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Pegmatites: The Hidden Gems of Igneous Rocks and Their Economic Potential

Alebiosu*, M. T. and Omotoso, O. A

Department of Geology and Mineral Sciences, University of Ilorin, Ilorin, Nigeria

Abstract

Pegmatite is a significant rock with far-reaching applications. Numerous valuable minerals such as quartz, feldspar, muscovite, spodumene, lepidolite, tantalite, beryl and varieties of tourmaline can be found in pegmatites and some of these economic minerals associated with pegmatite have been utilized in cell phones and, more recently, lithium batteries. Mineralogically, pegmatites could be simple or complex while chemically; granitic and rare-element pegmatites have been identified. The Basement Complex of Nigeria which has undergone various episodes of deformation comprises of rocks which are host to pegmatites. This review discusses the rock pegmatite, including its definition, occurrence, distribution, particularly in Nigeria, as well as its classification, chemistry affinity, age, and geotectonic environments. The knowledge of these peculiar characteristics of the rock pegmatite will help in their exploration, exploitation and utilization in the industry.

Keywords: Pegmatite, Classification, Geotectonic, Exploitation, Utilization

1. Introduction

For decades, the rock pegmatite (Figure 1) has piqued the curiosity of both international and local researchers, and there are still many open questions due to its economic potential, particularly rare element pegmatites. According to earlier studies on Precambrian rocks found in Nigeria, pegmatites are home to a wide range of minerals with significant economic potential that are used in a variety of industries, most notably in heat- and corrosion-resistant steels and alloys used in gas turbines and ships (Akintola *et al.*, 2012; Garba *et al.*, 2019; Okunlola and Akinola, 2010). Various authors have defined pegmatite as described in the following paragraphs: Jahns (1955) defined pegmatites as holocrystalline, typically leucocratic rocks with considerable grain size variations. Typically, common igneous rocks contain the minerals that make up their

Corresponding Author: Alebiosu M.T
Email: mercytitilayo@unilorin.edu.ng

primary constituents. Pegmatites may also contain rare rock-forming minerals. They are most easily distinguished from other types of igneous rocks by their striking similarities in structure, texture, and fabric (particularly for those that are deformed).

Figure 1: Field Photo of pegmatite (Source: geology.com; Retrieved 23/11/2021)

The size of an individual body might vary from a few centimeters to thousands of meters. Although they make up a relatively small portion of the Earth's crust, pegmatites are extremely common. Yet, because they are collections of common and uncommon minerals with incredibly diverse crystal forms, sizes, and interrelationships, these unique rocks have long drawn interest. They have been commercially valuable in numerous instances. London (2008), on the other hand, defined pegmatite as an essential and distinct igneous rock, typically of granitic composition. It’s extremely coarse but variable grain size and profusion of crystals with skeletal, graphic, or other strongly directed growth-habits help set it apart from other igneous rocks.

Pegmatites are found in igneous or metamorphic host rocks as strongly delimited homogenous to zoned masses. Nonetheless, Simmons and Webber (2008) provide a more thorough and unique description of the pegmatite rock. Pegmatites are intrusive igneous rocks with textures ranging from very coarse to colossal in size. The most well-known granitic pegmatites in the world are characterized by large crystal size and extreme rarity enrichment (Simmons and Webber, 2008). Any intrusive igneous rock type, from ultramafic to granitic to syenitic in composition, can produce pegmatitic textures. Generally speaking, the term refers to rock that has a granitic composition overall and is most frequently used to describe granitic pegmatites. The main constituents of granitic pegmatites are quartz and feldspar, with mica serving as an accessory. In summary, pegmatites are a type of igneous rock that is often holocrystalline, leucocratic, and has exceptionally coarse-grained crystals. They are associated with a huge volume of intrusive rocks in time and space. They frequently appear as dykes, sills or veins.

There are two (2) distinct forms of pegmatite based on mineralogy: simple and complex. Simple pegmatites are commonly referred to as "barren" since they include only quartz, feldspar, muscovite, and biotite (Cerny, 1991). In contrast, complex pegmatites also contain minerals such as tourmaline, beryl, spodumene, garnet, lepidolite, fluorite, apatite, and topaz in addition to their typical mineralogy. According to London (2014), the minerals in the complex variety are grouped in a zonal pattern.

