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Addis Ababa Institute of Technology

Center for Ethio-Mines Development Masters in Mineral Engineering

Characterizing the Ore Mineralogy of Kenticha Pegmatite for Lithium Beneficiation, Southern Ethiopia

**A Project Submitted to Center for Ethio-mines development in partial fulfillment of the
requirements for the degree of Master of Engineering in Mineral Engineering.**

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ABSTRACT

Lithium is a highly sought-after resource crucial for rechargeable batteries, and the Kenticha pegmatite ore deposit in Ethiopia holds potential as a source of this valuable element. The focus of this study was to investigate the mineralization of Kenticha, specifically the spodumene ore, and its suitability for beneficiation processes. Through XRD, AAS, and petrographic microscope analysis, the study identified the minerals present in the spodumene pegmatite ore, their average composition, and mineral texture for spodumene concentrate liberation. Spodumene was found to be the most abundant mineral, but its low degree of liberation from other minerals required additional processing steps for high yield. Weathering significantly impacted mineral identification and quantification, affecting diverse mineral morphology and liberation. The study's findings have implications for mining operations, exploration, and processing strategies, suggesting additional processing steps for spodumene recovery and highlighting the impact of weathering on mineral characterization. The study provides valuable information on mineral texture and liberation for selecting processing methods for beneficiation, contributing to a better understanding of the Kenticha pegmatite ore deposit's mineralization potential for lithium extraction.

Keywords: lithium, spodumene, pegmatite, mineralogy, Kenticha beneficiation, and mineral liberation.

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List of Acronyms

AAS	Atomic Absorption Spectrometry
ALS	Australia Laboratories Service
CGM	Columbite Group Mineral
EMPBC	Ethiopian Mineral Petroleum Biofuel Company
HFSE	High field strength element
HREE	Heavy rare earth element
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry
ICP-AE	Inductively Coupled Plasma-Atomic Emission
AES	Atomic Emission Spectrometry
ICP-OE	Inductively Coupled Plasma-Optical Emission
LCT	Lithium-cesium-tantalum family
PPL	Plane polarized light
Ppm	Part per million
REE	Rare earth elements
XPL	Cross polarized light
N-S	North-South
OFTB	Ophiolitic Fold and Thrust Belt
IENAA	instrumental epithermal neutron activation analysis
ICP-AES	Inductively coupled plasma atomic emission
MLA	Mineral Liberation Analysis
XRD	X-ray Diffraction
LOI	Loss On Ignition

Chapter 1: Introduction

1.1. Background

Lithium is the lightest metal on the periodic table and is a soft, silver-white alkali metal with atomic number 3. It is extensively dispersed at trace levels in most rocks, soils, and natural waterways. Its poor thermal expansion coefficient and electrochemical reactivity make it unstable. It also possessed the solid elements' highest specific heat. Some lithium compounds have flat viscosity-to-temperature ratios (Ebensperger et al., 2005). These characteristics of lithium and its derivatives have led to the emergence of numerous commercial applications since its discovery in the early 1800s. It has an application in lithium-ion batteries production for cars, ceramics and glass, lubricating greases, air treatment, continuous casting mold flux powders, polymer production, and primary aluminum production (Nazir et al., 2022)

Furthermore, the use of lithium-ion technology in electric vehicles has recently increased demand for lithium minerals (Dessemond et al., 2019; Ebensperger et al., 2005) to replace the usage of fossil fuel. Fossil fuel consumption raises a number of concerns, including increased demand for oil, the depletion of oil reserves, political unrest and insecurity in nations that produce oil, greenhouse gas emissions, and challenges with climate change (Grosjean et al., 2012). However, lithium batteries can address such problems by serving as renewable energy storage systems for electric vehicles in an environmentally friendly way.

The two economic sources of lithium are brine and hard-rock pegmatite ores. Lithium can be found in a variety of minerals, including spodumene ($\text{LiAlSi}_2\text{O}_6$), amblygonite ($(\text{Li,Na})\text{Al}(\text{PO}_4)(\text{F,OH})$), zinnwaldite ($\text{KLiFeAl}(\text{AlSi}_3)\text{O}_{10}(\text{F,OH})_2$), petalite ($\text{LiAlSi}_4\text{O}_{10}$), lithiophilite ($\text{Li}(\text{Mn}_2)\text{PO}_4$), and lepidolite $\text{K}(\text{Li,Al})_3(\text{Si,Al})_4\text{O}_{10}(\text{F,OH})_2$. Other potentially harmful or undesirable substances to the beneficiation, such as iron, phosphorus, or fluorine, may also be present in these minerals too (Scogings et al., 2016). However, this project is focused only on spodumene ($\text{LiAlSi}_2\text{O}_6$)-hosted pegmatite found at Kenticha, Southern Ethiopia, to characterize and document the mineralogy of spodumene-bearing pegmatite.

A metallogenic province of the Kenticha region is found in southern Ethiopia, inside the Adola green stone belt. This belt is distinguished by substantial intrusive activity made up of pegmatite and associated minerals. Large reserves and concentrations of tantalum, niobium, and lithium have demonstrated the commercial significance of geological prospecting and exploration since 1979 (Tadesse, 2001), as has rare metal mineralization that includes Ta, Nb, Be, Li, Cs, and Rb too (Bekele & Sen, 2020; Küster et al., 2009). Spodumene-bearing pegmatite deposits coexist with other silicate minerals such as feldspar, mica, and quartz, and have lithium head grades ranging from 1% Li₂O in low-grade deposits to 4% Li₂O in higher-grade deposits (Clarke GM, 2013).

When describing which lithium minerals are present and how they appear in the deposit, lithium mineralogy is just as crucial as the Li₂O content. Before moving on to the evaluation stages, it is important to consider the type, and concentration of potentially deleterious components, the main mineral species present, and their physical characteristics in a deposit (Scogings et al., 2016). Since it is difficult to understand the mineralogy of hard rock Li deposits (pegmatite), standard methods like X-ray diffraction (XRD) can only provide guidance to the principal Li phases (such as spodumene and petalite) when detectable levels (>2%) are present. However, XRD cannot accurately determine if Li occurs in low-grade materials (Grammatikopoulos et al., 2021). Automated mineralogy must therefore be combined with XRD and mineral chemistry. Since the principal elements of the various minerals will have an impact on their final end use, such as FeO in spodumene, it is useful to utilize electron probe micro-analysis (EPMA) to identify these elements. Li as well as other minor elements such as Ga, Cs, and Rb are quantified in minerals such as spodumene, petalite, micas, phosphates, and others through the technique of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). The Li distribution is then calculated, after which the data are paired to assess the deposit's mineralogy (Grammatikopoulos et al., 2021). However, in the project, X-ray diffraction (XRD), Atomic Absorption Spectroscopy (AAS), and petrographic microscope were used to analyze the distribution of lithium and its minerals.

Despite many studies conducted on the Kenticha lithium-bearing pegmatite, there is a critical gap in knowledge regarding its ore-processing mineralogy. The lack of information on the minerals

that make up the ore and gangue, as well as their composition, grain size distribution, and texture, has hindered the development of efficient and sustainable methods for extracting lithium concentrate from the ore. Therefore, the aim of this project is filling this gap by identifying the mineralogy of the Kenticha lithium-bearing pegmatite and providing valuable insights into its processing. By doing so, this project has the potential of contributing to the development of more sustainable and efficient methods for extracting lithium, which is a critical resource for the transition towards a more sustainable and renewable energy future.

1.2 Location, Accessibility and Physiograph

The Kenticha study area is located in the Seba Boru Woreda of the Guji Zone in the Oromia Region of Southern Ethiopia. It is approximately 54 km southeast of Shakiso town and 470 km south of Addis Abeba, the capital city of Ethiopia. The nearest towns to the mine's location are Shakiso and Adola, which are around 60 km and 490 km from the deposit area, respectively.

The physiography of the area is dominated by the Bale Mountains to the north and the Mega Mountains to the south. The Kenticha study area is situated on the eastern slopes of the Bale Mountains, which is composed of igneous and metamorphic rocks. The region is also characterized by a network of rivers and streams, which are important sources of water for the local communities and for industrial purposes. The climate of the area is generally tropical, with temperatures ranging from 10°C to 25°C. From June to September, there is a rainy season, with an average annual rainfall of 800 mm. The dry season lasts from October to May, with occasional showers occurring in November and December. The area is also prone to occasional droughts, which can have significant impacts on the local communities and on the mining operations.

Overall, the location and accessibility of the Kenticha study area, as well as its physiography and climate, provide favorable conditions for the extraction and processing of lithium ore, as well as for the development of infrastructure and transportation networks to support the mining operations. However, careful management of the natural resources and the environment is necessary to ensure sustainable development and to minimize the impacts on the local communities and ecosystems.

Table 1. Points at which the study area's corners meet (UTM-Zone 37° projection datum)

Corners	East (X)	North (Y)
A	502246.0	604861.0
B	503488.7	604870.0
C	503483.9	601791.9
D	501620.5	601787.4
E	501893.6	603319.7
F	502246.2	603824.0

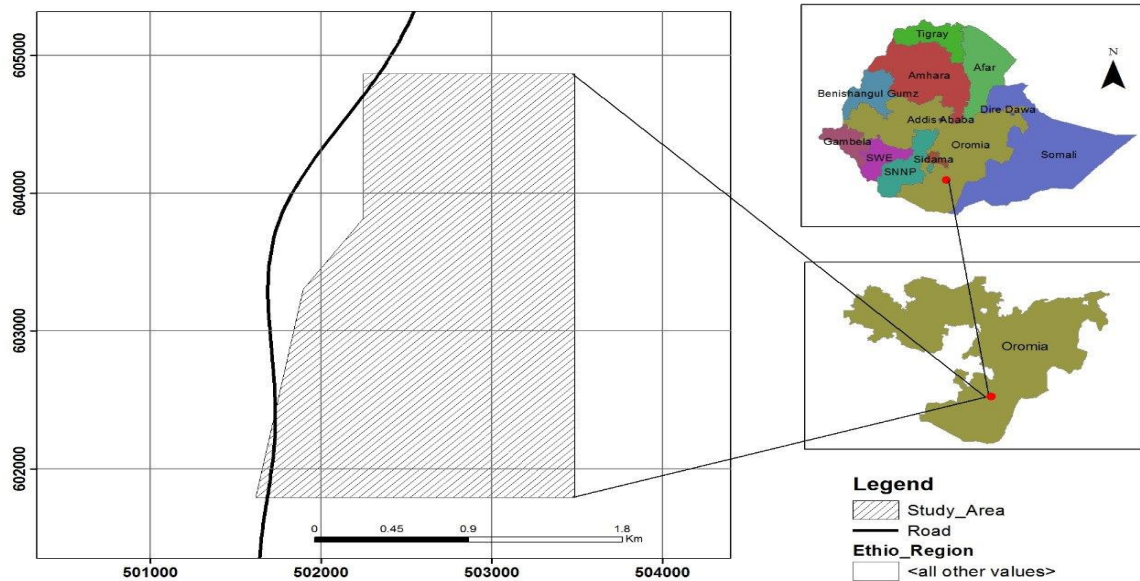


Figure 1. Map of the research area's layout

1.3. Statement of the Problem

The extraction of valuable minerals, such as lithium, from ore deposits is critical for the development of high-tech industries and the transition to clean energy sources. However, the limited knowledge on the mineralogical and chemical composition of ore deposits, particularly those found in pegmatite deposits, poses a significant challenge for the development of effective beneficiation processes. Therefore, there is an urgent need to investigate and improve our understanding of the mineralogy and chemical composition of such deposits. This information is essential for creating effective and sustainable processes for mining and processing minerals, which can help meet the rising demand for essential resources like lithium while reducing the environmental impact of mining. By improving our understanding of the mineralogy and chemical makeup of ore deposits, we can create more efficient and environmentally friendly processes for mining and processing important minerals, which can help create a more sustainable and just future.

