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*Review*

# Rare Earth Element Deposits in Mongolia

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**Abstract:** In Mongolia, rare earth element (REE) mineralization of economic significance is related either to the Mesozoic carbonatites or to the Paleozoic peralkaline granitoid rocks. Carbonatites occur as part of alkaline silicate-carbonatite complexes, which are composed mainly of nepheline syenites and equivalent volcanic rocks. The complexes were emplaced in the Gobi-Tien Shan rift zone in southern Mongolia where carbonatites usually form dikes, plugs or intruded into brecciated rocks. In mineralized carbonatites, REE occur mainly as fluorocarbonates (bastnäsite, synchysite, parisite) and apatite. Apatite is also present in the carbonatite-hosted apatite-magnetite (mostly altered to hematite) bodies. Alkaline silicate rocks and carbonatites show common geochemical features such as enrichment of light REE but relative depletion of Ti, Zr, Nb, Ta and Hf and similar Sr and Nd isotopic characteristics suggesting the involvement of the heterogeneous lithospheric mantle in the formation of both carbonatites and associated silicate rocks. Hydrothermal fluids of magmatic origin played an important role in the genesis of the carbonatite-hosted REE deposits. The REE mineralization associated with peralkaline felsic rocks (peralkaline granites, syenites and pegmatites) mainly occurs in Mongolian Altai in northwestern Mongolia. The mineralization is largely hosted in accessory minerals (mainly elpidite, monazite, xenotime, fluorocarbonates), which can reach percentage levels in mineralized zones. These rocks are the results of protracted fractional crystallization of the magma that led to an enrichment of REE, especially in the late stages of magma evolution. The primary magmatic mineralization was overprinted (remobilized and enriched) by late magmatic to hydrothermal fluids. The mineralization associated with peralkaline granitic rocks also contains significant concentrations of Zr, Nb, Th and U. There are promising occurrences of both types of rare earth mineralization in Mongolia and at present, three of them have already established significant economic potential. They are mineralization related to Mesozoic Mushgai Khudag and Khotgor carbonatites in southern Mongolia and to the Devonian Khalzan Buregtei peralkaline granites in northwestern Mongolia.

**Keywords:** rare earth elements; deposit; Mongolia; carbonatite; peralkaline granitic rocks; Central Asian Orogenic Belt



**Citation:** Dostal, J.; Gerel, O. Rare Earth Element Deposits in Mongolia. *Minerals* **2023**, *13*, 129. https://doi.org/10.3390/min13010129

Academic Editor: Stefano Salvi

Received: 8 December 2022
Revised: 9 January 2023
Accepted: 9 January 2023
Published: 16 January 2023



## 1. Introduction

Rare earth elements (REE) are increasingly important in high-technology applications. They are in high and crucial demand for applications in modern technology including use in magnets, lasers, batteries, computers, screens and many others. They are important in the quest for "green energy" where some of them are used e.g., in wind turbines and hybrid gas-electric vehicles. This is in addition to their traditional application as pigments in glass, as abrasives and bearings in ceramics and as catalysts in petroleum refining. The demand for these elements has increased dramatically since 2000. In addition, the political and economic issues recently associated with the global REE supply has given these elements more visibility and strategic importance than ever before. The growing strategic importance of REE has been reflected in their inclusion in the 2022 US Government's List of Critical Minerals and European Union's List of Critical Raw Materials.

Although the demands for REE have significantly increased in recent years leading to extensive mineral exploration, economic REE deposits are rare and geological information on some of them are not available or difficult to obtain. The purpose of this paper is to present information on significant or promising mineral deposits of rare earth elements in Mongolia (Figure 1), and to provide an overview of their geological, geochemical and mineralogical characteristics as well as of their resources. As Mongolia hosts a number of promising sites of REE mineralization and many of them were not sufficiently explored and investigated, this review will be useful for future prospecting and research of these rare metals.


**Figure 1.** Map of Mongolia showing the location of the sites of significant REE mineralization. Host rocks—Carbonatites: 1—Mushgai Khudag; 2—Khotgor; 3—Bayan Khoshuu; 4—Lugiin Gol; 5—Ulgii Khiid; 6—Bayan Obo. Peralkaline granites: 7—Khanbogd; 8—Khalzan Buregtei; 9—Ulaan Tolgoi; 10—Tsakhir; 11—Ulaan Del; 12—Shar Tolgoi; 13—Maihan Uul. Number 6 is a large Bayan Obo REE deposit in Inner Mongolia, China. Inset map shows a geologic sketch of northeastern Asia and the location of Mongolia.

## 2. Geologic Background

Mongolian territory, a collage of Neoproterozoic-Paleozoic rocks and terranes, is a part of the Central Asian Orogenic Belt (CAOB), which has been subdivided in Mongolia to Northern Caledonian and Southern Hercynian domains [1]. The Northern domain contains Proterozoic and lower Paleozoic rocks, including cratonic fragments of Proterozoic rocks. The Southern domain is mainly composed of mid- to late Paleozoic igneous arc rocks, and Ordovician to Carboniferous sedimentary rocks, which were all intruded by voluminous Permian-Carboniferous granitoids.

The amalgamation of continental blocks and magmatic arcs within the CAOB was largely completed by the end of the Paleozoic-early Mesozoic [2]. Subsequently, this part of the CAOB underwent several episodes of intracontinental extension producing prominent rift zones and syn-rift basins. Eastern and southern Mongolia, in particular, underwent a period of basin-and-range style extension, accompanied by continental rift-related magmatism [3].

## 3. Rare Earth Element Deposits

There are several types of primary and secondary REE mineralization. However, the most important REE resources are associated with four geological environments [4,5]: carbonatites, alkaline felsic igneous systems and two secondary deposit types: placer deposits and residual deposits of REE-bearing clays, called ion-adsorption clays. In Mongolia, REE deposits of economic significance occur only at the first two types of geological environments (i.e., primary deposits)—carbonatites and alkaline felsic igneous rocks (Figure 1).

REE occur together in a wide range of minerals including oxides, silicates, carbonates, phosphates and halides. However, only a relatively small number are commercially important and tend to be dominated by either light REE (LREE) or heavy REE (HREE). Most important are bastnäsite, monazite and xenotime. Bastnäsite (fluorocarbonate-[(Ca, La)($CO_3$)F]) and monazite [(La, Ce, Nd, Th) $PO_4$] are rich in LREE, while xenotime ($YPO_4$) contains mainly HREE including Y. Other important REE minerals in Mongolia are apatite [(Ca, REE)$_5$($PO_4$)$_3$(F, Cl, OH)], britholite [(REE, Th, Ca)$_5$($SiO_4$,$PO_4$)$_3$(OH, F)] and elpidite [$Na_2ZrSi_6O_{15} \cdot 3H_2O$]. The Khanbogd peralkaline granitic pluton in southern Mongolia is the site of the discovery of a new Ca-zirconosilicate named armstrongite ($CaZrSi_6O_{15} \cdot 3\,H_2O$) after the American astronaut Neil Armstrong [6].

### 3.1. Carbonatite-Associated Deposits

Carbonatites are defined as igneous rocks composed of >50 vol.% primary (i.e., magmatic) carbonate and containing <20 wt.% $SiO_2$ [7]. The parent magmas of carbonatites were formed by either (a) by partial melting of carbonatite-bearing metasomatized lithospheric mantle or (b) by silicate-carbonate liquid immiscibility following fractional crystallization of carbonate-bearing, silica-undersaturated magmas such as nephelinites [8]. Carbonatite-associated deposits typically include mineralization that occurs both within and in close spatial or genetic connection with carbonatites and related alkaline silicate rocks [9]. Carbonatites mainly form various minor intrusions such as plugs, pipes, dikes, and lopoliths and are commonly surrounded by an alteration zone (fenitization—a zone enriched in Na and/or K) of host rocks. Some of these intrusions may be up to 3–4 km in diameter although typically they are significantly smaller. Carbonatites also occur as volcanic rocks. All these carbonatites are associated with alkaline silicate rocks such as nepheline syenites, ijolites, and nephelinites [10]. They typically occur in an extensional setting mostly in stable, intraplate areas where the intrusions are associated with major faulting or rifting [8,11–13]. Carbonatites have high concentrations of REE (usually 250–8000 ppm, [14,15]), typically with a strong enrichment of LREE relative to HREE. The chondrite-normalized La/Yb ratio commonly ranges from 100 to 10,000 (Figure 2). The carbonatites may also contain economic concentrations of Nb, P (apatite), fluorite and vermiculite [16]. The REE are mostly hosted in fluorocarbonates and phosphates (mainly apatite).

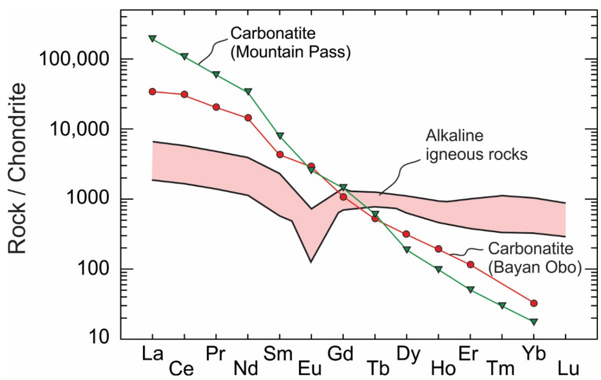


**Figure 2.** Chondrite-normalized REE patterns of mineralized carbonatites from Mountain Pass (California, USA) and Bayan Obo (Inner Mongolia, China), major carbonatite-hosted REE deposits [17,18] and the range of typical ores of the REE deposits associated with peralkaline igneous rocks. Normalizing values are after.

### 3.2. Peralkaline Rock-Associated Deposits

Peralkaline igneous rocks are alkaline rocks, which have a higher molecular content of alkalis than alumina [($Na_2O$ + $K_2O$) > $Al_2O_3$) mol.%]. Mineralogically, they typically contain alkali amphiboles and/or alkali pyroxenes and their CIPW norms include acmite and Na-metasilicate. Peralkaline rocks have a wide range of silica contents, ranging from granites through syenites to feldspathoid-bearing silica undersaturated rocks (e.g., nepheline syenite and nephelinite). These peralkaline rocks are rich in REE, uranium, thorium and high-field-strength-elements (HFSE) such as zirconium, and niobium (e.g., [17]). In contrast to the carbonatites and their deposits, peralkaline rocks and associated deposits are relatively enriched in yttrium and HREE [4,18]. For example, their chondrite-normalized La/Yb ratio is low, typically in the range of 2–10 (Figure 2; [14]). They occur in anorogenic settings, in continental rifts or crustal extension zones. Their mineralization is usually complex, composed of a variety of REE-bearing minerals, which show replacement textures due to multistage late magmatic or hydrothermal overprinting of primary mineral assemblages (e.g., [19–22]). Consequently, the intrusions and wall rocks are commonly highly altered and show distinct variabilities of mineralogy, grain size and textures. In addition to accessory minerals, alkali amphibole and pyroxene may also contain significant amounts of REE and play a role in their fractionation and concentration (e.g., [23–25]).