2. Chemical Affinity of Pegmatites

London (2008) classified pegmatites into two types: granitic pegmatites, which are made up of accessory minerals including tourmaline, garnet, and apatite as well as conventional granite-forming minerals like quartz, potassium feldspar, plagioclase feldspar, muscovite, and biotite. The second kind of pegmatites is known as rare-element pegmatites, and they are distinguished by the abundance of specific elements compared to the trace amounts seen in granitic pegmatites. Beryl, spodumene, lepidolite, tantalite, and pollucite are some of these minerals. From a compositional standpoint, there are two types of rare-element pegmatites: those containing lithium, caesium, and tantalum (LCT) and those containing niobium, yttrium, and fluorine (NYF).

2.1.The Lithium-Cesium-Tantalum (LCT) Pegmatites

LCT pegmatites are rocks defined by their unusually large grain size and remarkable mineral composition. As stated by the US Geological Survey (2011), they are responsible for generating 10% of the global beryllium output, the majority of tantalum, and nearly all cesium production. Additionally, they are responsible for around 25% of the global lithium production (Novak *et al.,* 2012). Tin, potassium feldspar, albite, kaolinite, high purity quartz, white mica, gem beryl, and many different kinds of tourmaline have been extracted from LCT pegmatites (Glover *et al.,* 2012 and Simmons *et al.,* 2012).

Lithium-Caesium-Tantalum (LCT) pegmatites usually originate from peraluminous, S-type granitic melts, however some may also be derived from metaluminous and I-type granites (Martins and De Vito, 2005). London (2008) explains that the melt from which LCT pegmatites crystallise typically possesses a substantial quantity of fluxing components such as H_2O, F, P, and B. The aforementioned components decrease the temperature at which a substance turns solid, decrease its density, and expedite the movement of ions. Minerals such as these are typically found in country rocks that have gone through metamorphism from low-pressure upper greenschist to amphibolite facies, particularly in metasedimentary or metavolcanic rocks (Cerny, 1992).

2.2.The Niobium-Yttrium-Flourine (NYF) pegmatites.

These pegmatites form as a result of intense anorogenic differentiation, which are often referred to as A-type granites. NYF pegmatites possess a high concentration of Nb, Ta, Ti, Y, REE, Zr, Th, U, Sc, and varying amounts of F. However, they have a low abundance of uncommon alkali elements like Li, Rb, and Cs (Cerny and Ercit, 2005). Earlier classified within the NYF family, this term now applies to the distinctive features of the initial magma's origin (provenance) and its chemical alterations as certain components are removed and others become more concentrated through fractional crystallization and differentiation. Although there may be additional rare elements with higher concentrations, the enrichment of these three elements (NYF) is particularly conspicuous. Yttrium and the lanthanides are rare-earth elements (REE) that display analogous geochemical characteristics. As a result, NYF pegmatites generally contain high concentrations of all the REE. High amounts of Scandium (Sc), Zirconium (Zr), Uranium (U), and Thorium (Th) are also frequently observed. However, certain pegmatites exhibit an integrated NYF-LCT signature, which has been interpreted as a consequence of NYF melt contamination from nearby sources (Martin and DeVito, 2005).

3. Occurrence and Distribution of Pegmatites in Nigeria

The occurrence of pegmatites has been reported all over the world specifically in Brazil, Madagascar, Russia, United States and Australia but important deposits have recently been discovered in Africa and Asia. Pegmatites evolved in Nigeria's Precambrian Basement Complex during the Pan-African Orogeny, approximately 65±20 billion years ago (Garba, 2003; Okunlola, 2005). They are a subordinate rock type that were formed and placed at this particular historical era. The presence of these Pan-African schist belts, which serve as host to pegmatites, (Figure. 2), spans a distance of 400 km from the Wamba region, near Jos Plateau, to Isanlu-Egbe in Central Nigeria, and further to the Ijero-Aramoko-llesha area in south-western Nigeria. These pegmatites follow a NE-SW trend and were first documented by Jacobson and Webb in 1946. Ero and Ekweme (2009) have recently reported the occurrence and spread of mineral-rich pegmatites in the Basement Complex encompassing the Obanliku (Oban massif) and Obudu districts of southeast Nigeria.

