The present work was submitted to the Faculty of Engineering

Research on the possibility of ore beneficiation of rare earth element deposits in the Khalzan Buregtei area

Bachelor Thesis

by

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Raw materials and Processing Engineering

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Research on the possibility of ore beneficiation of rare earth element deposits in the Khalzan Buregtei area

I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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ABSTRACT

This bachelor thesis explores the potential of flotation as a beneficiation method for low-grade rare earth element (REE) ore from the Khalzan Buregtei deposit located in the Dundgobi province of Mongolia, with a particular focus on light REEs (LREEs). As the demand for REEs continues to rise due to the global shift towards sustainable technologies, the need for cost-effective and efficient beneficiation methods is crucial.

The Khalzan Buregtei deposit is known to contain both LREEs and heavy rare earth elements (HREEs), but knowledge of their beneficiation is limited due to the recent popularity of REE research. Flotation is a promising technique for the selective separation of REE minerals from gangue minerals based on differences in surface chemistry. However, the flotation of REE ores can be challenging due to the complex mineralogy and surface chemistry of the REE minerals.

Therefore, this study aims to optimize the flotation process for the Khalzan Buregtei ore by conducting laboratory experiments using various reagents and process parameters. The effectiveness of the process will be analyzed using analytical techniques such as X-ray fluorescence (XRF) and mineralogical analysis using optical microscopy and scanning electron microscopy (SEM).

The results of this research will provide insights into the potential of flotation as a beneficiation method for REE ores from the Khalzan Buregtei deposit, specifically for the separation of LREEs. The study also acknowledges the limitation of flotation for the extraction of HREEs and suggests that additional beneficiation methods, such as magnetic separation or leaching, may be necessary to extract HREEs from the ore. The findings of this research will contribute to the development of efficient and cost-effective beneficiation methods for REE ores, which are essential for meeting the growing demand for REEs in sustainable technologies.

1. INTRODUCTION

1.1. General Background

1.1.1. Significance of Rare Earth Elements

Rare earth elements (hereafter referred to as REEs) have gained significant attention in recent years due to their importance in various modern technologies such as smartphones, electric vehicles, wind turbines, and many other green energy applications. They are also crucial in the defense and aerospace industries, making them a highly sought-after resource. According to the studies reviewed, the global demand for REEs is expected to grow rapidly in the coming years, with an estimated compound annual growth rate of 7.5% by 2030. Additionally, the studies show that the current supply of REEs is highly concentrated, with a few countries controlling the majority of the production. This concentration of supply, along with geopolitical tensions and environmental concerns related to mining and processing, has led to increased interest in finding alternative sources and developing more efficient and environmentally sustainable methods of extracting and processing REEs. Overall, the studies reviewed emphasize the significant role that REEs play in modern technology and highlight the urgent need for a sustainable and diversified supply of these critical elements.

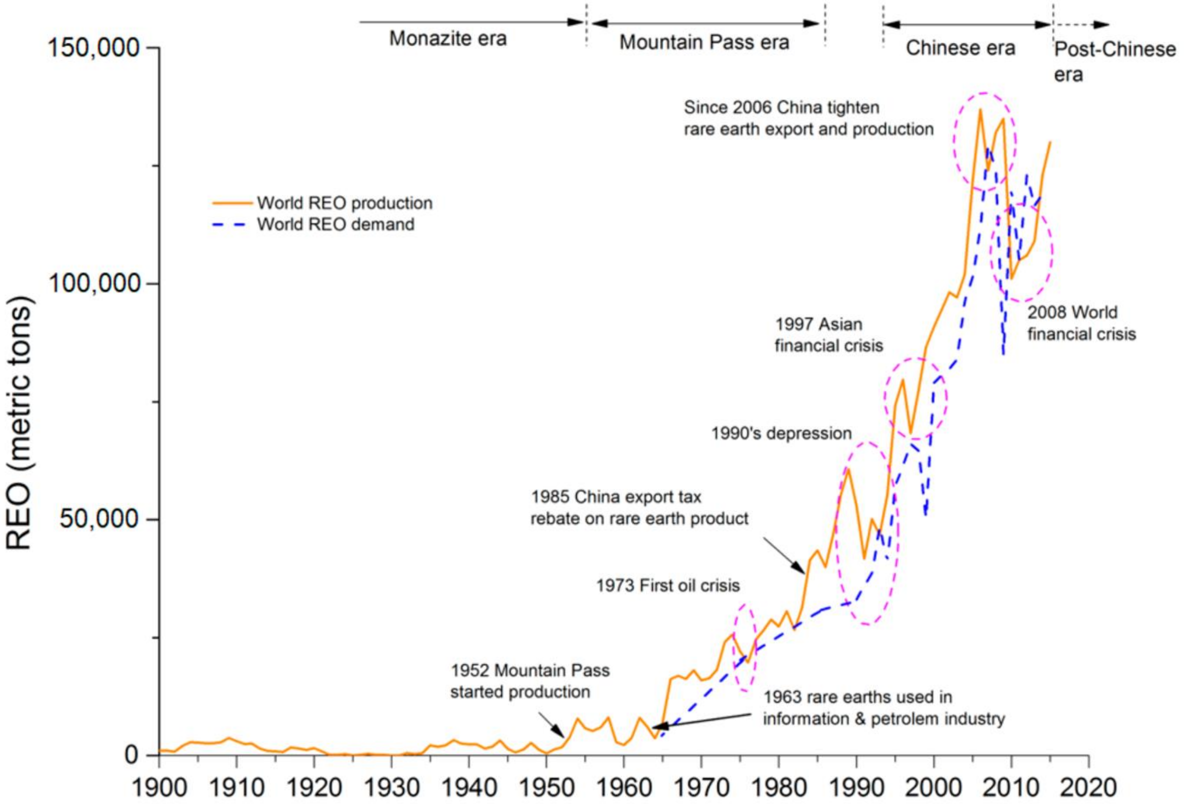


Figure 1 Global Rare Earth production and demand

In recent years, the demand for REEs has surged due to their widespread use in various modern technologies such as smartphones, rechargeable batteries, super magnets, LED lighting, and solar panels. They are also essential components in critical applications such as magnetic resonance imaging (MRI) agents and superconductors. The rapid and increasing consumption of REEs in these high-tech devices has raised concerns about their availability and sustainability. As a result, there is a growing interest in finding alternative sources and developing more efficient methods of extracting and processing these critical elements.[2] For example, neodymium (Nd) is widely utilized in the production of super magnets for disk drives, while cerium (Ce) plays a crucial role as an ingredient in autocatalysts. Furthermore, all REEs are essential in the manufacture of flat-panel TVs. Additionally, various compounds of REEs are present in smart-batteries that power electric vehicles and hybrid-electric vehicles.[2] REE's have excellent electronic, optic, catalytic, and magnetic properties that provide solutions for many challenges of modern technology, making them useful for a wide range of applications, the REE markets are commonly divided into nice sectors: catalysts, polishing, glass, phosphors and pigments, metallurgy, batteries, magnets, ceramics, and others. (Baolu Zhou, 2017) Table 1 shows application of REEs products into six different areas. Due to these areas emerging demand and progress REEs need would also increase.

Table 1 Examples of how REE are utilized

Area	**Applications**

Electronics	Television screens, computers, cell phones, silicon chips, monitor displays, long-life rechargeable batteries, camera lenses, light emitting diodes (LEDs), compact fluorescent lamps (CFLs), baggage scanners, marine propulsion systems
Manufacturing	High strength magnets, metal alloys, stress gauges, ceramic pigments, colorants in glassware, chemical oxidizing agent, polishing powders, plastics creation, as additives for strengthening other metals, automotive catalytic converters
Medical Science	Portable X-ray machines, X-ray tubes, magnetic resonance imagery (MRI) contrast agents, nuclear medicine imaging, cancer treatment applications, and for genetic screening tests, medical and dental lasers
Technology	Lasers, optical glass, fiber optics, masers, radar detection devices, nuclear fuel rods, mercury-vapor lamps, highly reflective glass, computer memory, nuclear batteries, high temperature superconductors
Renewable Energy	Hybrid automobiles, wind turbines, next generation rechargeable batteries, biofuel catalysts
Others	The europium is being used as a way to identify legitimate bills for the Euro bill supply and to dissuade counterfeiting. An estimated 1 kg of REE can be found inside a typical hybrid automobile Holmium has the highest magnetic strength of any element and is used to create extremely powerful magnets. This application can reduce the weight of many motors

From Figure 2. we can see that catalyst take the biggest part of utilization of REEs. Catalysts offer a highly efficient and cost-effective solution for addressing environmental challenges and promoting sustainable resource utilization by facilitating deeper processing and minimizing the generation of waste products that remain unutilized.[3] In According to an estimate made in 2013, the use of catalysts contributed to approximately 15% of Russia's gross domestic income, while in the United States, this contribution was nearly 30% of the material component of the country's gross domestic income. It is worth noting that this estimate is from 2013, and with the continued growth and development of the catalyst industry, it is likely that these percentages have increased in recent years. Nevertheless, these figures highlight the significant economic impact of the catalyst industry in both countries, and emphasize the importance of continued investment and development in catalyst research and technology.[3] Table 2. shows principal data of REE employed catalytic process. According to the information presented in Table 2, it can be observed that REE catalysts have a significant impact on various industrial sectors.

Table 2 Example principle data of catalytic processes employing REE

No.	**Catalyst**	**Process**
	Purification of vehicle exhaust gases[3]	
1	Pd, Pt, Rh (total content, 0.1–0.15 wt %). Al_2O_3 + CeO_2 (CeO2 up to 25 wt %) support doped with La, Mg, and Ca oxides	Catalysts may contain modifying additives along with their active component. Platinum (Pt) has been largely replaced by palladium (Pd) in many applications. Typically, a monolithic or honeycomb cordierite block consisting of $2MgO\cdot2Al_2O_3\cdot5SiO_2$ with a melting point of 1350°C is used to introduce the catalyst, making up approximately 20% of the total catalyst mass. These catalysts are also utilized for purifying exhaust gases in gas fuel vehicles.
2	Pt + Rh, Pd + Rh, Pt + Pd + Rh, Pd. CeO_2 + ZrO_2 support doped with alkaliearth metal (Mg, Ca) oxides	The main challenge is to enhance the noble metals' dispersion and the Al_2O_3's thermal stability. However, gas-phase catalytic reactions are significantly impaired by phosphorus compounds, to the maximum extent.
3	CeO_2 deposited directly onto a catalytic filter, sometimes with Fe and Cu compounds	The addition of iron (Fe) and copper (Cu) compounds encourages the creation of cerium oxide (CeO_2) and other particles made of oxides. These particles penetrate into soot as it forms and catalyze its oxidation.
	Hydrogenation/dehydrogenation, hydration/dehydration[3]	
4	CeO_2	A highly effective catalyst has been developed for the oxidative dehydrogenation of paraffins. The addition of CeO_2 to copper catalysts has been found to enhance their activity and selectivity in the dehydrogenation of methanol into methylformate by approximately 10-15%. This catalyst has also shown promise in the selective dehydration of phenols into aliphatic alcohols at temperatures below 400°C.
5	Ni/CeO_2	The process of converting propane to propylene through oxidative dehydrogenation can be carried out at a relatively low temperature of around 300°C

Waste water treatment

6	Co_3O_4–CeO_2, MnO_x–CeO_2	In the purification of wastewater containing ammonia, the oxidation process can be effectively carried out using MnOx-CeO2 (3:1) catalysts, which exhibit higher activity compared to industrial homogeneous copper-based catalysts. Cerium oxide plays a crucial role in mixed systems by increasing the redox activity of manganese oxide.
7	Co_3O_4–BiO(OH)–CeO_2	This catalyst has twice the activity compared to systems lacking CeO2 for the oxidation of ammonia in wastewater.

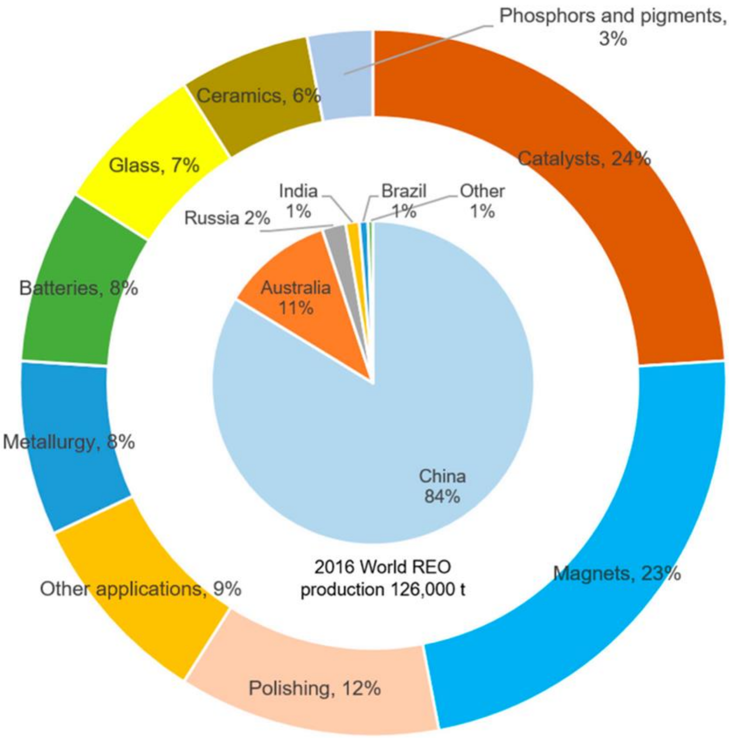
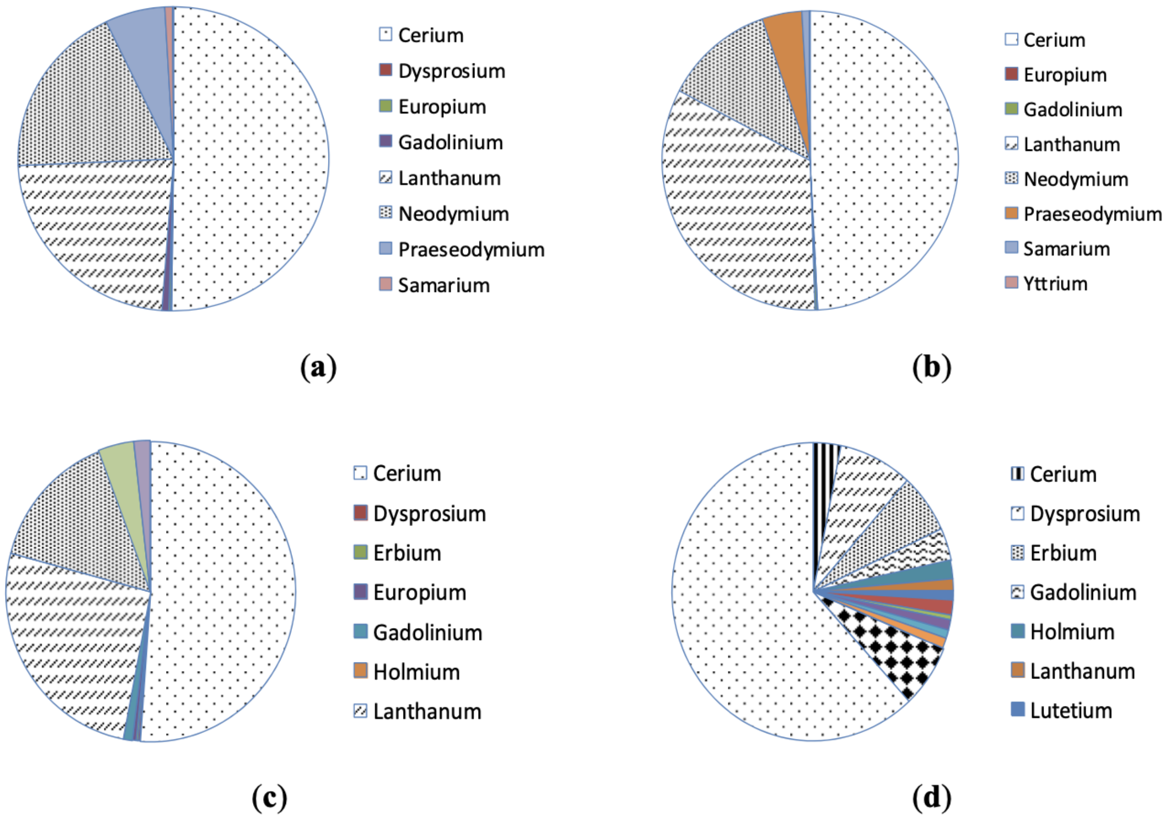


Figure 2 REE production by different countries and utilization 2017

While there may be over 850 identified deposits of rare earth elements (REE) worldwide, only a few of them are currently operating as mines. The notable operating mines include Bayan Obo in China, Mountain Pass in the US, and the recently opened Mount Weld in Australia. Figure 3 illustrates the distribution of rare earth elements in different mines. The mining industry of REE is characterized by a relatively small number of operating mines despite the large number of identified deposits globally. The prominent operating mines play a significant role in the production of rare earth elements. The distribution of these elements in various mines is an important factor to consider when examining the global REE supply. Further research and development in this field are crucial to ensure a sustainable and efficient supply of rare earth elements for various industries and technological advancements.



