ND	0.111	2.51	Pegmatite
TJ13c	2.940	ND	0.226	2.06	Pegmatite
Pegmatite mean	**1.07**	**0.05**	**0.18**	**2.25**	**Pegmatite**
TJ6	2.560	0.114	0.096	1.46	Host rock
TJ9	4.830	0.951	0.176	6.08	Host rock
TJ14	2.670	1.920	0.184	13.60	Host rock
TJ15	6.390	1.220	0.222	8.68	Host rock
Host-rock mean	**4.11**	**1.05**	**0.17**	**7.46**	**Host rock**

Note. Values are mass %. ND = not detected

3.1.3 Geochemical Classification

The Na_2O–Al_2O_3–K_2O ternary plot (Figure 5) illustrates the compositional characteristics of the analyzed rocks and provides evidence for their feldspar–mica-dominated nature. The relatively high K_2O and Na_2O contents of the pegmatites are consistent with their evolved felsic composition and indicate significant alkali enrichment during magmatic differentiation.

The total alkali–silica (TAS) diagram (Figure 6), based on the classification scheme of Cox et al. (1979), further demonstrates the predominantly felsic character of the analyzed rocks. The pegmatite samples plot within the high-silica and alkali-rich compositional field, distinguishing them from the comparatively less evolved host rocks. This geochemical signature supports an interpretation involving progressive fractional crystallization of the parental granitic magma.

3.1.3 Flame Photometry Analysis

The lithium concentrations determined by flame photometry for the pegmatite samples are presented in Table 4. Li_2O concentrations range from 0.11 to 0.67%, corresponding to Li concentrations of 0.051–0.311%. The highest Li_2O concentration occurs in sample TJ2f (0.67%), followed by TJ2e (0.58%), TJ2c (0.57%), TJ2d (0.53%) and TJ2b (0.51%). The lowest concentration occurs in TJ7 (0.11%).

The distribution of Li_2O relative to SiO_2 is further illustrated using the binary boxplot in Fig. 7. The plot demonstrates the variation in lithium enrichment among the pegmatite samples and provides a basis for distinguishing samples with relatively low and higher lithium contents. The combined results in Table 4 and Figure 7 indicate appreciable variation in lithium concentration among the studied pegmatites, with the TJ2 pegmatite samples generally showing comparatively higher Li_2O contents

3.2 Discussion

The TAS (Total Alkali – Silica) plot of rock samples above indicates a clear compositional spectrum from basic to acidic lithologies. No samples plot at lower SiO_2 (≈ 45 - 55 wt.%) in the gabbro – diorite field and display low to moderate total-alkali contents consistent with subalkaline/basic magmas. The intermediate samples (≈ 55 - 63 wt.% SiO_2) occupy the syenite – diorite/monzonitic fields and mark a transitional composition between mafic and felsic end-members. The most silica-rich samples are approximately 65 - 75 wt.% SiO_2 and plot within the granodiorite–granite domain, which indicates evolved and felsic compositions. Most points lie on the subalkaline side of the alkaline/subalkaline boundary, which, together with the basic → intermediate → acidic trend, is consistent with fractional differentiation of a subalkaline magmatic suite (possible crustal assimilation and/or fractional crystallization). Comparable magmatic differentiation trends have been documented in pegmatitic provinces of central Nigeria, where pegmatites and associated granitoids were interpreted as products of highly fractionated granitic melts derived from subalkaline magmatic sources (Akoh et al., 2015; Tanko et al., 2020). (Chappell & White, 1974)

Alumina (Al_2O_3) has an average of 13.7 wt.%, depicting an abundance of feldspar and mica as shown on molar Na2O-Al2O3-K2O Plot. This mineralogical implication is consistent with petrographic observations reported by Okunlola & Somorin (2005), who documented quartz, microcline and tourmaline as dominant minerals within pegmatites intruding metasediments in southwestern Nigeria. Similarly, the Madubi pegmatites likely contain a mineral assemblage dominated by quartz, K-feldspar, albite and muscovite, which are typical constituents of granitic pegmatites