Okunlola and Jimba (2006) found that most of these pegmatites are lens-shaped entities that are either discordant or concordant. They are commonly connected to schist rather than gneisses and granites, and can also be found as stocks, dykes, and veins. Despite the north-south tilt of the various pegmatite intrusions, the rare metal pegmatites in Nigeria form a clear belt that extends in a southwest to northeast direction from Ife to Jos. The pegmatites intersect the boundary between the eastern and western Nigerian terrain, as shown in Figure 3 (Kinnaird, 1984; Matheis and Caen-Vachette, 1983). According to Akintola *et al.* (2011) and Garba (2003) the Pan-African pegmatites in Nigeria are found in two structural trends: one running from northeast to southwest and the other from northwest to southeast. These trends intersect near the Jos Plateau. In contrast, the pegmatites located in western Nigeria, predominantly oriented in the NE-SW direction, contain a significant abundance of uncommon minerals.

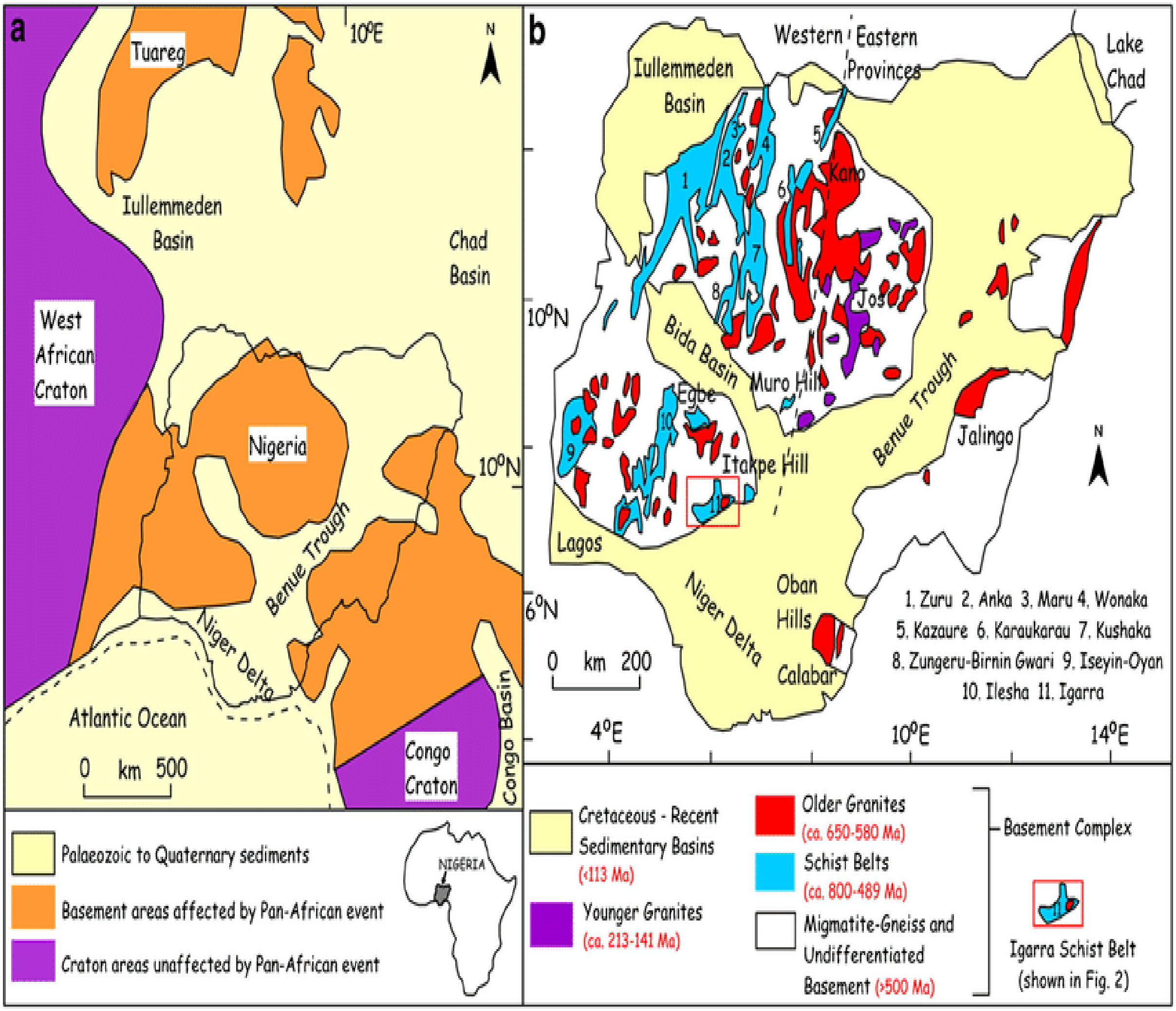

Figure 2: A regional geological map of Nigeria situated within the trans-Saharan African continent. (Ogunleye *et al.*, 2020)

Conversely, the pegmatites found in eastern Nigeria, are commonly oriented in the NW-SE direction (Oden *et al.*, 2011). Adetunji and Ocan (2010) reported that individual pegmatites can vary in length, ranging from 10 metres to over 2 kilometres, and in width, reaching up to 200 metres. These types of pegmatites are commonly located on the edges of plutons that are associated with peraluminous granite in western Nigeria.