The Kenticha pegmatite ore deposit in southern Ethiopia represents such a case, as it has been largely studied for its tantalum mineralogy, while attention has not been given to its potential for lithium extraction. As a result, during mining, the deposit's lithium-bearing minerals were treated as gangue and were covered in waste rock. The lack of knowledge about the mineralogy and chemistry of the Kenticha pegmatite ore deposit, which prevents the development of efficient and long-lasting beneficiation procedures for the extraction of precious minerals like lithium, is

the issue this study seeks to address. Previous investigation into the deposit was sparse and concentrated on the mineralogy of tantalum; lithium ore potential received no consideration. Future exploration and development activities may be restricted by the lack of knowledge of the deposit's geological characteristics, including mineral zoning and changes in mineralogy and chemistry.

The solution to this problem requires a multidisciplinary approach that integrates geological, mineralogical, and metallurgical expertise to characterize the mineralization of the Kenticha pegmatite ore deposit thoroughly. For the purpose of liberating lithium concentrate, this study seeks to offer a mineralogical identification of the ore and gangue minerals, average composition, grain size distribution in the pegmatite ore body, and ore texture. The results of this study can be used to direct future exploration and development projects, encourage sustainable management of mineral resources, and aid in the production of lithium and other precious minerals. In the end, this research can help create sustainable and more effective methods for mining lithium and other valuable minerals from pegmatite ore deposits, which are crucial for the development of high-tech products and the switch to renewable energy sources.

1.4. Objectives

1.4.1 General Objective

The primary goal of this study was to characterize the mineralization of the Kenticha pegmatite ore deposit by targeting lithium ore for further beneficiation processes.

1.4.2. Specific Objectives

- To identify minerals, present in a spodumene pegmatite ore and determine the quantities of each mineral, including the ore and gangue minerals.
- To characterize the distribution of grains in the minerals of interest in the ore before selecting processing methods for beneficiation.
- To identify the various ore textures that exist among spodumene and other mineral grain boundaries.

By achieving these specific objectives, the Kenticha mineralization pegmatite ore deposit was characterized, with a focus on targeting lithium ore for further beneficiation processes.

1.5. Significance

The Kenticha pegmatite ore deposit in southern Ethiopia has significant potential for extracting valuable minerals, including lithium, which is crucial for electric vehicles and other high-tech applications. Understanding the mineralogy and chemistry of the deposit is essential for developing effective and sustainable beneficiation processes. The importance of studying the mineralogy of the Kenticha pegmatite ore deposit can be summarized as follows:

- **Proper processing methods:** Characterizing the pegmatite ore in terms of mineral chemistry, particle size distributions, and textural properties is crucial for designing a processing plant for high mineral recovery.

- **Identification of mineral species:** Identification of mineral species is an essential step in the processing of ores, particularly for smelting purposes. A contamination's presence or unwanted mineral species in an ore can cause problems during smelting, such as reducing the efficiency of the process, producing low-quality metal products, or damaging the equipment. Therefore, it is crucial to identify all the mineral species present in an ore to prevent such issues. Furthermore, identifying the mineral species can provide valuable insights into the properties and composition of the ore. Some minerals, for instance, might be more difficult to work with to separate from the ore than others, which may require specialized processing methods. Additionally, knowing the mineral species present in an ore can help to optimize the processing parameters, such as temperature, pressure, and chemical agents, to ensure the most efficient and effective extraction of valuable metals. Moreover, identifying the mineral species present in an ore deposit can also help to assess its economic potential. For example, some minerals may be more valuable than others, and their presence in a deposit can increase the overall value of the ore. Additionally, the mineral species present can help to determine the deposit's geological history and evolution, which can provide important information for further exploration and development efforts.

- **Mineral quantities:** Knowing the amounts of each mineral in the ore and gangue minerals is necessary for choosing the proper plant design methods, chemicals, and reagents for beneficiation and further metallurgical processes.

- **Academic insights:** Studying the deposit provides valuable insights for academic research, contributing to the understanding of the geological processes involved in the formation and Pegmatite deposits' evolution.

- **Sustainable use of natural resources and minerals:** Understanding the mineral composition of the deposit can promote sustainable management of mineral resources and contribute to Ethiopia's economic development.

Overall, the lack of information on the mineralogy and chemistry of a pegmatite in Kenticha ore deposit has significant implications for the development of effective and sustainable beneficiation processes. Studying the deposit's mineralogy can help direct future exploration and development activities, advance sustainable resource management, and aid in the production of precious minerals like lithium. This multidisciplinary approach can lead to the development of more efficient and sustainable processes for extracting and processing valuable minerals from pegmatite ore deposits, which are crucial for the transition to clean energy sources and the production of high-tech products.

1.6 Scope

The focus of this project work was on the mineralogical characterization of samples taken from the spodumene-bearing layer of pegmatite ore in Kenticha. Both crushed and ground materials from laboratory testing, as well as uncrushed spodumene rich samples, were studied in detail to the greatest extent possible. The mineralogical investigations conducted aimed to determine the characteristics of the minerals, including the identification of major, and trace elements; compositions of the minerals that affected the process; quantity of the minerals; particle and grain size distributions and textures of the minerals; mineral liberations and identification of ore, gangue, and deleterious minerals.

1.7. Expected Outcomes

The expected outcomes from this research could include:

- A greater comprehension of mineralogy and chemistry of the Kenticha pegmatite ore deposit, with a particular focus on lithium ore and spodumene mineralization.

- Identification of all minerals present in the ore and quantification of their proportions, which will aid in developing effective beneficiation methods for the extraction of valuable minerals.
- Characterization of the minerals' of interest's particle size distribution (Spodumene), which will guide the selection of appropriate processing methods for beneficiation.
- Identification of ore textures among spodumene and other mineral grain boundaries, which will aid in understanding the amenability of the ore aggregate for beneficiation, especially mineral liberation.
- The development of efficient and sustainable beneficiation processes for extracting and processing valuable minerals, such as lithium, from the Kenticha pegmatite ore deposit.
- The promotion of sustainable management of mineral resources and contribution to the economic development of Ethiopia by identifying strategic mineral components of the deposit, such as lithium, and giving full attention to their extraction and utilization rather than dumping them with waste rock.

Chapter 2: Literature Review

There are three main geologic formations that contain lithium ore deposits: brines, pegmatites, and sediment-hosted deposits (Dessemond et al., 2019). Brines account for roughly 60% of the global lithium, with the majority found as dried salt lakes. Pegmatites host between 23% and 30% of the world's identified lithium reserves (U.S. Geological Survey, 2019), while sediment-hosted deposits of hectorite and jadarite account for less than 3% of the total global lithium, with only a few known deposits (Dessemond et al., 2019). While these sources of lithium require further study, this review focuses on pegmatite deposits, which are the most important source of lithium for industrial applications.

Previous studies have highlighted the unique characteristics of pegmatite ores compared to other rare metal pegmatites, based on structural, mineralogical, isotopic, and fluid inclusion factors (Partington & McNaughton, 1995). Spodumene ($\text{LiAlSi}_2\text{O}_6$) is the most economically valuable lithium-bearing mineral in pegmatites, while other important lithium ore minerals include petalite ($\text{LiAlSi}_4\text{O}_{10}$), lepidolite group minerals ($\text{K}[\text{Li,Al}]_3[\text{Si,Al}]_4\text{O}_{10}[\text{F,OH}]_9$), which can also be utilized to create Rb ore, and amblygonite-montebrazite.

To understand the pressures and temperatures of pegmatite crystallization under equilibrium conditions, the lithium-aluminosilicate phase diagram (Fig. 1) is used. Recent studies have provided more detailed insights into the pressure, temperature, and fluid chemistry conditions that influence lithium mineralization in pegmatites. For example, research has shown that spodumene typically crystallizes at pressures between 200 and 500 megapascals (MPa) and temperatures between 600 and 800 degrees Celsius ($^{\circ}\text{C}$) (Cerny et al., 2012; Linnen et al., 2012). In contrast, petalite typically crystallizes at lower pressures (<100 MPa) and higher temperatures ($>800^{\circ}\text{C}$) than spodumene (Cerny et al., 2012).

Furthermore, recent studies have focused on the role of fluid chemistry and the availability of lithium in pegmatite formation. There have been suggestions that the solubility of lithium in fluids and the saturation state of the fluids with respect to lithium-bearing minerals control the availability of lithium in pegmatites (Tindle et al., 2016). The presence of boron in fluids can also influence the formation of lithium-bearing minerals in pegmatites (Hanson et al., 2017).

Understanding the pressure, temperature, and fluid chemistry conditions that influence lithium mineralization in pegmatites is crucial for developing effective methods for the extraction of lithium from pegmatite ores. By considering these factors, it may be possible to better understand the formation and distribution of lithium-bearing minerals and optimize mining and processing practices to maximize the recovery of lithium. Furthermore, recent research has demonstrated that the use of sophisticated analytical methods, such as laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS), can provide in-depth details on the distribution of lithium and associated elements in pegmatites, which can further assist in exploration and resource assessment (e.g., Thomas et al., 2019).

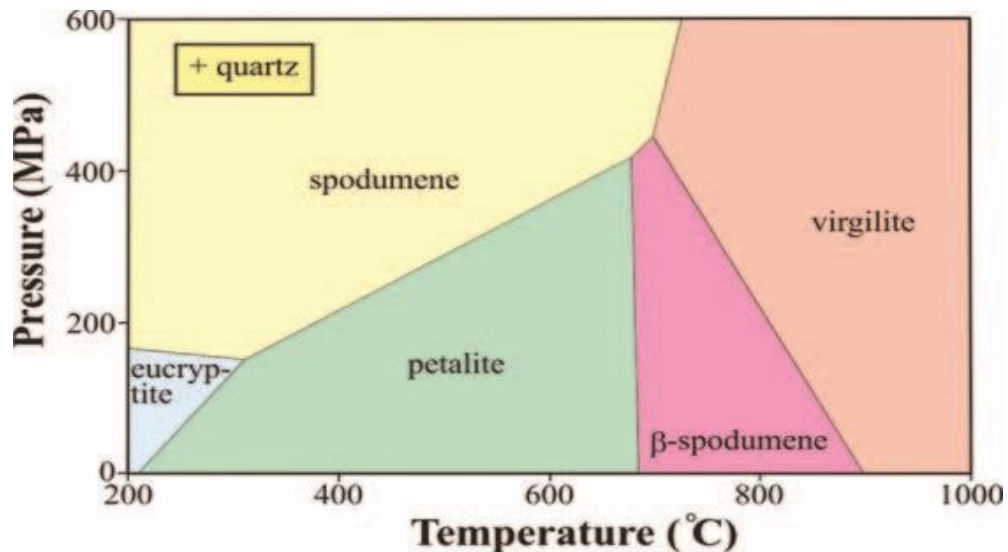


Figure 2. Quartz-saturated phase relationships of Li aluminosilicate minerals. Used after (Linnen et al., 2012) and London (2005).

Spodumene is classified as a primary mineral if it forms during the pegmatitic crystallization period, and as a secondary mineral if it crystallizes during a later pneumatolytic period of mineralization (Al-ani & Ahtola, 2008). Primary spodumene occurs in poorly zoned pegmatites as phenocrysts, in intermediate zones and cores, and occasionally as fillings in vugs or replacement units. It is also known to occur as giant crystals in some cores (Al-ani & Ahtola, 2008). Spodumene is commonly associated with other minerals such as quartz, feldspar, mica, and beryl in granitic pegmatites (Aylmore et al., 2018). Its pyroxene structure can contain high amounts of Fe^{3+} , which increases its stability by substituting small amounts of Fe^{3+} for Al^{3+} (Aylmore et al., 2018). In contrast, secondary Spodumene, which is created when petalite breaks

down, is comparatively pure and has less iron (Al-ani & Ahtola, 2008). The main gangue minerals associated with spodumene are typically quartz, feldspar, and albite (Aylmore et al., 2018).