## 4. Mongolian REE Deposits

Carbonatites or alkaline silicate-carbonatite volcano-plutonic complexes, which host significant mineralization of rare earth elements, occur in Southern Mongolia (or Southern Gobi Desert). These Mesozoic complexes are located in the Permian-early Triassic Gobi-Tien Shan rift zone within grabens, which are subparallel to major tectonic lineaments and are related to continental rifting. Prominent Mesozoic carbonatite-hosting intrusions include the Mushgai Khudag, Bayan Khoshuu, Khotgor, Lugiin Gol and Ulgii Khiid complexes (Figure 1). The complexes were emplaced during two periods. The first period is the Late Paleozoic [26]–Early Mesozoic [27]. (Lugiin Gol complex: ~225–258 Ma [28]; and the second is of the Late Mesozoic age), (Mushgai Khudag: ~138 Ma; Bayan Khoshuu: ~134 Ma; Khotgor: ~135 Ma; Ulgii Khiid: 147–158 Ma) [29–32].

The alkaline silicate-carbonatite volcano-plutonic complexes associated with REE mineralization are comprised of nepheline syenites and related rocks or their volcanic equivalents. Carbonatites mostly occur as plugs and dikes (up to 1.5 m thick and 2000 m long) crosscutting igneous silicate rocks. They are made up predominantly of calcite and may contain REE mineralization, mainly composed of fluorocarbonates (bastnäsite, synchysite, parisite). In these complexes, REE are also concentrated in apatite-magnetite rocks, which occur as dikes or pipes or in calcite-fluorite-celestine and barite-celestine veins or breccia with carbonatite cement.

The second type of primary REE deposits is mineralization associated with fractionated peralkaline granites and pegmatites. Most of these sites are in northwestern Mongolia (Figure 1). The most prominent is the Devonian Khalzan Buregtei deposit. Several other promising occurrences of REE mineralization, which are related to Paleozoic peralkaline granitic rocks (Figure 1) are Ulaan Tolgoi, Shar Tolgoi, Tsakhir, Ulaan Del and Maihan Uul in Mongolian Altai. Similar deposits also occur in an adjacent part of Russia (southeastern region of the Tuva Republic e.g., Ulug-Tanzek, Zashikhinskoe and Sol Beldyr economically significant rare metal deposits [33–35]). In addition, peralkaline granitic rocks containing REE mineralization are also known from southern Mongolia. One of such bodies is the Khanbogd complex, which is located close to the giant Oyu Tolgoi Cu-Mo-Au porphyry deposit. Gerel et al. [36] lists numerous publications describing various aspects of the REE deposits in Mongolia.

### *4.1. Carbonatite Deposits*

#### 4.1.1. Mushgai Khudag

The deposit is hosted in a Cretaceous alkaline silicate-carbonatite complex in southern Mongolia in the Gobi Desert, about 100 km north of the city Dalanzadgad. The mineralization was discovered in the early 1970's. Country rocks are Paleozoic volcano-sedimentary sequences and Carboniferous granitoids. The complex has roughly a circular shape with about 27 km in diameter, spreads over an area of >100 km$^2$ and is composed mainly of volcanic rocks (Figure 3). Their emplacement started with nephelinites and associated pyroclastic rocks. This volcanic episode was followed by the extrusion of subalkaline trachytes and phonolites and subsequently by trachydacite and latites. Stocks, dikes and pipes of related syenitic rocks, which are up to 0.5 to 1 km in diameter, crosscut the volcanic sequence (Figure 3). The complex was also intruded by abundant non-silicate rocks, which contain most of the REE mineralization. They include carbonatites, quartz-fluorite-celestine and apatite-magnetite rocks. These rocks are contemporaneous with the emplacement of trachytes. The carbonatite dikes range in thickness from a few cm to 10 meters and are up to several hundred meters long. Apatite-magnetite rocks typically form pipe-like bodies, which are up to 3 m in diameter and 30 m long. These rocks also outcrop as plugs up to about 10 × 30 m in size [37].

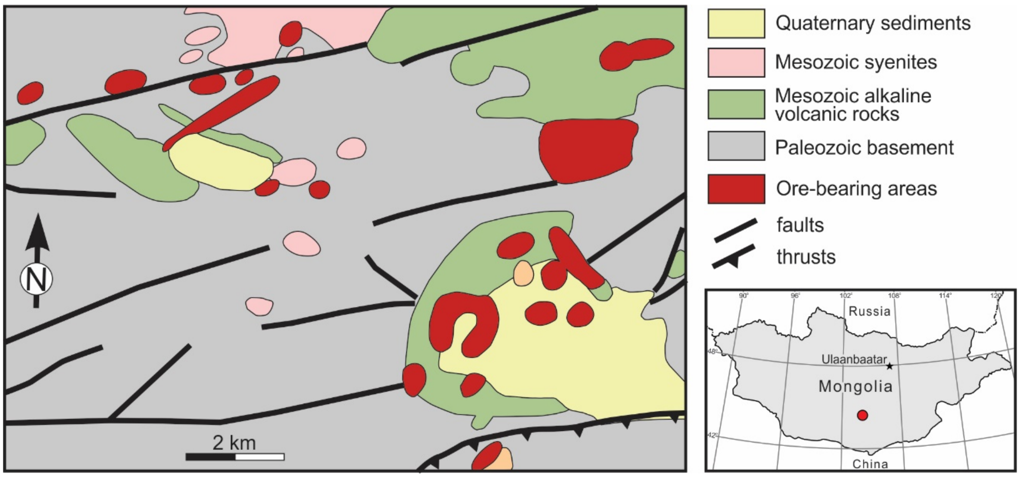


**Figure 3.** Generalized geological map of a part of the Mushgai Khudag complex (modified after [31,37]). Inset map shows the location of the Mushgai Khudag complex (red dot).

K-Ar dating of apatite-magnetite and silicate rocks yielded ages around 145–135 Ma [29]. The Rb-Sr isochron age of alkaline syenite was estimated to be 140 ± 6 Ma [30]. The age is in a good agreement with the Sm/Nd age of 138 ± 3 Ma also obtained by Baatar et al. [30]. Nikolenko et al. [31] reported Ar-Ar ages for phlogopites and groundmass from nephelinites, syenites and magnetite-apatite rocks ranging from 133 to 145 Ma.

Carbonatites contain calcite, which usually constitutes >90 vol.% of the rocks. Other minerals in this rock-type are fluorite, celestine, and barite and locally phlogopite, magnetite, apatite, britholite and fluorocarbonates (bastnäsite, synchysite and parisite). Brecciated intrusive rocks and eruptive breccias also host carbonatites, which occur as a cement. Magnetite-apatite rocks have massive or trachytic textures and are composed of magmatic apatite, magnetite, phlogopite and ilmenite. They also contain hydrothermal goethite, phosphosiderite, monazite, celestine, fluorite, barite, gypsum and rutile. The modal proportions of apatite (fluorapatite) and magnetite are variable but together they typically constitute ~90 vol.% of the rocks. Fine veins of fluorite (75–95 vol.%), which are widespread in the complex, contain minor to accessory amounts of calcite, barite, celestine, apatite, parisite, synchysite and monazite. In addition, the mineralized zone also contains fluorite-celestine-magnetite-apatite dikes and breccia [28].

The carbonatites and magnetite-apatite rocks have significantly higher total REE abundances than the non-mineralized silicate rocks [31,37]. The chondrite-normalized REE patterns of carbonatites and apatite-magnetite rocks are distinctly enriched in LREE (Figure 4). The primitive mantle normalized patterns of both rock types show negative anomalies for HFSE (Nb, Ta, Zr, Ti) implying subduction imprint in their source (Figure 5). Furthermore, geochemical similarities of carbonatites and associated silicate suggest derivation from a common source. The Sr and Nd isotopic data of the rocks of the Mushgai Khudag complex show variations with $^{87}Sr/^{86}Sr_{(i)}$ ranging from 0.70532 to 0.70614 and $\varepsilon_{Nd}(t)$ from −1.23 to +1.25 [30,31,36–39]. The ranges are comparable to many other Triassic-Cretaceous magmatic rocks in southern Mongolia [28].

The volcanic rocks contain ~40–68 wt.% of silica and have $K_2O$ > 3.55 wt.% and can be classified as shoshonitic. Nikolenko et al. [31] suggested that the silicate rocks were generated by fractional crystallization of nephelinitic parental magma, which was derived from a heterogeneous subduction modified lithospheric mantle source. The magnetite-apatite rocks are the results of a silicate-salt liquid immiscibility at an advanced stage of magma evolution, during the syenite crystallization [31].

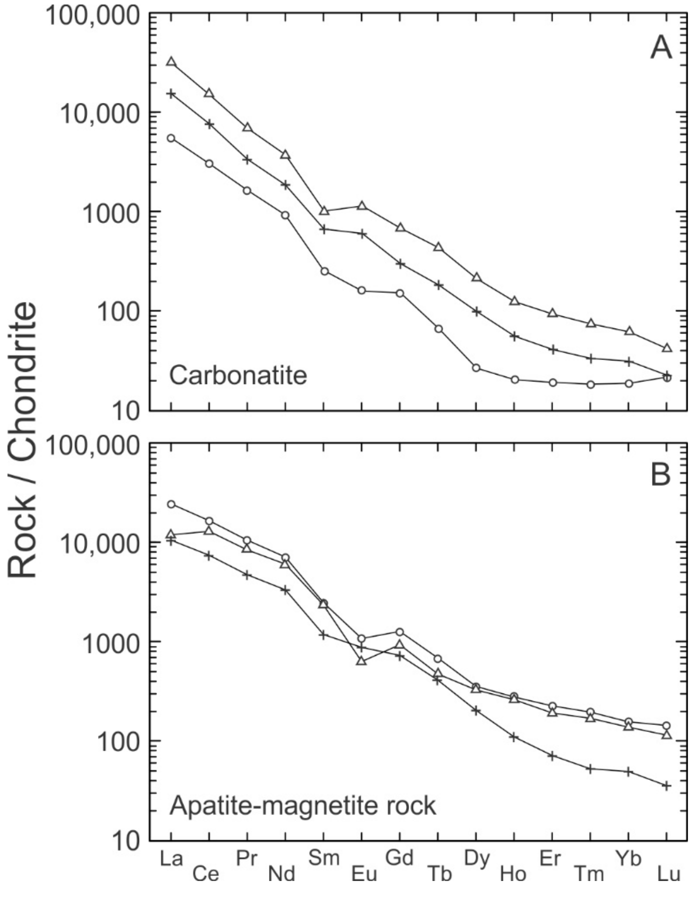


**Figure 4.** Chondrite-normalized REE abundances of the rocks from the Mushgai Khudag and Khotgor complexes. (**A**)—Mushgai Khudag: +—nephelinite; o—shonkinite; Δ—mineralized carbonatite (data from Nikolenko et al. [31]); (**B**)—apatite-magnetite rocks: Mushgai complex (o—Vladykin, [28] and Δ—Nikolenko et al. [31]) and Khotgor (+—Nikolenko et al. [31]). Normalizing values after [27].

