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(Review Article)

Igneous pegmatite lithium deposit: Formation processes, mineralogy, and implications for sustainable Lithium extraction

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Abstract

The increasing demand for lithium-ion battery-powered electronics and electric vehicles has underscored lithium as an essential resource. Pegmatites, despite being smaller and possessing less estimated resources than brine deposits, hyaccount for more than fifty percent of the global lithium supply. This paper reviews the formation, mineralogy, and economic significance of lithium-bearing igneous pegmatites, explaining the role of fractional crystallization in the production of LCT pegmatites and highlighting the essential minerals spodumene, lepidolite, and petalite that enhance their worth. It also analyzes how geological and textural characteristics affect mining decisions and delineates the primary processing stages, from crushing and grinding to flotation and spodumene conversion. Environmental concerns, such as excessive water consumption and tailings hazards, are evaluated. The study underscores that pegmatites are significant lithium sources but necessitate meticulously regulated, environmentally sustainable extraction practices.

Keywords: Pegmatites; Lithium; Spodumene; Host rock; Deposit; Flotation; Calcination; Leaching.

1. Introduction

Lithium is a critical mineral, as recent technology relies heavily on its production in lithium-ion batteries for electric vehicles, as well as renewable energy technologies. Within the lithified geological suites of economically valuable lithium mineralization, the igneous pegmatites constitute notable and substantial sources of the critical metal (Bradley et al., 2017; Kesler et al., 2012). The formation of pegmatites is a result of mineral-rich magma intruding from the magma chamber into the crust. When the magma erupts, it undergoes fractional crystallization to form the pegmatite deposits (London,2018; Sykes and Schodde, 2019). Temperature and pressure play a crucial role in the formation of pegmatites.

Pegmatites are coarse-grained igneous rocks that form during the last stages of magmatic crystallization. They are known for their enormous crystals and unique mineral assemblage (Bradley et al., 2017). Among them, lithium-cesium-tantalum (LCT) pegmatites, granitic pegmatites enriched in lithophile elements, serve as the primary hard-rock sources of lithium. London (2008) further notes that while pegmatites share a granitic composition, they stand apart from other igneous rocks due to their extremely coarse textures and abundant large crystals, reflecting their development during the last phase of magma cooling (see Figure 1).

The composition of pegmatites is like that of granite with a lot of quartz, mica, albite, and potassium feldspar, hence the name "granitic pegmatites," plus some trace of tourmaline, biotite, garnet, and apatite (refer to Figure 2). Pegmatites contain trace amounts of tourmaline, biotite, and garnet. An example is the Greenbush pegmatite deposit in Australia, which was formed a billion years ago. This deposit has the highest lithium grade of about 5 wt.% Li_2O. The countries

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that mainly extract lithium from pegmatites are Australia (Greenbushes), Zimbabwe (Bikita Pegmatite), China, Brazil, Portugal, the US (Kings Mountain, NC), Canada (Tanco Mine), etc.

Figure 1 Pegmatite composed of crystals

Source: https://geology.com/rocks/pegmatite.shtml

Figure 2 Pegmatite granite from Mt Evans Batholith

Sources:https://www.geologyin.com/2024/01/pegmatite-formation-composition.html

2. Formation and Sources of Pegmatites

The formation of igneous pegmatite lithium deposits is generally linked to strong fractional crystallization of granitic magmas, with pegmatite provinces showing zoning around parent intrusions. Lithium-rich pegmatites often develop farther from the source granite and are most likely to form when lithium-enriched melts intrude into relatively cool country rocks (Kesler et al., 2012; Zhou et al., 2025).

Generally, the large crystals found in igneous rocks can be attributed to the slow rate of magma crystallization that erupts from the chamber. This situation is different with pegmatites in that the large crystals are a result of low-viscosity fluids that allow the ions to be mobile. The LCT pegmatites are in metamorphic-igneous interiors of orogenic belts as well as the result of plate convergence (Xu et al., 2023). Ore deposition is more likely to come from magma than from an exsolved hydrothermal fluid. Černý (1992) reports that metasedimentary and metaigneous belts of amphibolite contain most economic deposits. For more competent host rocks, the pegmatites follow fractures present within the deposits.