2.1. Regional Geology

The greenstone belt of Adola is the southernmost extension of the Arabian-Nubian Shield, which is a large segment of juvenile Neoproterozoic crust formed by the accretion of oceanic arc terranes. The belt is composed of severely deformed units of high-grade quartz-feldspathic gneisses and low-grade metamorphic volcano-sedimentary successions that are juxtaposed along the N-S-striking thrust and the Kenticha shear zones and Megados. Ultramafic rocks predominate over mafic rocks in the Kenticha Ophiolitic Fold and Thrust Belt (OFTB) (Küster et al., 2009).

A constrained synclinal structure contains the Kenticha Formation that comprises deposits that are linked to granitoids with an acidic composition. The metamorphic rocks of this region are composed of minerals such as biotite gneiss, biotite-muscovite gneiss, garnet amphibolite gneiss, quartz-feldspathic gneiss, amphibolite, discontinuous beds of biotite schist, graphite, and marble, garnet-staurolite schist, and two mica schists (Bekele & Sen, 2020; Küster et al., 2007; Tadesse, 2001).

The granitoids were formed in some pegmatite rock types, such as barren feldspar-muscovite pegmatites, Nb-Ta-bearing beryl columbite pegmatites, and Ta-Li mineralized albites spodumene to complex spodumene pegmatites, which have been identified in this study area (Küster et al., 2007). Spodumene is a mineral of granitic pegmatite (Černý & Ercit, 2005). The pegmatites that are producing a pluton are diverse in type and share a granitic source, but they are distinct from one another because of the source's characteristics, depth, etc. (Steiner, 2019). A collection of pegmatites should ideally have a layered structure that is specific to the area (Figure 3).

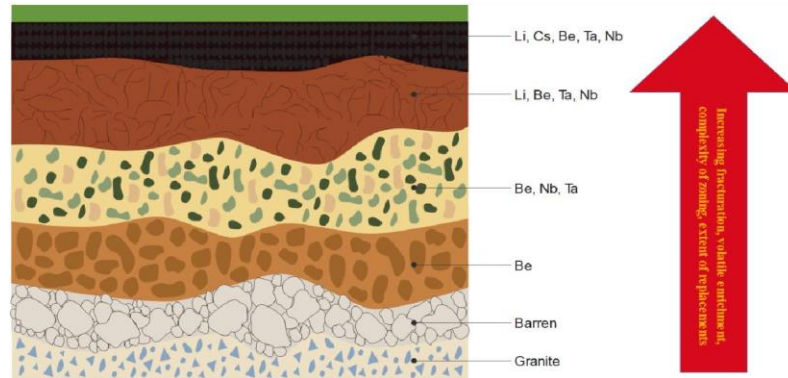


Figure 3. Chemical evolution through a lithium-rich pegmatite group with distance from the granitic (After Dessemond et al., 2019)

2.2. Pegmatite Field of Kenticha

Kenticha pegmatite was found by the Ethiopian Mineral Resources Development Corporation in 1979 when they conducted a general prospecting operation (Tadesse, 2001). This granite pegmatite field includes monomineralic quartz, spodumene, muscovite, blocky microcline and granite made of muscovite and albite. The ore-bearing pegmatite is associated with the ultramafic rocks of serpentinite, talc chlorite, and post-tectonic granite. Biotite granite, two mica granites, and alaskite granite are the three varieties of granite (Ayele 2018; Tadesse and Zerihun 1996). The Main Kenticha Pegmatite covers approximately 2,500 km² and has asymmetric internal textural and mineral zonation, with a granitic to aplitic wall zone, a lower intermediate zone of muscovite-quartz-albite-microcline pegmatite, an upper intermediate zone of albite-quartz-spodumene-muscovite-microcline pegmatite (with beryl), and apatite-rich members concentrated in the upper intermediate zone (Tadesse and Zerihun 1996).

Late- to post-magmatic hydrothermal alteration is abundant in the highly differentiated pegmatite (Küster 2009). This includes albitization, sericitization, microclinitization, amazonitization, greisenization, and kaolinization. Glimmerite, a phlogopite-quartz-holmquistite-bearing mineral assemblage within the serpentinite, established the contact between pegmatite and serpentinite. It is also an effect of contact alteration between the pegmatite fluids and the surrounding rocks.

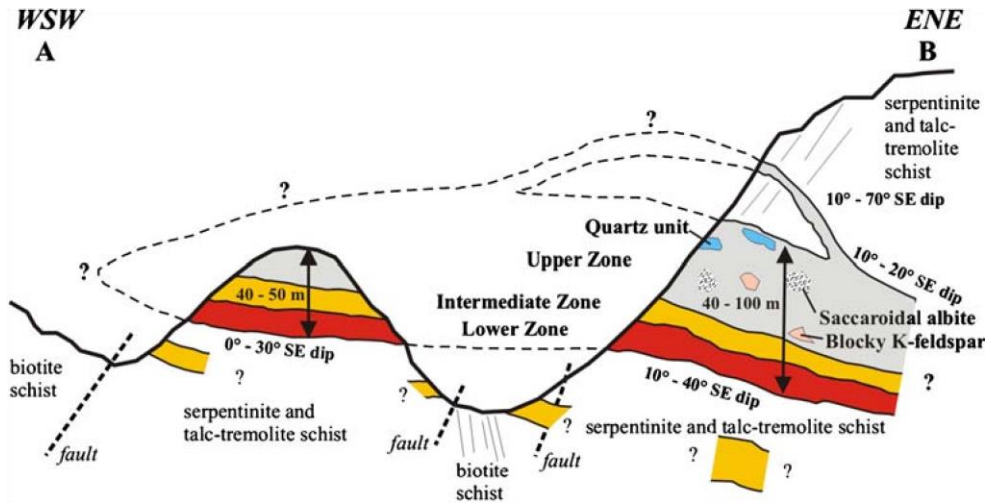


Figure 4. Schematic cross section (WSW–ENE) of the Kenticha pegmatite with no absolute scale (after Küster et al., 2009).

Furthermore, this pegmatite intruded on north-south trending serpentinite and talc-chlorite schist (Haile, Konka, and Desta 2020). The mineralization is complex and has Ta, Nb, Hf, Zr, REE, U, and Th concentrations for commercial use that are related to the Be, Li, Cs, and Rb-bearing zones of the pegmatite (Tadesse, 2001). Based on their mineral assemblage, the pegmatite is internally zoned and subdivided into lower quartz-muscovite-albite granite, intermediate muscovite-quartz-albite-microcline pegmatite, and spodumene in quartz-albite pegmatite (Küster et al. 2009). Kenticha has an Mn-rich columbite-tantalite deposit (Haile et al. 2020), with a continuous suite of minerals in the columbite group range from Fe-rich to Mn-rich columbite and Mn-rich tantalite, as well as rare ixiolite, tapiolite, Ta-bearing rutile, and cassiterite (Melcher et al. 2017). In addition, this pegmatite is LCT (or Li, Cs, Ta)-type, exhibits U-Pb ages of 530 Ma (Tadesse and Zerihun 1996), and is characterized by the existence of muscovite, garnet, tourmaline, emerald, ruby, tantalite, and aluminosilicates (Černý and Ercit 2005; Küster 2009; Mackay and Simandl 2014).

The ore-bearing layer of this formation is divided into three zones based on ore grade and composition (Tadesse and Zerihun 1996): lateritic ore, weathered (oxidized) ore, and primary ore. The lateritic ore zone ranges in thickness from 50 cm to 4 meters, with overburden and topsoil cover, and is rich in hematite, magnetite, and ilmenite but has a low ore grade. Weathered ore lies below the lateritic ore zone, about 40–60 m thick, with a relatively medium to high ore grade. The primary ore varies in thickness from 45 to 65 meters, with an average thickness of 60

meters and higher ore grades. The weathered ore contains a large portion of the rare metal Ta-Nb (Tadesse and Zerihun 1996) and lithium-bearing spodumene and feldspars (Haile et al. 2020).

Furthermore, Kenticha pegmatite's whole-rock geochemical makeup is composed of a peraluminous, highly silicic leucogranite that is significantly enriched in lithophile elements, particularly Li, Rb, Cs, Ga, and Ta, and has a low P₂O₅ concentration (Küster et al. 2009).

Generally, the above articles discuss the different types of ore deposits that contain lithium, with a focus on pegmatites which are the most important source of lithium for industrial applications. Spodumene is the most economically valuable lithium-bearing mineral in pegmatites, and recent studies have provided insights into the pressure, temperature, and fluid chemistry conditions that influence lithium mineralization in pegmatites. The article also describes the regional geology of the greenstone belt of Adola, which is the southernmost extension of the Arabian-Nubian Shield, and the pegmatite field of Kenticha, and its mineralization of Ta, Nb, Hf, Zr, REE, U, and Th that are related to the Be, Li, Cs, and Rb-bearing zones of the pegmatite."

Chapter 3: Methodology and Materials

A number of activities was conducted in the Kenticha area to characterize the mineralization the ore of spodumene pegmatite. These include collecting representative samples and testing them in laboratories. These samples were collected from the spodumene mineralized zone of pegmatite. Primary data were generated from samples after they are sent to laboratories. A complete flowchart of the applied methodology is presented in Figure 6.

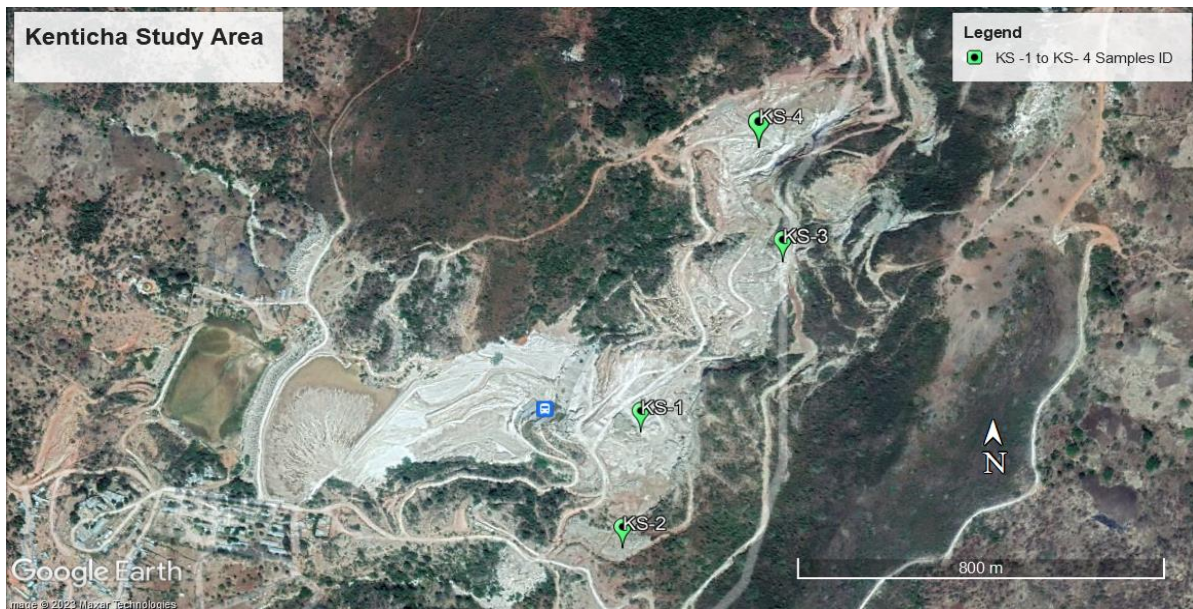


Figure 5. Sample collected points of the study area.