The REE mineralization is associated with carbonatites, magnetite-apatite and fluorite-celestine-magnetite-apatite rocks, and quartz-fluorite-rich veins (Figure 4). The most important economically are apatite-bastnäsite carbonatite and apatite-magnetite ores [41,42]. The main REE minerals are apatite (with up to 13.5 wt.% REE) and fluorocarbonates (bastnäsite, synchysite and parisite). Monazite is also locally important. The complex hosts at least six ore zones. The main ore zone is about 4 km long and 0.5 km wide and contains a number of ore bodies of various shapes and sizes. Individual ore bodies are 1–30 cm wide and can be followed for over 10-150 m along strike. The resources of the deposit are about 34 Mt of TREO (REE + Y calculated as oxides). The average grade in the whole deposit is 1.36 wt.% TREO [42] although it reaches up to 6.15 wt.% in the high-grade zones. In this complex, there are more than 200 additional carbonatite dikes ranging from 20 m to 2 km in length and from 0.2 to 1 m in width. Some of them are mineralized but occur outside of the main ore zone.

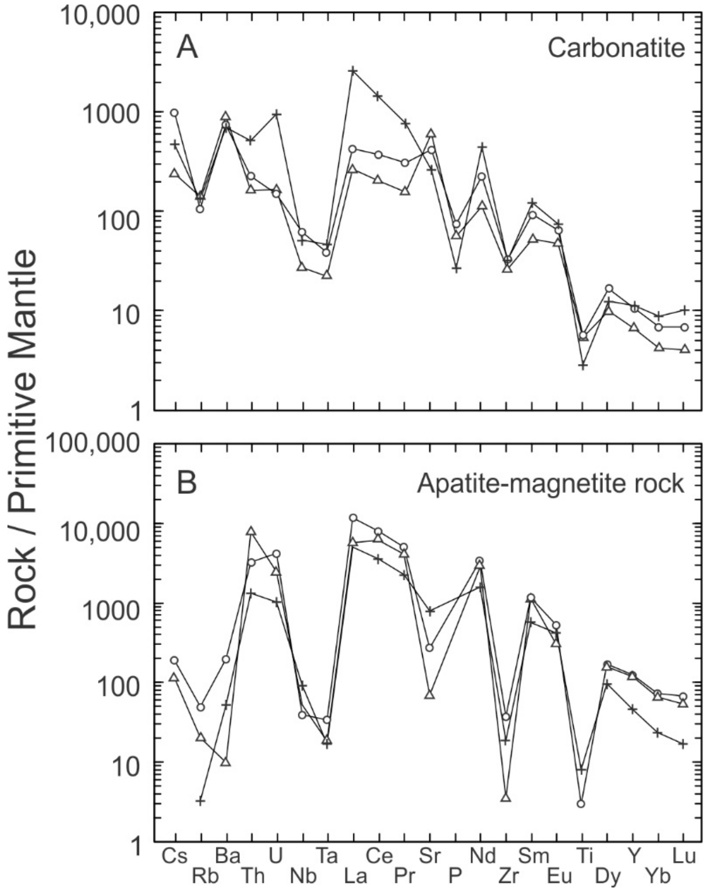


**Figure 5.** Primitive mantle-normalized incompatible element abundances of the rocks from the Mushgai Khudag and Khotgor complexes. (**A**)—Mushgai Khudag: o—nephelinite; Δ—shonkinite; +—mineralized carbonatite (data from Nikolenko et al. [31]); (**B**)—apatite-magnetite rocks: Mushgai complex (o—Vladykin [28]) and Δ—Nikolenko et al. [31]) and Khotgor (+—Nikolenko et al. [31]). Normalizing values after [40].

#### 4.1.2. Khotgor

Another significant deposit also located within the Gobi-Tien Shan rift zone is Khotgor (Figure 1). The deposit, discovered in early 1980′, is hosted in a pipe-shape stock of nepheline syenite, which intruded Silurian metasediments. The nepheline syenite, dated at 135 Ma [29,32] is composed of K-feldspar, nepheline and subordinate phlogopite, Fe-Ti oxides, fluorite, apatite and celestine. The intrusion contains carbonatite breccia and carbonatite dikes both of which carry REE mineralization. Mineralized parts of the intrusion are altered and strongly brecciated. The mineralized carbonatite dikes and pipes are steeply dipping, typically about 30 cm thick and can be followed for about 30–40 m. Some of these dikes and breccia contain “apatite ore” [42]: magnetite-apatite or fluorite-celestine-magnetite-apatite associations. Mineralized apatite-rich bodies are tubular, steeply dipping, 1 to 30 m wide and 10 to 150 m long and contain nets of lilac-colored fluorite. The main ore minerals in the deposit are apatite, bastnäsite and also britholite, parisite and synchysite. The rare earth mineralization is similar to that of the Mushgai Khudag

(Figures 4 and 5). Estimated resources in this deposit are 40 Mt of TREO with an average content of 1.22 wt.% [41,42].

#### 4.1.3. Lugiin Gol

The Lugiin Gol REE deposit is hosted in a nepheline syenite pluton in southern Mongolia in the South Gobi Desert, ~60 km north of the Mongolian-Chinese border and <200 km north-west of the giant REE carbonatite deposit Bayan Obo in Inner Mongolia, China (Figure 1). The Lugiin Gol pluton occurs in a graben associated with a prominent tectonic lineament in the Gobi-Tien Shan belt. The Lugiin Gol pluton has a sub-circular outline with a diameter of 3.5 km (Figure 6). The pluton intruded the Permian sedimentary rocks and is surrounded by the contact metamorphic zone. Vladykin [28] reported the U-Pb zircon and baddeleyite ages of nepheline syenite of 253–258 Ma.


**Figure 6.** Generalized geological map of Lugiin Gol complex (modified after [28,30,36,43]. Inset map shows the location of the Lugiin Gol complex (red dot).

The rocks of the pluton include, in addition to dominant nepheline syenite, alkali gabbro and shonkinite. Nepheline syenite is coarse to medium-grained equigranular to porphyritic composed of predominant K-feldspar and also of plagioclase, amphibole, clinopyroxene, nepheline, biotite and accessory apatite (up to 1.5 vol.%), titanite, zircon, cancrinite, and Fe-Ti oxides. Alkali gabbro and shonkinite have mineral assemblages similar to nepheline syenite but have higher proportions of mafic phases. The radial dikes are composed of nepheline syenites, tinguaites (phonolites) and carbonatites. These dikes range from several cm to 3 m in width and are up to 1000 m long.

The nepheline syenitic rocks have silica ranging from ~50 to 60 wt.%, have high contents of alkalis (10–17 wt.%.) and alumina (~20 wt.%) as well as Ba and Sr and are nepheline-normative. They have high initial $^{87}Sr/^{86}Sr$ ratios (0.707 to 0.708) and negative $\varepsilon_{Nd}(t)$ (~−1.2 to −2.7) [39,43].

The pluton hosts numerous, nearly vertical carbonatite dikes ranging in thickness from a few cm to 2 meters and are 5–200 m long [28]. Carbonatite dikes are coarse- to medium-grained massive rocks composed mainly of calcite. In addition, the carbonatites also occur as cements in eruptive breccia. The carbonatite dikes may contain significant amounts of fluorocarbonates. Some carbonatites contain up to 30% fluorite and 30% bastnäsite and resemble carbonatites from the giant Bayan Obo REE deposit [28].

The primary mineral assemblages of carbonatites were overprinted by hydrothermal-metasomatic processes, which led to an REE enrichment with a formation of a secondary association of fluorite-fluorocarbonates [31]. In addition to bastnäsite, the main REE minerals are synchysite and parisite. Some of the alteration zones of carbonatites are ~0.3 m thick and 50 to 100 m long and contain on average ~3.23 wt.% TREO. Metasomatized (mineralized) carbonatites are enriched in LREE compared to the original magmatic carbonatites (Figure 7). The chondrite-normalized REE patterns of mineralized carbonatites and of carbonatites show a distinct enrichment of LREE and moderately sloping HREE with $(La/Yb)_n$ ~500 and 15, respectively (Figure 7). The primitive mantle normalized trace element plots of the carbonatites display not only an enrichment in LREE but also in Th and U. The plots also show distinct negative anomalies for Nb, Ta, Zr and Ti, implying a subduction imprint, and are comparable to those of host silicate rocks (Figure 8). The REE resources were reported as 0.5 Mt with 2.67 wt.% TREO [41,42].