The result of flame photometry for lithium is provided above and the plot indicates that the pegmatites have a Li_2O range from 0.11 to 0.67%. It can be deduced that the percentage of Li_2O concentration in the study area is generally low. However, the sample with the lowest concentration is sample TJ 7, while the sample TJ 2 series, that is, TJ 2a, TJ 2b, TJ 2c, TJ 2d, TJ 2e and TJ 2f, has relatively higher Li_2O concentration, with sample TJ 2f having Li_2O of 0.67% and 0.3% lithium content. From the plot above, the pegmatites identified in the study area can be classified into three classes based on the lithium content. Samples TJ 3, TJ 4, TJ 5, TJ 6, TJ 7, TJ 13a and TJ 13b are low, having < 0.1%. Samples TJ 1a, TJ 1b, TJ 8, TJ 10, TJ 11b, TJ 12a, TJ 12b, TJ 12c and TJ 13 are moderate with Li of 0.1- 0.2%. Samples TJ 2a, TJ 2b, TJ 2c, TJ 2d, TJ 2f and TJ 11a are classified as high (lithium content of > 0.2%) when compared with the rest of the samples. Based on proximity to the host rock, it can be deduced that the pegmatites closer to the host rock are less mineralized in terms of lithium content. This pattern may reflect the **internal zoning commonly observed in pegmatite bodies,** where rare elements such as lithium tend to concentrate in the **intermediate or core zones** rather than at the margins adjacent to the host rock. Similar zoning patterns have been described in pegmatite systems by Okunlola & Ocan, 2009; and Akoh et al., 2015, where lithium enrichment occurs predominantly in the inner zones of pegmatite bodies as a result of prolonged magmatic differentiation and fluid-assisted redistribution of incompatible elements. Overall, the lithium distribution pattern in the Madubi pegmatites indicates **variable, but generally moderate - low lithium enrichment,** with localized zones of higher concentration represented by the TJ2 series samples. Although the lithium content is lower than that reported for some economically significant pegmatite deposits in Nigeria, further detailed investigations, including mineralogical studies and additional trace element analysis (e.g., Rb, Cs, Ta and Nb), would therefore be necessary to fully evaluate the rare-metal mineralization potential of the pegmatite around Madubi. (Černý, 1991; Černý & Ercit, 2005)