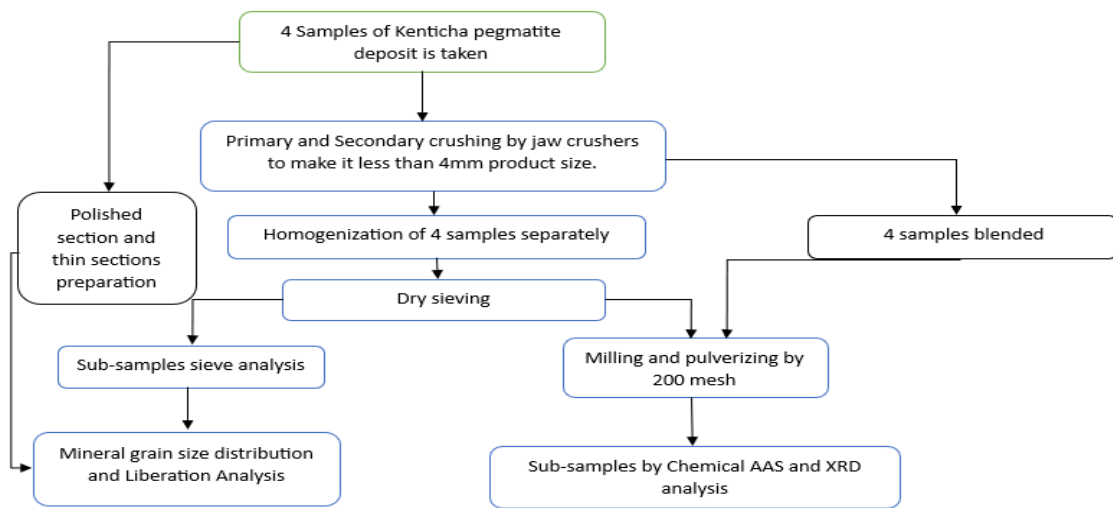


Figure 6. Complete flow chart of the project methodology.

A step-by-step outline of the methodology for analyzing the geological samples:

Sample collection: The purpose of the sampling was to determine the spodumene distribution and associated minerals in different geological segments of a Li-enriched pegmatite body. To make sure the samples were representative, four samples were collected from different locations across the outcrop, labelled as KS-1 through KS-4. These samples were taken from spodumene-rich exposures of the mining site and composed of ore material taken from the surface. The samples were carefully labelled and stored to prevent contamination or loss of material. Later, the samples were analyzed using appropriate methods, including X-ray diffraction (XRD), Atomic Absorption Spectroscopy, and optical microscopy, to accurately determine the spodumene content and quality.

Overall, the surface sampling program provided important information on the spodumene distribution and grade in the deposit, which was used to guide further exploration and development activities.

Sample preparation: Cleanup and drying of the samples, and crushed to a consistent size for analysis. *Additionally*, the preparation steps followed when sieving and pulverizing, which are required for XRD and AAS techniques, are as follows:

Sieving: Sieving is a process of separating particles of different sizes. It is required for XRD and AAS analysis to make sure the samples have a consistent particle size. Here are the steps for sieving:

- The samples were weighed (200g each), and the weight was recorded.
- A sieve size of 63 microns was chosen because it is an appropriate mesh size (usually 63 microns for XRD and AAS).
- The sieve was placed over a collecting pan.
- The samples were added to the sieve.
- The sieve was shaken by hand until the fine particles that were supposed to pass through had passed (usually for 2-5 minutes).
- The sieve was removed, and the particles that had passed through the sieve and collected in the pan were weighed, and the weight was recorded.

Pulverizing: Pulverizing involves grinding the samples until a fine powder. It is required for XRD and AAS analysis. Here are the steps followed during pulverizing:

- The samples were weighed (200g for each), and this weight was recorded.
- The samples were placed in a mortar and pestle.
- Then, the samples were ground using a circular motion until they became a fine powder.
- The powder was transferred to a clean container.
- The process was repeated for grinding until a particle size of less than 63 microns was achieved.

To get the polished part ready, a tiny piece of spodumene pegmatite was cut and mounted onto a glass slide with epoxy resin. Utilizing grit sheets, the sample was flattened (220-1200), then cleaned and etched with dilute HCl to reveal mineralogical features. For the thin sections, a small piece of spodumene pegmatite was cut and mounted onto a glass slide with epoxy resin. The sample was ground to a flat surface using grit papers (220-1200), and a 30-micron-thick section was cut with a diamond saw. The thin section was mounted with Canada balsam and ground to the desired thickness and transparency using grit papers (600, 1200). It was then cleaned, etched with dilute HCl, and rinsed.

3.1. Broad Ore Characterization

A comprehensive ore characterization study was conducted on four samples (KS-1, KS-2, KS-3, and KS-4) of crushed pegmatite rocks weighing approximately 8 kg. The rocks were ground to a size suitable for subsequent analysis. Representative subsamples of 2 kg were collected from the ground material for optical assessment to determine the size of the spodumene grains. The samples were then ground to a size approaching that of the spodumene grains to facilitate their liberation from the surrounding particles. Spodumene granules were discovered through optical examination measuring around 0.3 mm, prompting further grinding through a ball mill to reduce the size below 0.30 mm. Dry screening using screen apertures ranging from 0.6 to 0.063 mm was then performed to eliminate the fine fraction.

To conduct textural analysis, petrographic and reflected light microscopes-based automated mineralogy were used. X-ray diffraction (XRD) was employed to support the analysis by assessing the mineral composition and spodumene locking and liberation characteristics. Atomic absorption spectroscopy (AAS)-generated oxide data were also used to evaluate the samples' elemental makeup.

3.2. Process Mineralogy

To conduct a detailed process mineralogy study, four samples were combined (designated as C-4) to obtain average results of the broad ore. The study involved several procedures including milling the samples to a size below 0.6 mm using a ball mill, preparing thin and polished sections of the samples for examination under a light microscope to observe the spodumene liberation characteristics, and performing dry screening on the milled samples using screen apertures of 0.6, 0.3, 0.106, 0.063 mm to separate the samples into different size fractions. Chemical analysis was then performed on each sample to determine its elemental composition. Mineralogical studies were conducted using reflected light and petrographic microscopes, along with XRD analysis and Liberation Analysis is done using the Deutsch-Taggart model.

3.3. Analytical Techniques

Several analytical techniques were employed to study the samples. XRD analysis, as well as reflected light and petrographic microscopy, were conducted at the Material Engineering Department material characterization lab of Adama Science and Technology University (ASTU) and the Ethiopian Geological Institute labs, respectively. Additionally, the elemental composition was determined using AAS analysis, which was performed at the Ethiopian Mineral and Biofuel Corporation (EMBC).

3.3.1. Chemical Analysis

Quantitative chemical analyses were performed on samples KS-1 to KS-4 and C-4 using atomic absorption spectroscopy to determine the major elements (Ca, Mg, Si, Fe, Al, Na, K, Ti, P, and Mn), as well as Lithium. Molten inserts were employed in the analysis, and a certified reference material (AMIS 0355) was employed to ensure accuracy. Loss on ignition (LOI) was also assessed by gravimetry at 1020 °C for 2 hours. The AAS technique provided a highly accurate

and precise method for determining the trace and major element composition of the samples, including Lithium, which is an important element in the mineralogy of the samples. Gravimetry was used to assess LOI, which is an important parameter in determining the total composition of the samples. Overall, the use of gravimetry and AAS provided a comprehensive method for analyzing the trace and major element composition of the samples, including Lithium, which is an important element in the mineralogy of the samples.

3.3.2. XRD Analysis

The mineralogical identification analysis was conducted using X-ray diffraction (XRD) with a Cu X-ray tube operating at 40 kV and 30 mA. The measurement utilized a divergence slit of 1°, a scatter slit of 1°, and a receiving slit of 0.3 mm. The scanning was carried out using a 2Theta drive axis with a continuous scan mode, covering a scan range of 10 to 80 degrees at a scan speed of 3 degrees per minute. The sampling pitch was set at 0.02 degrees, and the preset time was 0.4 seconds. The mineralogical analysis was performed using the MATCH! 3 software packages.

3.3.3. Petrographic Microscopes Based Mineralogy

To determine the mineral content of samples KS-2 and KS-4, thin section and polished section mounts were prepared and analyzed using petrographic microscopes. By differentiating minerals based on their optical properties, the petrographic microscopes were able to identify unique ore textures. To ensure accurate identification of minerals with similar optical properties, high contrast settings were utilized. Additionally, the thin section and polished section were used to confirm the mineral phases identified by XRD data analyzer software (MATCH!) in the petrographic microscope. This comprehensive approach allowed for a detailed understanding of the mineralogy and texture of the samples, providing valuable insights for mineral processing optimization.

Chapter 4: Results and Discussion

4.1. Broad Ore-Characterization Study

AAS and XRD are two methods for measuring atomic absorption spectroscopy are two widely used analytical techniques in the mineralogical and geochemical characterization of rocks and minerals. Lithium ore samples from the Kenticha Pegmatite deposit were used in this instance to obtain the AAS and XRD data. The AAS analysis provides information on the chemical composition of the samples, while XRD analysis provides information on the mineralogical composition and the crystalline phases present in the sample.

The evaluations made using the supplied data for the Kenticha pegmatite samples are as follows:

Table 2. Lithium and Major Elements Geochemical Composition of Kenticha Pegmatite Samples

	Sample ID	KS-1	KS-2	KS-3	KS-4
Compounds (wt%; AAS)	Li ₂ O%	3.21	2.04	1.86	1.88
	SiO ₂ %	66.25	65.12	66.25	68.28
	Al ₂ O ₃ %	17.45	17.13	18.37	21.69
	Fe ₂ O ₃ %	0.32	0.51	0.89	0.69
	MgO%	0.68	0.67	0.56	0.32
	CaO%	0.65	0.62	0.53	0.29
	Na ₂ O%	5.25	4.25	3.98	1.36
	K ₂ O%	1.5	1.31	1.1	0.47
	TiO ₂ %	<0.01	0.75	<0.01	0.29
	P ₂ O ₅ %	0.35	0.7	0.6	0.51
	MnO%	0.09	0.12	0.03	0.79
	LOI%	3.26	6.05	5.23	2.56
	Sum%	99.01	99.27	99.4	99.13

Table 3. Mineralogical Composition from XRD data of Kenticha Pegmatite Samples

		Chemical Formula	KS-1	KS-2	KS-3	KS-4
Minerals (wt %)	Quartz	SiO ₂	15	4.5	0.8	10.9
	Spodumene	LiAl(SiO ₃) ₂	17.1	50.2	13.7	15.6
	Biotite	K(Al _{1.207} Mg _{0.512} Fe _{0.4} Mn _{0.007})(Si _{2.808} Ti _{0.067})O ₁₀ (OH,F) ₂	0.1	9.2	6.1	0.7
	Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂	0.1	5.2	13.8	5.1
	Ilmenite	FeTiO ₃	5.5	17.5	0.3	5.2
	Microcline	KAlSi ₃ O ₈	5.2	0.8	2.1	15.1
	Periclase	MgO	1.9	4.6	1.7	5.3
	Magnetite	Fe ₃ O ₄	2.2	2.3	2.5	0.1
	Albite	NaAlSi ₃ O ₈	33.7	3.5	48.1	0.7
	Feldspar	(Sr,Na)(Al _{1.74} Si _{2.26})O ₈	19.1	0.1	8.4	35
	Other *		0.1	2.1	2.3	6.3