These entities are distinguished by their association with peraluminous or S-type granites (Černý *et al.*, 2012). Okunlola (2005) categorised the rare metal pegmatites in Nigeria's Basement Complex into seven distinct fields: Keffi Nasarawa, Lema-Share, Kabba-Isanlu, Ijero-Aramoko, Oke-Ogun, Ibadan-Osogbo, and Kushaka-Birin-Gwari (Figure 3).

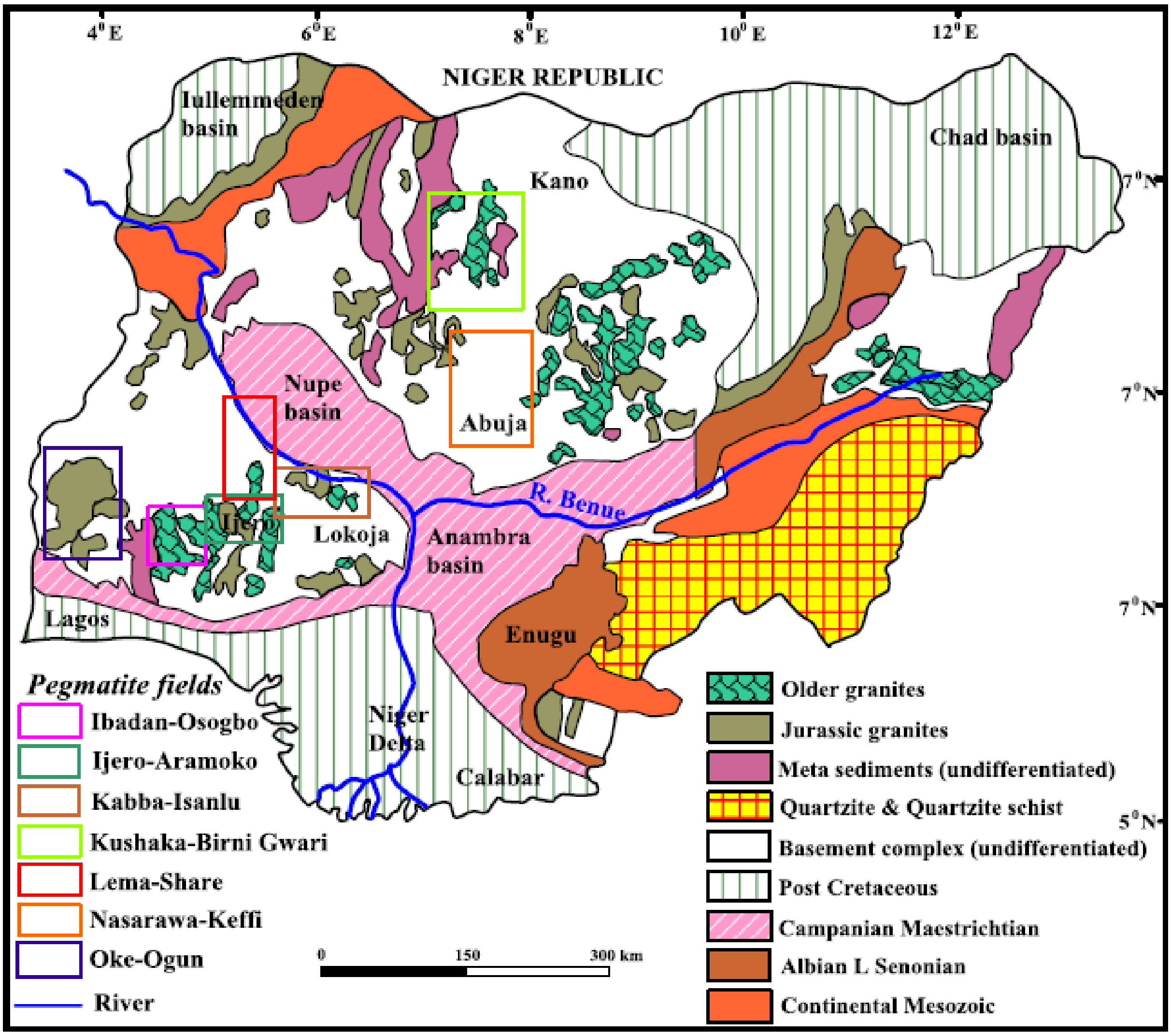

Figure 3: Geological map displaying the distribution of rare-metal pegmatite metal deposits in Nigeria. Metallogeny highlighted with boxes that have coloured edges (Okunlola, 2005).