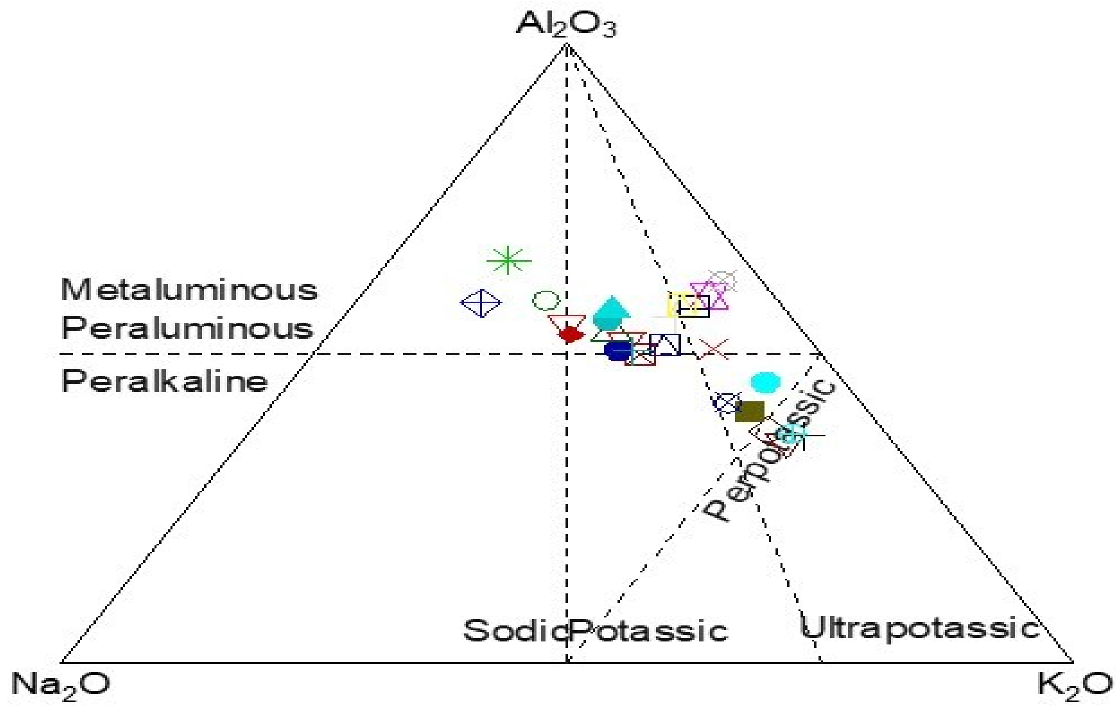

Fig. 4: Molar Na_2O-Al_2O_3-K_2O Plot

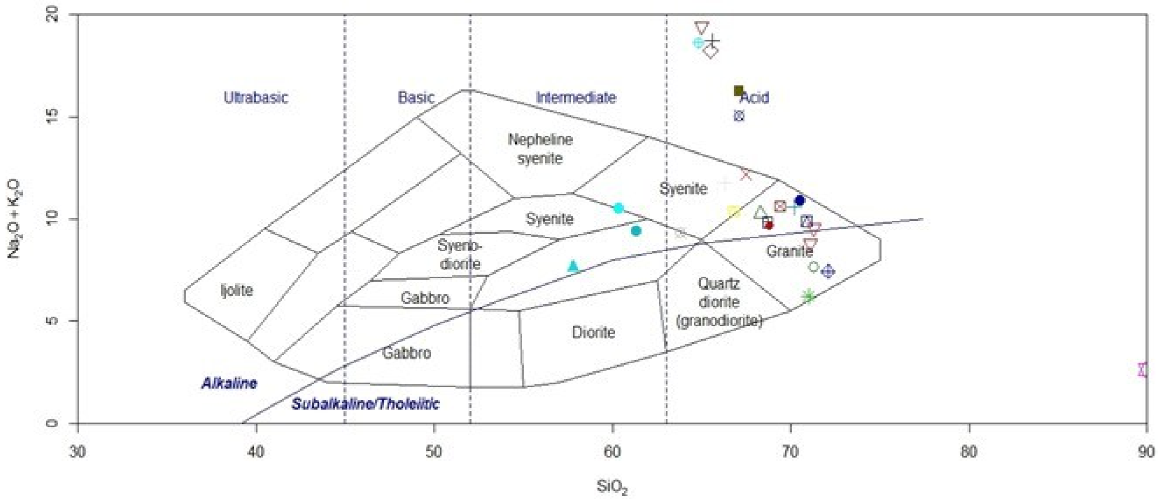

Fig. 6: Binary plot of TAS Alkali-Silica (After Cox-Bell-Pank, 1979)

Table 3: Results of test for Lithium concentration in pegmatites

Sample Id	Li2O %	Li %
TJ 1a	0.23	0.107
TJ 1b	0.37	0.172
TJ 2a	0.45	0.209
TJ 2b	0.51	0.237
TJ 2c	0.57	0.265
TJ 2d	0.53	0.246
TJ 2e	0.58	0.269
TJ 2f	0.67	0.311
TJ 3	0.18	0.084
TJ 4	0.12	0.056
TJ 5	0.15	0.070
TJ 7	0.11	0.051
TJ 8	0.24	0.112
TJ 10	0.32	0.149
TJ11a	0.46	0.213
TJ11b	0.35	0.163
TJ 12a	0.28	0.130
TJ 12b	0.42	0.195
TJ 12c	0.39	0.181
TJ13a	0.18	0.084
TJ 13b	0.13	0.060
TJ 13c	0.27	0.125

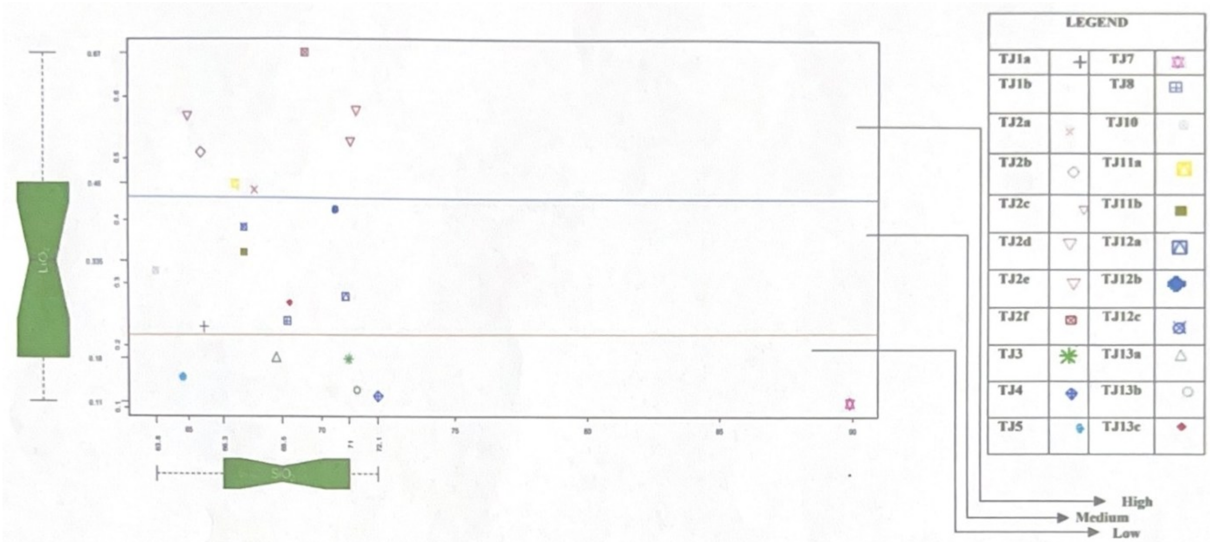

Fig. 6: Binary Boxplot of Li_2O Vs SiO_2 showing the mineralization boundary of low, moderate and low enrichment of lithium in pegmatites.