3. Mineralogical Characteristics

Principal Minerals Containing Lithium:

- Spodumene ($LiAlSi_2O_6$) has a high concentration of lithium, between 6-9% Li_2O. Spodumene is found in various colors, including white, green, pink, or purple, simply referred to as kunzite. Spodumene occurs in two forms, alpha (α) and beta (β), with the α-form being most common in nature (Olade, 2025).
- Lepidolite (Li-mica, $KLi_2Al(Si_4O_{10})(F,OH)_2$) has a lithium content range from 3-5% (Bowell, 2020).
- Petalite ($LiAlSi_4O_{10}$) contains relatively low lithium grades, averaging about 3.42% Li_2O, and crystallizes under low-pressure conditions (Pandey, 2025).
- Amblygonite ($LiAlPO_4(F, OH)$): This lithium phosphate mineral is widespread but rarely of major economic importance on its own. In the Bastar Craton (India), significant quantities of amblygonite (with Li concentrations varying from 1.7% to 4.06%) have been identified alongside lepidolite (Pandey, 2025).

4. Texture, Grain Size, and Structure

Pegmatites are characterized by extremely coarse but irregular grain sizes, with crystals several meters in length and even up to tens of meters. A typical example is from Etta Mine in Black Hills of South Dakota, which is known to have produced the largest spodumene crystal, which was 14.3 meters in length (Refer to Figure 3). LCT Pegmatite deposits have various forms such as lenticular bodies, tabular dikes, and tabular sills (Cameron et al., 1949). Pegmatites exhibit a range of distinctive textures beyond their coarse grain size, including graphic quartz–feldspar intergrowths, skeletal crystal growth, miarolitic cavities, and unidirectional solidification textures. They may also contain layered or banded aplite, commonly referred to as “line rock” (Bradley et al., 2017)