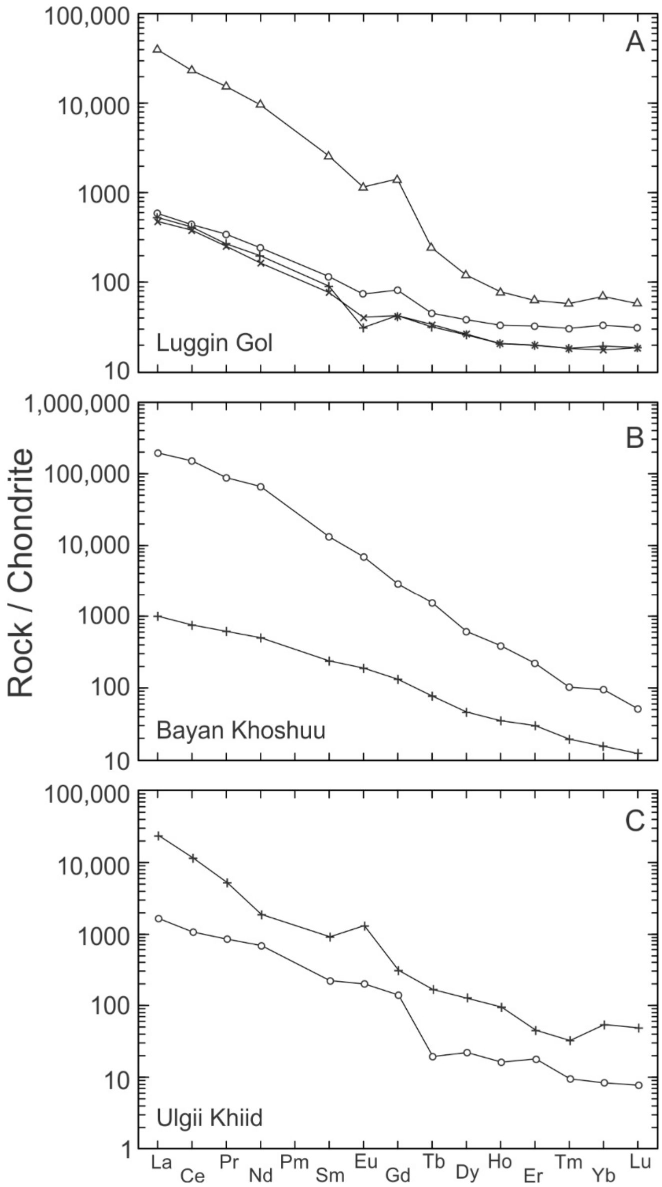


**Figure 7.** Chondrite-normalized REE abundances of the rocks from the Lugiin Gol, Bayan Khoshuu and Ulgii Khiid complexes. (**A**)—Lugiin Gol complex: o—carbonatite and Δ—mineralized carbonatite [28]; +—nepheline syenite and ×—monzonite [30]. (**B**) Bayan Khoshuu complex: o—mineralized carbonatite, +—carbonatite [30]. (**C**)—Ulgii Khiid complex: +—mineralized carbonatite; o—carbonatite [44]. Normalizing values after [27].

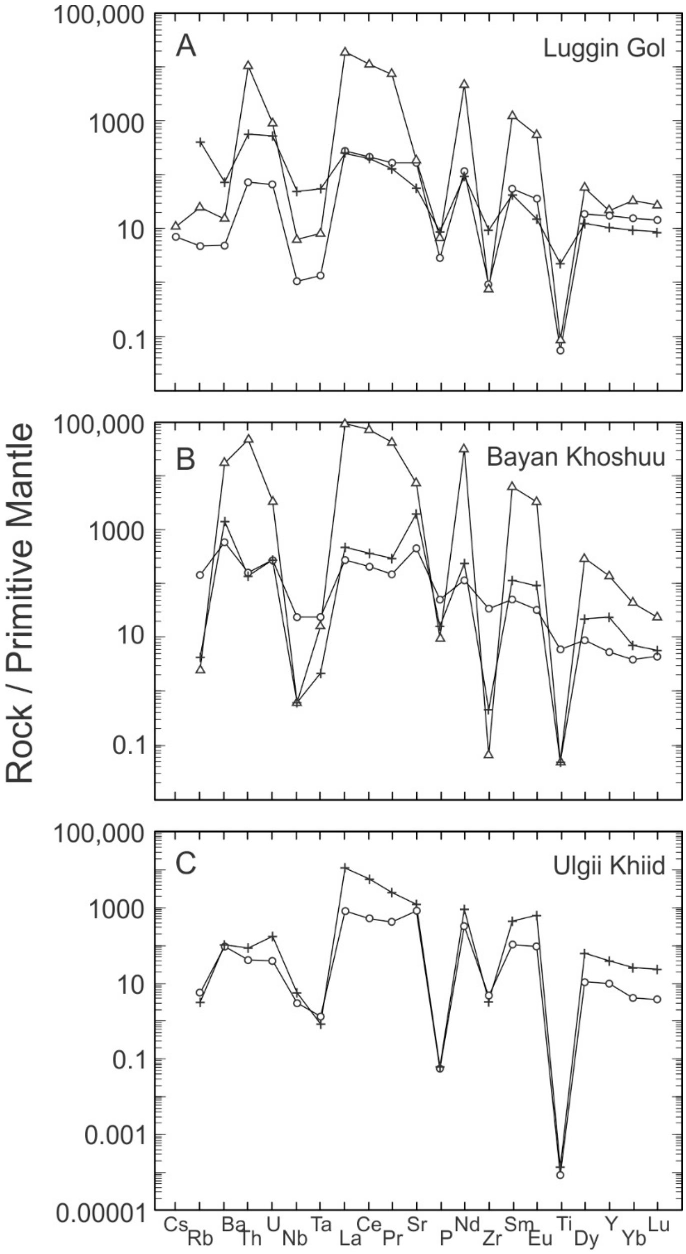


**Figure 8.** Primitive mantle- normalized incompatible element abundances of the rocks from the Lugiin Gol, Bayan Khoshuu and Ulgii Khiid complexes. (**A**) Lugiin Gol complex: o—carbonatite [28], Δ—mineralized carbonatite [28], + nepheline syenite [30]. (**B**) Bayan Khoshuu complex: o—nepheline syenite, Δ—mineralized carbonatite, +—carbonatite [30]). (**C**) Ulgii Khiid complex: +—mineralized carbonatite; o—carbonatite [44]. Normalizing values after [40].

4.1.4. Bayan Khoshuu and Ulgii Khiid

The Bayan Khoshuu complex (Figure 1) is composed of Cretaceous syenites, which intruded Late Paleozoic granitic rocks and Silurian volcanic rocks. The intrusion, partly covered by Quaternary sediments, is a poorly exposed elongated body, which is about 1 km long and 0.5 km wide. It contains circular stockworks of carbonatite veins (Figure 9). Stockworks are up to about 150 m in diameter. The intrusions also host carbonatite breccia, isolated carbonatite dikes as well as apatite-magnetite and carbonate-fluorite-barite-celestine veins. Rb-Sr whole rock-mineral isochron ages range from 130 to 139 Ma [38]. Rare earth element mineralization is similar to that of the Mushgai Khudag [36,38]. The mineralized carbonatites are enriched in LREE compared to the carbonatites (Figure 7) and the primitive mantle normalized trace element patterns of both types of carbonatites display negative anomalies for Nb, Ta, Zr and Ti (Figure 8).

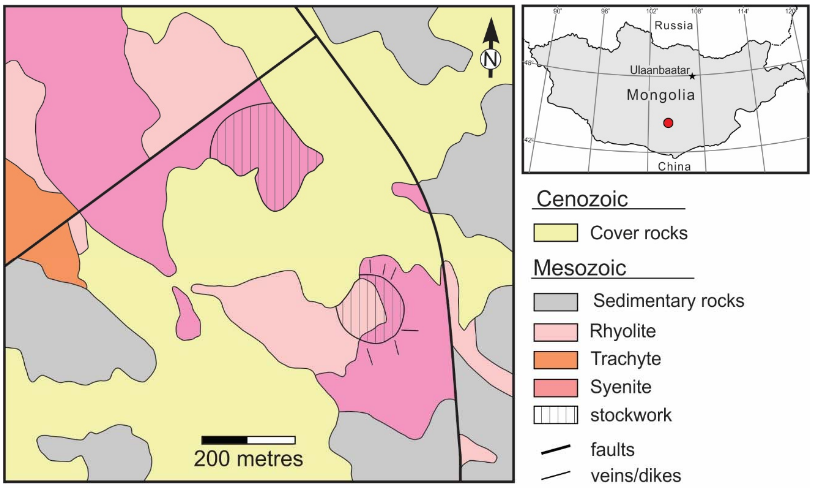


**Figure 9.** Generalized geological map of Bayan Khoshuu complex (modified after [38]). Inset map shows the location of the Bayan Khoshuu complex (red dot).

The Ulgii Khiid alkaline silicate-carbonatite complex (Figure 1) intruded Lower Carboniferous volcano-sedimentary sequences. The complex has a circular outline about 3 km in diameter (Figure 10). It is a zoned intrusion with a core composed of alkaline syenite, surrounded by an outer zone composed of peralkaline granites. The complex was intersected by an E-W trending fault accompanied by brecciated rocks. Carbonatites occur as dikes up to 1.5 m wide and 200 m long cross-cutting the syenite zone. There is also carbonatite breccia, which is controlled by the fault. Carbonatites contain minor amounts of apatite and fluorocarbonates (mainly synchysite) as well as apatite-magnetite dikes/veins. The mineralized carbonatites have higher abundances of REE compared to the other carbonatites (Figure 7). The primitive mantle normalized patterns of these rocks, like those of other Mongolian carbonatites show depletions in HFSE and P (Figure 8). The reserves of the REE mineralization in both these complexes have not yet been estimated.

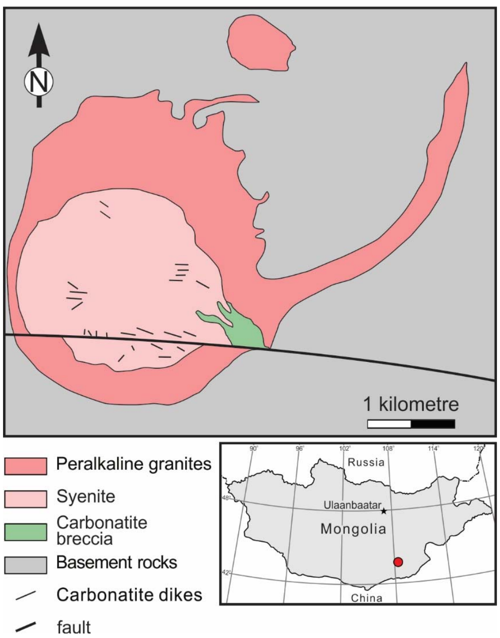


**Figure 10.** Generalized geological map of the Ulgii Khiid complex (modified after Feng et al. [44,45]. Inset map shows the location of the Ulgii Khiid complex (red dot).

## *4.2. Peralkaline Granitic Deposits*

### 4.2.1. Khalzan-Buregtei

The Khalzan-Buregtei massif (Figure 1) is a composite intrusion of peralkaline granitoids occurring along the eastern margin of the Mongolian Altai, northwestern Mongolia [46–52]. The massif, located ~45 km northeast of the city of Khovd, is a part of a Paleozoic belt of alkaline intrusions associated with the prominent Tsagaan Shiveet fault. These intrusions were emplaced in graben-like structures associated with an extension and controlled by deep faults. This oval-shaped complex, which is about 30 km long and up to 8 km wide, was emplaced during the Devonian (390–395 Ma; [47,48]. It is formed by medium to coarse-grained rocks ranging in composition from syenite to granite. According to Kovalenko et al. [46–48], nordmarkite (peralkaline quartz syenite) forms the outer rim of the complex, while the inner part of the pluton is composed of younger peralkaline granite. These rocks were intruded by dikes of peralkaline granites as well as by two small-mineralized stocks (Figure 11), which are composed of medium-grained arfvedsonite- and aegirine-bearing peralkaline granite. A small body of fine- to medium-grained miarolitic peralkaline granite in turn intruded one of the mineralized stocks.