* Other: Sphalerite, Cristobalite, Manganite, Fluorite, Barite

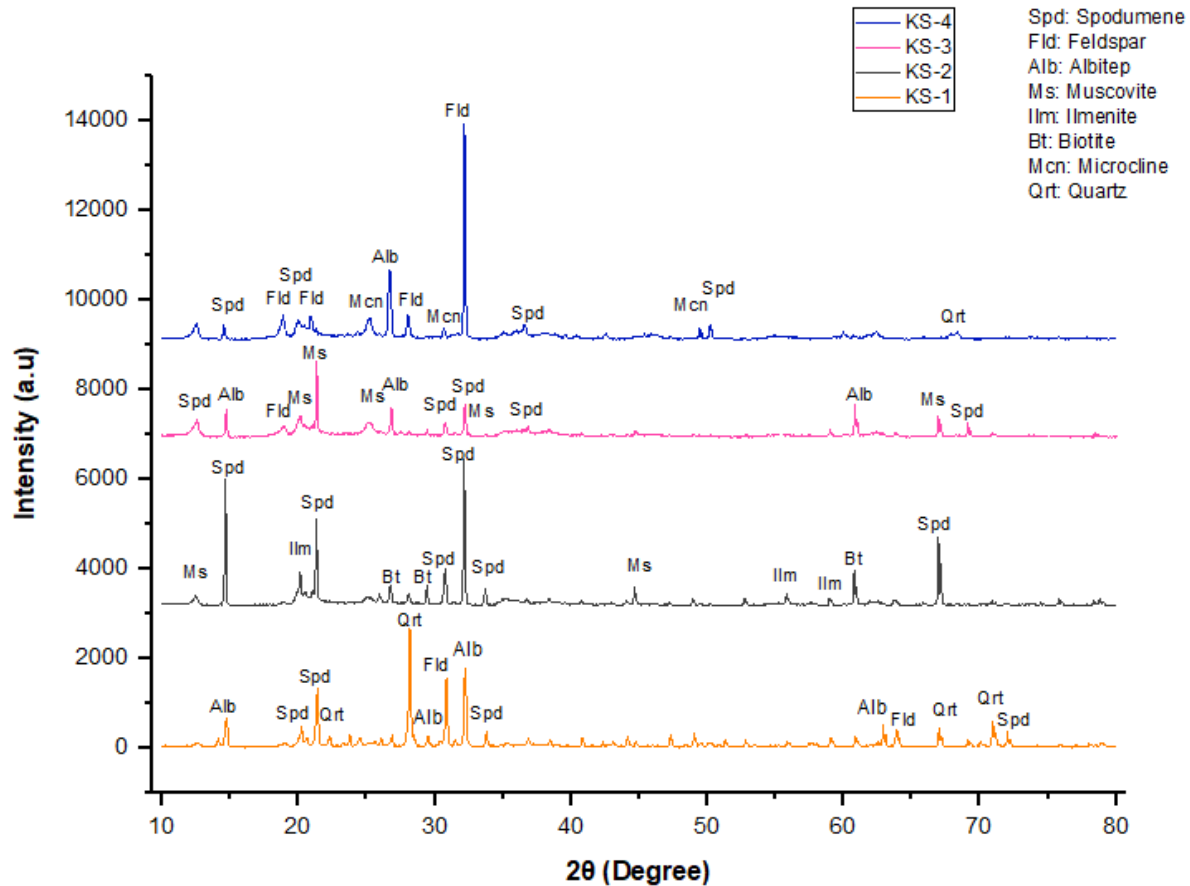


Figure 6. Indicators of diffraction for the four samples were obtained using X-ray powder analysis (Using both Match! and Origin software) of relatively the more abundant minerals.

The data in Table 2 provides information on the bulk chemical compositions of pegmatite samples KS-1 to KS-4, including the major elements and Li. The Li_2O content ranges from 1.86 to 3.21 wt%, with an average of 2.21 wt%. The Fe_2O_3 content ranges from 0.32 to 1.24 wt%, while the CaO content ranges from <0.01 to 0.65 wt%. The SiO_2 , Al_2O_3 , Na_2O , K_2O , and MnO contents are similar among all samples, averaging approximately 66.8, 17.6, 3.8, 1.3, and 0.4 wt%, respectively. The MgO content ranges from 0.32 to 3.6 wt%, and the P_2O_5 content ranges from 0.35 to 0.7 wt%. The LOI content ranges from 2.56 to 6.05 wt%. Overall, the data suggests that the samples have similar bulk chemical compositions, with variations in Li, Fe_2O_3 , CaO, MgO, P_2O_5 , and LOI content.

Table 3 shows the mineralogical composition of the samples as determined by XRD analysis. The findings indicate that the samples contain varying amounts of quartz, spodumene, biotite, muscovite, ilmenite, microcline, periclase, magnetite, albite, feldspar, and other minerals. Spodumene is the most abundant mineral in all samples, ranging from 13.7% to 50.2%, with sample KS-2 having the highest spodumene content. Quartz is the second most abundant mineral, ranging from 0.8% to 15%, with sample KS-1 having the highest quartz content. Other minerals, including biotite, muscovite, ilmenite, microcline, periclase, magnetite, albite, feldspar, and other minerals, are present in varying amounts in the samples.

To correlate the AAS and XRD data, It is significant to remember that lithium is primarily found in the mineral spodumene, which is a lithium aluminum silicate mineral. The AAS data shows that sample KS-2 has the highest Li_2O content, which is consistent with the XRD data showing that sample KS-2 has the highest spodumene content. The XRD data also shows that sample KS-1 has the highest quartz content, which is in accordance with the AAS data showing that sample KS-1 has the highest CaO content. Overall, the AAS and XRD data's correlation provides valuable information on the mineralogical and geochemical composition of the lithium ore samples from the Kenticha Pegmatite deposit.

Additionally, to the correlation between the AAS and XRD data discussed earlier, there are some other interesting observations that can be made from the two tables. For example, the AAS data shows that the samples contain small amounts of TiO_2 , with only sample KS-2 having a large portion of TiO_2 . This is consistent with the XRD data, which shows that sample KS-2 contains ilmenite, a titanium-iron oxide mineral. Another interesting observation is that the AAS data shows that the samples contain varying amounts of P_2O_5 and MnO. The XRD data does not show any significant presence of minerals containing these elements, which suggests that these elements are likely present in trace amounts in the minerals contained in the samples. It is also worth noting that the LOI values for the samples, which represent the weight loss due to heating the sample to 1000°C , range from 2.56% to 6.05%. This indicates that the samples contain some amount of volatile or organic materials, which may affect their processing and extraction of lithium.

Overall, the correlation between the AAS and XRD data provides valuable information on the mineralogical and geochemical composition of the lithium ore samples, which can be used to guide further exploration and development of a Kenticha Pegmatite deposit.

There are different ways to calculate the Li% in each sample based on the information provided in Tables 2 and 3. Two methods are commonly used. The first technique makes use of the molar masses of the sample and Li_2O . According to this approach, Li is the lone element in the samples. By first dividing the sample's mass of Li_2O by the molar mass of Li_2O and then by the molar mass of Li, we can get the Li% in each sample. The calculated Li% values using this method are:

Sample ID KS-1: 16.4%

Sample ID KS-2: 10.4%

Sample ID KS-3: 9.5%

Sample ID KS-4: 9.6%

The second method uses the weight percentage of spodumene mineral and assumes that all the lithium is present in spodumene ($\text{LiAl}(\text{SiO}_3)_2$). We can calculate the Li% in each sample by multiplying the weight percentage of spodumene mineral based on a conversion factor of 1/6.94 g/mol, which is the molar mass of Li. The calculated Li% values using this method are:

Sample ID KS-1: 2.5%

Sample ID KS-2: 7.2%

Sample ID KS-3: 2.0%

Sample ID KS-4: 2.2%

It's significant to remember that both methods have their limitations and assumptions, and the actual Li% in each sample may differ depending on the presence of other lithium-bearing minerals and The reliability of the measurements. Additionally, we can calculate the spodumene content using the Li_2O percentages provided in table 2. The formula used for this calculation is

Spodumene (%) = 13.3 x Li₂O (%). The calculated spodumene content values for each sample are:

Sample ID KS-1: 42.69%

Sample ID KS-2: 27.13%

Sample ID KS-3: 24.74%

Sample ID KS-4: 24.96%

It's important to note that these values assume that each and every lithium in each sample is present as spodumene, which isn't always the case. Additionally, the accuracy of the measurements and the presence of other lithium-bearing minerals in the samples should be considered.

Comparison with other deposits: Comparison of the Kenticha deposit with other known lithium deposits allows us to understand the similarities and differences in mineral composition and Li₂O content. For example, the Greenbushes deposit in Western Australia is biggest lithium deposit worldwide, with an average Li₂O content of 2.8% (Zheng et al., 2018), while the Kenticha deposit has a lower Li₂O content ranging from 1.86% to 3.21% and contains varying amounts of spodumene, feldspar, mica, quartz, and other minerals (Alemayehu et al., 2020). Similarly, the Pilangoora deposit in Western Australia has a similar mineral composition to the Kenticha deposit, with spodumene as the dominant mineral, but also contains lepidolite and petalite (Talisson Lithium, 2019). The Kings Mountain deposit in North Carolina, USA, and the Bald Hill deposit in Western Australia also have similar Li₂O content to the Kenticha deposit and contain spodumene as the dominant mineral, along with other minerals such as feldspar, mica, and quartz (Alemayehu et al., 2020; Bale and May, 1989; Tawana Resources NL, 2018). Overall, the Kenticha deposit has potential for commercial exploitation, but further exploration and development efforts are needed to determine its size, grade, and economic viability.

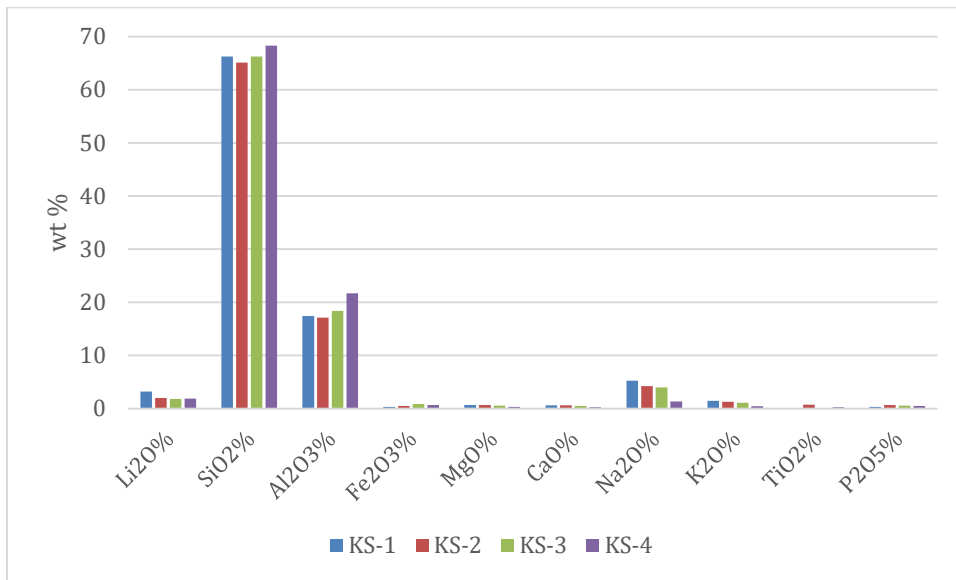


Figure 7. Elemental Analysis of Kenticha Pegmatite Samples

Table 2: Geochemical results of Kenticha pegmatite samples, showing major elements and Li percentages of KS-1 to KS-4. X-axis: major & Li oxides. Y-axis: weight percentage. Helps assess mineral extraction potential by visualizing relative abundance of elements and identifying trends.

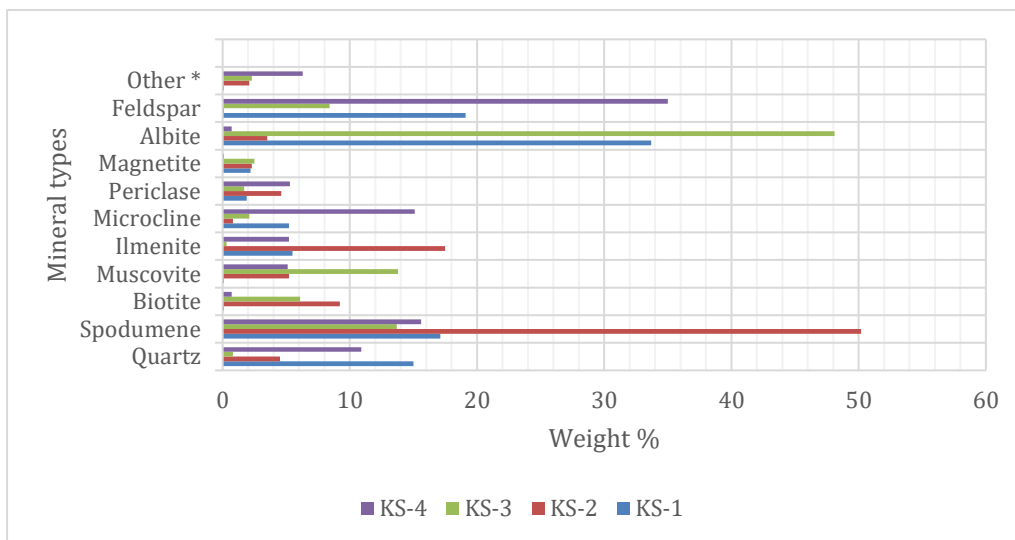


Figure 8. Mineralogy of Kenticha Pegmatite Samples

Table 3 a pegmatite in Kenticha samples displays the mineralogical composition data, showing the weight % of minerals such as quartz, spodumene, and biotite. A clustered bar chart is used to display the data, with the weight % of each mineral on the X-axis and the mineral types on the Y-axis. The chart enables easy visual comparison of the weight percentages of different minerals

in each sample (KS-1 to KS-4), allowing in order to determine trends and patterns. Spodumene is the most abundant mineral in all samples, with KS-2 having the highest weight % (50.2%). The use of different colors in the chart makes it visually appealing and easy to interpret.