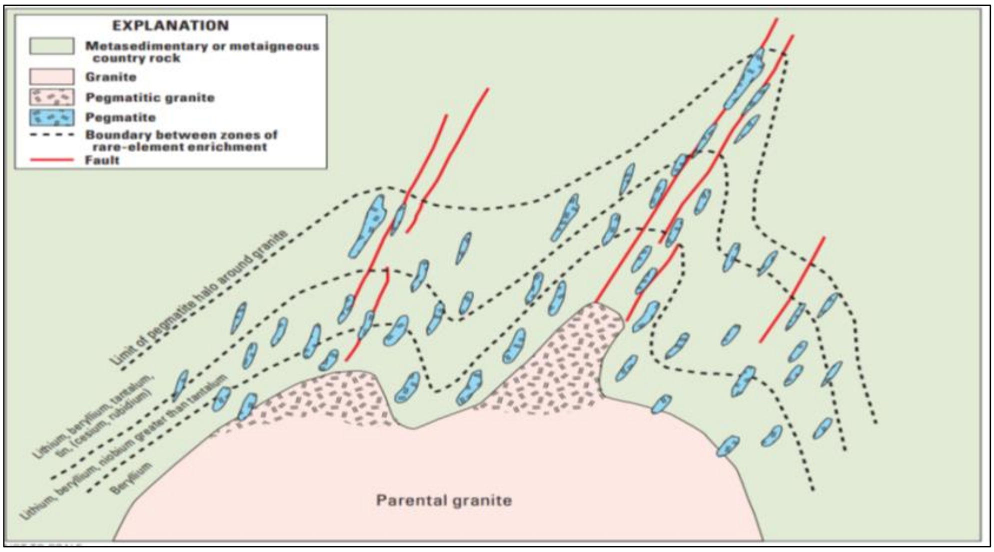

Figure 3 Idealized concentric, reginal zoning pattern in a pegmatite field

Source: https://pubs.usgs.gov/sir/2010/5070/o/sir20105070o.pdf

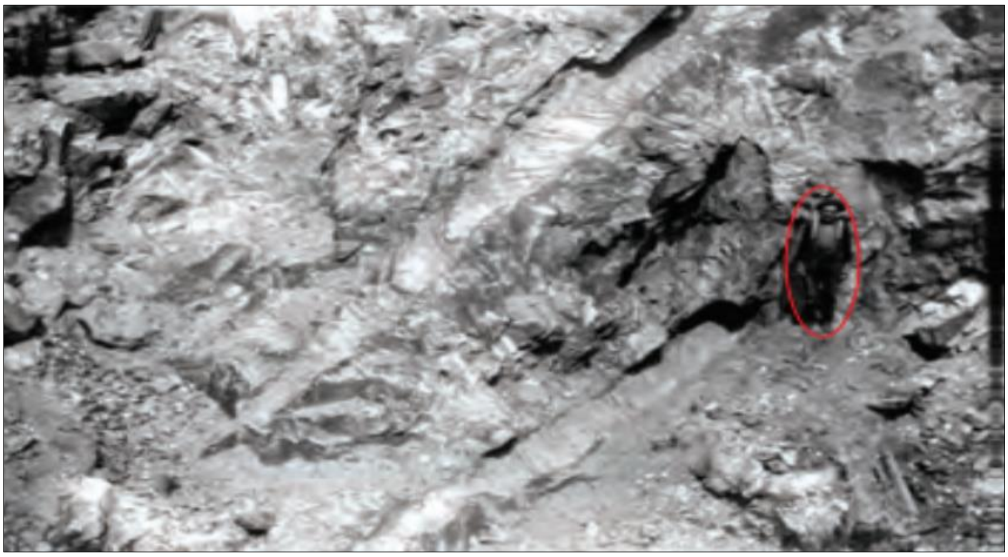

Figure 4 Spodumene found at Etta Mine in Black Hills

Source: https://pubs.usgs.gov/sir/2010/5070/o/sir20105070o.pdf

5. Alteration

Spodumene often undergoes metasomatic alteration that reduces grain size and produces replacement textures with albite and quartz. Intergrowths or symplectites of spodumene with quartz, feldspar, and muscovite are common and can significantly hinder mineral liberation (Djanetey et al, 2025).. In later stages, hydrothermal fluids may further alter the mineral through sericitization and the formation of secondary minerals along fractures (Lai et al., 2023)

Figure 5 Samples of Lepidolite and Spodumene Lithium ore

6. Economic Importance of Pegmatites

Lithium-bearing igneous pegmatites have significant economic importance due to their high lithium grades, valuable by-product metals (such as tin (Sn), tantalum (Ta), beryllium (Be), rubidium (Rb), and cesium (Cs)), and broad global distribution (Bowell et al., 2020; Pandey, 2025). Their extraction benefits from established mining and processing technologies that rely on mineral concentration and roasting or acid digestion.

However, the economic viability of pegmatite deposits is often constrained by their typically small size, variable lithium enrichment, and the fact that only a small fraction of granitic pegmatites host economic mineralization (Yin et al., 2024; Pandey, 2025). Exploration can also be costly and technically demanding, requiring specialized geochemical methods and extensive drilling (Bowell et al., 2020; Kesler et al., 2012). Processing challenges arise when contaminants such as magnesium, iron, and other trace elements complicate lithium recovery (Bowell et al., 2020; Pandey, 2025). Additionally, geological controls—including magma chemistry, fractional crystallization, and the thermal state of country rocks—strongly influence the formation of economic pegmatite deposits (Zhou et al., 2025).