(a) **(b)**

(c) **(d)**

Figure 3 Average distribution of rare earth elements in each deposit[22]. (a) Bayan Obo, China; (b) Mountain pass, USA; (c) Mount Weld, Australia; (d) Lahat, Malyasia]

The mining of rare earths can be classified into three distinct eras: the monazite-placer era, the Mountain Pass era, and the Chinese era. The Chinese era began in the mid-1980s and was characterized by the availability of rare earths at prices that significantly undercut other mining operations. As a result, many mines outside of China were forced to close. Currently, China possesses approximately 55% of all known rare earth deposits and exercises control over 85% of the global supply through integrated mining, refining, and supply chains. This dominance in the rare earth market has positioned China as a major player in the industry.[22]

1.2. Problem Statement

In the current trajectory of technological development, there is a growing emphasis on green technology due to the negative effects of global warming. As a result, many nations are increasingly directing their attention towards transitioning to a less carbon-intensive economy. In such a future economy, having affordable and easily accessible material resources is of paramount importance. Given this trajectory, there is a growing demand for materials used in the production of green technologies, such as batteries and electric motors, among others. To meet these demands and ensure chemical sustainability, it is crucial to identify and understand the beneficiation possibilities of new deposits.

Currently, around 84% of rare earth element (REE) production is centered in China, making it important for the market to expand and study more ore deposits and their properties. Therefore, a comprehensive understanding of the geological features, mineralogical properties, and chemical compositions of REE deposits can provide valuable insight into their beneficiation possibilities, thus promoting sustainable production of REEs. Furthermore, exploration of new REE deposits and development of efficient beneficiation methods will not only expand the market, but also contribute to the establishment of a more sustainable and environmentally friendly future. With the increased demand for rare earth end products such as catalysts, batteries, and permanent magnets, understanding the fundamentals behind rare earth separation processes, such as flotation, is paramount to maximizing operational efficiency.[5] The research on froth flotation of Mongolian rare earth element (REE) deposits is currently limited. Flotation is a crucial process in the extraction and concentration of REE minerals, and its optimization is essential for maximizing recovery and producing high-quality concentrates. The scarcity of research in this area poses several challenges and limitations.

Firstly, the understanding of the flotation behavior of Mongolian REE minerals is limited, including their response to various flotation reagents, process parameters, and operating conditions. Without a detailed understanding of the mineralogical and chemical characteristics of these ores, it is difficult to design optimal flotation circuits and develop tailored reagent regimes.

Secondly, the lack of systematic research on the flotation kinetics and mechanisms of Mongolian REE minerals restricts the ability to optimize the flotation process. Understanding the factors influencing the flotation kinetics, such as particle size, pH, pulp density, and reagent dosages, is crucial for achieving high recovery and selectivity. However, without extensive investigation and characterization of the flotation kinetics, it is challenging to optimize the flotation process and improve overall performance.

Furthermore, the absence of comprehensive studies on the interaction between flotation reagents and REE minerals located in Mongolia limits the selection and optimization of suitable reagents. Different minerals may exhibit varying degrees of floatability and response to specific collectors, frothers, and modifiers. Thus, the lack of research in this area inhibits the development of effective reagent strategies tailored to Mongolian REE ores. Overall, the lack of understanding of the flotation behavior, kinetics, and reagent interactions hinders the development of efficient and economically viable flotation processes for these valuable resources. Addressing this research gap is crucial for maximizing the recovery of REEs, optimizing the beneficiation process, and supporting the sustainable development of Mongolia's REE mining industry.

1.3. Research Objective

1.3.1. General objective

In this bachelor thesis study paper, the possibility of beneficiation by of REE ore from Khalzan Buregtei area is investigated. Samples taken from the mentioned area will be experimented with different methods of beneficiation in a process laboratory with heavily focusing on the method of froth flotation. The froth flotation method has been selected as the primary beneficiation method due to its potential for effective enrichment of the rare earth elements (REEs). However, it should be noted that this method has certain complexities and limitations, as evidenced by the relatively limited literature available on the topic. By conducting experiments and focusing on froth flotation in the process laboratory, this study aims to contribute to the existing body of knowledge on the beneficiation of REE ores.

1.3.2. Specific objectives

In essence, the present study aims to address the following key research questions:

- REE content in the Khalzan Buregtei deposit;
- Particle size distribution of the sample;
- Primary grinding time to get optimum particle size;
- Froth flotation method to the sample;
- Evaluate the possibility of beneficiation;

1.4. Hypothesis

The beneficiation of REEs from the Khalzan Buregtei area using the froth flotation method is expected to be challenging primarily because of the composition of the ore. The presence of gangue minerals, particularly oxides, poses a significant obstacle to the effective separation and concentration of the desired rare earth elements.

Oxide minerals, which are commonly found in REE deposits, exhibit similar surface properties to the target REE minerals, making their separation difficult through conventional froth flotation techniques. The selective adsorption of collectors onto the mineral surfaces relies on differences in surface chemistry, and when the gangue minerals and REE minerals have similar chemical characteristics, achieving adequate selectivity becomes more challenging. Consequently, there is a risk of low mineral recovery and poor grade of the REE concentrate.

Additionally, the analysis of REE concentration in the ore samples poses certain challenges due to the expenses associated with laboratory analysis. Accurate and reliable analysis of REEs requires sophisticated and specialized equipment, which can be costly to operate. Limited resources and budget constraints may lead to potential errors and variations in the analytical results, affecting the accuracy and precision of the obtained data.

Based on these challenges, the hypothesis for this study could be formulated as follows: "**The froth flotation method may face difficulties in effectively separating and enriching REEs from the Khalzan Buregtei ore due to the presence of oxide gangue minerals, leading to lower mineral recovery and compromised concentrate grade. Moreover, the accuracy of the obtained results may be influenced by the limitations and expenses associated with laboratory analysis techniques.**"

2. LITERATURE REVIEW

2.1. Rare Earth Elements Geochemical Properties

2.1.1. Physical properties of the REE

Rare earth elements, commonly abbreviated as REEs, are a group of 17 metallic elements that include the lanthanide series of the periodic table ranging from atomic number 57 (lanthanum) to 71 (lutetium), as well as the elements scandium (Sc) and yttrium (Y). The lanthanide series consists of the 15 elements that follow lanthanum in the periodic table, namely, cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) shown in Figure 3. These elements exhibit similar chemical and physical properties, making them difficult to separate and extract individually from ores. Scandium and yttrium are often considered REEs due to their similar properties and close association with the lanthanides in ores.[5]

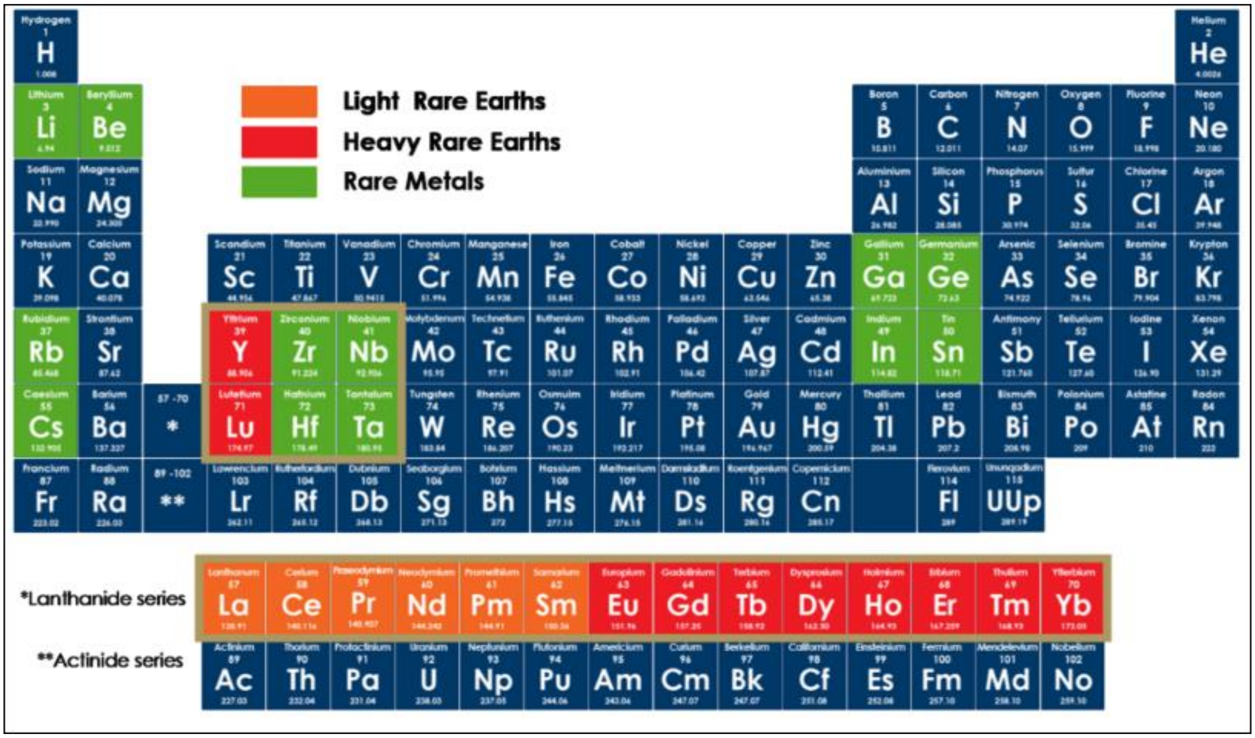


Figure 4 Periodic Table Source: Australianrareearth.com

To clarify, the term "rare earth elements" can be misleading as they can actually be quite abundant in the Earth's upper crust. For instance, the element cerium (Ce) is more abundant than copper (Cu) and lead (Pb) by a factor of 2.3 and 3.7, respectively.[10] However the Oddo-Harkins effect states that rare earth elements (REE) with odd atomic numbers are typically less abundant than those with even atomic numbers[14], as observed in Figure 4. This effect is not unique to REE, as it applies to all elements, and has been recognized since 1914. As a result, some REE with odd atomic numbers are found to be less abundant than 94% of other elements in the Solar System, according to the research conducted by Anders and Grevesse in 1989.[12] Rare earth elements (REEs) typically have a valence of three, denoted as 3+. However, there are two exceptions: cerium (Ce) can be quadrivalent (4+) and europium (Eu) can be divalent (2+). The atomic radii of REEs are relatively small, and they possess a high cationic charge, leading to a high field strength[9], hence it is part the High Field Strength Element group. The High Field Strength Elements (HFSE) group together several elements, including REE, Nb, Ta, Zr, Hf, U, Th, Sn, and Ti. These elements are generally considered to be incompatible during magmatic processes, meaning that they do not readily incorporate into solid crystals and tend to become enriched in melts as magmas differentiate.[13] REE are often classified into two groups based on their atomic weight, namely light rare earth elements (LREE) and heavy rare earth elements (HREE). The boundary between the two groups is typically defined by the element europium (Eu), although the exact location of this boundary can vary depending on the criteria used by different authors. In this study, light rare earth elements (LREE) as those ranging from lanthanum (La) to europium (Eu), and heavy rare earth elements (HREE) as those from gadolinium (Gd) to lutetium (Lu) and yttrium (Y). LREE have larger atomic radii but smaller atomic numbers, resulting in lighter atomic masses compared to HREE, which have smaller atomic radii and higher atomic numbers. Due to the fact that LREE have a greater incompatibility than HREE and the Earth's crust is formed through the partial melting of the upper mantle, LREE are typically more abundant than HREE in most natural crustal systems.[9] REE have long been considered as immobile as they are not soluble in aqueous solutions. However, studies of natural and artificial samples showed they are able to form stable aqueous complexes with ligands such as Cl−, F−, OH−, CO2− or PO3−[14].

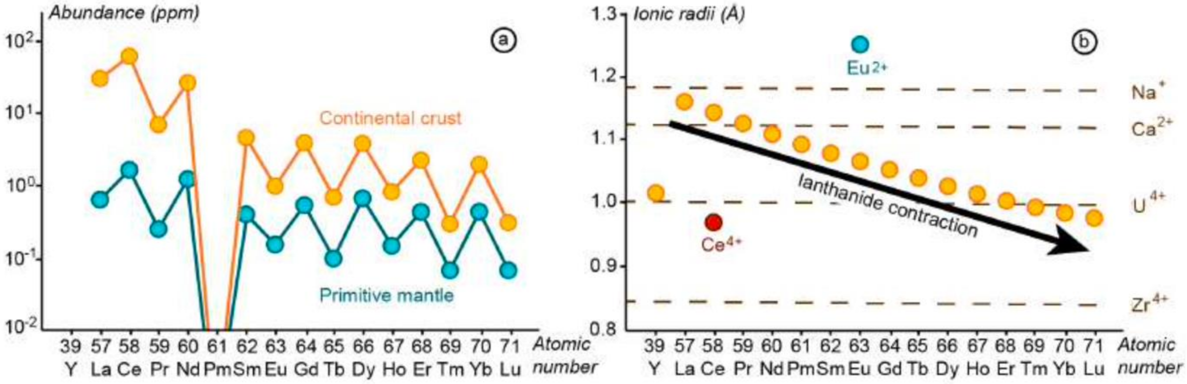


Figure 5 (a) REE abundances in primitive mantle and continental crust and Oddo-Harkins effect; (b) ionic radii of REE cations in eight-fold coordination plotted against atomic number and compared with other elements. (Bernard, 2020)

2.1.2. Mineralogy of the REE

REE are not found in their pure form in minerals, but they are present in small quantities in many different mineral types such as silicates, carbonates, oxides, phosphates, fluorides, borates and sulfates(Figure 5). LREE tend to have a preference for larger coordination numbers (7-11), resulting in their presence mainly in carbonates and phosphates. In contrast, HREE prefer smaller coordination numbers (6-8), leading to their preferential occurrence in oxides.[9] To this day there have been over 480 REE minerals described,[15] but only 10 minerals are currently mined. The most well-known minerals are bastnäsite-(Ce), monazite-(Ce), and xenotime-(Y), other well-known minerals that contain rare earth elements include loparite-(Ce), fergusonite-(Y), gadolinite-(Y), and euxenite-(Y). These minerals can be found in a variety of geological environments, including pegmatites, alkaline igneous rocks, and hydrothermal veins. Most of the minerals that contain REE are predominantly composed of Ce, Y, La, or Nd. However, some minerals may contain significant amounts of REE that substitute for other elements with similar atomic radii and charges. For instance, apatite, zircon, and platinum group minerals (PGMs) are some examples of minerals that can host REE. Apatite is particularly important as it can contain both LREE and HREE and is often used as a source of phosphate fertilizer, while zircon is a common accessory mineral in igneous rocks and can contain significant amounts of HREE. PGMs, on the other hand, are mainly used as catalysts in various industrial processes and may contain trace amounts of REE.[15]