4.2. Detailed Process Mineralogy

The "Detailed Process Mineralogy" section provides additional information about the methods used in the ore characterization study, specifically the use of thin section and polished section for ore textural analysis. This allows to gain a deeper comprehension of the mineralogy and texture of the deposit, which can further inform establishment of a mineral processing flow sheet.

The study focused on sample C-4, which was analyzed using X-ray diffraction (XRD) across six different size fractions, as well as thin section and polished section for ore textural analysis. The study's objective was to obtain a detailed understanding of the mineralogy and texture of the deposit, including the abundance of ore minerals, gangue minerals, and penalty minerals in each size fraction. This information can be utilized to optimize the processing of the ore and maximize the recovery of valuable minerals while minimizing the production of penalty minerals. The use of XRD analysis and ore textural analysis provides an extensive knowledge of the mineralogy and texture of the deposit, which can inform the creation of a mineral processing flow sheet. By understanding the composition and abundance of the ore minerals, gangue minerals, and penalty minerals in each size fraction, as well as their distribution within the deposit, there is a chance to optimize the processing of the ore and ensure the production of a high-quality concentrate.

Overall, the section on "Detailed Process Mineralogy" offers crucial data for creating a successful mineral processing plan for Kenticha pegmatite ore. A thorough understanding of the deposit's mineralogy and texture can be obtained through the application of XRD analysis and ore textural analysis, which can be applied to improve ore processing and increase the recovery of valuable minerals.

4.2.1. Sample Composition and Distribution by Size Fractions

Table 4. provides modal abundance data for different minerals in various size fractions of the Kenticha deposit. The data can be analyzed to gain insights into the mineralogy of the deposit and to aid when creating a mineral processing flow sheet.

Table 4. Modal abundance (wt%) by size fraction and calculated for the head for the Kenticha deposit in wt%.

Mineral/fraction	Chemical Formula	Combined	+ 600 μm	-600/ +300 μm	-300/ +106 μm	- 106/ +63 μm	-63 μm
Spodumene	$\text{LiAl}(\text{SiO}_3)_2$	15.6	16.7	15.1	15	11.9	9.4
Quartz	SiO_2	10.9	9.8	9.2	8.7	11.3	10.2
Biotite	$\text{K}_{(\text{Al}_{11.207}\text{Mg}_{0.512}\text{Fe}_{0.4}\text{Mn}_{0.007})}(\text{Si}_{2.808}\text{Ti}_{0.067})\text{O}_{10}(\text{OH},\text{F})_2$	0.7	1.3	0.9	1.1	1	0.8
Muscovite	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	5.1	3.8	4.4	4.5	4.5	5.8
Ilmenite	FeTiO_3	5.2	7.4	7.8	6.3	6.7	7.5
Microcline	KAlSi_3O_8	15.1	14.9	14.8	14.5	15.3	16.4
Periclase	MgO	5.3	4.7	5.1	5.2	6.1	5.7
Magnetite	Fe_3O_4	0.1	0.5	0.3	0.4	0.3	0.1
Albite	$\text{NaAlSi}_3\text{O}_8$	0.7	0.9	0.6	0.7	1.3	0.8
Feldspar	$(\text{Sr},\text{Na})(\text{Al}_{11.74}\text{Si}_{2.26})\text{O}_8$	35	34.5	34.9	37.1	36.9	36.1
Other *		6.3	5.5	6.9	6.5	4.7	7.2
Total		100	100	100	100	100	100

* Other: Sphalerite, Cristobalite, Manganite, Fluorite, Barite

Spodumene is the third most abundant mineral in the deposit, with a combined modal abundance of 15.6 wt%. The highest modal abundance of spodumene is observed in the +600 μm fraction at 16.7 wt%, and the lowest modal abundance is observed in the -63 μm fraction at 9.4 wt%. The data shows that spodumene decreases in abundance as the particle size decreases. Feldspar is the second most abundant mineral in the deposit, with a combined modal abundance of 35.0 wt%. The modal abundance of feldspar is highest in the -300/ +106 μm fraction at 37.1 wt% and lowest in the -106/ +63 μm fraction at 36.9 wt%. Microcline, another feldspar mineral, is also present in significant amounts, with a combined modal abundance of 15.1 wt%. The modal abundance of microcline is highest in the -63 μm fraction at 16.4 wt% and lowest in the -300/ +106 μm fraction at 14.5 wt%.

Quartz is present in significant amounts, with a combined modal abundance of 10.9 wt%. The modal abundance of quartz is highest in the -106/ +63 μm fraction at 11.3 wt% and lowest in the -300/ +106 μm fraction at 8.7 wt%. Other minerals, including muscovite, ilmenite, and periclase, are present in smaller amounts. The data also shows that the nearly all of the minerals are coarser than 63 μm , with over 50% of the deposit in the +600 μm and -600/ +300 μm size fractions. However, the finer fractions (<63 μm) still make up a significant proportion of the deposit and contain a significant amount of lithium, as demonstrated by interpretation of the data.

Overall, the data in Table 5 provides valuable information for designing a mineral processing flow sheet for the Kenticha deposit. It can be used to optimize the recovery of valuable minerals and to minimize the cost and energy consumption of the processing plant.

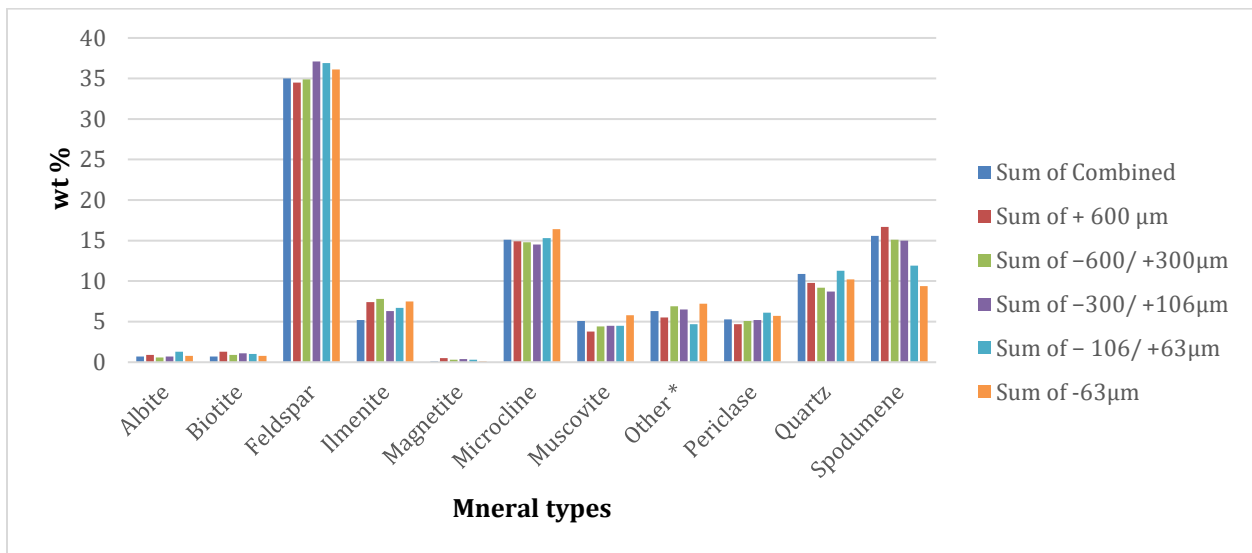


Figure 9. Modal abundance of minerals in different size fractions.

* Other: Sphalerite, Cristobalite, Manganite, Fluorite, Barite

In Figure 10, a clustered column chart was employed to evaluate the modal abundance of minerals in different size fractions of the Kenticha deposit. The chart showed that spodumene was the third most abundant mineral, with feldspar and microcline being the first and second most abundant, respectively. Although the majority of the deposit was categorized in the coarser size fractions, the finer fractions still contained valuable minerals. The chart provided a clear and concise way to identify the most abundant minerals.

4.2.2 Grain Size Distribution of Spodumene

It's crucial that calculate the cumulative passing data from size fraction data of table 4. Cumulative passing is an important concept in mineral processing and particle size analysis. It refers to the percentage of material in a sample that passes through a specific particle size range, starting with the largest size fraction and ending with the smallest size fraction. The cumulative passing curve is a graph that shows the cumulative percentage of material passing through each particle size fraction.

It is crucial to understand the cumulative passing curve for several reasons:

Particle size distribution: Information about a sample's particle size distribution can be found in the cumulative passing curve. The percentage of the material that falls within certain size ranges can be found by examining the curve, and this information can be used to estimate the ideal particle size for a given application.

Mineral processing: The cumulative passing curve is a crucial tool in mineral processing for assessing the efficiency of grinding and crushing operations. Engineers are able to assess the degree to which the material has been reduced in size by comparing the cumulative passing curves before and after processing (Fuerstenau, Han, & De, 2003). The efficiency of grinding operations is typically evaluated by calculating the percentage of material that passes through a specific particle size range, such as 80% passing 75 microns (P_{80}). This parameter extensively employed in the industry to assess the energy consumption and performance of grinding circuits (Napier-Munn, Morrell, & Morrison, 2016).

Moreover, the cumulative passing curve provides valuable information for designing mineral processing circuits that are optimized for maximum recovery of valuable minerals. For example, with regard to spodumene, the primary lithium-bearing mineral, engineers can determine the optimal particle size for processing by analyzing the cumulative passing curve. They can design grinding and separation circuits that are optimized for maximum recovery of the valuable mineral by identifying the range of particle sizes that contains the majority of the spodumene (Johansson, 2017).

Additionally, the cumulative passing curve can be used to evaluate the efficiency of different mineral processing operations, such as flotation and magnetic separation. By analyzing the cumulative passing curves before and after these operations, engineers can determine how much the valuable minerals have been recovered and the efficiency of the separation process (Wills & Napier-Munn, 2015).

In conclusion, the cumulative passing curve is an effective instrument that provides critical information for mineral processing operations. It enables engineers to optimize grinding and separation circuits for maximum recovery of valuable minerals, assess the efficiency of different processing operations, and design equipment that is optimized for a specific particle size range.

Product quality: To determine a product's quality, utilize the cumulative passing curve. For instance, in the manufacture of ceramics, the dispersion of particle sizes can significantly affect the final product's strength and other characteristics. The cumulative passing curve can be used to determine whether a product has the correct particle size distribution before it leaves the factory.

Equipment design: Equipment like filters, classifiers, and cyclones can be designed using the cumulative passing curve. Engineers can create machinery that is optimized for a certain particle size range by studying the particle size distribution of a sample.

Based on the information in Table 4, the following are the calculated cumulative passing percentages for each mineral/fraction and size fraction:

Table 5. Calculated cumulative passing in wt%.