The result of flame photometry for lithium is provided above and the plot indicates that the pegmatites have a Li_2O range from 0.11 to 0.67%. It can be deduced that the percentage of Li_2O concentration in the study area is generally low. However, the sample with the lowest concentration is sample TJ 7, while the sample TJ 2 series, that is, TJ 2a, TJ 2b, TJ 2c, TJ 2d, TJ 2e and TJ 2f, has relatively higher Li_2O concentration, with sample TJ 2f having Li_2O of 0.67% and 0.3% lithium content. From the plot above, the pegmatites identified in the study area can be classified into three classes based on the lithium content. Samples TJ 3, TJ 4, TJ 5, TJ 6, TJ 7, TJ 13a and TJ 13b are low, having < 0.1%. Samples TJ 1a, TJ 1b, TJ 8, TJ 10, TJ 11b, TJ 12a, TJ 12b, TJ 12c and TJ 13 are moderate with Li of 0.1- 0.2%. Samples TJ 2a, TJ 2b, TJ 2c, TJ 2d, TJ 2f and TJ 11a are classified as high (lithium content of > 0.2%) when compared with the rest of the samples. Based on proximity to the host rock, it can be deduced that the pegmatites closer to the host rock are less mineralized in terms of lithium content. This pattern may reflect the internal zoning commonly observed in pegmatite bodies**,** where rare elements such as lithium tend to concentrate in the **intermediate or core zones** rather than at the margins adjacent to the host rock. Similar zoning patterns have been described in pegmatite systems by Okunlola & Ocan, 2009; and Akoh et al., 2015, where lithium enrichment occurs predominantly in the inner zones of pegmatite bodies as a result of prolonged magmatic differentiation and fluid-assisted redistribution of incompatible elements. Overall, the lithium distribution pattern in the Madubi pegmatites indicates variable, but generally moderate - low lithium enrichment**,** with localized zones of higher concentration represented by the TJ2 series samples. Although the lithium content is lower than that reported for some economically significant pegmatite deposits in Nigeria, further detailed investigations, including mineralogical studies and additional trace element analysis (e.g., Rb, Cs, Ta and Nb), would therefore be necessary to fully evaluate the rare-metal mineralization potential of the pegmatite around Madubi. (Černý, 1991; Černý & Ercit, 2005)

4.0 Conclusion

From the geological and geochemical analysis, it can be concluded that:

i. The pegmatites in Madubi are products of late-stage magmatic differentiation derived from granitic parent rocks. (Černý, 1991; Černý & Ercit, 2005)

ii. The results of this study indicate that the Madubi pegmatites represent highly evolved granitic pegmatite systems formed through prolonged magmatic differentiation and fluid-assisted crystallization (Černý, 1991)

iii. Their mineralogical composition and chemical characteristics, especially the enrichment in alkalis and depletion in mafic oxides are diagnostic of highly evolved pegmatites of the lithium – caesium – tantalum (LCT) family. This interpretation is consistent with earlier studies on Nigerian pegmatites, which have shown that most pegmatite bodies within the Basement Complex were formed from highly evolved granitic magmas associated with the Pan-African tectono-magmatic event (Burke and Dewey, 1972; Dada, 2006). (Černý, 1991; Černý & Ercit, 2005; Dada, 2006)

iv. Lithium oxide concentrations up to 0.67 wt.% suggest moderate lithium enrichment within the pegmatite bodies. Although these values are lower than those reported in some highly mineralized pegmatite fields, such as the Kakafu pegmatites, where Li_2O concentrations range from 0.82 to 2.27 wt.% (Tanko et al., 2024). The variability in lithium concentrations across the samples also reflects the typical internal zonation of pegmatite bodies, where rare elements tend to accumulate in specific mineralogical zones during the final stages of magmatic evolution (Tanko and Dzigbodi-Adjima, 2021). For future trace-element work, relationships among Rb, Ba and Sr may provide additional information on granitoid evolution (El-Bouseily & El-Sokkary, 1975), while normalized trace-element patterns can be compared using the primitive-mantle framework of Sun and McDonough (1989).

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