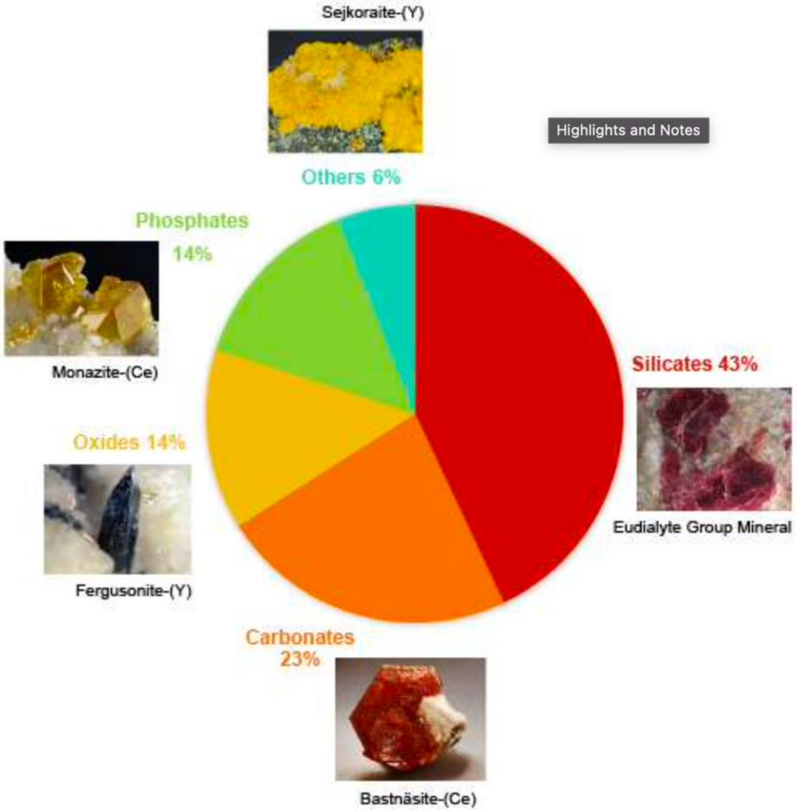


Figure 6 A diagram showing the proportions of the different families of REE-bearing minerals, with macroscopic photographs of an example of mineral for each family, data from Chakhmouradian and Wall (2012) and photographs from mindat.org.[9]

2.2. Rare Earth Element Deposit Types

REE deposits are typically categorized into two types: high-temperature primary deposits (magmatic and hydrothermal) and low-temperature secondary deposits (sedimentary and weathering). This classification is widely accepted by experts in the field, including Bloodworth (2010), Kanazawa and Kamitani (2006), Linnen et al. (2014), and Marquis (2019).[9] Primary deposits of REE are typically found in alkaline rocks, carbonatites, iron-oxide deposits, and hydrothermal veins. These deposits are formed through geological processes such as magmatic activity, which leads to the concentration of REE within the rock. Hydrothermal fluids can also play a role in enriching REE within primary magmatic deposits, although the exact mechanisms behind this process are not fully understood. Nonetheless, primary deposits remain an important source of REE and are a target for exploration and mining to extract these valuable elements. Secondary deposits of rare earth elements (REE) are typically found in three main types of geological settings: placers, laterites, and ion-adsorption clays. Placer deposits are formed by the erosion and transport of primary REE-bearing rocks, with the heavy REE minerals settling in stream beds or other low-energy environments. Laterite deposits form through weathering and leaching of primary REE-bearing rocks, with the REE becoming concentrated in the residual soils. Ion-adsorption clays are formed by the weathering of REE-bearing rocks, which release ions that are then adsorbed onto clay particles. These secondary deposits can be economically important sources of REE, and are commonly mined for their valuable rare earth elements.[9]

The type and grade of rare earth element (REE) resources provided by primary and secondary deposits(*Table 3, Table 4*) depend on several factors related to the geological processes that form them. These include the primary igneous source of the REE, the degree of partial melting and fractional crystallization in the melt, the circulation of hydrothermal fluids, weathering, and the geodynamic setting. For example, the composition of the primary igneous rock will determine the types and proportions of REE minerals that form during the cooling and solidification process. The degree of partial melting and fractional crystallization can affect the concentration of REE within the rock. The circulation of hydrothermal fluids can introduce additional REE into the deposit and modify its composition. Weathering can also alter the mineralogy and grade of a deposit by leaching out certain elements and concentrating others. Finally, the geodynamic setting, such as plate tectonic activity, can influence the formation and distribution of REE deposits in different regions of the world. Taken together, these factors contribute to the diversity of REE deposits and their unique characteristics, which are important to consider when assessing their economic viability and potential for extraction.

Table 3 A classification of primary REE deposits with key-examples, table taken from (Bernard, 2020)

Primary Deposit Group					
Deposit Type	Main Characteristics	REE resources	Main REE minerals	Genetic Model	Example of major deposits
Alkaline rock	Abundant alkali minerals, high differenciation	Generally low grade granites contain more HREE	Zircon, xenotime-(Y), fergusonite-(Y), allanite-(Y), bastnasite-(Ce), eudialyte group minerals	Magmatic/hydrothermal	Khibina and Lovozero, Russia; Strange Lake, Canada;
Carbonatites	At least 50% of carbonate minerals	LREE	Bastnasite-(Ce), monazite-(Ce), synchisite-(Ce), apatite	Magmatic/hydrothermal	Mountain Pass, USA; Bayan Obo, China
Iron-Oxide-Gold-Copper	Magmatic with magnetite, or hydrothermal rich in Cu, Au, U	All REE	Bastnasite-(Ce), monazite-(Ce), xenotime-(Y), britholite-(Ce)	Magmatic/hydrothermal	Olympic Dam, Australia
Hydrothermal	Hydrothermal phosphate, quartz and fluorite veins which can carry a wide variety of metals	LREE	Apatite, monazite-(Ce)	Hydrothermal	Nolans Bore and Browns Range, Australia

Table 4 A classification of secondary REE deposit with key-examples, table taken from (Bernard, 2020)

Secondary Deposit Group					
Deposit Type	Main Characteristics	REE resources	Main REE minerals	Genetic Model	Example of major deposits
Placer	Mechanical accumulation of resistant heavy minerals redeposited and concentrated during sedimentation processes in river, estuarine or shallow marine enviroments	All REE	Monazite-(Ce), xenotime-(Y)	Physical weathering, erosion, transport and redeposition	Elliot Lake, Canada; Manavalakuruchi, India
Laterite, bauxite	Clay and iron-rich soils formed under tropical climate. Bauxites are laterites with > 40% Al_2O_3	All REE	Clays and secondary apatite rhabdophane-(Ce, Y)	Weathering	Mount Weld, Australia
Ion-adsoprtion	Near Surface chemically weathered granitoid rocks (biotite and muscovite granites)	HREE	Clays	Weathering of REE-rich granitoids	Longnan, China

2.2.1. Khalzan Buregtei Deposit

Mongolia possesses significant potential for harnessing the benefits of Rare Earth Elements (REEs) due to the presence of four major REE deposits: Khalzan Buregtei, Mushgai Khudag, Khotgor, and Luginin Gol. These deposits collectively hold reserves of around 1.25 million metric tons of Rare Earth Oxides (REO) (Ilhwan Park, 2021). Among them the Khalzan Buregtei deposit, situated in western Mongolia, holds significant significance among the REE deposits in the region. It is located around 50 kilometers north of the city of Khovd. This particular deposit stands out due to its abundance of heavy Rare Earth Elements (HREE), which are considered more valuable than the light Rare Earth Elements (LREE). Additionally, the Khalzan Buregtei deposit is enriched in high field-strength elements (HFSEs) such as zirconium (Zr), niobium (Nb), tantalum (Ta), and yttrium (Y). These HFSEs possess their own industrial importance and contribute to the overall economic potential of the deposit [6]. The Khalzan Buregtei deposit was first discovered by geologists from the former Soviet Union in the year 1984.[17] The Khalzan Buregtei deposit spans an extensive area measuring approximately 30 kilometers in length and 8 kilometers in width. It primarily consists of alkaline syenite to granitic rocks. These rock formations are believed to be connected with early Devonian extensional tectonic activity. This suggests that the deposit's formation and characteristics are closely linked to geological processes that occurred during the early Devonian period, which involved significant stretching and pulling apart of the Earth's crust in that region.[17]

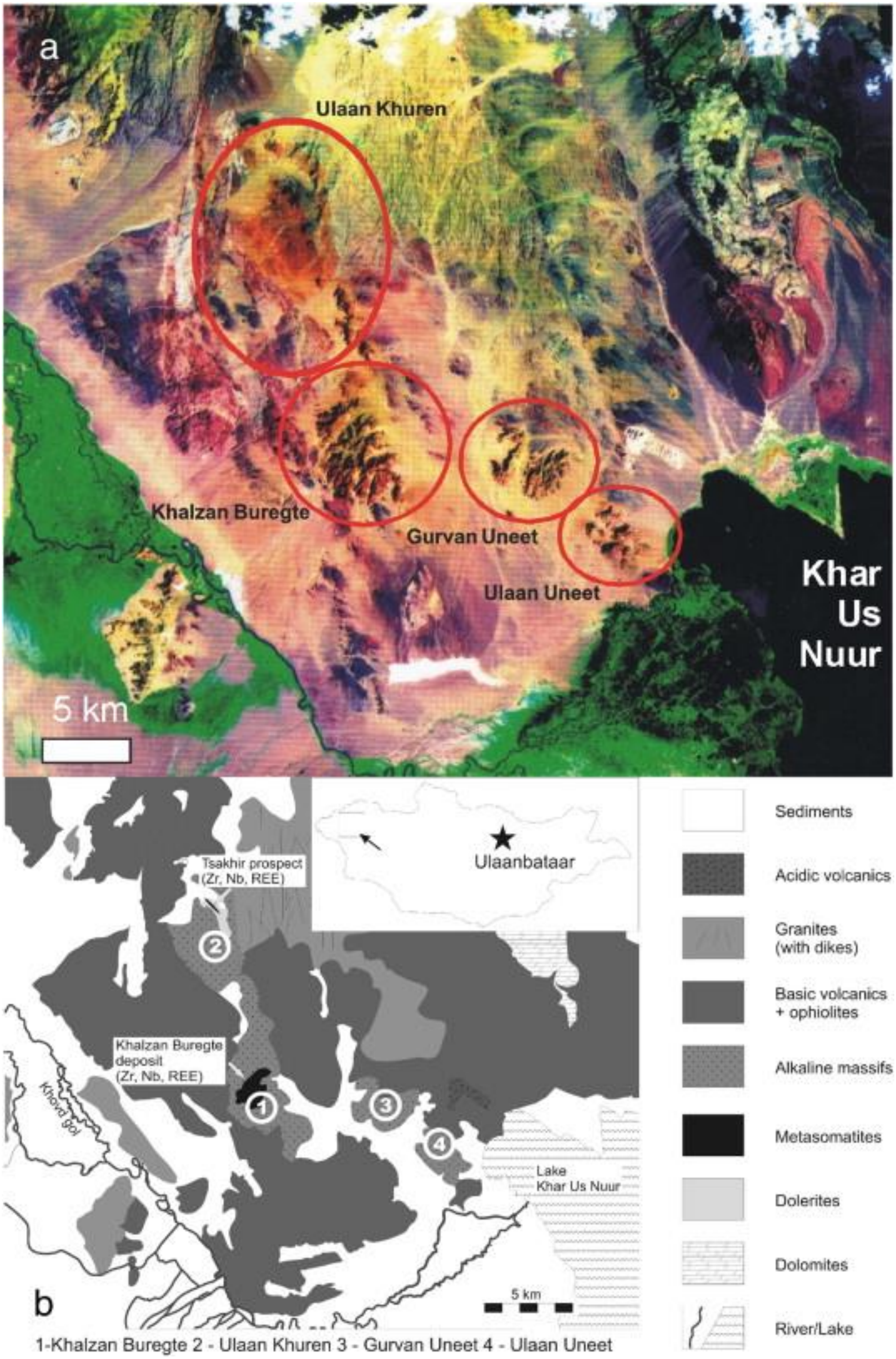


Figure 7 Geological setting of alkaline massifs at Khalzan Buregtei. (a) Landsat image (b) Sketch map of the Khalzan Buregte area showing the locations of the Khalzan Buregte deposit, Tsakhir prospect and the alkaline massifs: Khalzan Buregte, Ulaan Khuren, Gurvan Uneet and Ulaan Uneet.[25]

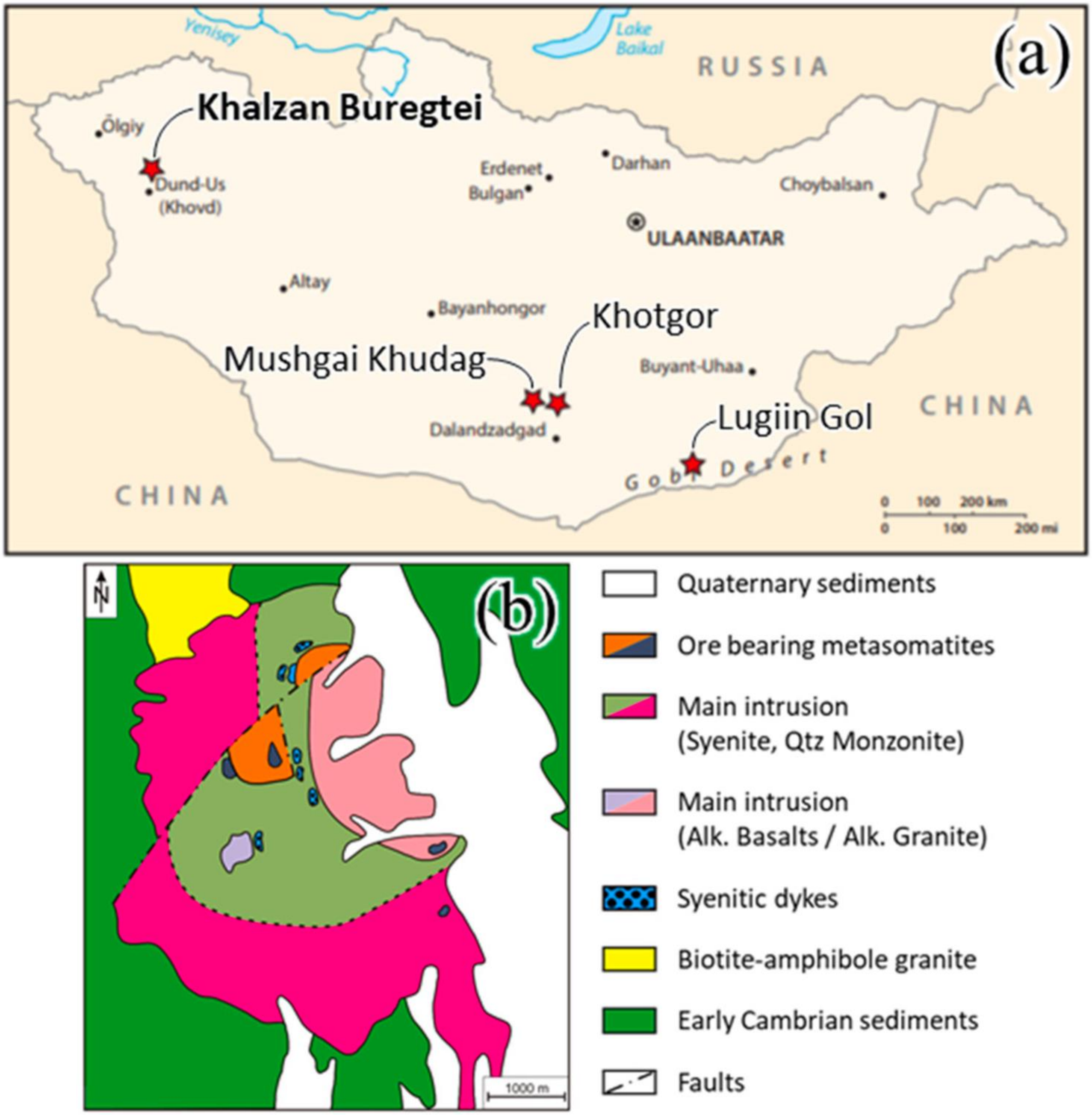


Figure 8 (a) A schematic location map of major Mongolian REE deposits, figure from (Ilhwan Park, 2021). (b) Geological map of the Khalzan Buregtei deposit, figure from (Lars Hans Gronen, 2019)

According to (U. Kempe a, 2015), the Khalzan Buregtei deposit, which is a significant rare metal deposit, contains approximately 2.4 million metric tons of Zirconium dioxide (ZrO_2), 350,000 metric tons of Niobium pentoxide (Nb_2O_2), and 490,000 metric tons of Rare Earth Oxides (REE_2O_2) along with 130,000 metric tons of Yttrium oxide (Y_2O_3). The rock formations found in the Khalzan Buregtei deposits can be classified into seven intrusive phases (Table 5). The mineralized rocks within these deposits, which are of particular interest due to their rare-metal content, have been identified as rare-metal granites associated with two specific intrusive phases.