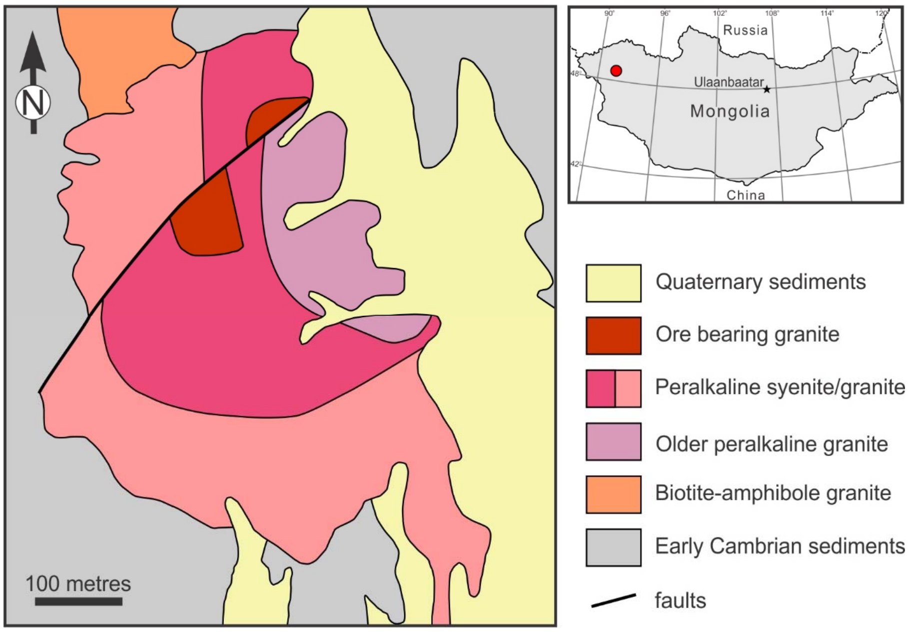


**Figure 11.** Generalized geological map of a part of the Khalzan Buregtei complex with two ore-bearing peralkaline granitic stocks; modified after [49]. Inset map shows the location of the Khalzan Buregtei complex (red dot).

The geochemical characteristics, including the high positive $\varepsilon_{Nd}(t)$ values (~+4.4—+6.5), suggest that the rocks of this multiphase intrusion were derived from the same subduction-modified mantle source [47,48]. The chondrite-normalized REE patterns of the mineralized rocks show a slight enrichment of LREE with $(La/Yb)_n$ ~1.2–3.4 (Figure 12). The rare metal minerals are disseminated through the mineralized zones within both mineralized stocks and include bastnäsite, synchysite, monazite, xenotime, elpidite, gittinsite, zircon, columbite and pyrochlore and are accompanied by fluorite. Many of these minerals are secondary although melt inclusion studies [52] indicate that the original magma was enriched in rare metals. The ore zones underwent multistage hydrothermal late/post-magmatic modification that led an enrichment of HFSE and REE [49–51]. The primitive mantle normalized plots (Figure 13) exhibit an enrichment of Th, U, Nb, Ta, Zr and REE. Sarangua et al. [53] recognized the three types of zircons—magmatic, metasomatic and late hydrothermal and observed that zircons experienced remobilization and recrystallization during the transition from a magmatic to a hydrothermal stage.

The massif hosts one large Zr-Nb-REE deposit (Khalzan-Buregtei; [46–51]) and several smaller ones. The reserves of the deposit have not yet been calculated but the Mongolian Geological Information Centre reported the reserves as 49 Mt of ore containing 0.6 wt.% TREO [42]. In addition, in the ore zones, there are significant resources of Ta (average grade 0.011 wt.% $Ta_2O_5$), Nb (0.2 wt.% $Nb_2O_5$) and Zr (1.46 wt.% $ZrO_2$) [42,46,47,51]. Pyrochlore and columbite are the main carriers of Ta and Nb while zircon hosts most of Zr.

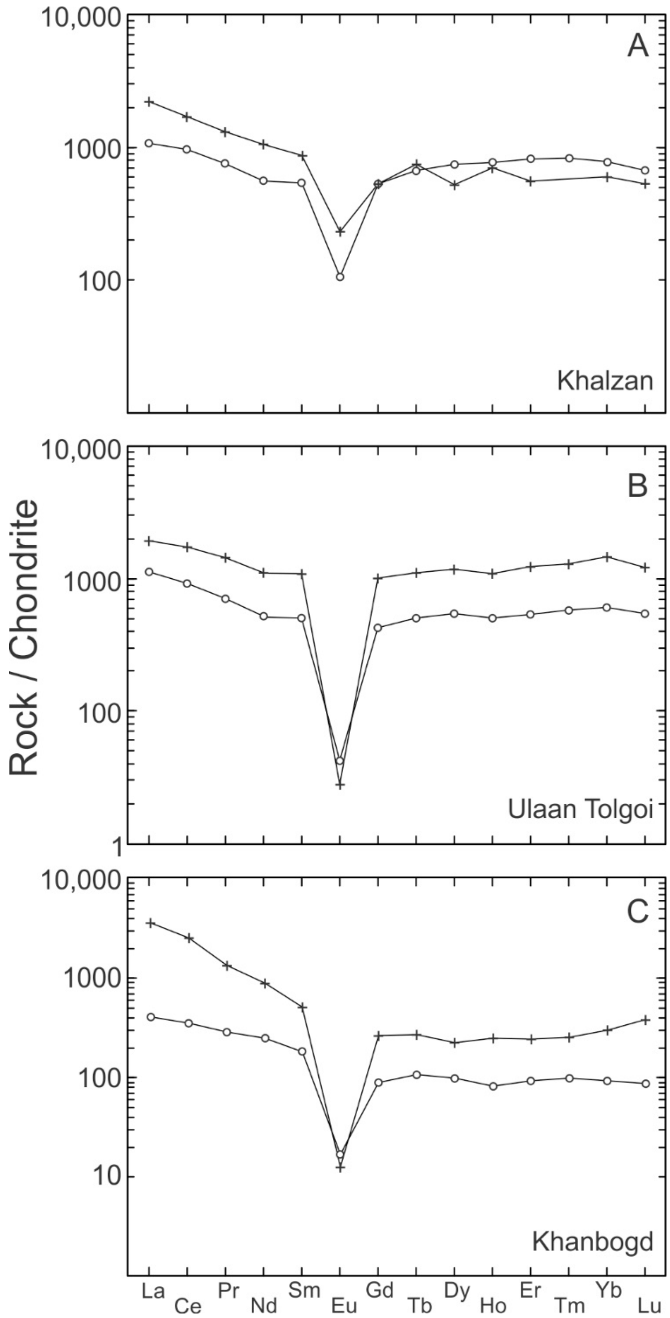


**Figure 12.** Chondrite-normalized REE plots of rocks from peralkaline granitic complexes of Mongolia. Normalizing values after [27]. (**A**) Ore-bearing peralkaline granites from Khalzan Buregtei complex: +—average of mineralized granites [46]; o—average of mineralized granites [51]; (**B**) Peralkaline granites from Ulaan Tolgoi complex: o—average of barren peralkaline granites; +—average of mineralized peralkaline granites [54]. (**C**) Peralkaline granitic rocks from Khanbogd (+—average of mineralized pegmatite; o—average of main phase granite [55]).

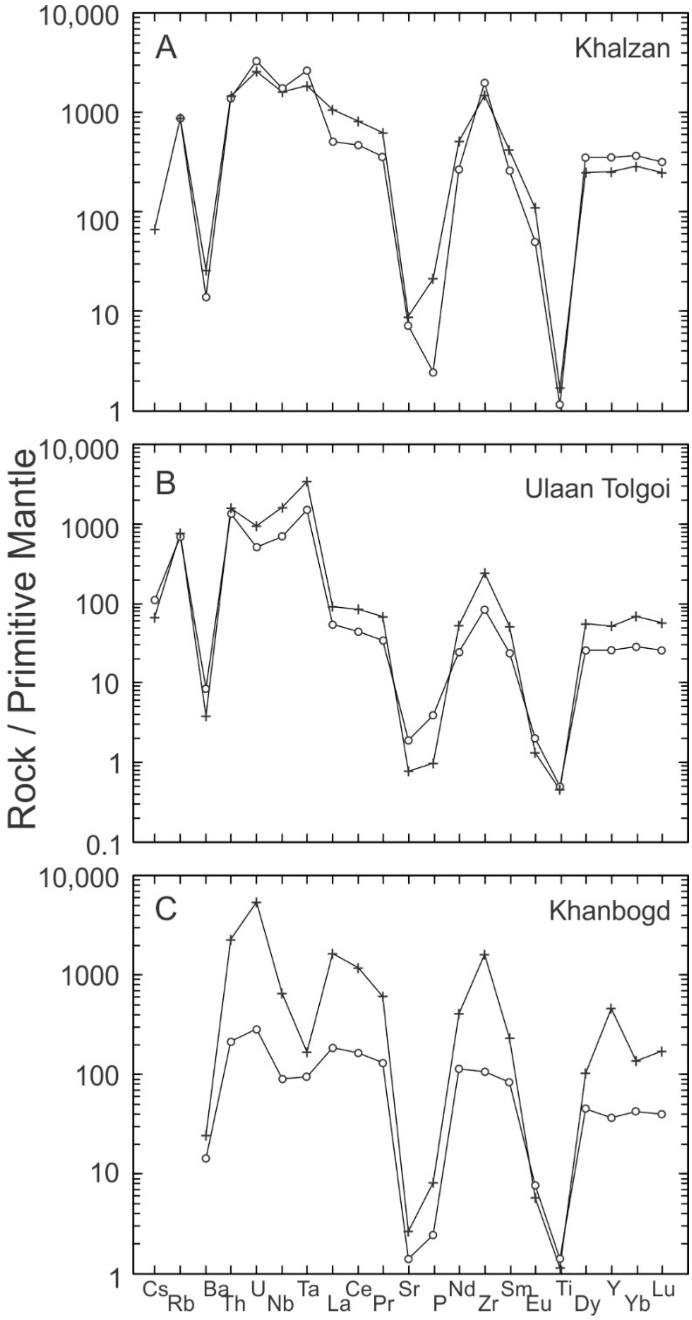


**Figure 13.** Primitive mantle-normalized trace element plots of peralkaline granites from Mongolia. (**A**) Khalzan Buregtei: +—average of mineralized peralkaline granites [46]; o—average of mineralized peralkaline granites [51]; (**B**) Ulaan Tolgoi: o—average of barren peralkaline granites; +—average of mineralized peralkaline granites [54]. (**C**) Khanbogd: +—average of mineralized pegmatites; o—average of peralkaline granites of the main phase [55]. Normalizing values after [40].