4. Classification of Pegmatites

The categorization proposed by Cerny in 1991, which takes into account the depth of emplacement, metamorphic grade, and concentration of minor elements, has been utilised for a limited period of time. Cerny (1991) categorised pegmatites into four primary sorts or classifications. The four varieties are miarolitic (low level), abyssal (high grade, high to low pressure), rare-element (low temperature and pressure), and muscovite (high pressure, lower temperature). The Rare-Element Classes are categorised into two groups based on their composition: NYF, which stands for enrichment of Niobium, Yttrium, and Fluorine, and LCT, which stands for enrichment of Lithium, Caesium, and Tantalum.

The above approach has been employed in the majority of recent investigations on pegmatites. Although the majority of pegmatites may be classified into these categories, recent investigations undertaken within the past decade have revealed the existence of pegmatites that do not conform to these classifications. Research indicates that pegmatites related with the Niobium, Yttrium, and Fluorine (NYF) group exhibit increased diversity, necessitating a more comprehensive classification (Simmons *et al.*, 2024)

An issue arises when certain pegmatites are classified as NYF, despite their minimal or nonexistent presence of yttrium and niobium. In addition, there has been a lack of success in establishing a connection between pegmatite classes or subtypes and tectonic regimes or magma genesis, similar to the challenges faced with granite classifications (Simmons, 2007). In addition, Cerny's (1991) classification fails to consider the concept that pegmatites are formed through direct anatexis. In recent years, various new revisions to Cerny's taxonomy have been suggested.

Wise (1999) introduced a more comprehensive classification system for NYF pegmatites. The categorization implies a connection between pegmatites exhibiting NYF geochemistry and A-type granite plutons. He connected post-tectonic pegmatites with the formation of anorogenic plutons in rift zones, whether they are located in the ocean or on land. He has categorised granite into three primary classifications based on the aluminium saturation of the original granite. Metaluminous, peraluminous, and peralkaline are the three groups. Pegmatite types are differentiated within each group based on their geochemical and mineralogicalfeatures. This taxonomy comprises six kinds and nine subcategories. Based on his classification, the mineral composition of NYF pegmatite is influenced by changes in the alkalinity of the original granitic melts. Cerny and Ercit (2005) have introduced a new classification for petrogenesis, which distinguishes three families. The first family is a combination of NYF and LCT, with diverse origins. This includes NYF plutons that have been contaminated by the digestion of undepleted supracrustals. The second family is peraluminous LCT, characterised by the significant accumulation of Li, Cs, and Ta, as well as Rb, Be, Sn, B, P, and F. These elements are mainly derived from S-granites, although less commonly from I-granites. Ercit (2005) provides further details regarding the categorization employed in the research conducted by Cerny and Ercit, 2005 on Rare Earth Element-Enriched Granitic Pegmatites. After analysing over 500 descriptions of pegmatites, they discovered a moderate relationship between the types of minerals present and the depth at which NYF pegmatites are formed. Cerny and Ercit suggested that NYF pegmatites can be classified into the Abyssal, Muscovite-

Rare-Element, Rare-Element, and Miarolitic categories. In addition, they made a clear distinction between the abyssal class subclasses that are abundant in LREE (Light Rare Earth Elements) and those that are enriched in HREE (Heavy Rare Earth Elements). The Rare Element Class consists of the subtypes Allanite–monazite, Euxenite, and Gadolinite, in addition to the Rare Earth type.