These intrusive phases refer to distinct episodes of molten rock, known as magmas, that intruded into the surrounding rocks and solidified underground over time. Each intrusive phase represents a different event of magma emplacement, characterized by its unique composition, age, and geological characteristics. The presence of multiple intrusive phases in the deposit indicates a complex geological history involving multiple episodes of magmatic activity and subsequent cooling and solidification.[18]

Table 5 Subdivision of rocks making up the alkaline intrusions of the Khalzan Buregte area.[25]

Magmatic phases according to Kovalenko et al.
1. Phase: nordmarkite and dolerite
2. Phase: alkaline granite and dolerite
3. Phase: dikes of ekerite
4. Phase: dikes of pantellerite
5. Phase: rare metal granitoids
6. Phase: syenite and syenite dikes
7. Phase: miarolitic rare metal granite

In the study (Ilhwan Park, 2021), the 5th phase ore was used which within the geological units of the Khalzan Buregtei deposit, the 5th and 7th intrusive phases are particularly significant as they consist of mineralized rocks that form the rare-metal peralkaline granitic ore. These phases represent specific episodes of magmatic activity that resulted in the formation of rocks rich in rare metals within the deposit[18]. The 5th and 7th phase ores mineral compositions are very similar [6]. The 5th phase ore sample was grounded to <50 μm and analyzed by X-ray fluorescence spectroscopy (XRF, MultiFlex) and X-ray powder diffraction (XRD, MultiFlex). The results of the analysis are shown in (Table 6, Table 7, Figure 7).

Table 6 Elemental composition of REE-bearing sample from the Khalzan Buregtei deposit, Mongolia. From (Ilhwan Park, 2021)

Non-REE	**Content (%)**	**REE**	**Content (ppm)**
SiO_2	69.0 ± 2.2	La_2O_3	548 ± 184
Al_2O_2	16.1 ± 0.8	CeO_2	1376 ± 460
Fe_2O_3	4.1 ± 0.79	Eu_2O_3	1004 ± 493
K_2O	3.5 ± 0.42	Gd_2O_3	391 ± 63
ZrO_2	3.6 ± 0.63	Y_2O_3	1809 ± 339
CaO	1.3 ± 0.12	Dy_2O_3	525 ± 117
Nb_2O_5	0.4 ± 0.11	Er_2O_3	73 ± 21
TiO_2	0.4 ± 0.07	Yb_2O_3	181 ± 36
Na_2O	0.05 ± 0.12	Other REEs	813 ± 282
Others	0.8 ± 0.18	TREO	6720 ± 1257

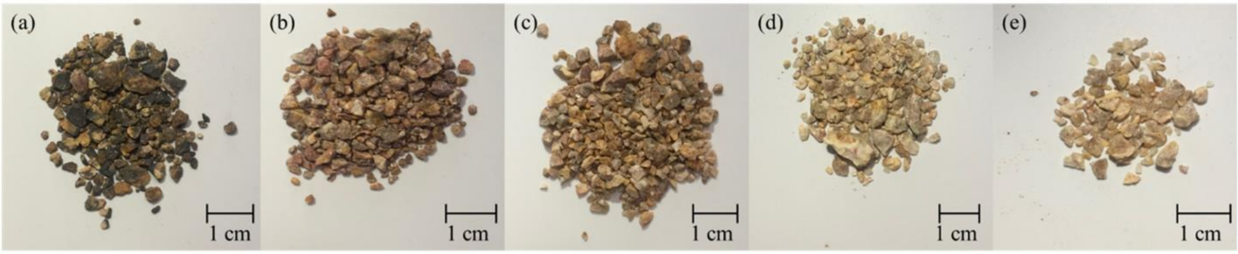


Figure 9 Photographs of samples of (Ilhwan Park, 2021) sorted based on color: (a) black, (b) brown, (c) brownish yellow, (d) yellow, and (e) transparent particles.

Table 7 Elemental composition of samples sorted based on color, table from (Ilhwan Park, 2021)

Elements		**(a)**	**(b)**	**(c)**	**(d)**	**(e)**
Non-REE (%)	SiO_2	66.2 ± 0.1	68.6 ± 0.4	71.2 ± 0.1	75.6 ± 0.2	93.9 ± 0.0
	Al_2O_3	14.4 ± 0.1	15.4 ± 0.5	18.6 ± 0.1	14.3 ± 0.1	4.0 ± 0.01
	Fe_2O_3	8.2 ± 0.03	4.6 ± 0.03	1.3 ± 0.01	2.0 ± 0.00	0.4 ± 0.00
	K_2O	2.8 ± 0.12	3.1 ± 0.04	6.8 ± 0.03	2.7 ± 0.10	0.8 ± 0.01
	ZrO_2	3.1 ± 0.03	5.9 ± 0.09	0.9 ± 0.01	0.7 ± 0.01	0.6 ± 0.00
	CaO	1.6 ± 0.01	2.3 ± 0.01	0.1 ± 0.01	1.1 ± 0.01	0.3 ± 0.01
	Nb_2O_5	0.4 ± 0.00	0.3 ± 0.00	0.2 ± 0.00	0.2 ± 0.00	n.d.*
REE (ppm)	La_2O_3	150 ± 9	240 ± 8	140 ± 6	160 ± 8	n.d.*
	CeO_2	490 ± 38	660 ± 17	270 ± 15	460 ± 7	70 ± 8
	Nd_2O_3	n.d.*	420 ± 0	n.d.*	n.d.*	n.d.*
	Sm_2O_3	n.d.*	280 ± 9	510 ± 79	n.d.*	50 ± 9
	Eu_2O	3310 ± 650	1360 ± 910	420 ± 148	n.d.*	130 ± 57
	Gd_2O2	1290 ± 50	n.d.*	120 ± 20	570 ± 30	n.d.*
	Y_2O_3	1960 ± 10	2960 ± 40	1020 ± 10	210 ± 2	160 ± 1
	Dy_2O_3	1090 ± 92	1410 ± 70	200 ± 17	230 ± 28	60 ± 7
	Er_2O_3	n.d.*	40 ± 47	100 ± 13	n.d.*	20 ± 8
	Tm_2O_3	230 ± 93	460 ± 30	150 ± 13	60 ± 20	40 ± 9
	Yb_2O_3	120 ± 50	100 ± 18	100 ± 4	n.d.*	30 ± 6
	TREO	8640 ± 526	7930 ± 183	3030 ± 213	1690 ± 26	560 ± 33

2.3. Beneficiation And Mineral Processing

2.3.1. Magnetic Separation

Magnetic separation, a widely used technique in mineral processing and materials separation, can be classified into two main types: wet and dry magnetic separation. Wet magnetic separation involves suspending the sample in a liquid medium, while dry magnetic separation operates on dry samples. This technique exploits the magnetic properties of minerals and can be applied to various materials, including rare earth elements (REEs). In the context of REE separation, magnetic separation can be utilized to selectively extract or concentrate specific REE minerals based on their magnetic properties, allowing for the efficient separation and purification of REEs from complex ore or mineral samples.[19]

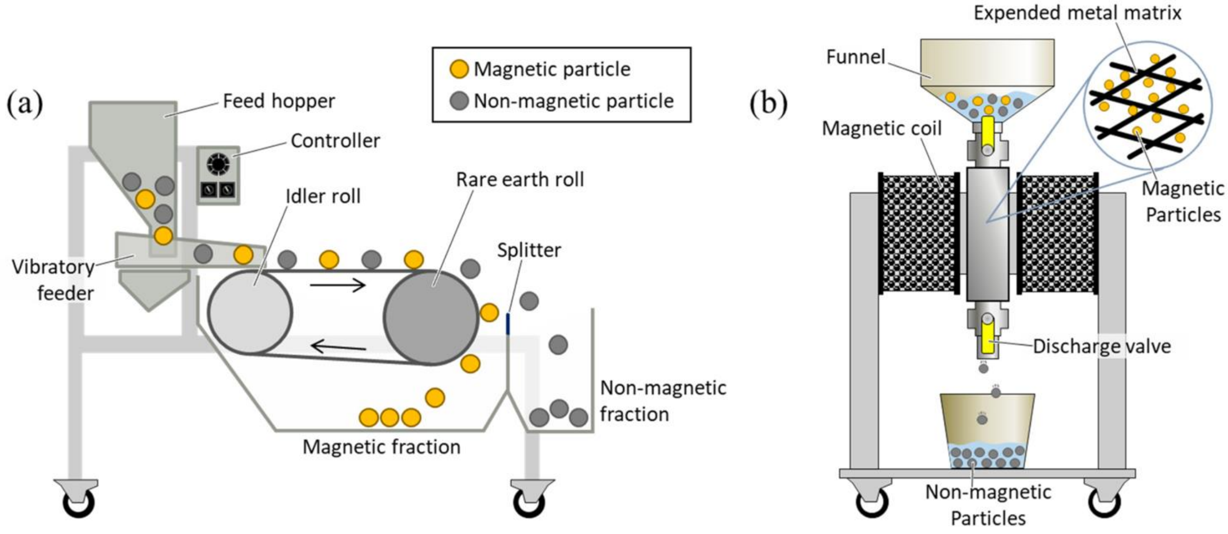


Figure 10 Schematic diagrams of (a) dry high-intensity magnetic separator and (b) wet high-intensity magnetic separator

The research conducted on the Beneficiation of Low-Grade Rare Earth Ore from the Khalzan Buregtei Deposit in Mongolia has provided compelling evidence that the combination of dry and wet magnetic separation proves to be a successful preliminary stage for pre-concentration. This process has shown significant improvements in the grade of Total Rare Earth Oxides (TREO), with an enrichment of more than five times (approximately 39,800 ppm). Additionally, it has demonstrated the removal of approximately 90% of gangue minerals from the magnetic concentrates. To further enhance the concentration of Rare Earth Oxides (REO) in the magnetic concentrates, the study suggests implementing a finer grinding technique (below 75 µm) followed by froth flotation.[6]

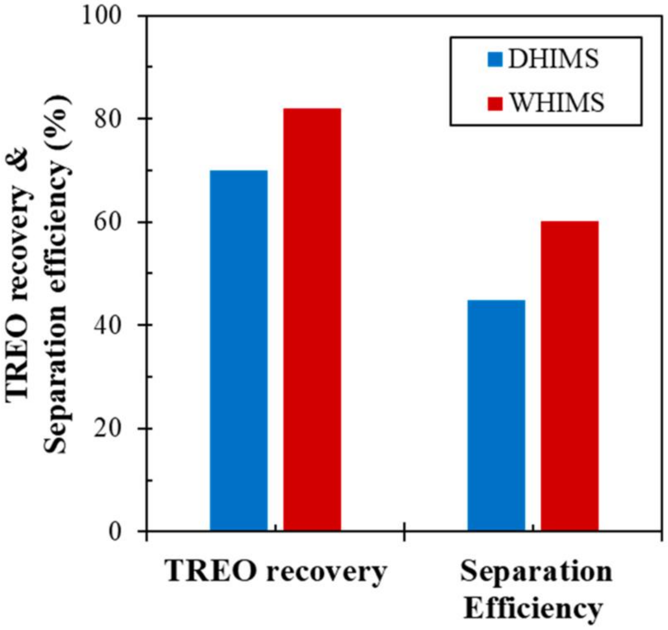


Figure 11 Comparison of TREO recovery and separation efficiency by dry high-intensity magnetic separator (DHIMS) and wet high-intensity magnetic separator (WHIMS).[6]

2.3.2. Froth Flotation

Froth flotation is a widely used process in mineral processing for separating valuable minerals from their ore. It relies on the differences in surface properties of minerals, such as hydrophobicity, to selectively separate them using air bubbles. The process involves introducing a mixture of finely ground ore and water into a flotation cell, where reagents are added to create a froth on the surface. The hydrophobic mineral particles attach to the air bubbles in the froth(Figure 9), while the hydrophilic gangue particles remain in the water. The froth containing the valuable minerals is then collected and further processed to obtain the desired concentrate. Froth flotation is a complex and versatile technique that has applications in various industries, including mining, metallurgy, and environmental remediation[19].

Froth flotation is based on utilizing the differences in chemical properties of particles in a solution. By selectively adsorbing specific organic reagents onto the surfaces of desired minerals, variations in interfacial properties are exploited. To gain insights into the adsorption processes occurring at the particle surfaces, fundamental surface chemistry techniques like zeta potential, adsorption density, and microflotation are employed. These methods aid in understanding the underlying phenomena and contribute to the effectiveness of froth flotation as a mineral separation technique.[5]

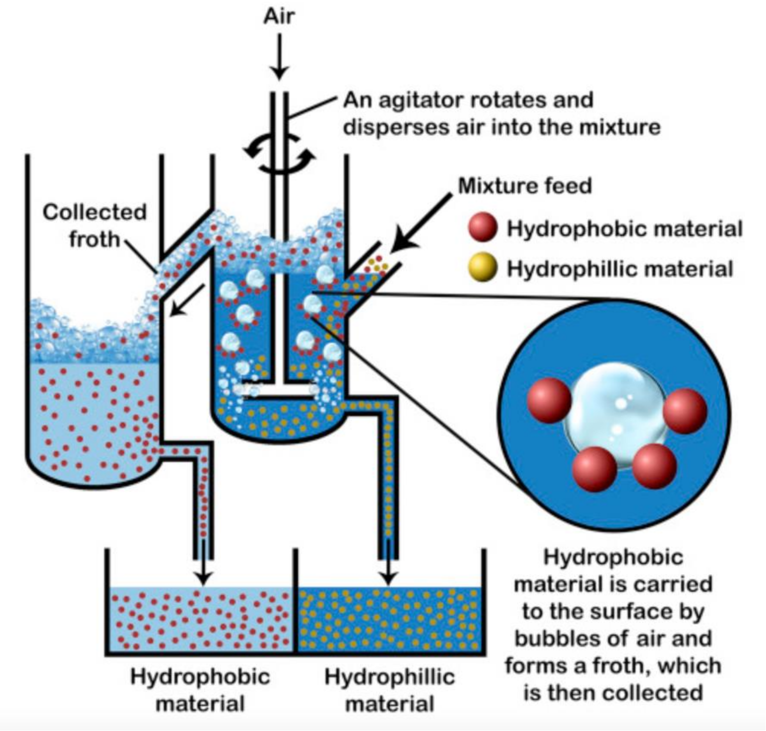


Figure 12 Process of froth flotation

The adsorption of flotation reagents on mineral surfaces and its effect on flotation response are influenced by the electrical double layer, which plays a vital role in surface characteristics. The isoelectric point (IEP), representing the pH at which the zeta potential becomes zero, is a crucial property for characterizing the electrical double layer. By determining the IEP, it becomes possible to anticipate the charge on a mineral surface within a specific pH range. Having knowledge of the zeta potential and IEP of a mineral, along with the collector's ionization behavior at different pH levels in aqueous conditions, allows for predicting how the collector is adsorbed onto the mineral surface.[25]

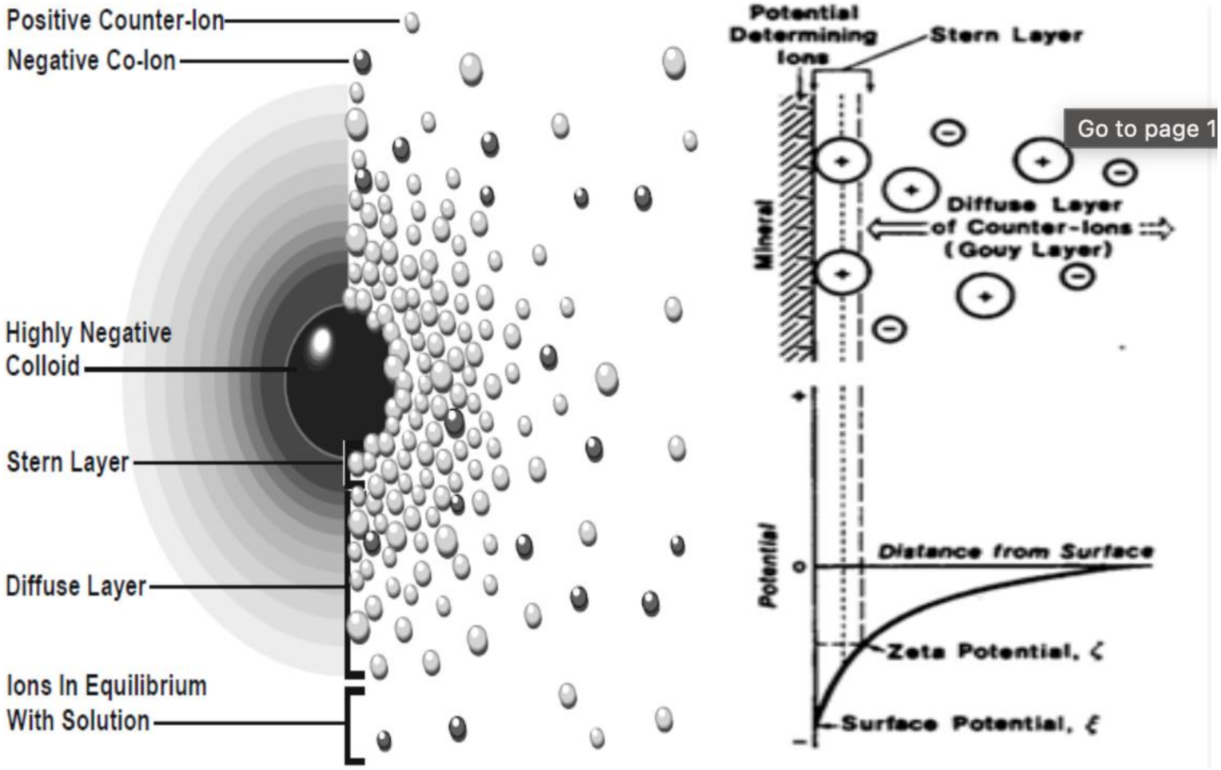


Figure 13 Electrical Double Layer model of a negatively charged particle.[5]

Froth flotation plays a crucial role in various industrial applications. It can be classified into three primary categories: mechanical flotation, column flotation, and pneumatic flotation. These categories represent different approaches and techniques employed to achieve effective mineral separation through the froth flotation process.