#### 4.2.2. Ulaan Tolgoi

The intrusion is a part of the Late Paleozoic peralkaline granitoid province, which spreads from Russia to northwestern Mongolia [35]. In Russia (southeastern Tuva), the province hosts several economically important deposits of REE, Ta, Nb and Zr (e.g., Ulug Tanzek, Zashikhinskoe, Sol Beldyr; [34]). The province extends to northwestern Mongolia where it includes the Ulaan Tolgoi massif. The rare metal mineralization and the composition of the pluton resemble those of the mineralized Russian counterparts [35] as well as that of the Khalzan-Buregtei [54]. The Ulaan Tolgoi massif, dated at ~298 Ma [35], is an elongated rift-related intrusion about 700 m long and 400 m wide, hosted by Ordovician

(~495 Ma) granites [54]. It is a multiphase intrusion composed of older peralkaline syenites, which constitutes the southern portion of the intrusion and younger peralkaline granites, which cover an area of about 300 × 400 m in the northern part of the massif. Yarmolyuk et al. [35] and Lykhin et al. [54] subdivided granites into barren (<100 ppm Ta) and ore-bearing (> 100 ppm Ta) types. Both magmatic and post-magmatic processes played a role during the genesis of the mineralization. The mineralized granites were modified by late magmatic/hydrothermal fluids and contain various rare-metal minerals including zircon, columbite, thorite, bastnäsite, pyrochlore, monazite and xenotime. Chondrite-normalized REE normalized patterns as well as the primitive mantle normalized plots of incompatible elements in the barren and mineralized peralkaline granites of the Ulaan Tolgoi intrusion (Figure 12) show that "barren" granites were fractionated felsic rocks with relatively high contents of rare metals, which were subsequently enriched by post-magmatic processes. Total REE in the mineralized granites range from 380 to 535 ppm. The rocks also contain high concentrations of Nb, Ta and Zr (Figure 13).

#### 4.2.3. Khanbogd

The mineralization is hosted in a peralkaline granitic complex in the South Gobi Desert (Figure 1). The complex, located close to the Oyu Tolgoi Cu-Mo-Au porphyry deposit, was emplaced in a Late Paleozoic basin in a rift zone of the Gobi-Tien Shan belt [28,55,56]. The pluton is about 50 km long and 30 km wide and intruded into the Paleozoic continental sedimentary and volcanic rocks. It is a shallow-seated complex with numerous roof-pendants and consists of two parts—western and eastern (Figure 14). The larger western part displays a distinct concentric structure highlighted by numerous ring dikes and roof-pendants. The pluton includes several intrusive phases. The first phase is the aegirine –arfvedsonite peralkaline granite that forms most of the western part of the pluton. It was followed by the emplacement of similar peralkaline granite of the second phase, which constitutes the bulk of the eastern loop of the pluton. Kovalenko et al. [56] speculated that the eastern part of the pluton is a sub-horizontal intrusive sheet that is about 100 m thick. Subsequently, after the emplacement of the granites, the complex was intruded by several generations of pegmatitic and granitic dikes, which also have characteristics of the peralkaline granites. The various age dating shows that the various intrusive phases including pegmatite dikes were emplaced within a short time interval at 290–292 Ma [3,56,57].

The granite of the pluton is medium to coarse grained, composed of quartz and perthitic K-feldspar with minor amounts of aegirine and alkali amphibole. The accessory minerals are titanite, rutile, fluorite and apatite. Altered samples also contain calcite and rare-earth fluorocarbonates, typically bastnäsite and synchysite. The pluton hosts numerous pegmatite dikes in the apical part ("cupola") of the western section of the intrusion [55]. The pegmatite dikes, which are 5 to 100 m long, are the most evolved rock-type at the Khanbogd complex [55].

The granites are peralkaline, high in alkalis, Zr, Nb, heavy REE and Y but low in MgO, CaO, Sr, Ba Ti and P, characteristic of the A-type granites [36]. The chondrite-normalized REE patterns have a relatively low $(La/Yb)_n$ ratio of ~4 accompanied by a negative Eu anomaly (Figure 12). The granites of the complex have low initial Sr isotopic ratios (0.703–0.705) and moderately high initial Nd values ($\varepsilon_{Nd}$(t) +5 to +7) [28,57]. Relative to the peralkaline granites of the pluton, the pegmatites have significantly higher contents of several incompatible elements, particularly Y, REE, Zr, Nb, Th and U (Figure 13) accompanied by higher $(La/Yb)_n$ ~10 (Figure 12).

The main rare metal-bearing ore mineral is elpidite, which occurs in all the granitic types and typically contains 0.1 to 1 wt.% of REE+Y. Elpidite is enriched in HREE with $(La/Yb)_n$ ranging mostly from 0.1 to 1. Although present in all the rock types, the highest concentrations are in pegmatites. In pegmatites, its modal abundance can reach up to 30 wt.%. Other ore minerals abundant in the mineralized pegmatites are zircon, bastnäsite, parisite, synchysite, armstrongite, and gittinsite ($CaZrSi_2O_7$).

The significant REE mineralization is confined to pegmatite dikes in the apical parts of the intrusion. These host rocks are the result of extreme fractional crystallization accompanied in the final stages of magma evolution by a release of orthomagmatic fluids, which produce an initial deposition of rare metal minerals. However, these minerals were replaced by secondary minerals, including pyroxene, during the hydrothermal late/post magmatic stage, which led to an enrichment of the rare metals in these rocks and the formation of the mineralized zones in the pegmatites [23,55]. Hydrothermal alteration was most intense in apical parts of the intrusion, particularly pegmatite, which hosts the bulk of the rare metal mineralization that includes both incompatible elements such as Th, U and Zr and also REE, and Y (Figures 12 and 13). Average TREO content of the ore zone is 0.65 wt.% [36].

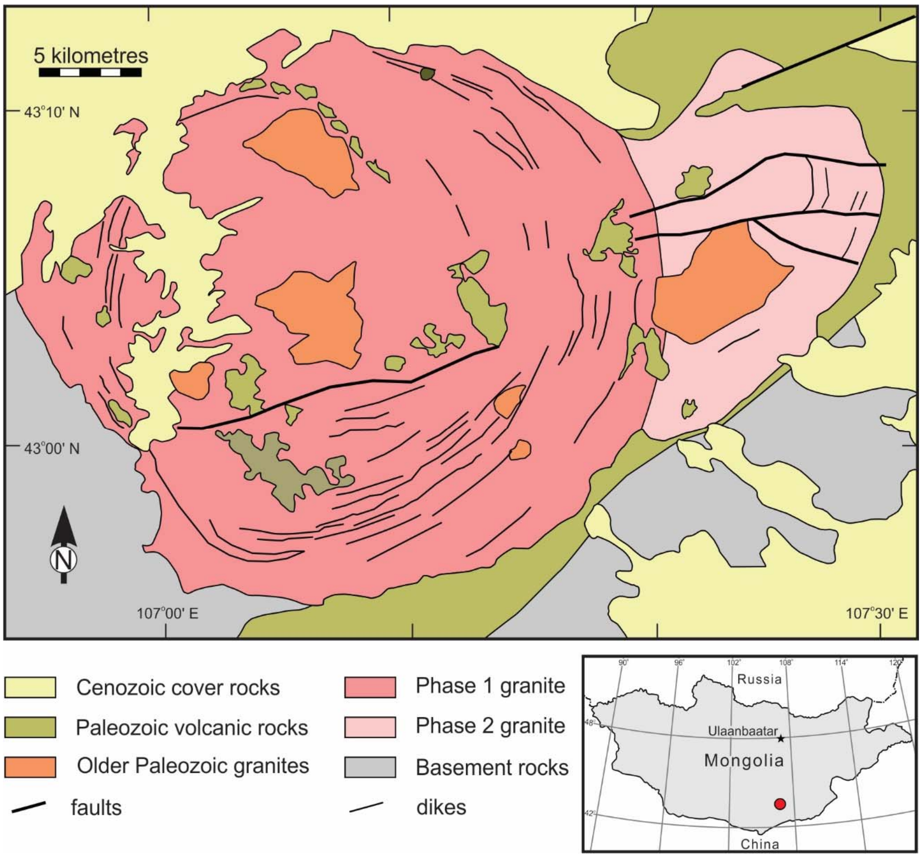


**Figure 14.** Generalized geological map of Khanbogd complex (modified after [36,55]). Inset map shows the location of the Khanbogd complex (red dot).

## 5. Conclusions

There are two types of the REE mineral deposits in Mongolia. The first one is associated with carbonatites and the second with peralkaline granitic rocks. Carbonatites are typically hosted in alkaline silicate-carbonatite complexes composed of nepheline syenite and related rocks and their volcanic equivalents. Mineralized carbonatites form dikes, pipes and plugs; they also form matrix in eruptive breccia. REE occur mainly as fluorocarbonates (bastnäsite, synchysite) and apatite. These rocks are also associated with the apatite-magnetite (mostly altered to hematite) dikes and pipes where REE are hosted in apatite. Similar trace element and isotopic characteristics of the carbonatites and associated alkaline silicate rocks (including a relative depletion of several HFSE) suggest the involvement of the subduction modified heterogeneous lithospheric mantle in the formation of both carbonatites and associated silicate rocks. Although carbonatites and carbonatite magmas have high contents of REE, the origin of carbonatite-hosted REE deposits is still being debated (e.g., [8,11,14]). Carbonatite-hosted REE deposits were traditionally considered to be of magmatic origin (e.g., [18,58]). However, recent studies proposed a magmatic-hydrothermal model (e.g., [14,59–61]) whereby carbonatite-derived hydrothermal fluids played a key role during the formation of these REE deposits. Currently, the discussion mainly focusses on the relative importance of magmatic and hydrothermal processes (e.g., [59,60]). REE mineralization of some of the Mongolian carbonatites resembles that of the Mountain Pass and Bayan Obo carbonatites.