According to Martin and De Vito (2005), the classification of depth zones is not enough to fully describe the two primary geochemical forms of pegmatites, which are known as LCT and NYF. They suggest that the tectonic setting influences the characteristics of both the original magma and the resulting magmas that are enriched with rare elements. As a result, LCT pegmatites are formed in areas with compressional tectonic settings, known as orogenic suites, while NYF comes from areas with extensional tectonic settings, known as anorogenic suites. The presence of mixed NYF and LCT rocks is believed to be caused by contamination during either the magmatic or post magmatic phases. This occurs when NYF rocks are exposed to a fluid that contains Li and B from the surrounding rock, as well as Ca and Mg. Furthermore, they propose that pegmatites may have originated from rocks in the mantle and crust that had previously undergone metasomatic changes through the process of anatexis.
In an effort to include pegmatite variations that were not covered by prior classification schemes, a new categorization scheme (Table 1) for granitic pegmatites is introduced. The recent study conducted by Muller *et al.* (2021) introduces a novel methodology to classify three distinct categories of pegmatites. These pegmatites are closely associated with granite plutons and are formed through the anatexis of metaigneous and metasedimentary protoliths. The study employs a diverse range of accessory minerals to establish these genetic relationships. Anatexis is responsible for the formation of Groups 1 and 2. Group 3 pegmatites, on the other hand, are derived from residual melts of S-, A-, and I-type granite magmatism (RGM) and direct products of anatexis (DPA) (Wise *et al.,* 2021).

Table 1: Key features of RMG and DPA Type Pegmatite (Wise *et al.*, 2021)

RMG (Residual melts of granite magmatism)			
Petrogenetic type mineralogical group	**RMG-Group 1**	**RMG-Group 2**	**RMG-Group 1+2**
Typical source rock Granite chemistry	S-type granites Peraluminous	A-type granites Peralkaline & metaluminous to mildly Peraluminous	I-type granites Peraluminous to metaluminous
Relation of pegmatites to source	Interior to marginal	Interior to marginal	Interior to marginal
Typical geochemical signatures	Be, Nb, Ta, P, Sn, Li, Cs	REE, Be, Nb,F	B, Be, REE, Nb, Ti, Li, Ca
DPA (Direct products of anatexis)			
Petrogenetic type mineralogical group	**DPA-Group 1**	**DPA-Group 2**	**DPA-Group 3**
Typical source rock	Granulite to amphibolite facies metasediments and metaigneous rocks of granitic S-type signature	Granulite to amphibolite facies F-rich amphibolites and metaigneous rocks of granitic A-type signature	Granulite to amphibolite facies metagraywackes and metaigneous Al-rich rocks
Relation of pegmatites to source	Segregation of anatectic melts	Segregation of anatectic melts	Segregation of anatectic melts
Typical geochemical signatures	Be, Nb, Ta, P, Li	REE, U, Be	Al, Be, B

Age and Tectonic Settings

Granitic pegmatites have been formed since 3.1 Ga in the evolutionary history of the Earth. Their peak formation dates aligned with events of supercontinent convergence, indicating a genetically inherent link between pegmatite production and orogeny. The pegmatite-forming peaks at roughly 2.6, 1.8, 0.962, 0.529–0.485, and 0.309–0.274 Ga is representative of the supercontinent assembly that took place during collisional orogenies, according to McCauley and Bradley (2014). The assembly of the Sclavia and Superia, Nuna, Rodinia, Gondwana, and Pangea supercontinents, respectively, is specifically correlated with these peaks.

At the New Consort Gold Mine in South Africa, the first pegmatites containing spodumene and elbaite date back to the Archean (3.1 Ga), which is equivalent to the formation of Kenorland, one of the planet's earliest supercontinents (Grew, 2020). Certain rare metal minerals also make their initial appearance in the geological record during these orogenies. The earliest substantial terrigenous sediment accumulations occurred in specific epochs and areas, which are home to the first generation of rare-element pegmatites in the Earth's crust (Tkachev, 2011). The anatexis of terrigenous sediment in the orogenic belts is considered to be a crucial factor in the creation of pegmatite melts during orogeny (e.g., Černý, 1991, London, 2008, Shaw *et al.,* 2016, Kunz *et al.,* 2022).

These characteristics show how granitic pegmatite production is a product of Earth's evolutionary past and is intimately related to plate movements and rock deposits during an orogeny. The Togo-Benin-Nigeria Shield, the southern part of the grouping of allochthonous terranes in West Africa, includes the Nigeria Basement Complex (Ajibade and Wright, 1989). The Togo-Benin-Nigeria Shield was impacted by the Pan-African orogeny, which is present throughout the continent.