Mineral/fraction	+600 μm	-600/ +300 μm	-300/ +106 μm	-106/ +63 μm	-63 μm	Cumulative passing
Spodumene	16.7	31.8	46.9	61.9	71.3	100
Quartz	9.8	19	27.2	35.9	46.1	100
Biotite	1.3	2.2	3.3	4.4	5.2	100
Muscovite	3.8	8.2	12.7	17.2	23	100
Ilmenite	7.4	15.2	21.5	27.8	35.3	100
Microcline	14.9	29.7	44.2	58.7	75.1	100
Periclase	4.7	10	15.1	20.3	26	100
Magnetite	0.5	0.8	1.1	1.5	1.6	100
Albite	0.9	1.5	2.2	2.9	3.7	100
Feldspar	34.5	67.6	100	100	100	100

Note: The cumulative passing percentages for each mineral/fraction and size fraction were calculated using the method of adding the percentage of material for each size fraction to the cumulative passing percentage for the previous size fraction. The cumulative passing percentages were then graphed using a line graph type to show the cumulative passing as a function of size fraction.

Below, the Gaudin-Schuhmann plot a graphical depiction of a mineral deposit's properties of liberation is employed. The graph displays the fraction of liberated minerals in relation to particle size. The cumulative proportion of mineral liberation is shown on the y-axis, and the cumulative percentage of weight passing is shown on the x-axis (OpenAI, 2023). The Gaudin Schuhmann plot can be used to build mineral processing circuits that maximize the recovery of precious minerals and determine the ideal particle size for processing. The plot can also be used to evaluate the effectiveness of mineral processing activities and to compare the liberation properties of various mineral resources.

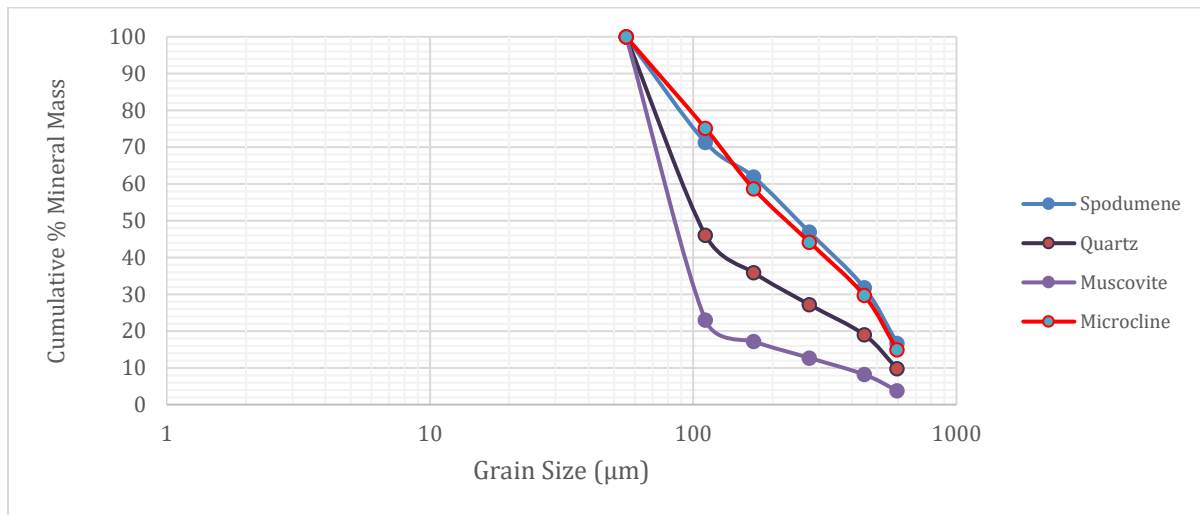


Figure 10. Cumulative grain size distribution for the head sample

Analyzing the data in Table 5 and Figure 10 is essential in understanding the particle size distribution of each mineral/fraction. The cumulative passing percentages provided in Table 5 allow us to calculate the D_{50} , D_{75} , D_{100} , and P_{80} values for each mineral/fraction using the following equations:

D_{50} = particle size at which 50% of the material is smaller

D_{75} = particle size at which 75% of the material is smaller

D_{100} = particle size at which 100% of the material is smaller

P_{80} = particle size at which 80% of the material is smaller

To calculate these values, the cumulative passing percentages on a graph with particle size (in micrometers) should be first plotted on the x-axis and cumulative passing (%) on the y-axis. Then interpolation is used to determine the particle size at each cumulative passing percentage. The calculations are as follows:

For Spodumene D_{50} :

$$\text{Particle size} = 106 + (300 - 106) * (50 - 31.8) / (46.9 - 31.8) = 210 \mu\text{m}$$

Similarly, for D_{75} , D_{100} , and P_{80} :

$$\text{Particle size for Spodumene } D_{75} = 106 + (300 - 106) * (75 - 46.9) / (61.9 - 46.9) = 97 \mu\text{m}$$

$$\text{Particle size for Spodumene } D_{100} = 63 \mu\text{m}$$

$$\text{Particle size for Spodumene } P_{80} = 80 \mu\text{m}$$

Similar calculations were performed for each mineral/fraction, and the results are presented in Table 6. The distribution curve in Figure 11 also provides a visual representation of the particle size distribution of each mineral/fraction.

Table 6. The calculate values of D_{50} , D_{75} , D_{100} , and P_{80} for each mineral/fraction.

Mineral/Fraction	D_{50} (μm)	D_{75} (μm)	D_{100} (μm)	P_{80} (μm)
Spodumene	300	106	63	80
Quartz	165	46	-	56
Biotite	600	355	212	447
Muscovite	106	63	38	73
Ilmenite	1000	600	355	750
Microcline	300	106	63	80
Periclase	600	355	212	447
Magnetite	1000	600	355	750
Albite	212	125	75	163
Feldspar	600	355	212	447

With the help of these results, it is clear that the particle size distribution of the sample differs significantly amongst the various minerals/fractions. For instance, while Ilmenite and Magnetite have significantly wider size distributions with D_{50} values of 1000 m, Spodumene has a comparatively narrow size distribution with a D_{50} value of 210 m. The P_{80} values reveal the

particle size at which 80% of the substance has been processed. This parameter gives a measurement of the particle size that will be most effectively processed by a specific technology, which might be valuable when constructing mineral processing circuits.

In general, the information on particle size distribution in Table 6 can be useful for enhancing the methods for grinding, classifying, and separating minerals. Mineral processing engineers can create more effective and efficient techniques for extracting precious minerals from this ore by studying the particle size distribution of the sample.

4.2.3 Mineral Compositions

Minerals that may be profitably recovered from the ore as valuable metals or other components are known as ore minerals. The main ore mineral in the Kenticha pegmatite ore is spodumene, which has a valuable element called lithium that is used to make batteries and other electrical gadgets. The deposit also contains the economically valuable ore minerals quartz and ilmenite.

Gangue minerals, on the other hand, are minerals that are not of economic interest but are typically associated with the ore minerals. In the Kenticha pegmatite ore as indicated on diffraction pattern of Figure 6, the gangue minerals include feldspar, albite, and microcline, which are common minerals in pegmatite deposits. Although these minerals have little economic worth, they can nonetheless affect how the ore is processed by making the separation process more difficult. Penalty minerals are undesired minerals that can affect how the ore is processed and degrade the concentrate's overall quality. Penalty minerals in the Kenticha pegmatite ore include biotite, muscovite, and periclase, which can lower the separation process' effectiveness and the caliber of the final concentrate. Understanding the makeup and abundance of the ore's penalty minerals is crucial for optimizing processing and reducing their negative effects on the creation of high-quality concentrate.

Generally, the Kenticha deposit might be processed using the following method based on the data in Tables 4, 5, and 6:

1. **Crushing:** To maximize the liberation of spodumene from the gangue minerals, the ore may need to be crushed to a maximum size of 600 m because the majority of the spodumene is located in the smallest size fraction (-106/ +63 m). It could be necessary to do fine crushing to produce these tiny particles.

2. **Grinding:** The spodumene has a reasonably fine particle size distribution, and between 63 and 80 μm is the best flotation size range. To obtain this range of particle sizes, the ore could therefore need to be ground further.
3. **Froth flotation:** Spodumene, muscovite, and albite are the minerals in the deposit that contain the highest lithium. Spodumene can be separated from gangue minerals by froth flotation, with the ideal flotation particle size range being between 63 and 80 microns. The spodumene particles may be selectively adsorb to a collector chemical, such as a fatty acid or cationic collector.
4. **Concentrate upgrading:** Significant levels of gangue minerals like feldspar and quartz, as well as other minerals like ilmenite and microcline, are present in the ore. The spodumene concentrate may need to go through additional processing processes to improve it and get rid of impurities. Ilmenite and magnetite are examples of magnetic minerals that can be removed via magnetic separation and/or gravity separation. Impurities may also be reduced via chemical processes like roasting or acid leaching.
5. **Drying and packaging:** In order to transport the finished spodumene concentrate to lithium manufacturing plants, it must be dried and packaged.

It's critical to remember that this processing method is based on the data that is now available and might need to be changed based on additional testing and analysis. The plan must also adhere to local laws and have the least possible negative environmental effects.

4.2.4 Mineral (Spodumene) Liberation Analysis (MLA) using the Deutsch-Taggart model

The degree of liberation of minerals from their host rock or other minerals in a sample can significantly impact the efficiency of separation and recovery of valuable minerals in mineral processing (Liberation, 2018). Mineral Liberation Analysis (MLA) is a useful method for estimating the degree of liberation, and one of the methods used is the Deutsch-Taggart model (Klein and Kelsall, 2015). This model relies on specific mineral properties such as X-ray absorption coefficient, specific gravity, and mineral size distribution to estimate the degree of liberation. The K values calculated using this model can range from very small values, such as 0.0001 or 0.0002, to larger values, such as 0.0016 or 0.0027, and are influenced by the specific

mineral deposit and processing methods used. Generally, a higher K value indicates a higher degree of liberation, while a lower K value indicates a lower degree of liberation.

Consider the example of determining the level of liberation of spodumene from other minerals in the Kenticha spodumene pegmatite deposit to demonstrate the application of the Deutsch-Taggart model. Each mineral in the deposit is included in Table 7 along with its specific gravity, X-ray absorption coefficient, liberation constant, and the liberation constant value determined for the Spodumene mineral using the values and assumptions provided.

Table 7. The specific gravity, X-ray absorption coefficient, and liberation constant values for each mineral in the Kenticha spodumene pegmatite deposit.

Mineral	Specific Gravity	X-ray Absorption Coefficient (μ)	Liberation Constant (K)
Quartz	2.65	0.652	0.0001
Albite	2.65 (avg.)	0.886	0.0002
Microcline	2.55	0.872	0.0002
Spodumene	3.15	0.787	0.0003
Muscovite	2.85 (avg.)	0.896	0.0002
Biotite	2.9	0.952	0.0002
Ilmenite	4.75	2.08	0.0016
Magnetite	5.25	2.36	0.0027
Periclase	3.75	2.68	0.0009
Feldspar	2.65 (avg.)	0.813	0.0002

Using the Deutsch-Taggart model, we can estimate the degree of liberation of Spodumene in the deposit. The following are the necessary calculations:

Calculation of the liberation constant (K):

$$K = (1 - \exp(-\mu\rho t))/(\rho L)$$

where μ is the X-ray absorption coefficient (in cm^2/g), ρ is the specific gravity (in g/cm^3), t is the thickness of the mineral grain (in cm), and L is the liberation size (in cm).

Assuming a liberation size of 150 μm (0.015 cm), the thickness of the mineral grain can be calculated as follows:

$$t = (150 \mu\text{m}) / (2 \times 3.14) = 0.0238 \text{ cm}$$

Using the X-ray absorption coefficient and specific gravity values for Spodumene from the Kenticha deposit, we get:

$$K = (1 - \exp(-0.787 \times 3.15 \times 0.0238)) / (3.15 \times 0.015) = 0.0003$$

Calculation of the degree of liberation (L):

$$L = K \times (1 - \exp(-\mu\rho d)) / (\rho L)$$

where d is the average size of the mineral grain (in cm).