Mechanical flotation involves the use of mechanical agitating devices, such as impellers or stirrers, to disperse air into the pulp and generate bubbles. The agitation helps in the attachment of hydrophobic particles to the air bubbles, forming a froth layer on the surface of the flotation cell. This froth, containing the desired mineral particles, is then collected for further processing. A column flotation machine is designed with a tall and narrow structure, giving it a large height-to-diameter ratio. When the machine is operating, a mixture of reagentized feed slurry is introduced into the top part of the column through a header system. The slurry then flows downward through the column under the force of gravity until it reaches a discharge port equipped with a control valve. At the bottom of the column, gas sparging systems inject compressed air, air-slurry or air-water mixtures, or other gases. This causes the gas bubbles to rise against the downward flow of the feed slurry. Hydrophobic particles, which are the desired mineral particles, come into contact with the rising gas bubbles and attach themselves to the bubbles. As a result, they are carried upwards to the froth bed that forms on the top of the column. To prevent unwanted hydrophilic particles from entering the froth bed, wash water is evenly distributed across the froth bed. This wash water helps to keep these fine particles out of the froth bed. Eventually, when the froth reaches the top of the column, it overflows and is collected as a high-grade hydrophobic product.

Pneumatic flotation involves the introduction of air or gas directly into the flotation cell, without the need for mechanical agitation. The air bubbles generated by the gas sparging system interact with the mineral particles in the pulp, leading to the formation of a froth layer. This method offers advantages such as higher flotation rates and reduced energy consumption[19].

In addition to the main categories of froth flotation there are other subcategories used in specific applications. These include rougher-scavenger and cleaner-scavenger units, as well as unit cells or flash flotation cells. Rougher cells are typically the first set of cells in a flotation plant. They are designed to recover both coarse and fine particles of the valuable mineral while maintaining a desired level of selectivity. In some cases, roughers may be operated to increase selectivity, especially in complex ore systems or plants producing multiple products. The concentrate from roughers is further processed in the cleaner section, while the rougher tailings are sent to the rougher-scavengers or final tailings. Rougher-scavengers are used to maximize the recovery of valuable minerals from rougher tailings. The valuable minerals in the tailings can be in the form of course, fine, or locked particles, or a combination of these, depending on the mineralogy and the operation of the rougher cells. The concentrate from rougher-scavengers may be directed to a regrind circuit to release trapped particles or sent directly to the cleaners. Scavengers are operated with a shallower froth layer and variable aeration to achieve the desired recovery rates. Cleaners, on the other hand, aim to improve the grade of the concentrate to meet downstream specifications and avoid penalties for unwanted constituents. Cleaners produce a thicker froth, resulting in a higher-grade concentrate. They also operate at a lower pulp density and have a finer particle size distribution compared to roughers and rougher-scavengers. Cleaner-scavengers, similar to rougher-scavengers, are used to maximize the recovery of valuable minerals from cleaner tailings. By selecting the appropriate flotation machines for each component of the flotation circuit, the desired grade and recovery in the concentrate can be achieved. Laboratory tests are conducted to determine the required residence time for achieving the desired outcomes, and scale-up factors are applied to determine the number and size of machines needed.

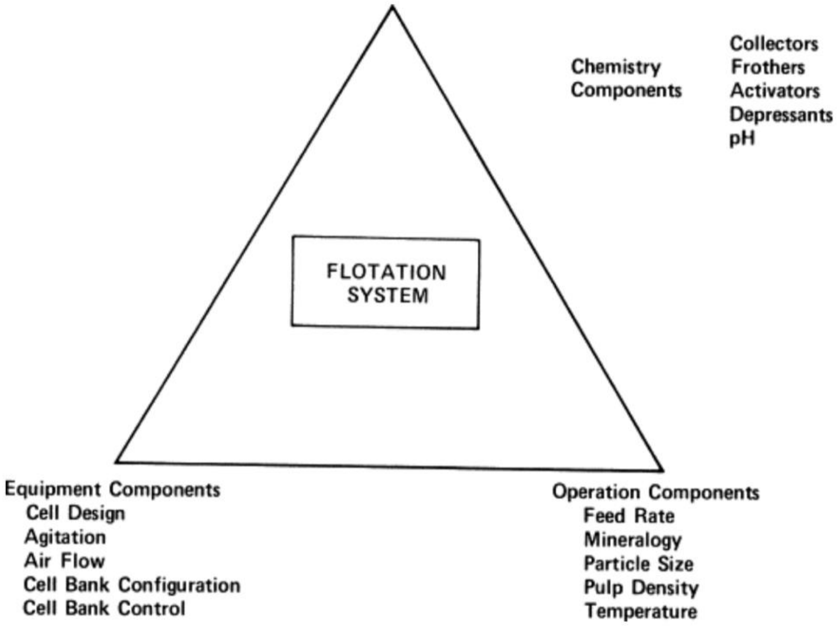


Figure 14 The froth flotation system illustrated as a three-cornered interactive system.[20]

The effective implementation of froth flotation in industrial practice necessitates a comprehensive analysis of the process from an interactive systems perspective, as depicted in Figure 14. This approach recognizes the interdependence and interplay among the three key components of the flotation system: chemistry, equipment, and operations. Within each component, there exists a range of factors that can be intentionally adjusted or manipulated to optimize flotation performance. One of the intriguing aspects of flotation is that many of the factor settings associated with these components exhibit self-compensating properties or possess the ability to significantly influence and enhance the desired or undesired performance of the overall system. This inherent characteristic of flotation underscores the dynamic and intricate nature of the process, where careful manipulation of multiple factors within the chemistry, equipment, and operations realms can lead to remarkable improvements in system performance and the attainment of desired outcomes. By acknowledging and considering the complex interactions and feedback loops among the different components and their associated factors, practitioners can effectively navigate the challenges and intricacies of flotation, thus enabling the efficient and optimal flotation operations in diverse industrial applications[20]. This flexibility arises from the interdependence and interplay among the various components of the flotation system. For instance, if there are shortcomings in equipment performance, these can often be mitigated by carefully selecting appropriate chemical reagents. Similarly, adjustments to equipment and reagent factors can compensate for limitations associated with operating factors, such as the production of an excessive amount of course or fine feed particles, or a throughput that exceeds the capacity of a particular flotation cell. This adaptability and compensatory nature of the flotation process enable operators to optimize system performance by strategically manipulating the factors within their control. By judiciously adjusting equipment, reagent, and operating parameters, flotation operators can overcome challenges and constraints, ultimately leading to the achievement of desired outcomes. Overall, the ability to navigate the complex relationships between various factors and components empowers flotation operators to tailor the flotation process to specific requirements, effectively addressing performance goals and maximizing the efficiency and effectiveness of flotation operations.

Table 8 Classification of reagents[21]

Reagents	Functional Category or Attribute	Practical Classification (in industry)
Collector	Sulfide collectors	Xanthate, dithiophosphate, thiocarbamate
	Non-sulfide collectors	Carboxylates, sulfonates, amines, hydroxamates
Frother	Froth stability, froth mobility, carrying capacity	Aliphatic alcohols, polyglycols
Modifier	pH and EPmodifiers, activators, depressants, dispersants, slime or fines control reagents, coagulation, flocculation, metal hydroxy species formation and adsorption control, froth control	Acids (sulfuric), bases (sodium hydroxide, lime, soda ash), redox reagents(sodium hydrosulfide, sodium sulfide, Nokes),metal salts ($Cu2+$),depressants and dispersants (silicate, phosphate, carboxylate, carbonate, sulfonates, polysaccharides), complexing reagents (cyanide, sulfite, sulfoxy species, alcohols, coagulants (high-charge metal ions, low-molecular-weight polymers) and many others)

In the chemistry component of froth flotation, the reagents can be separated into three groups (Table 8) collector, frother, modifier. These reagents play specific roles in the flotation process, and it is important to note that a single reagent can serve multiple functions. Each reagent has a specific purpose and contributes to the overall effectiveness of the flotation process.

Frothers: During the process of froth flotation in industry, air is introduced beneath the surface of a mixture containing both solids and liquids (Figure 12). The purpose of this is to facilitate the attachment of specific hydrophobic mineral particles to air bubbles, causing them to rise to the top. As a result of the buoyancy of the air-particle aggregates, a three-phase mixture consisting of air, solid particles, and water forms at the top of the flotation cell. This mixture, known as the froth, represents the uppermost layer in the cell. Its lower density compared to the rest of the mixture allows for the separation and concentration of the desired hydrophobic minerals. A frother reagent is often introduced to enhance the stability of both the formed bubbles and the froth phase itself. This is crucial for effectively concentrating the desired minerals. The stability of the froth is important as it needs to carry the floated particles to the point where they can overflow the launder lip and exit the flotation cell. Typically, the highest concentration difference between the target hydrophobic minerals and the gangue minerals occurs at the uppermost surface of the froth. This concentration difference is a result of the phenomena of bubble coalescence and particle redistribution.[19] Frothers in froth flotation are surfactants that are typically organic compounds such as alcohols or polyglycol ethers. These frothers possess a heteropolar structure, enabling them to adsorb at the air/water interface. This adsorption leads to a reduction in water surface tension. Consequently, smaller bubbles are formed, and more importantly, the froth formed at the top of the slurry is stabilized. Stabilizing the froth is crucial because if the bubbles burst upon reaching the air/water surface, any minerals they carry will sink back into the slurry, resulting in a scum on the surface. The primary function of the frother is to maintain the stability of the froth at the interface long enough for the concentrate to be extracted from the flotation cell. Once the concentrate is removed, the froth needs to break to allow the mineral particles to be re-pulped for further processing.[23]

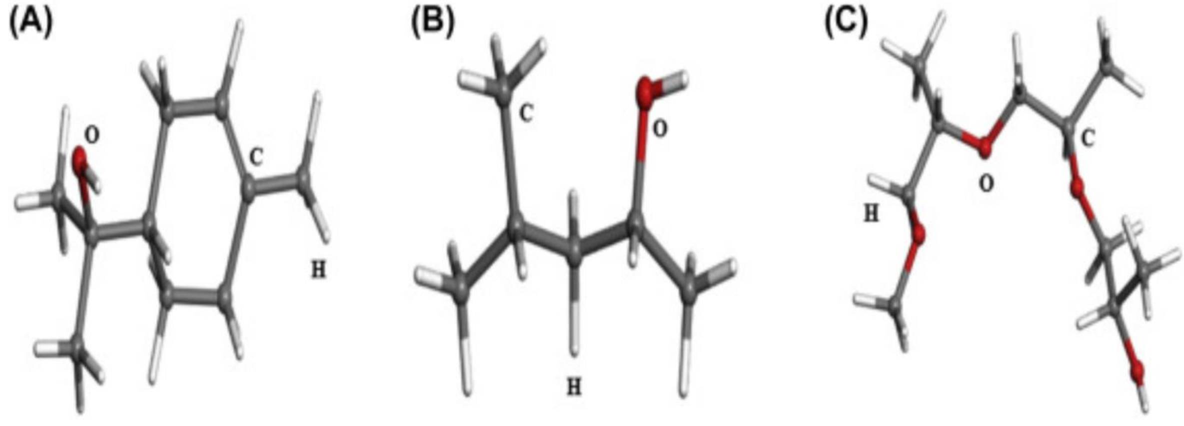


Figure 15 Molecule structures: (A) α-terpineol-C10H18O, (B) MIBC-C6H14O, and (C) DF200-C10H22O4.[24]

Collector: The collector plays a crucial role in froth flotation by making the mineral surface more hydrophobic. This hydrophobicity enhances the attachment of bubbles to mineral particles and reduces their detachment. In order to achieve this, the collector molecules adsorb onto the mineral surface, effectively altering its properties and promoting effective bubble-particle interaction. Moreover, froths have an impact on the transient stability of thin liquid films found in the froth zone, which in turn affects the rate at which bubbles merge, the amount of water held in the froth, the mobility of the froth, and its capacity to transport mineral particles. In the past, fatty (carboxylic) acid was commonly used as the collector for flotation of rare earth ore (REO) due to its affordability and widespread availability. However, as research in rare earth flotation has progressed, there has been a shift in this conventional approach. Fatty acid collectors, although widely used, exhibit a high level of non-selectivity on their own. To achieve the desired concentrate grades and recoveries, significant amounts of depressants need to be added. This additional use of depressants adds complexity and cost to the flotation process.[5] The adsorption of fatty acid and hydroxamate collectors onto bastnasite mineral surfaces is believed to occur through a chemisorption mechanism. This is supported by the fact that both anionic collector types, such as sodium oleate and hydroxamate, have been observed to adsorb onto the mineral surface at pH conditions where the zeta potential of the mineral is negative.[25]

The need for improved selectivity in REO flotation has led to advancements in collector development. Researchers have been exploring alternative collectors with enhanced selectivity for specific REO minerals. These new collectors aim to improve the efficiency of the flotation process by reducing the reliance on depressants and minimizing the quantity of gangue minerals in the final concentrate. Table 9 and 10 shows studies performed on bastnasite and monazite.