The REE mineralization in peralkaline felsic rocks (peralkaline granites, syenites and pegmatites) is present mainly in accessory minerals, which can reach percentage levels in mineralized zones. The parental magma of these rocks was sourced from metasomatised mantle probably enriched in REE [62,63]. The magma underwent protracted fractional crystallization that led to an enrichment of REE, especially in the late stages of magma evolution. Hydrothermal processes also played a key role in enhancing the concentrations of these elements (e.g., [14,20,64]). The primary magmatic mineralization was mostly replaced (remobilized and enriched) by late magmatic to hydrothermal fluids. The mineralization associated with peralkaline granitic rocks also contains significant concentrations of Zr, Nb, Ta, Th and U. Similar deposits, which are economically significant, occur not only in a neighbouring part of Russia but in many other parts of the world [26,46,64–68].

Although there are numerous occurrences of both types of rare earth mineralization in Mongolia, at present only three of them have significant economic importance [36,42]. They are mineralization related to the Mesozoic Mushgai Khudag and Khotgor carbonatites and to the Devonian Khalzan-Buregtei peralkaline granites. These deposits have significant REE reserves and Khalzan-Buregtei also hosts important Nb-Ta-Zr mineralization. Several other promising rare earth occurrences have not yet been explored and deserve further investigations.

**Author Contributions:** J.D. and O.G. developed the idea and wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by funding provided by NSERC Canada (Discovery grant) to J.D.

**Data Availability Statement:** The authors declare that all analytical data supporting the findings of this study are available within the paper or cited in peer-review references.

**Acknowledgments:** We thank Randy Corney for technical assistance.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Badarch, G.; Cunningham, W.D.; Windley, B.F. A new terrane subdivision for Mongolia: Implications for the Phanerozoic crustal growth of Central Asia. *J. Asian Earth Sci.* **2002**, *21*, 87–110. [CrossRef]
2. Şengör, A.M.C.; Natalin, B.A.; Burtman, V.S. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. *Nature* **1993**, *364*, 299–307. [CrossRef]
3. Kovalenko, V.I.; Yarmolyuk, V.V. Endogenous rare metal ore formations and rare metal metallogeny of Mongolia. *Econ. Geol.* **1995**, *90*, 520–529. [CrossRef]
4. Verplanck, P.L.; Van Gosen, B.S.; Seal, R.R.; McCafferty, A.E. A deposit model for carbonatite and peralkaline intrusion-related rare earth element deposits. In *U.S. Geological Survey Scientific Investigations Report 2010–5070-J*; U.S. Geological Survey: Reston, VA, USA, 2014; 58p. [CrossRef]
5. Huleatt, M.B. *Australian Resource Reviews: Rare Earth Elements*; Geoscience Australia: Canberra, Australia, 2019; ISBN 978-1-925848-44-1.
6. Vladykin, N.V.; Kovalenko, V.I.; Kashaev, A.A.; Sapozhnikov, A.N.; Pisarskaya, V.A. Armstrongite—A new silicate of calcium and zirconium. *Doklady Acad. Nauk. SSSR* **1973**, *20*, 1185–1188. (In Russian)
7. Le Maitre, R.W.; Streckeisen, A.; Zanettin, B.; Le Bas, M.J.; Bonin, B.; Bateman, P.; Woollet, A.R. *Igneous Rocks. A Classification of Igneous Rocks and Glossary of Terms*, 2nd ed.; Cambridge University Press: Cambridge, NY, USA, 2002; 236p.
8. Yaxley, G.M.; Anenburg, M.; Tappe, S.; Decree, S.; Guzmics, T. Carbonatites: Classification, Sources, Evolution, and Emplacement. *Annu. Rev. Earth Planet. Sci.* **2022**, *50*, 261–293. [CrossRef]
9. Kamenetsky, V.S.; Doroshevich, A.G.; Elliott, H.A.L.; Zaitsev, A.N. Carbonatites: Contrasting, complex, and controversial. *Elements* **2021**, *17*, 307–314. [CrossRef]

10. Woolley, A.R.; Kjarsgaard, B.A. Paragenetic types of carbonatite as indicated by the diversity and relative abundances of associated silicate rocks: Evidence from a global database. *Can. Mineral.* **2008**, *46*, 741–752. [CrossRef]
11. Bell, K. *Carbonatites: Genesis and Evolution*; Unwin Hyman: London, UK, 1989; 618p.
12. Mitchell, R.H. Carbonatites and carbonatites and carbonatites. *Can. Mineral.* **2005**, *43*, 2049–2068. [CrossRef]
13. Woolley, A.R.; Church, A.A. Extrusive carbonatites: A brief review. *Lithos* **2005**, *85*, 1–14. [CrossRef]
14. Chakhmouradian, A.R.; Zaitsev, A.N. 2012 Rare earth mineralization in igneous rocks: Sources and processes. *Elements* **2012**, *8*, 347–353. [CrossRef]
15. Verplanck, P.L.; Mariano, A.N.; Mariano, A.N., Jr. Rare earth element ore geology of carbonatites. In *Reviews in Economic Geology*; Verplanck, P.L., Hitzman, M.W., Eds.; Society of Economic Geologists, Inc.: Littleton, CO, USA, 2016; Volume 18, pp. 5–32.
16. Richardson, D.G.; Birkett, T.C. Carbonatite-associated deposits. In *Geology of North America*; Geological Society of America: Boulder, CO, USA, 1996; Volume P-1, pp. 541–558.
17. Long, K.R.; Van Gosen, B.S.; Foley, N.K.; Cordier, D. *The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and A Global Perspective; U.S. Geological Survey, Scientific Investigations Report 2010–5220*; U.S. Geological Survey: Reston, VA, USA, 2010; 96p.
18. Castor, S.B. The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California. *Can. Mineral.* **2008**, *46*, 779–806. [CrossRef]
19. Salvi, S.; Williams-Jones, A.E. The role of hydrothermal processes in the granite-hosted Zr, Y, REE deposit at Strange Lake, Quebec/Labrador: Evidence from fluid inclusions. *Geochim. Cosmochim. Acta* **1990**, *54*, 2403–2418. [CrossRef]
20. Salvi, S.; Williams-Jones, A.E. The role of hydrothermal processes in concentrating high-feld strength elements in the Strange Lake peralkaline complex, northeastern Canada. *Geochim. Cosmochim. Acta* **1996**, *60*, 1917–1932. [CrossRef]
21. Dostal, J.; Kontak, D.J.; Karl, S.M. The Early Jurassic Bokan Mountain peralkaline granitic complex (southeastern Alaska): Geochemistry, petrogenesis and rare-metal mineralization. *Lithos* **2014**, *202–203*, 395–412. [CrossRef]
22. Ersay, L.; Greenough, J.D.; Larson, K.P.; Dostal, J. Zircon reveals multistage, magmatic and hydrothermal Rare earth mineralization at the Debert Lake, Nova Scotia, Canada. *Ore Geol. Rev.* **2022**, *144*, 104780. [CrossRef]
23. Bernard, C.; Estrade, G.; Salvi, S.; Beziat, D.; Smith, M. Alkali pyroxenes and amphiboles: A window on rare earth elements and other high field strength elements behaviour through the magmatic-hydrothermal transition of peralkaline granitic systems. *Contrib. Mineral. Petrol.* **2020**, *175*, 81. [CrossRef]
24. Siegel, K.; Williams-Jones, A.E.; van Hinsberg, V.J. The amphiboles of the REE-rich A-type peralkaline Strange Lake pluton fingerprints of magma evolution. *Lithos* **2017**, *288–289*, 156–174. [CrossRef]
25. Vasyukova, O.V.; Williams-Jones, A.E. Tracing the evolution of a fertile REE granite by modelling amphibole-melt partitioning: The Strange Lake story. *Chem. Geol.* **2019**, *519*, 79–89. [CrossRef]
26. Dostal, J. Rare Earth Element Deposits of Alkaline Igneous Rocks. *Resources* **2017**, *6*, 98–109. [CrossRef]
27. Boynton, W.V. Cosmochemistry of the rare earth elements; meteorite studies. In *Rare Earth Element Geochemistry*; Henderson, P., Ed.; Elsevier: Amsterdam, The Netherlands, 1984; pp. 63–114.
28. Vladykin, N.V. Petrology and composition of rare-metal alkaline rocks in the South Gobi Desert, Mongolia. *Russ. Geol. Geophys.* **2013**, *54*, 416–435. [CrossRef]
29. Samoilov, V.S.; Kovalenko, V.I. *Complexes of Alkaline Rocks and Carbonatites in South Mongolia*; Nauka: Moscow, Russia, 1983; 196p. (In Russian)
30. Baatar, M.; Ochir, G.; Kynicky, J.; Iizumi, S.; Comin-Chiaramonti, P. Some notes on the Lugiin Gol, Mushgai Khudag and Bayan Khoshuu Alkaline Complexes, Southern Mongolia. *Int. J. Geosci.* **2013**, *4*, 1200–1214. [CrossRef]
31. Nikolenko, A.M.; Doroshkevich, A.G.; Ponomarchuk, A.V.; Redina, A.A.; Prokorpyev, I.R.; Vladykin, N.V.; Nikolaeva, I.V. Ar-Ar geochronology and petrogenesis of Mushgai-Khudag alkaline-carbonatite complex (southern Mongolia). *Lithos* **2020**, *372*, 15675. [CrossRef]
32. Nikiforov, A.V.; Yarmolyuk, V.V. Late Mesozoic carbonatite provinces in Central Asia: Their compositions, sources and genetic settings. *Gondwana Res.* **2019**, *69*, 56–72. [CrossRef]
33. Yarmolyuk, V.V.; Nikiforov, A.V.; Salnikova, E.B. Rare-metal granitoids of the Ulug Tanzek Deposit (Eastern Tyva): Age and tectonic setting. *Dokl. Earth Sci.* **2010**, *430*, 95–100. [CrossRef]
34. Yarmolyuk, V.V.; Kuzmin, M.I. Late Paleozoic and Early Mesozoic rare-metal magmatism of Central Asia: Stages, provinces, and formation settings. *Geol. Ore Depos.* **2012**, *54*, 313–333. [CrossRef]
35. Yarmolyuk, V.V.; Lykhin, D.A.; Kozlovskii, A.M. Composition, sources, and mechanisms of origin of rare metal granitoids in the Late Paleozoic Eastern Sayan Zone of alkaline magmatism: A case study of the Ulaan Tolgoi Massif. *Petrology* **2016**, *24*, 447–496. [CrossRef]
36. Gerel, O.; Majigsuren, Y.; Munkhtsengel, B. Rare Earth Mineral Deposits. In *Mineral Resources of Mongolia*; Gerel, O., Pirajno, F., Batkhishig, B., Dostal, J., Eds.; Modern Approaches in Solid Earth Sciences; Springer: Singapore, 2021; pp. 185–210.
37. Nikolenko, A.M.; Redina, A.A.; Doroshkevich, A.G.; Prokopyev, I.R.; Ragozin, A.L.; Vladykin, N.V. The origin of magnetite-apatite rocks of Mushgai-Khudag complex, South Mongolia: Mineral chemistry and studies of melt and fluid inclusions. *Lithos* **2018**, *320–321*, 567–582. [CrossRef]