The Pan-African orogenic event, a continent-wide occurrence that led to the reworking of the older crust, imposed a polycyclic basement and overall N–S structural inclinations on the region. Due to the widespread emplacement of granites and charnockites brought on by the magmatism that accompanied the Pan-African Plateau, nearly all of the rocks in the region, including those in Nigeria, show the mark of 5.0–6.0 Ga mineral ages (Ominigbo, 2022). The rare-metal pegmatites of most deposits in southern Nigeria have been interpreted as Volcanic Arc Granite (VAG) and Syn-Collisional Granite (SCG) using whole rock geochemical analysis; however, some have been interpreted as Within Plate Granite (WPG). This suggests that the pegmatites were generated either by (i) the extreme fractionation of syn- to late-tectonic granites or (ii) by partial melting or the anatexis process of the nearby metasedimentary rocks (London, 2005).

5. Genetic Models

The prevailing concept of pegmatite formation during the 1970s and 1980s was proposed by Jahns (1955). According to this model, pegmatites were formed from residual molten granite that contains both water vapour and silicate melt. Based on this idea, the combination of the molten and gaseous phases leads to the formation of pegmatitic textures. The transition from granite to pegmatite starts when the H_2O-fluid reaches its saturation point. Therefore, the aqueous vapor phase plays a crucial role in the formation of pegmatite crystals and helps to explain why pegmatites have such large crystal sizes.

Cerny and London's experimental work on mineralogy and geochemistry has significantly enhanced our comprehension of the specific processes involved in the formation of pegmatites. London's research in 1995 and 2005 demonstrates that the formation of pegmatitic texture does not necessarily depend on the presence of a moist vapor phase. This is because the conditions of emplacement and initial solidification do not always align with the equilibrium liquidus field. The trace element characteristics seen in pegmatites are mostly caused by the partial melting of rocks in the intermediate to deep regions of the Earth's continental crust, which leads to the formation of granitic magmas.

When examining the several concepts put out to explain the process of how pegmatites are formed and mineralized, there are two main hypotheses that are being debated. These theories are (a) fractional melt crystallization and (b) liquefy-aqueous fluid interaction (Figure 4). The concentration of fluxing segments and other incongruent components intensifies near the middle of the magma chamber as crystallization progresses, causing synthetic fractionation to move from the periphery to the centre of the pegmatites (Oyebamiji *et al.*, 2018).