Table 9 Fundamental Studies on Bastnasite Flotation.[5]

Author	**Year**	**Mineral**	**Source**	**pH of max recovery**	**Collector**	**Depressant**	**Frother**	**Max Recovery**
Jordan	2014	Bastnasite	Madagascar; Mountain Pass, CA	9.0	Benzohydroxamic Acid, Phosphoric Acid, Sodium Oleate	Sodium Silicate	MIBC, F150	95
Pradip/ Fuerstenau	2013, 1985, 1992, 1983	Bastnasite, Calcite, Barite	Mountain Pass, CA; Kansas; South Carolina	9.5	K-Octyl Hydroxamate, Fatty Acid(sodium oleate)	Lignin Sulfonate	N/A	≈95
Ren	2000	Bastnasite	China	5.0	Benzoic Acid	Potassium Alum	N/A	≈95
Pavez	1995	Bastnasite	Brazil	9.0	K-Octyl Hydroxamate, Fatty Acid (sodium oleate)	N/A	N/A	≈95
Ren	1997	Bastnasite	China	8.5-9.5	Modified Hydroxamic Acid	Sodium Sulfide	N/A	≈95

Table 10 Fundamental Studies on Monazite/Xenotime.[5]

Author	Year	Mineral	Source	pH opt.	Collector	Depressant	Frother	Max Recovery
Ren	2000	Monazite	China	5.0	Benzoic Acid	Potassium Alum	N/A	≈95
Pereira and Peres	1997	Xenotime, Zircon	Brazil	10	Hydroxamte (Flotinor V35759)	Lignin Sulfonate, Sodium silicate, Starch, Quebracho, Amylopectim	N/A	≈98
Pavez	1995	Monazite	Brazil	9.0	K-Octyl Hydroxamate, Fatty Acid (sodium oleate)	N/A	N/A	≈95
Pavez and Peres	1994	Monazite, Rutile, Zircon	Brazil	10	Hydroxamate (Flotinor V3759), Sodium Oleate	Sodium Silicate	N/A	95
Harada	1993	Monazite, Xenotime	Australia, Malaysia, Thailand	≈9.0	Sodium Dodecylsulfate, Dodecylammonium Chloride	N/A	N/A	≈90
Pavez	1992	Monazite, Rutile, Zircon	Brazil	10	Commercial Hydroxamate (Flotinor V3759), Pure Hydroxamte, Sodium Oleate	Sodium silicate, Sodium Sulfide	N/A	≈95
Cheng	1992	Monazite, Xenotime	Australia	8.5, 7.5	Sodium Oleate	N/A	N/A	≈98
Andrews et al.	1990	Monazite, Xenotime	Australia		Fatty Acid (Actinal FA2), Phosporic Acid Esters	Sodium Silicate, Sodium Silicofluoride	N/A	≈98
Ozeren and Hutchinson	1990	Xenotime	Australia	10	F74286	Sodium Silicate	N/A	≈85

In their study, Pavez and Peres (1993) demonstrated that the use of a hydroxamate collector in the flotation process resulted in an improvement in the grade of the rougher concentrate. This improvement was attributed to the enhanced selectivity of the hydroxamate collector towards the desired minerals. However, it was observed that sodium oleate, another collector, yielded higher overall grades and recoveries. Furthermore, the research findings indicated that increasing the temperature had a positive effect on the depression of rutile and zircon. This means that at higher temperatures, the undesired minerals, rutile and zircon, were more effectively suppressed during the flotation process. The increased depression of these minerals contributed to the overall improvement in concentrate grade and selectivity.[25]

Overall, the study highlights the influence of different collectors and temperature conditions on the flotation performance. While the hydroxamate collector showed increased selectivity and improved rougher concentrate grade, sodium oleate exhibited better overall grade and recovery. Moreover, the findings emphasized the significance of temperature in achieving optimal depression of specific minerals, such as rutile and zircon, during the flotation process.

Modifier: Modifiers are substances used to alter the surface properties of the minerals involved in the flotation process. Their role is to selectively activate or depress specific minerals, thereby improving the selectivity of the flotation process. The efficiency of modifiers depends on factors such as reagent conditioning, flotation conditions, and the composition of the ore. It is worth noting that the chemistry of modifiers in flotation pulps is very complex. For example, cyanide is commonly used in froth flotation to selectively separate copper minerals from pyrite. Its well-known depressing action on pyrite allows for the targeted separation of these minerals on many flotation plants. In case of REE sodium silicate, lignin sulfonate is widely used as shown in Table 9 and 10.

2.3.3. Comminution and Classification

Comminution is the mechanical process of reducing the size of solid materials through methods such as crushing and grinding. It plays a vital role in industries like mining, mineral processing, and materials science. The main objective of comminution is to break down large particles into smaller fragments or particles, enabling easier handling, improved liberation of valuable minerals, increased surface area for chemical reactions, or more efficient separation processes. Different techniques, such as jaw crushing, cone crushing, and grinding mills, are employed based on material properties and the desired particle size distribution.[19]

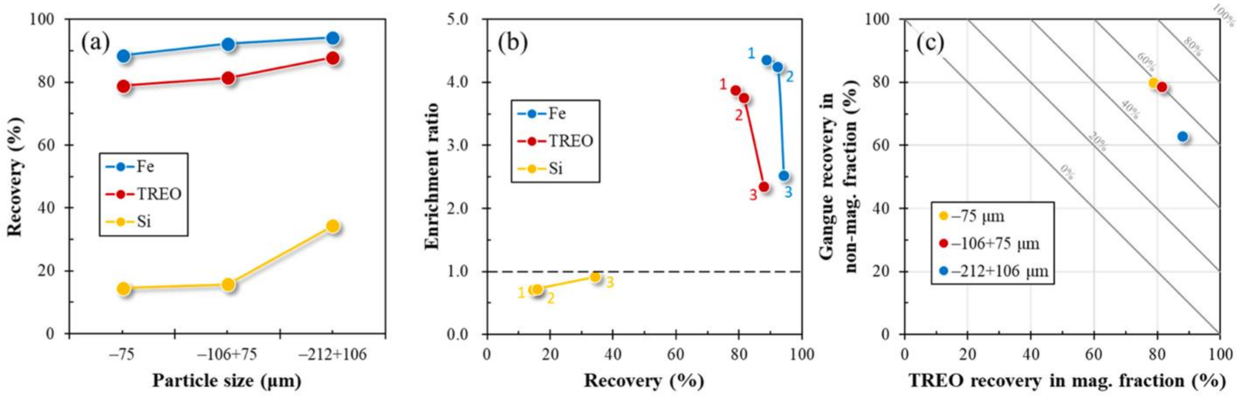


*Figure 16 Effect of particle size on (a) the recovery of TREO, Fe, and Si from REE ore, (b) enrichment ratio as a function of recovery, and (**c**) relationship between TREO recovery in magnetic fraction and gangue recovery in non-magnetic fraction.[6] Magnetic separation study.*

The recovery of TREO, Fe and Si are influenced by the size of the particles resulting from the comminution process, as depicted in Figure 16. both of which slightly decreased with decreasing particle size. Which is not always the case while the decrease in particle size had a minor impact on the recovery of total rare earth oxides (TREO), it had a significant effect on reducing the recovery of major gangue minerals, such as quartz and other silicate minerals. For instance, the recovery of silicon (Si) decreased from approximately 34% in the size fraction of -212 + 106 μm to around 15% when the particle size dropped below 106 µm. This reduction in Si recovery led to an improved enrichment ratio of TREO, increasing from 2.4 to approximately 3.8-3.9.[6] The findings suggest that the size fraction ranging from -106 to +75 µm demonstrated better performance in terms of upgrading and recovering rare earth oxides (REOs) compared to the other size fractions.

To reduce the size of the sample, a series of primary crushing and grinding steps are employed until the desired particle size is achieved. Primary crushing involves the initial breaking down of the ore into smaller fragments using mechanical force. This step is typically carried out using jaw crushers or gyratory crushers, which apply pressure to the ore to break it into more manageable sizes. Which typically has reduction ratio of 70 to 90.

Following primary crushing, the ore undergoes grinding, where it is further reduced in size by the action of grinding media such as steel balls or rods. The grinding process is performed in rotating mills, such as ball mills or SAG (Semi-Autogenous Grinding) mills, where the ore is finely pulverized through the impact and attrition caused by the grinding media. This process helps to liberate the valuable minerals from the gangue material and increase the surface area for subsequent processing. The grinding has over 1000 reduction ratio, typically desired size of sample for froth flotation >74µm.

The desired size of the sample is achieved through careful control of the crushing and grinding parameters, such as the feed size, the type of equipment used, and the duration of the grinding process. The final particle size obtained is crucial, as it affects the efficiency of subsequent mineral separation processes, such as flotation or leaching, by allowing for better liberation of the valuable minerals and improved interaction with reagents. Overall, the primary crushing and grinding stages play a vital role in reducing the sample size and preparing it for further processing, ensuring optimal particle size distribution and enhancing the efficiency of downstream mineral recovery processes.

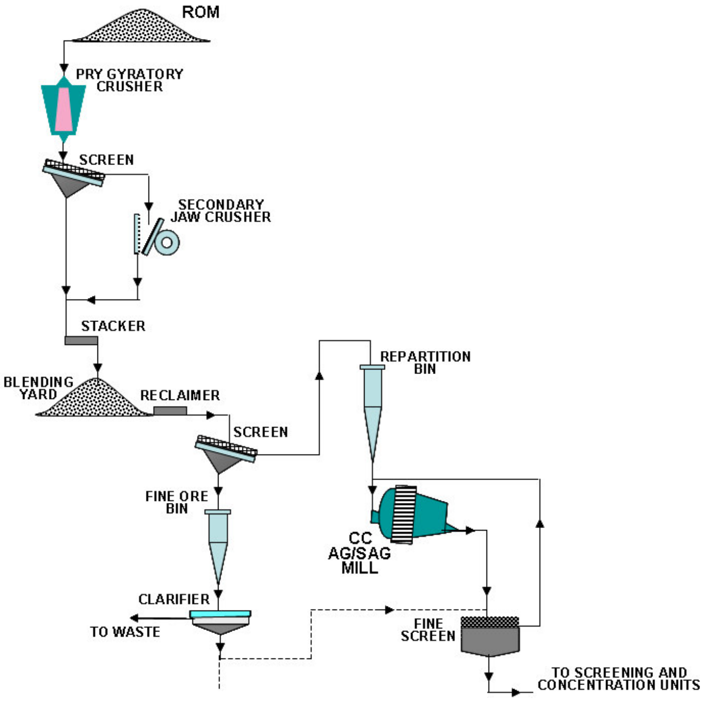


Figure 17 Example diagram for typical comminution

2.3.4. Dewatering

Dewatering of sample can be done in multiple different ways such as gravity sedimentation, pressure filtering, vacuum filtering and convection drying. Gravity sedimentation or thickening is a widely used and cost-effective method for separating solids from liquids. It is particularly suitable for aggregating small particles together without requiring excessive energy consumption. The thickener plays a crucial role in this process by increasing the concentration of the suspension through sedimentation, leading to the formation of a clear liquid. However, sometimes the suspension's concentration is too high, hindering the settling process. Thickeners can be either batch or continuous, and they consist of shallow tanks where the clear liquid is extracted from the top while the thickened suspension settles at the bottom. The sizing of a thickener is crucial as it involves significant capital costs and selecting the appropriate size is essential for optimal performance in a given application. Filtration is another commonly used method for separating solids from liquids. It is a cost-effective process that does not require a significant amount of energy, making it suitable for various applications. In filtration, a porous medium, such as a filter media or a filter membrane, is used to trap solid particles while allowing the liquid to pass through. The solid particles accumulate on the surface or within the filter media, forming a filter cake. Filtration can be performed through different mechanisms, such as gravity filtration, pressure filtration, or vacuum filtration, depending on the specific requirements of the process. Gravity filtration relies on the force of gravity to drive the liquid through the filter medium, while pressure filtration applies external pressure to facilitate faster filtration. Vacuum filtration, on the other hand, utilizes suction or negative pressure to enhance the filtration rate. The choice of filter media, pore size, and operating conditions (such as pressure or vacuum level) are critical factors in achieving efficient filtration. The goal is to retain the solid particles while maximizing the flow of the liquid. Once the filtration process is complete, the collected solid particles, often referred to as the filter cake, can be further processed or disposed of, while the filtered liquid is separated for further use or treatment. Overall, filtration provides an effective means of separating solids from liquids, offering versatility in terms of scale, equipment, and filtration mechanisms, and finding applications in various industries such as water treatment, pharmaceuticals, food processing, and chemical manufacturing.[19]

3. METHODOLOGY

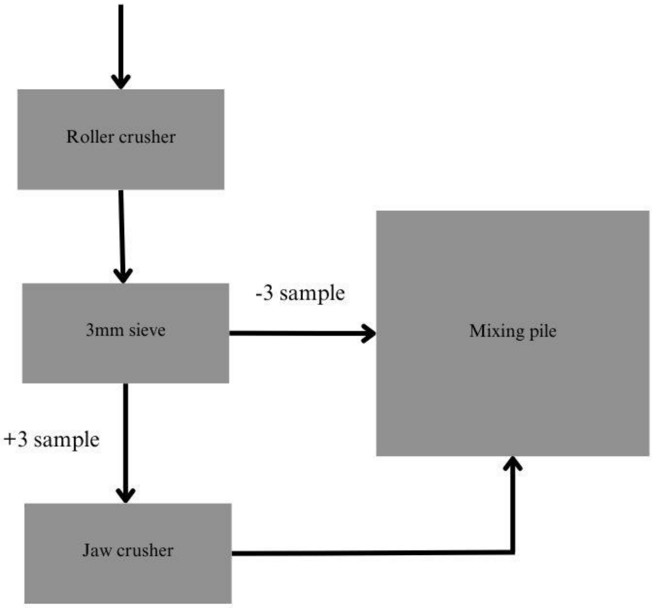


Figure 18 Diagram of sample size reduction

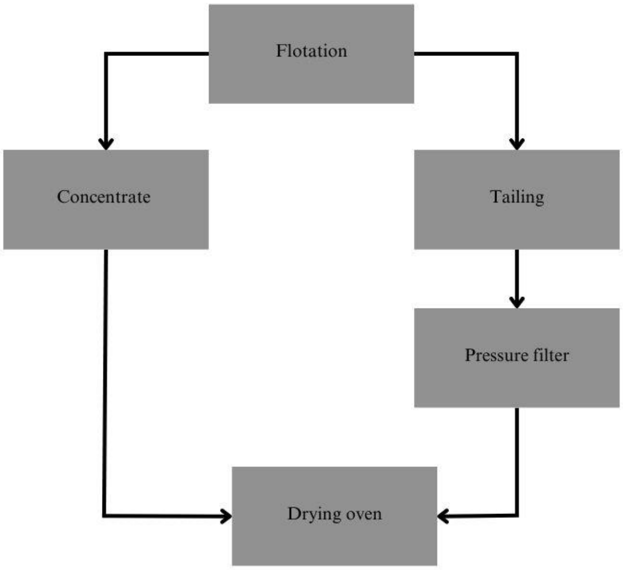


Figure 19 Simple diagram for flotation test

3.1. Sample Preparation

The sample used in this study was prepared at the laboratory of the German-Mongolian Institute for Resources and Technology, using a standard sampling method involving a chute-type sample splitter which have low deviation (Table 11, Figure 20). A total of approximately 45 kilograms of rocks up to 100mm in size were collected from the Khalzan Buregtei deposit and crushed with a roller crusher until they reached 10-15mm in size. The crushed sample was then sieved with a 3mm opening, with the +3mm coarse sized sample being further crushed to -3mm using a jaw crusher. The under-class (-3mm) samples were mixed together, and a 1000-gram sample was prepared for grinding optimization and froth flotation testing. This sample was then divided into two piles of roughly 20kg each, and further subdivided into 10kg samples using a sample divider. Four 10kg samples were then split into 5kg samples using systematic sampling with a riffle splitter, under the supervision of the laborant Mr. M. Baasandorj, to ensure a representative and well-mixed sample of the ore. The 1000-gram samples will then be sent to the rod mill for finding grinding time optimization before proceeding to froth flotation testing. A total of 40 samples were weighed and stored for later use in the bachelor thesis testing, while some ore was discarded at the start of the sample preparation to avoid possible slime creation. Thirty froth flotation experiments were scheduled, and the remainder of the sample was reserved for grinding time optimization.

Table 11 Standard deviations of samples[21]

Sampling Method	Standard deviation of samples, %
Cone and quarter Grab sampling	6.81
Grab sampling	5.14
Chute-type sample splitter	1.01
Rotary riffle	0.125
Random deviation for a theoretically perfect sampler	0.076

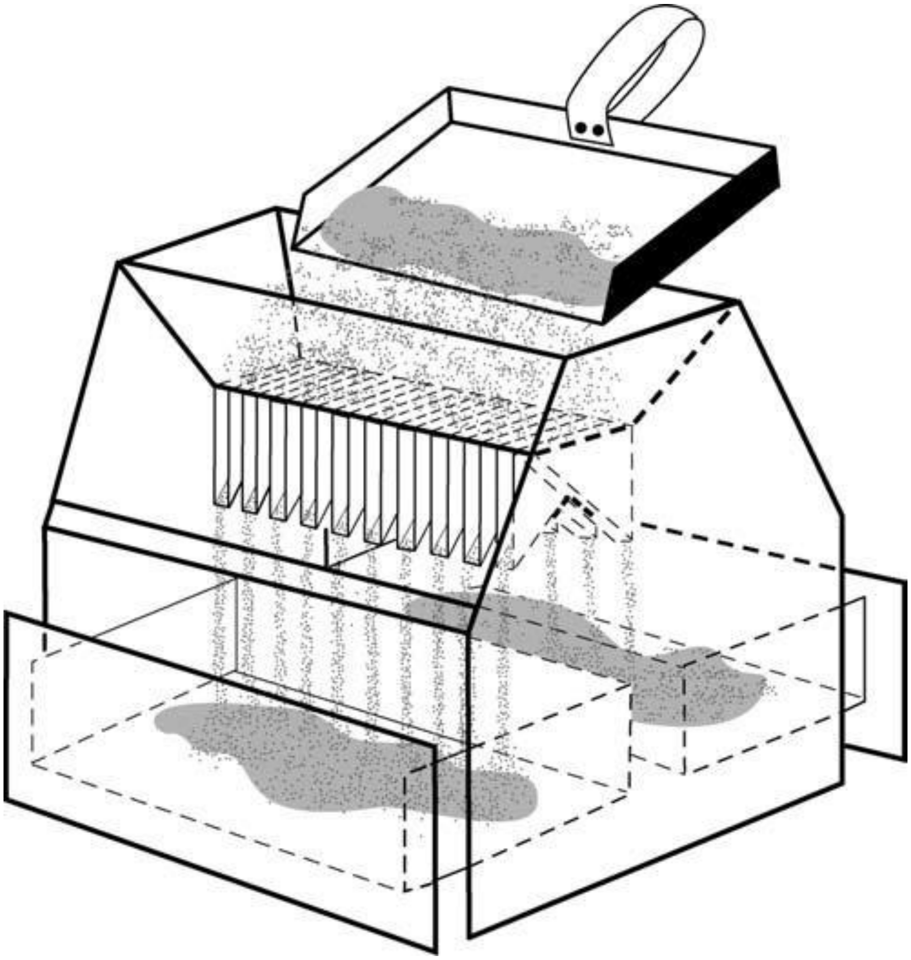


Figure 20 Chute-type sample splitter[26]

3.2. Grinding Time Optimization

To determine the grinding time for achieving a target particle size (P80 = 74 µm), pre-prepared samples were utilized. Six different grinding times were selected for the rod mill: 8, 12, 16, 20, 24, and 30 minutes (as shown in Tables 12 and 13).