7. Mining of Pegmatites

Mining methods depend on the mineral deposit, economic factors and the geology (Effah et al, 2025). For LCT pegmatites, it is difficult to make a clear distinction between ore and gangue. This fact is because potassium feldspar, muscovite, quartz, and plagioclase constitute the bulk of all pegmatites. In the past, most pegmatites were mined by hand, either in shallow open pits or underground workings. The selection of mining methods for LCT pegmatites largely depends on their vertical extent and structure (Garrett, 2004). The Greenbushes open pit mine has developed steeply dipping pegmatites of more than 200 m (Fetherston, 2004). Furthermore, according to Garrett (2004), the underground room and pillar method was used to mine the Tanco pegmatite, and as a result, 89 percent of the ore was recovered. Variations in rock strength within granitic or metamorphic rocks impact stability. Geologic structures such as fractures and faults influence mine design and the safety of every operation. Given the large crystals in pegmatites, selective mining is crucial to focus on the high-grade section, thereby reducing dilution.

8. Mineral Processing of Pegmatite

To enhance lithium recovery, the ore processing method was modified in 1969. The techniques employed for processing LCT pegmatite largely differ based on the specific minerals extracted and the grade of the final product. The degree of processing needed for silicate ores varies depending on the final use of lithium. Most mining operations utilize crushing, grinding, and gravity separation for ore processing (Hatcher and Elliot, 1986). The dissolved lithium may be transported with the processing water directly to the tailings ponds, potentially reaching concentrations of approximately 13 ppm. Spodumene is typically processed by roasting its insoluble alpha form ($LiAlSi_2O_6$) at temperatures above 1,100 °C to transform it into the more reactive beta phase ($LiAlSiO_4$). For ceramic applications, crushed spodumene, petalite, and eucryptite concentrates can be used directly. Tantalum presents additional processing challenges because its properties closely resemble those of niobium, requiring chemical separation rather than traditional smelting methods (Fetherston, 2004).

9. Water Demand and Disposal of Waste

Water demand is particularly high for purification and leaching processes, especially in arid regions. Although much of the waste from LCT pegmatite mining, such as quartz, feldspar, and muscovite, is relatively benign due to slow weathering, several environmental risks remain. These include potential groundwater contamination from fluorine-bearing minerals like lepidolite, chemical residues in tailings, and improper waste disposal (Hudson-Edwards,, 2024). Operations, therefore, require strict controls on water use, water quality monitoring, waste management, and land reclamation, as seen at Greenbushes, which operates under EPA permitting requirements (Erue et al., 2024: Amuah et al., 2025). Additionally, dissolution of lithium minerals during screening and grinding can increase lithium concentrations in tailings ponds, further emphasizing the need for robust environmental safeguards (Tadesse et al., 2019).

10. Uses of Pegmatite

- Pegmatites are important sources of industrial minerals such as quartz and feldspar. Quartz, known for its high purity, is utilized in electronics and solar panels, whereas feldspar is commonly used in ceramics, glass, and paints (Černý, P., & Ercit, T. S., 2005).
- Certain pegmatites with graphic granite textures are utilized as decorative stones for monuments, countertops, and floor tiles, prized for their aesthetic appeal and coarse mineral intergrowths (USGS, 2017).
- Pegmatites are significant sources of rare and strategic elements such as tantalum, niobium, beryllium, lithium, cesium, and tin, which are vital for applications in electronics, batteries, aerospace, and defense technologies (Bradley et al., 2017).
- Pegmatites can contain monazite, a rare-earth mineral used in high-tech applications like magnets and lasers (USGS, 2023).

11. Conclusion

Igneous pegmatites remain important lithium sources, valued for their distinctive geology and economic potential despite being smaller and more variable than other deposit types. Although well-established extraction and processing methods exist, challenges arise from inconsistent grades, complex mineralogy, and limited deposit size. Their development also carries environmental risks, particularly regarding water use, waste disposal, and land reclamation, requiring strong regulatory controls. Even so, pegmatites are expected to remain key contributors to global lithium supply and other strategic elements essential to energy technologies, electronics, and advanced industries.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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