38. Gerel, O.; Munkhtsengel, B.; Enkhtuvshin, H.; Iizumi, S. Mushgai Khudag and Bayan Khushuu volcanic-plutonic alkaline complexes with REE Ta, Nb, Fe carbonatite mineralization. In *Geodynamics and Metallogeny of Mongolia with Special Emphasis on Copper and Gold Deposits*; Seltmann, R., Gerel, O., Kirwin, D., Eds.; IAGOD, Guidebook Series, v. 11; CERCAMS/NHM: London, UK, 2005; pp. 215–221.
39. Vladykin, N.V. Sr and Nd isotope geochemistry of Siberian and Mongolian alkaline and carbonatite complexes and some geodynamic implications. In *Problems of Sources of Deep-Seated Magmatism and Plumes*; Glazkovskaya Printing House: Irkutsk, Russia, 2005; pp. 13–29. (In Russian)
40. McDonough, W.F.; Sun, S.-S. The composition of the Earth. *Chem. Geol.* **1995**, *120*, 229–253. [CrossRef]
41. Elsner, H.; Buchholz, P.; Schmitz, M.; Altangerel, T. Industrial minerals and selected rare metals in Mongolia. In *An Investor's Guide*; Mineral Resources Authority of Mongolia, Bundesanstalt für Geowissenschaften und Rohstoffe: Ulaan Baatar, Mongolia; 322p.
42. Muff, R.; Tamiraa, A. *Rare Earths of Mongolia: Evaluation of Market Opportunities for the Principal Deposits of Mongolia*; Technical Report; Mineral Resources Authority of Mongolia, Ulaanbaatar/Bundesanstalt für Geowissenschaften und Rohstoffe: Hannover, Germany, 2013; 63p.
43. Munkhtsengel, B.; Iizumi, S. Petrology and geochemistryof the Lugiin Gol nepheline syenite complex, southern Mongolia. In *Geodynamics and Metallogeny of Mongolia with a Special Emphasis on Copper and Gold Deposits*; Seltmann, R., Gerel, O., Kirwin, D., Eds.; IAGOD, Guidebook Series, v. 11; CERCAMS/NHM: London, UK, 2005; pp. 203–214.
44. Feng, M.; Song, W.; Kynicky, J.; Feng, B.; Fang, G. Geochronology and C-O-Sr-Nd isotopic study of the Ulgii Khiid carbonatite from the Southern Mongolian alkaline province and its implications for the mantle sources. *Ore Geol. Rev.* **2021**, *139*, 104495. [CrossRef]
45. Feng, M.; Song, W.; Kynicky, J.; Smith, M.; Cox, C.; Kotlanova, M.; Brtnicky, M.; Fu, W.; Wei, C. Primary rare earth element enrichment in carbonatites: Evidence from melt inclusions in Ulgii Khiid carbonatite, Mongolia. *Ore Geol. Rev.* **2020**, *117*, 103294. [CrossRef]
46. Kovalenko, V.I.; Tsaryeva, G.M.; Goreglyad, A.V.; Yarmolyuk, V.V.; Troitsky, V.A.; Hervig, R.L.; Farmer, G.L. The peralkaline granite-related Khalzan–Buregtey rare metal (Zr, Nb, REE) deposit, western Mongolia. *Econ. Geol.* **1995**, *90*, 530–547. [CrossRef]
47. Kovalenko, V.I.; Kozlovski, A.M.; Yarmolyuk, V.V. Trace element ratios as indicators of source mixing and magma differentiation of alkali granitoids and basites of the Khalzan-Buregtey massif and the Khalzan-Buregtey rare-metal deposit, western Mongolia. *Petrology* **2009**, *17*, 158–177. [CrossRef]
48. Kovalenko, V.I.; Yarmolyuk, V.V.; Kovach, V.P.; Kovalenko, D.V.; Kozlovskii, A.M.; Andreeva, I.A.; Kotov, A.B.; Salnikova, F.B. Variations in the Nd isotopic ratios and conical ratios of concentrations of incompatible elements as an indication of mixing sources of alkali granitoids and basites in the Khalzan-Buregtei massif and the Khalzan-Buregtei rare metal deposit in Western Mongolia. *Petrology* **2009**, *17*, 227–252.
49. Gronen, L.H.; Sindern, S.; Katzmarzyk, J.L.; Bormann, U.; Hallmann, A.; Wotruba, H.; Meyer, F.M. Mineralogical and Chemical Characterization of Zr-REE-Nb Ores from Khalzan Buregtei (Mongolia)—Approaches to More Efficient Extraction of Rare Metals from Alkaline Granitoids. *Minerals* **2019**, *9*, 217. [CrossRef]
50. Kempe, U.; Götze, J.; Dandar, S.; Habermann, D. Magmatic and metasomatic processes during formation of the Nb–Zr–REE deposits Khalzan Buregtei and Tsakhir (Mongolian Altai): Indications from a combined CL-SEM study. *Mineral. Mag.* **1999**, *63*, 165–177. [CrossRef]
51. Kempe, U.; Möckel, R.; Graupner, T.; Kynicky, J.; Dombon, E. The genesis of Zr-Nb-REE mineralisation at Khalzan Buregtey (Western Mongolia) reconsidered. *Ore Geol. Rev.* **2015**, *64*, 602–625. [CrossRef]
52. Andreeva, I.A. Genesis and mechanisms of formation of rare-metal peralkaline granites of the Khalzan Buregtey massif, Mongolia: Evidence from melt inclusions. *Petrology* **2016**, *24*, 462–476. [CrossRef]
53. Sarangua, N.; Watanabe, Y.; Echigo, T.; Hoshino, M. Chemical Characteristics of Zircon from Khaldzan Buregtei Peralkaline Complex, Western Mongolia. *Minerals* **2019**, *9*, 10. [CrossRef]
54. Lykhin, D.A.; Yarmolyuk, V.V.; Nikiforov, A.V.; Kozlovsky, A.M.; Magazina, L.O. Ulaan-Tolgoi Ta-Nb deposit: The role of magmatism in the formation of rare metal mineralization. *Geol. Ore Depos.* **2018**, *60*, 461–485. [CrossRef]
55. Kynicky, J.; Chakhmouradian, A.R.; Xu, C.; Krmicek, L.; Galiova, M. Distribution and evolution of zirconium mineralization in peralkaline granites and associated pegmatites of the Khanbogd complex, southern Mongolia. *Can. Mineral.* **2011**, *49*, 947–965. [CrossRef]
56. Kovalenko, V.I.; Yarmoluyk, V.V.; Salnikova, E.B.; Kozlovsky, A.M.; Kotov, A.B.; Kovach, V.P.; Savatenkov, V.M.; Vladykin, N.V.; Ponomarchuk, V.A. Geology, geochronology, and geodynamics of the Khanbogd alkali granite pluton in southern Mongolia. *Geotectonics* **2006**, *40*, 450–466. [CrossRef]
57. Amara-Amgalan, S. Petrographical and Geochemical Studies on the Khanbogd Alkaline Complex in Southern Mongolia. Master's Thesis, Shimane University, Matsue, Japan, 2004.
58. Mariano, A.N. Economic Geology of Rare Earth Minerals. In *Geochemistry and Mineralogy of the Rare Earth Elements*; Lipin, B.R., McKay, G.A., Eds.; Mineralogical Society of America: Washington, DC, USA, 1989; Volume 21, pp. 309–337.
59. Beland, C.M.J.; Williams-Jones, A.E. The mineralogical distribution of the REE in carbonatites: A quantitative evaluation. *Chem. Geol.* **2021**, *585*, 120558. [CrossRef]
60. Beland, C.M.J.; Williams-Jones, A.E. The genesis of the Ashram REE deposit, Quebec: Insights from bulk-rock geochemistry, apatite-monazite-bastnäsite replacement reactions and mineral chemistry. *Chem. Geol.* **2021**, *578*, 120298. [CrossRef]

61. Simandl, G.J.; Paradis, S. Carbonatites: Related ore deposits, resources, footprint, and exploration methods. *Appl. Earth Sci.* **2018**, *127*, 123–152. [CrossRef]
62. Bonin, B. A-type granites and related rocks: Evolution of a concept, problems and prospects. *Lithos* **2007**, *97*, 1–29. [CrossRef]
63. Marks, M.A.; Markl, G. A global review on agpaitic rocks. *Earth-Sci Rev.* **2017**, *173*, 229–258. [CrossRef]
64. Dostal, J. Rare metal deposits associated with alkaline/peralkaline igneous rocks. In *Reviews in Economic Geology*; Verplanck, P.L., Hitzman, M.W., Eds.; Society of Economic Geologists, Inc.: Littleton, CO, USA, 2016; Volume 18, pp. 33–54.
65. Salvi, S.; Williams-Jones, A.E. Alkaline granite-syenite deposits. In *Geological Association of Canada Short Course Notes*; Geological Association of Canada: St. John's, NF, Canada, 2005; Volume 17, pp. 315–341.
66. Kovalenko, V.I.; Yarmolyuk, V.V.; Kozlovsky, A.M.; Kovach, V.P.; Salnikova, F.B.; Kotov, A.B.; Vladykin, N.V. Two types of magma sources of rare-metal alkali granites. *Geol. Ore Depos.* **2007**, *49*, 442–466. [CrossRef]
67. Estrade, G.; Salvi, S.; Beziat, D.; Rakotovao, S.; Rakotondrazafy, R. HFSE mineralization in peralkaline granites of the Ambohimirahavavy alkaline complex, Ampasindava peninsula, Madagascar. *J. Afr. Earth Sci.* **2014**, *94*, 141–155. [CrossRef]
68. Salvi, S.; Fontan, F.; Monchoux, P.; Williams-Jones, A.E.; Moine, B. Hydrothermal mobilization of HFSE in alkaline igneous systems: Evidence from the Tamazeght complex (Morocco). *Econ. Geol.* **2000**, *95*, 559–576.