The rod mill was loaded with a 1000 g sample, and 650 g of water was added, resulting in a solid-to-liquid ratio of 60% by weight. The rod mill operated at a spin frequency of 10 Hz. Once the grinding process was completed, the slurry was subjected to desliming using a sieve with an opening size of 74 µm. The deslimed slurry was then transferred to a convection oven with a maximum temperature of 110°C for drying.

After drying, the slurry was subjected to dry screening using four sieves with opening sizes of 74, 106, 150, and 300 µm. The oversize fractions were weighed for optimization purposes and size analysis.

Figure 21 Dry screening

Figure 22 Laboratory rod mill

Figure 23 Laboratory rod mill(b)

3.3. Particle Size Analysis

In this study, the particle size analysis was conducted using the sieve analysis method, which is one of several available techniques for determining particle size distribution. Other commonly used methods for particle size analysis include laser diffraction, optical microscopy, electron microscopy, elutriation (cyclosizer), sedimentation (gravity), and sedimentation (centrifuge).

1. Laser Diffraction: This method utilizes the principle of light scattering to measure particle size. A laser beam is passed through the sample, and the scattered light is analyzed to determine the particle size distribution. It is widely used for both dry and wet samples and can provide rapid and accurate results.

2. Optical Microscopy: This method involves the visual observation of particles under a microscope. Particles are sized based on their dimensions and shape. It is particularly useful for irregularly shaped particles and can provide valuable morphological information.

3. Electron Microscopy: Electron microscopy techniques, such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM), utilize high-energy electron beams to image particles at high magnification. These methods offer detailed information on particle shape, size, and surface characteristics at the micro- and nano-scale.

4. Elutriation (Cyclosizer): Elutriation separates particles based on their settling velocities in a fluid flow. The sample is introduced into a fluid stream, and particles are separated according to their sedimentation rates. The Cyclosizer is a commonly used elutriation device that provides size fractionation of particles based on their settling velocities.

5. Sedimentation (Gravity): Sedimentation involves allowing particles to settle under the influence of gravity in a liquid medium. The settling velocity is related to the particle size, and by measuring the settling time, the particle size distribution can be determined. This method is suitable for larger particles and may require longer settling times.

6. Sedimentation (Centrifuge): Similar to gravity sedimentation, centrifugal sedimentation utilizes centrifugal force to accelerate the settling process. By subjecting the sample to high-speed rotation, particles are forced to settle at different rates depending on their size. This method is particularly useful for fine particles and provides rapid results.

The sieve analysis is weighing the material collected on each sieve and determining percentage weight in each size fraction which is done while the grinding time is determined. The particle size analysis in this study involved the use of a particular set of sieves. These sieves had openings with sizes of 74, 106, 150, and 300 µm. The selection of these sieve sizes was based on the desired particle size range and the characteristics of the sample being analyzed.

During the sieving process, the sample was passed through the sieves in a sequential manner, starting from the largest sieve (300 µm) and progressing to the smallest sieve (74 µm). This allowed for the separation of particles based on their size, with larger particles being retained on the higher-mesh sieves and smaller particles passing through to the lower-mesh sieves.

Choosing the appropriate sieve sizes is crucial to ensure accurate particle size distribution data. The selected sizes should be suitable for capturing the full range of particle sizes in the sample, preventing particles from getting trapped in the sieve openings or passing through too easily. The specific sieve sizes used depend on the study's requirements and the expected particle size distribution.By weighing the particles retained on each sieve after sieving, the study was able to determine the weight or mass fraction of particles in different size fractions corresponding to the specific sieve openings. This data was then analyzed to understand the particle size distribution characteristics of the sample.

3.4. Froth Flotation Experiment

The flotation test involved introducing the finely ground slurry into a flotation cell with a volume of 3000ml, containing 30% solids by weight. The flotation machine was equipped with an impeller rotating at a speed of 1000 to 1050 rpm. The pH level in the cell was monitored using a pH meter to ensure optimal conditions, and if necessary, soda ash was added to adjust the pH. The reagents (collector, depressant, frother) were added to the slurry with a conditioning time of 1 minute. The sequence of addition was depressant followed by collector, and finally frother. Each test was conducted twice to ensure reliable results, resulting in a total of 28 experiments. Sodium oleate ($C_{36}H_{66}Na_2O_4$) was used as the collector with varying quantities, water glass/sodium silicate (Na_2SiO_3) served as the depressant, and MIBC ($C_6H_{14}O$) was used as the frother.

The experiment was done in 7 minutes into only one tray for the concentrate, and scraped for every 6 seconds (70 scraps in total).

Table 12 Flotation experiment reagent usages

No	Collector usage(g/ton)	Depressant usage(g/ton)	Frother usage(g/ton)
1	70	2000	Not used
2	70	2000	70
3	70	3000	70
4	70	2000	140
5	70	2000	70
6	70	3000	70
7	70	2000	140
8	140	2000	140
9	210	2000	140
10	140	2000	210
11	280	2000	140
12	140	2000	280
13	420	2000	140
14	140	2000	420

Figure 24 Froth flotation testing

3.5. Apparatus And Equipment

3.5.1. Sample Preparation Equipment

Splitter: The unit serves as an advanced automated solution for sample preparation in laboratory environments. Its primary purpose is to swiftly and accurately divide and blend solid materials for further analysis. With the ability to regulate the division ratio, it ensures precise splitting of samples. Moreover, its sealed design prevents any dust emissions, creating a clean working area while reducing the risk of manual errors during operation. For this particular thesis project, a automatic sample divider with a capacity of 300-1000 kg(Figure 24) per hour is utilized to compose the samples and obtain representative 5kg portions. The representative portions then divided by Retsch sample splitter RT 6.5 (Figure 25) which is a manual splitter into 1kg samples to get ready for upcoming tests.

Figure 25 GM/ZS-A Automatic Divider

Figure 26 Retsch sample splitter RT 6.5

3.5.2. Sample Comminution Equipment

Rod mill: Laboratory rod mill consists of 2 separate components, motor driving the shell to spin (Figure 23), the shell that contains the sample, water and the rods (Figure 22). The is 16.755 kilograms in weight and have 3 different radiuses but same height. The frequency of the spin can be controlled by controller near the motor. The rods need cleaning before use due to corrosion and it is same with the shell.
Roller crusher: The laboratory crusher is LMRC100 Roll Crusher from Laarmann. Roll crushers are designed to minimize the generation of dust and produce a material with a narrow size range that contains very few fine particles.

Figure 27 LMRC100 Roll Crusher

3.5.3. Froth Flotation Equipment

Flot machine: METSO D12 Lab Flotation Machine is used in this study. It has a stainless-steel standpipe and shaft with a suspended type of mechanism. Air supply and revolution of impeller can be controlled. The air is supplied by a compressor in the laboratory and is measured by airflow meter with m^3/h unit. Other operations are done manually such as scraping and adding water. The flotation cell is a stainless-steel cell.

Figure 28 METSO D12 Lab Flotation Machine

3.5.4. Sample Analysis Equipment

XRF: Niton XL2 Goldd (Figure 29) is used in the laboratory for X-Ray fluorescence spectroscopy analysis. This non-destructive technique promptly assesses the metal composition across a broad spectrum of 30 elements, encompassing sulfur to uranium, along with impurities and minor elements.

Figure 29 Niton 2XL Goldd

Figure 30 PHS-25CW microprocessor pH/mV meter

pH meter: The benchtop pH meter, equipped with a 0.05 pH accuracy and a two-point calibration, allows precise pH measurement and adjustment within the range of 0.00 to 14.00 pH at temperatures ranging from 0 to 100°C. This pH meter is specifically designed for educational and laboratory settings, facilitating chemical experiments and quality monitoring. In the flotation cell, the pH of the slurry was monitored and regulated using this reliable pH meter (Figure 30).

3.5.5. Dewatering Equipment

Drying oven: The electric blast drying oven is equipped with a digital display for temperature control, allowing for a temperature range of +10°C to 250°C. This oven is specifically designed to rapidly dry a wide range of heat-sensitive, easily decomposable, and oxidized materials. The filtered materials can be thoroughly dried using this efficient electric blast drying oven.

Figure 31 Lichen Technology Electric Blast Drying Oven

Pressure filter: Mascalab filter presses (Figure 32) are extensively used in mining and metallurgical laboratories for the purpose of separating water from slurries. During the experiments, both the concentrate and tailings obtained from the flotation test are introduced into a stainless-steel container. The container is then sealed with a lid, and air pressure of 600kPa is applied to facilitate the separation of solids and liquids.

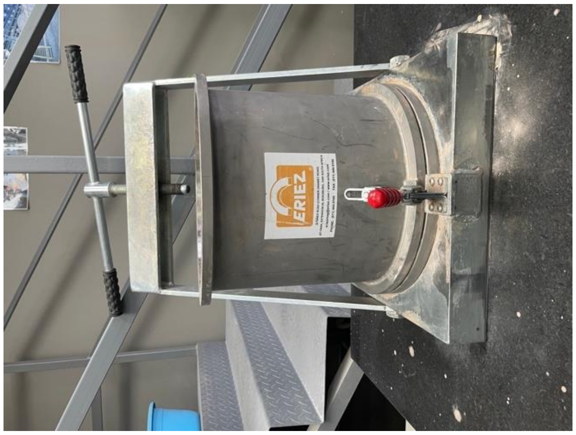


Figure 32 MascaLab Filter Press

4. Results And Discussion

4.1. Grinding Time Optimization

Table 13 Test sequence for grind time optimization

Test No	Grind time (sec)	Target Grind P80
1	480	150
2	720	150
3	960	150
4	1200	106
5	1250	106
6	1800	74

Table 14 Grinding optimization for p80 of 150µm

Time, sec	P80 of 150µm, %
480	54.49
960	95.05
942	80

Table 15 Grinding optimization for p80 of 106µm

Time, sec	P80 of 106µm, %
480	40.41
1250	92.01
1309	80

Table 16 Grinding optimization for p80 of 74µm

Time, sec	P80 of 74µm, %
480	32.49
1800	86.08
1674	80

During the optimization process for grinding time, the ore is subjected to wet grinding using a rod mill. The rod mill had 10hz frequency as written before. Subsequently, the particle size distribution is determined through the wet sieving method. By analyzing the collected data and utilizing the "forecast" formula in Microsoft Excel, the appropriate grinding time for three primary grind sizes (74µm, 106µm, and 150µm) can be determined (Table 12).

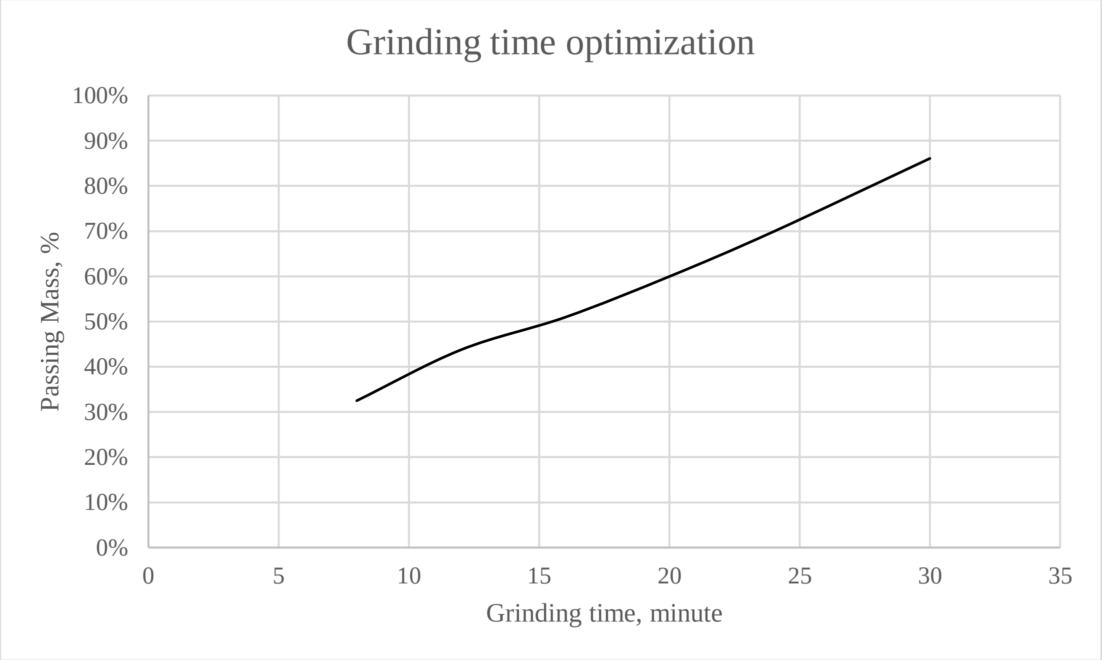


Figure 33 Grinding time optimization at 74µm

4.2. Size Distribution Analysis

Table 17 Size distribution for p80, 150µm

Sieve size range(µm)	Sieve fractions		Nominal aperture size (µm)	Cumulative, %	
	Weight, g	Weight, %		Collected	Passing
300	2.91	0.29	300	0.29	99.71
-300, +150	176.38	17.64	150	17.93	82.07
-150, +106	192.62	19.26	106	37.19	62.81
-106, +74	118.83	11.88	74	49.07	50.93

-74	509.26	50.93			
Total	1000	100			

Table 18 Size distribution for p80, 106µm

Sieve size range(µm)	**Sieve fractions**		**Nominal aperture size (µm)**	**Cumulative, %**	
	Weight, g	Weight, %		Collected	Passing
300	1.81	0.18	300	0.18	99.82
-300, +150	58.44	5.84	150	6.02	93.98
-150, +106	141.94	14.19	106	20.22	79.78
-106, +74	142.97	14.30	74	34.52	65.48
-74	654.86	65.48			
Total	1000	100			

Table 19 Size distribution for p80, 74µm

Sieve size range(µm)	**Sieve fractions**		**Nominal aperture size (µm)**	**Cumulative, %**	
	Weight, g	Weight, %		Collected	Passing
300	1.47	0.14	300	0.18	99.82
-300, +150	2.8	0.28	150	6.02	93.98
-150, +106	30.07	3.01	106	20.22	79.78
-106, +74	161.50	16.15	74	34.52	65.48
-74	804.17	80.42			
Total	1000	100			

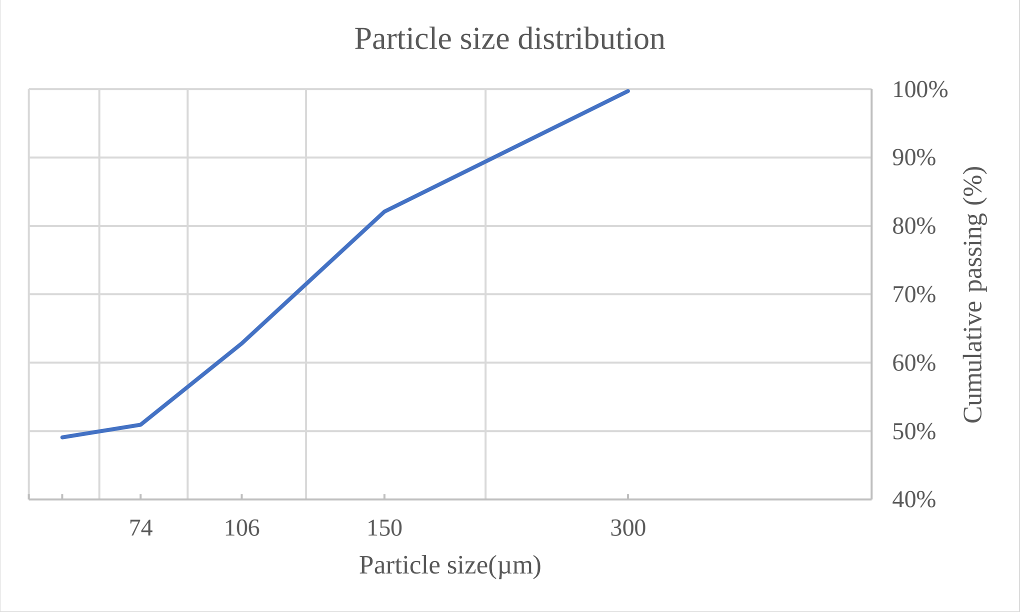


Figure 34 Particle size distribution at p80, 150µm

Figure 34 shows that 60% percent of the sample is passing 100µm which means the sample is has very fine particles so only primary grinding is deemed necessary. But the literature suggests for maximum recovery of REEs the ore should be grinded to p80=54µm. In this study due to the fine particles we chose 80% passing of 74µm for the froth flotation tests.