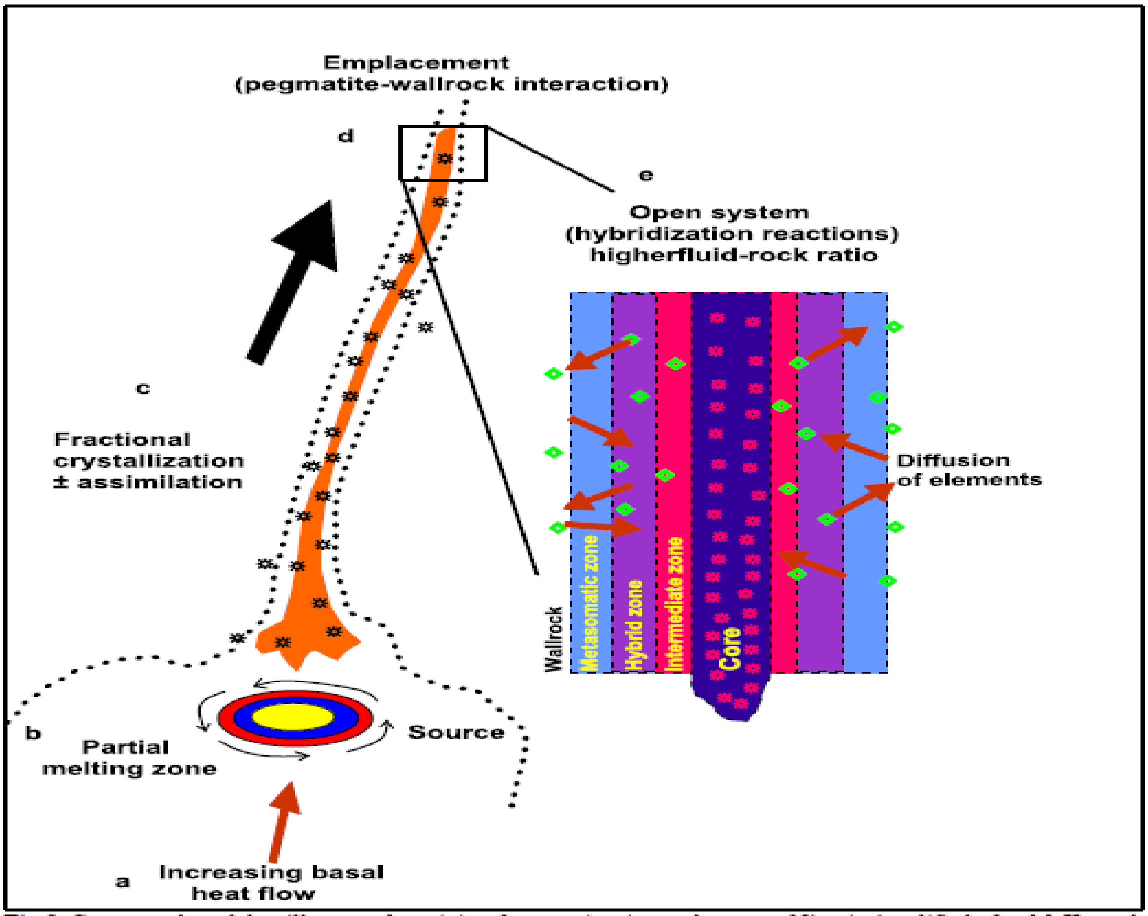

Figure. 4: Conceptual model depicting the genesis of pegmatites in the southwestern region of Nigeria (Adapted from Mckeough *et al.*, 2013).

6. Economic Importance

London and Kontak (2012) states that pegmatite are recognized for their abundance of uncommon minerals and metals, such as tantalum, niobium, tungsten, lithium, cassiterite, and columbite. These materials are employed in the manufacturing of microchips and microprocessors for computers and electronics, aircraft fabrication, electroplating, and the creation of metal components, batteries, and containers. The global energy transitions are increasing the demand for pegmatites that are rich in rare metals (Oyediran *et al.,* 2020).

Granite pegmatite has a diverse range of uncommon metals and rare-earth metals, as stated by Černý (1994). Pegmatites contain strategic metals (Linnen *et al.,* 2012), industrial minerals (Glover *et al.,* 2012), colored gemstones (Simmons *et al.,* 2012), as well as prospects for financial gain and scientific progress. Strategic elements refer to crucial resources that are vital for a nation's economy or defense, but are also very vulnerable to disruptions in supply. Typically, these elements are metallic in nature. The list of elements include rare earth elements (REEs), Ta, Nb, Be, Sb, and W, which vary depending on the country. These elements are widely found and several of them are also classified as strategic metals. These elements are characterised by their high field strength and their tendency to preferentially bond with larger ions. They are not compatible with rare-element pegmatites. Strategic metals have a crucial role in civilization, although being largely unknown to the general public (Linnen *et al.*, 2012). Tantalum capacitors are used in computers, cellphones, and automobiles (for things like ABS and airbag activation systems). Technical-grade lithium is used in glassware and ceramics, whereas chemical-grade lithium is used in lubricants and is a crucial part of rechargeable batteries in electric cars. Caesium formate is produced for use in high-temperature, high-pressure drilling during petroleum exploration. Because of its photoemissive properties, cesium is also used in solar photovoltaic cells. Automotive, aeronautical, and electronic components are made of copper and beryllium alloys.

7. Summary and Conclusion

In summary, pegmatites are a type of igneous rock that is often holocrystalline, leucocratic, and has exceptionally coarse-grained crystals. They are associated to a huge volume of intrusive rocks in time and space. They frequently appear as dykes, sills or veins. They are high in minerals like quartz, feldspar, mica, and other accessory minerals. They occur in two (2) distinct forms based on mineralogy: simple and complex. Chemically, they occur as LCT and

NYB pegmatites. They are distributed worldwide and have been found in all the zones in Nigeria. Recent classification employed a diverse range of accessory minerals to establish the genetic relationships in pegmatites. Anatexis is responsible for the formation of Groups 1 and 2. Group 3 pegmatites, on the other hand, are derived from residual melts of S-, A-, and I-type granite magmatism (RGM) and direct products of anatexis (DPA). Their age ranges from 2.6-2.74 Ga and a genetic model of fractional melt crystallization and liquefy-aqueous fluid interaction have been postulated for their genesis.

Pegmatites therefore are rocks with a high potential for economic prosperity, yet many aspects of the field of study remain unexplored, particularly in Nigeria. Pegmatite has been described in great detail in this article and has provided an overview of the rock. The rich rock with buried gems should be explored and exploited using all necessary instruments.

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