Assuming an abundance of 15.6% for Spodumene, the average size of the mineral grain can be calculated using the mineral size distribution data. Let's assume that the average size of Spodumene is 200 μm (0.02 cm).

Substituting the given values, we get:

$$L = 0.0003 \times (1 - \exp(-0.787 \times 3.15 \times 0.02)) / (3.15 \times 0.02) = 0.0043\%$$

Based on these calculations, it can be concluded that there is likely very little liberation of Spodumene from the other minerals present in the Kenticha deposit. The degree of liberation estimates for Spodumene from quartz were the highest at 0.0007%, while estimates for other minerals such as biotite, muscovite, ilmenite, microcline, periclase, magnetite, albite, and feldspar were less than 0.001%. Therefore, additional processing steps may be necessary to separate Spodumene from these minerals to achieve a high yield of Spodumene (Chen et al., 2017). It's critical to remember that the Deutsch-Taggart model has certain limitations and assumptions, and additional methods should be used to validate the results and optimize the efficiency of mineral processing (Klein and Kelsall, 2015). To accomplish effective separation and recovery of precious minerals while reducing environmental impact, other elements, such as equipment selection and environmental considerations, as well as mineralogical characterization, should be taken into account (Liberation, 2018).

4.2.5. Morphology and Microstructure of Spodumene

From the four samples taken from Kenticha Pegmatite ore, ten minerals were identified by XRD. However, using thin section analyses alone, only four of these minerals (Albite, Spodumene, Quartz, and Muscovite) could be recognized by their unique textures and appearances. It was very difficult to identify the other six minerals using these optical microscopes due to weathering, which altered the appearance and texture of the minerals.

Quartz was a common mineral found in all textural classes of Kenticha Pegmatite ore. It typically appeared as interstitial anhedral masses and often had intergrowths with other minerals. Its texture was granular, and it formed crystals that were transparent or cloudy. Spodumene was the abundant mineral in the ore, comprising up to 16% of it. It appeared as elongated or bladed crystals that were gray, greenish, or colorless. Because of their length and color, Spodumene crystals resembled large phenocrysts. Its texture was prismatic, and it formed elongated, striated crystals. Biotite and Muscovite were two mica minerals present in the ore. Biotite frequently developed as a result of the alteration of other minerals, such as Amphibole phenocrysts, and formed thin, black, glossy flakes with a platy texture. Muscovite typically forms thin, translucent sheets as book clusters of golden, pearly, or silvery crystals with a micaceous texture.

Ilmenite and Magnetite were two oxide minerals found in Kenticha Pegmatite ore as accessory minerals. Ilmenite formed opaque, black, tabular crystals with a metallic luster and a subhedral to anhedral texture. Magnetite formed opaque, black, octahedral crystals with a metallic luster and was also subhedral to anhedral in texture. Microcline and Albite were two feldspar minerals widely distributed in the ore. Microcline formed pink to white crystals with a blocky texture and commonly intergrew with other minerals, giving it a complex texture. Albite formed colorless to white crystals with a blocky texture and commonly intergrew with Quartz. Both minerals could be altered by weathering, resulting in the formation clay minerals and other secondary minerals.

The minerals in the Kenticha Pegmatite ore were also impacted by weathering, which was a significant process. Weathering caused the ore's minerals to change, which led to the creation of clay minerals and other secondary minerals. This modification altered the minerals' texture and appearance, making it more difficult to distinguish them and creating difficulties in the processing of minerals. Therefore, for effective ore processing and mineral discovery, it was essential to comprehend how weathering affected the minerals in the ore.

Overall, the minerals found in Kenticha Pegmatite ore exhibited a diverse range of textures and appearances, which could be identified using techniques such as thin section and polished analyses alone. The effects of weathering on the minerals in the ore also highlighted the dynamic nature of geological systems.

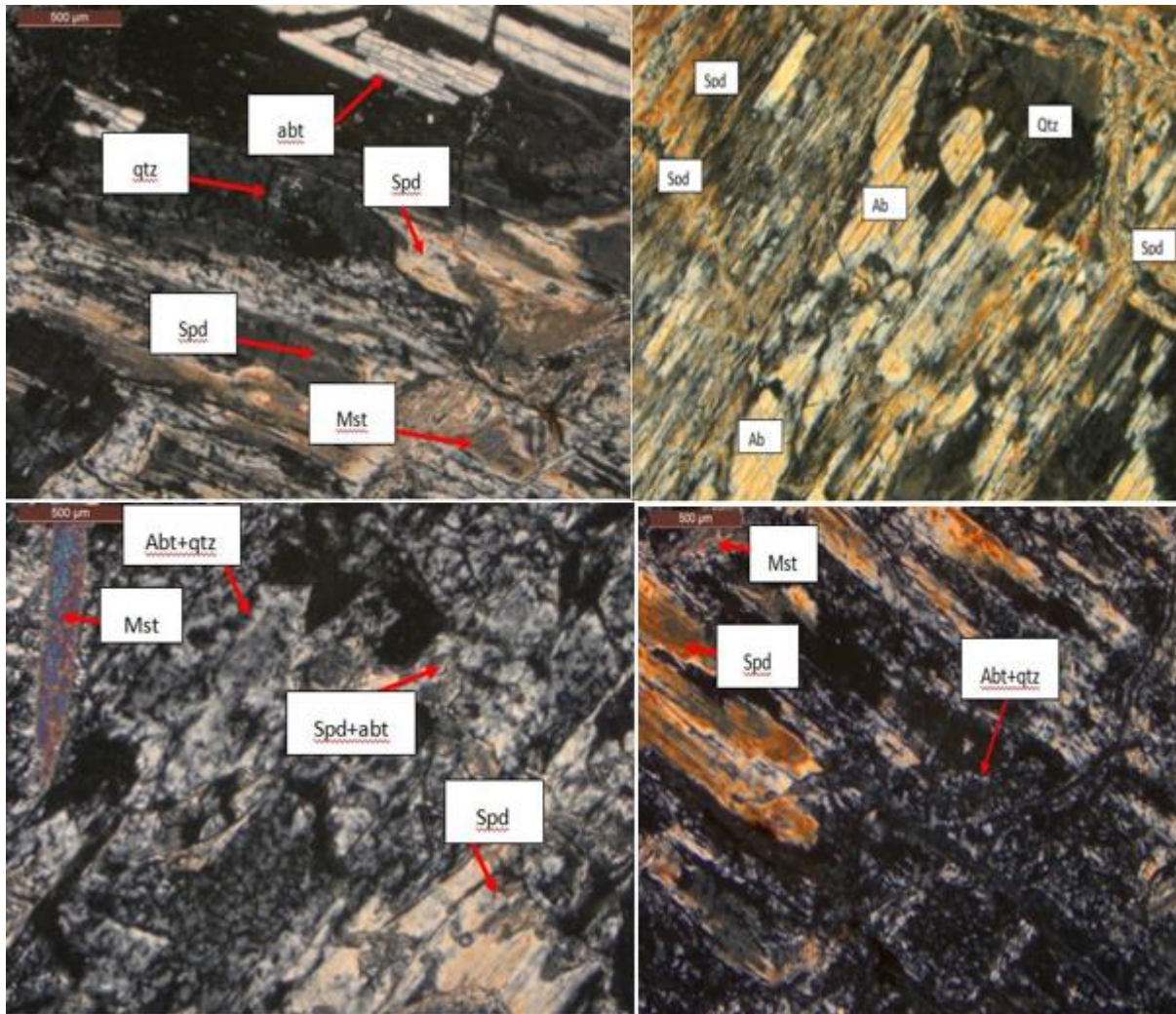


Figure 11. shows a microphotograph taken from four thin sections, which illustrate different mineral types and their texture and morphology. The minerals in the picture are abbreviated as follows: Albite (Abt), Quartz (qtz), Muscovite (Mst), and Spodumene (Spd).

Note that the textures and morphologies of the unidentified minerals are taken from their general properties, as they could not be identified using optical microscopy due to weathering, which altered their appearance and texture.

Chapter 5: Conclusion and Recommendation

5.1 Conclusion

It's crucial to make sure that a study's goals are met exactly as intended. This supports the validity and dependability of the study's findings and recommendations. Planning is an essential step in any research project since it makes sure the research is well-designed, doable, and likely to produce valuable insights. The research process should be regularly monitored and evaluated in order to make sure the study continues on track and achieves its goals.

What minerals can be found in the Kenticha pegmatite ore deposit and what are their quantities?

Using X-ray diffraction (XRD) analysis, the study successfully identified every mineral that could be detected in a spodumene pegmatite ore and verified their existence using thin section photographs. The investigation also identified the ore and gangue minerals, as well as the amounts (average composition) of each mineral. In all samples, spodumene was determined to be the most prevalent mineral, with KS-2 having the highest weight percentage (50.2%). Utilizing this knowledge will improve ore processing and increase the amount of valuable minerals recovered.

What is the grain size distribution of the minerals of interest (i.e., spodumene) and how can this information be used to develop a successful mineral processing strategy?

Before choosing processing strategies for beneficiation, the study described the grain size distribution of the relevant minerals. The information in the data was crucial for creating a successful mineral processing plan for the Kenticha deposit. The data can be utilized to optimize the processing plant's recovery of valuable minerals and lower the output of undesirable minerals.

What ore textures exist among spodumene and other mineral grain boundaries?

By employing thin section investigations to examine the morphology and microstructure of the minerals in the ore, the study was able to identify the ore textures that were present between

spodumene and other mineral grain boundaries. The findings demonstrated that the minerals' textures and appearances varied. It is essential for effective ore processing and mineral exploration to comprehend how weathering affects the minerals in the ore.

Additionally, mineral liberation analysis (MLA) using the Deutsch-Taggart model was used to estimate the degree of liberation of minerals from their host rock in the Kenticha Pegmatite deposit. The results showed that spodumene was the most abundant mineral in the ore but had a low degree of liberation from the other minerals present. This suggests that additional processing steps may be required to separate spodumene from other minerals to achieve a high yield.

By describing the mineralization of the Kenticha Pegmatite deposit with an emphasis on identifying lithium ore for additional beneficiation operations, the study successfully accomplished its goals. The results include important information about the geochemical and mineralogical makeup of the samples, which may be utilized to enhance the ore's processing and increase the recovery of valuable minerals. The information provided in this study can be used to plan and develop mining operations as well as to continue exploring the Kenticha Pegmatite deposit.

5.2 Recommendation

On the basis of the study's findings, the following suggestions can be made:

1. To have a more thorough understanding of the mineralization of the Kenticha pegmatite ore deposit, carry out additional exploration and sampling. This can help identify areas of high-grade mineralization and assess the spatial distribution and variability of the mineralization throughout the deposit.
2. To offer more thorough details on the mineralogy and texture of the ore deposit, use sophisticated mineralogy techniques including scanning electron microscopy and electron probe microanalysis. These methods can aid in the identification and quantification of minor and trace minerals that may affect how the ore is processed.

3. Using the mineralogical and textural data gleaned from the study, optimize the ore's processing. To increase the recovery and grade of the important minerals, evaluating various beneficiation techniques such grinding, flotation, and leaching may be necessary.
4. To identify and reduce any potential environmental effects of the mining and processing activities, conduct an environmental impact assessment. This can involve putting best practices for managing waste and water into practice, avoiding the use of dangerous chemicals, and restoring affected areas when mining operations are over.
5. Consider issues like energy use, reagent use, and equipment expenses when assessing the economic viability of mining and processing the lithium ores. This may entail performing a cost-benefit analysis, determining the market demand and prices for lithium products, and taking into account the project's advantages and disadvantages for the local communities' social and economic well-being.
6. When developing a processing strategy, take into account the consequences of mineralogical and textural variability within the ore deposit. It is important to do in-depth geological and mineralogical research in order to comprehend the ore deposit's diversity and create processing plants that are customized to the ore's unique properties.

By using these suggestions, mining companies can create processing plans that maximize the recovery of precious minerals, reduce the impact of penalty minerals, and assure the long-term viability of the project.

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