4.3. Sample Characterization

The Khalzan Buregtei deposit was characterized by few researches [6][18][25] which was used in this study. Mentioned studies characterization has been written in the literature review.

From Table 6 and 7 we can see that silicon dioxide is the majority, this is the primary gangue. The REE content is very low with the TREO is being the highest occurring with in highest case having 8640 ± 526 ppm.

Figure 35 Khalzan Buregtei deposit

The mineralogical composition of the sample was analyzed using X-ray diffraction (XRD) in the study [6]. The XRD pattern revealed the presence of quartz and aluminosilicates, such as albite

($NaAlSi_3O_8$) and microcline ($KAlSi_3O_8$), as the primary gangue minerals in the sample. This finding aligns with the results obtained from X-Ray fluorescence (XRF) analysis, as presented in Table 7. Additionally, minor non-REE constituents, including hematite, aegirine, zircon and columbite were identified. These minerals contain elements such as Fe, Zr and Nb. Since the sample had a low grade of REE, no REE-bearing minerals were identified in the XRD analysis, which is why the characterization is hard to perform. In the study [6] to gain further insight into the specific types of REE-bearing minerals present, thin sections of the example were subjected to scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) analysis. The main minerals containing rare earth elements (REE) are bastnäsite-(Ce) and pyrochlore. These minerals are embedded within a matrix of quartz and albite. Bastnäsite-(Ce) is composed of $Ce(CO_3)F$, while pyrochlore is represented by $(Na,Ca,REE)_2Nb_2O_2(OH,F)$. These minerals contain valuable rare earth elements and are commonly found together in geological formations.

4.4. Froth Flotation Experiment Results

A total of 14 experiments were performed using froth flotation as the method. The initial 8 tests resulted in no significant yields, meaning that there was no substantial concentration of the desired material. In the remaining 7 experiments the air supply was changed from $0.4m^3/h$ to $0.6m^3/h$, a minimal amount of yield was obtained; however, it was not sufficient to conduct a proper analysis on the concentrate obtained.

Although it was possible to analyze the tailings for their grade, the cost associated with performing such analysis was prohibitively high. Consequently, a detailed assessment of the composition of the tailings, specifically the concentration of the desired material, could not be carried out due to economic constraints.

The objective of the testing was to attain a high yield through froth flotation in order to determine if it could be a viable method for the beneficiation of the Khalzan Buregtei deposit. Previous literature indicated that the deposit had a low content of rare earth elements (REE). Therefore, the aim was to investigate the feasibility of only utilizing froth flotation to effectively increase the concentration of REEs in the ore. This will be concluded from the yield amount produced from the testing.

According to the literature, the presence of a significant quantity of gangue elements in the ore necessitates the use of a substantial amount of depressant during froth flotation [5]. A specific study [27] suggested that for achieving maximum recovery, the optimal dosage of depressant should be around 2500 grams per ton of ore. This indicates that a relatively high dosage of depressant is required to effectively suppress the unwanted gangue minerals and enhance the recovery of the desired rare earth elements during the froth flotation process. The usage of other reagents in the experiments was initially modeled after the flotation plant practices employed by Molycorp. This means that the quantities and types of reagents used in the tests were initially determined based on the established practices and methodologies employed at Molycorp's flotation plant. By adopting these known industry practices, it was hoped to replicate the successful flotation conditions and optimize the separation and recovery of rare earth elements in the experimental setup. The last 7 testing yields are given in Table 22.

Table 20 Flotation experiment concentrate yield

Test No	First testing yield, g	Second testing yield, g
8	0.25	0.42
9	3.2	3.4
10	5.3	5.4
11	5.8	6.2
12	7.8	6.2
13	13	12.4
14	16.3	17.8

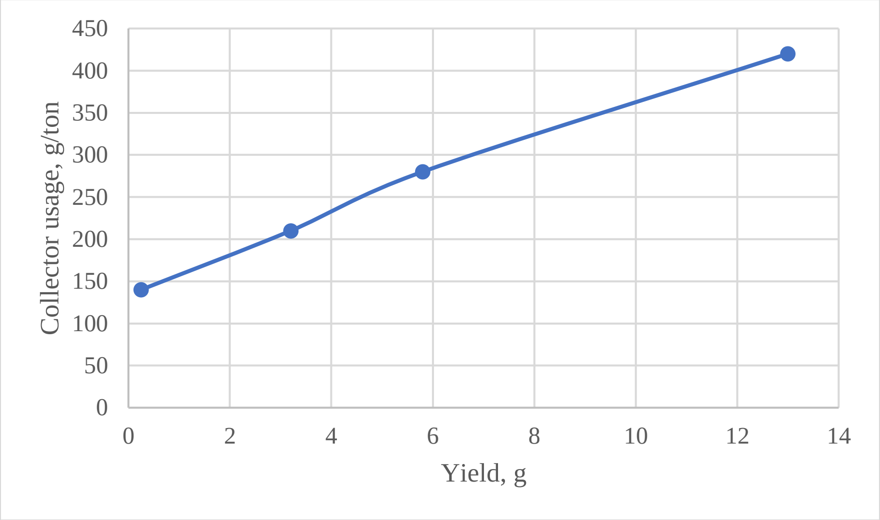


Figure 36 Yield change compared to collector usage change (frother, depressant constant) for first testing

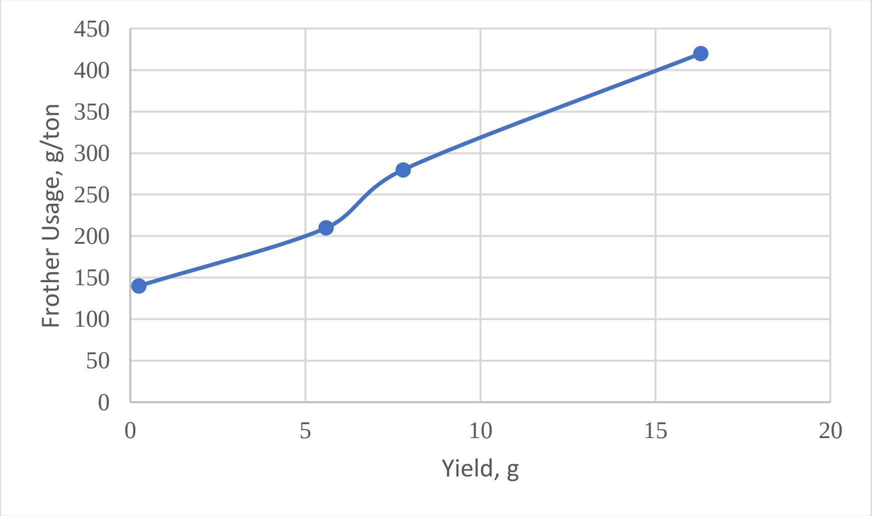


Figure 37 Yield change compared to frother usage change(collector, depressant constant) for first testing

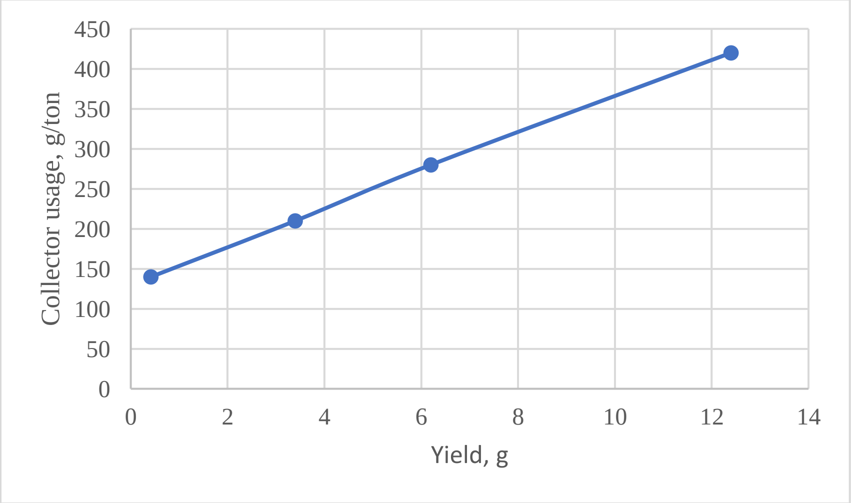


Figure 38 Yield change compared to collector usage change(frother, depressant constant) for second testing

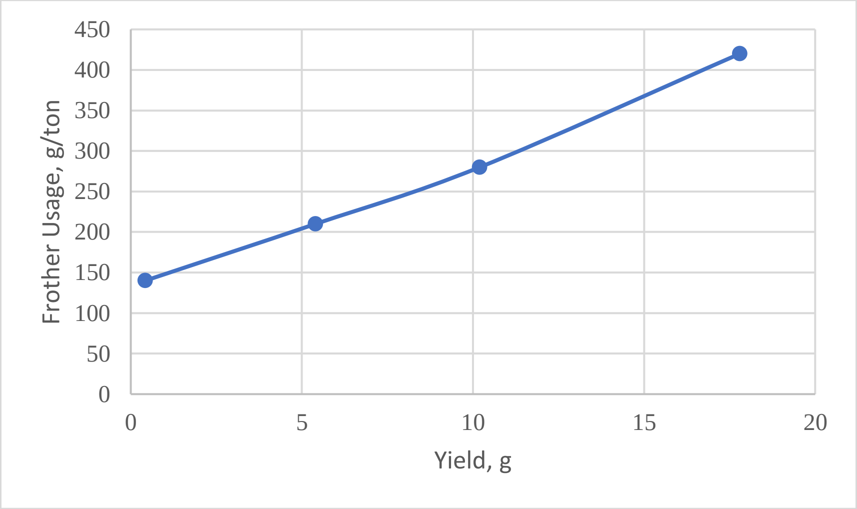


Figure 39 Yield change compared to frother usage change (collector, depressant constant) for second testing

The analysis of the obtained results revealed some important insights regarding the froth flotation of rare earth elements (REEs) from the Khalzan Buregtei deposit. Although the concentrate grade analysis could not be conducted, certain trends and observations were observed, particularly with respect to the collector reagent and its influence on yield.

The findings indicated that increasing the dosage of the collector reagent led to an increase in yield. This suggests the possibility of obtaining a higher-grade concentrate by utilizing a greater quantity of the collector. These results align with previous studies that have demonstrated the critical role of the collector in REE flotation, as it facilitates the attachment of hydrophobic REE particles to air bubbles, promoting their recovery in the froth phase.

However, it is important to consider the economic implications of utilizing larger amounts of the collector reagent. The cost associated with its usage is considerable, and further increasing the dosage may render the process economically unfeasible. Thus, a balance must be struck between maximizing recovery and optimizing reagent consumption to ensure a cost-effective approach.

Alternative strategies could be explored to address this economic challenge. One possible approach is to investigate the use of alternative, more cost-efficient collector reagents. Research has shown that different collectors can exhibit varying degrees of selectivity towards REEs, offering potential cost-saving opportunities while maintaining or even improving recovery rates. Furthermore, the utilization of advanced analytical techniques, such as electron microscopy and mineral liberation analysis, could provide valuable insights into the mineralogical characteristics of the concentrate and tailings. This information can aid in identifying potential avenues for process optimization and tailoring the flotation circuit to suit the specific mineralogy of the Khalzan Buregtei deposit.

5. CONCLUSION

In summary, the Khalzan Buregtei deposit predominantly contains bastnäsite and pyrochlore minerals, which have been extensively studied for their magnetic separation properties. Previous research has also demonstrated the successful application of froth flotation in the beneficiation of bastnäsite minerals. In industrial settings, a combination of flotation and magnetic separation is often employed to achieve high recovery rates.

However, it is important to note that the Khalzan Buregtei deposit exhibits a low concentration of rare earth elements (REEs), which is a common characteristic observed in many REE ore deposits. The results obtained from the flotation tests conducted in this study indicate that solely relying on flotation is insufficient to generate a concentrated REE product from the ore.

Nevertheless, the findings suggest that by integrating flotation with other beneficiation techniques aimed at reducing the presence of gangue minerals, it is indeed possible to extract and concentrate REEs, including total rare earth oxides (TREO) and heavy rare earth elements (HREE), from the bastnäsite mineral, with a particular focus on elements such as cerium.

Therefore, future research and development efforts should prioritize the exploration of combined approaches that incorporate flotation and complementary beneficiation processes. These additional techniques aim to effectively diminish the gangue mineral content, ultimately enhancing the recovery of valuable REEs from the Khalzan Buregtei deposit. Such an integrated approach holds great potential for improving the overall efficiency and economic viability of REE extraction from this deposit, considering its low-grade nature.

Further investigations should focus on optimizing the flotation process parameters, exploring alternative collector reagents, and employing advanced mineralogical analysis techniques to gain a better understanding of the ore's mineralogical characteristics. By doing so, researchers can develop a comprehensive and cost-effective beneficiation strategy tailored to the specific challenges posed by the Khalzan Buregtei deposit. Ultimately, these efforts will contribute to the sustainable and efficient extraction of REEs from this deposit and support the growing demand for these critical elements in various industries.

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APPENDIX

Table 21 Grinding time optimization results

Grinding time, min	**Sieve opening, µm**	**Collected Weight, g**					**Sum Weight, g**	**Collected Weight, %**					**Sum Weight, %**
		300	150	106	74	-74		300	150	106	74	-74	
8		7.3	447.8	140.8	79.2	324.9	1000	0.73%	44.78%	14.08%	7.92%	32.49%	100.00%
12		1.2	244.3	225.4	91.6	437.5	1000	0.12%	24.43%	22.54%	9.16%	43.75%	100.00%
16		1.4	48.1	312.7	128.3	509.5	1000	0.14%	4.81%	31.27%	12.83%	50.95%	100.00%
20		1.7	7.4	265.5	125.7	599.7	1000	0.17%	0.74%	26.55%	12.57%	59.97%	100.00%
24		1.6	4.1	74.2	221.1	699	1000	0.16%	0.41%	7.42%	22.11%	69.90%	100.00%
30		1.4	2.1	6.3	129.4	860.8	1000	0.14%	0.21%	0.63%	12.94%	86.08%	100.00%

Table 22 Grinding time optimization result, cumulative

Cumulative passing, %					**74 passing, %**	**grinding time, min**
300	150	106	74	-74		
99.27%	54.49%	40.41%	32.49%	0.00%	30%	6.94
99.88%	75.45%	52.91%	43.75%	0.00%	40%	11.13
99.86%	95.05%	63.78%	50.95%	0.00%	50%	15.32
99.83%	99.09%	72.54%	59.97%	0.00%	60%	19.50
99.84%	99.43%	92.01%	69.90%	0.00%	70%	23.66
99.86%	99.65%	99.02%	86.08%	0.00%	80%	27.90