

Article

Characteristics of Lithium Deposits in Mongolia

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Abstract: Lithium is a strategic metal due to its use in green technologies, particularly battery manufacturing. It is on the US List of Critical Minerals and the European Union's List of Critical Raw Materials. In Mongolia, there are three major types of potentially economic Li deposits: (1) Deposits related to granites, granitic pegmatites and associated rocks; (2) Li-rich clay deposits; (3) Salar (Li brine) deposits. The first type of mineralization is associated with the lithium–fluorine-rich peraluminous A-type granites and related rocks (greisens, pegmatites, ongonites, ongorhyolites). The mineralization includes Li and also Sn, W, Ta and Nb. Lithium is hosted in Li-rich micas, unlike the world-class Li-bearing pegmatite deposits where the bulk of Li is in spodumene. In Mongolia, particularly promising are Li brines of endorheic basins in the Gobi Desert with an arid environment, high evaporation rates and low precipitation.

Keywords: lithium; Mongolia; granite; pegmatite; Li–mica; brines; deposits



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1. Introduction

Lithium (Li), the lightest metal on Earth, has been used in a wide range of applications from psychiatric medicine to lubricating grease to the glass and ceramics industry. It has excellent electric and heat conductivity and low density, thus making it a strategic compound for battery manufacturing. Interest in this element in the global market has exploded in recent years because of its use in rechargeable batteries for electric and hybrid cars, which are seen as key to reducing climate-changing carbon emissions produced by gas-powered cars. However, Li is also used in the batteries of laptops, cell phones, power tools, lawnmowers and many others. This has led to a significant increase in the demand for Li and a worldwide “lithium rush”. In fact, the strategic importance of Li has been reflected in its inclusion in the US Government's List of Critical Minerals and the European Union's List of Critical Raw Materials. Identification and assessment of mineral resources of Li are critical steps for the discovery of new mineral deposits. The purpose of this paper is to report on the mineral resources of Li in Mongolia, particularly on their geological and mineralogical characteristics, and to provide new whole-rock chemical analyses of some of the sites. The review will be useful for future prospecting, particularly as its neighbors, China and Russia, have significant Li resources in nearby areas.

2. Lithium Deposit Types

Lithium does not occur in native (elemental) form in nature. However, more than 100 minerals contain Li as an essential constituent [1,2], but only a few of these species are of economic interest (Table 1). Most of the Li-bearing minerals are silicates (~73%) and phosphates (19%). The rest are either carbonates, fluorides, oxides, hydroxides, borates or arsenites [1]. Among these minerals, spodumene is the most economically important Li-bearing mineral, which occurs in granites and pegmatites. Other economically important Li-bearing minerals that occur in pegmatite and granite deposits are micas—lepidolite and zinnwaldite (Table 1). A mineral that is not currently extracted for Li but has the potential to

be a significant source in the future is hectorite [3]. This mineral is a clay mineral produced during the alteration of volcanoclastic rocks by hydrothermal or hot spring activity. Another mineral that could be an important Li source is jadarite [4]. Four other minerals from which Li was formerly extracted but are now of lesser economic importance are eucryptite, amblygonite, montebrasite and petalite (Table 1). These four minerals occur in Li-bearing pegmatites. In addition, Li is also extracted from brines.

Table 1. Main lithium minerals, their chemical formula and Li₂O content.

Name	Formula	Li ₂ O (wt.%) *
Eucryptite	LiAlSiO ₄	11.86
Spodumene	LiAl (Si ₂ O ₆)	8.03
Petalite	LiAl (Si ₄ O ₁₀)	4.88
Lepidolite	K(Li,Al) ₃ (Si,Al) ₄ O ₁₀ (OH,F) ₂	7.70
Zinnwaldite	KLiFeAl(Al,Si ₃)O ₁₀ (OH,F) ₂	4.12
Triphylite	Li(Fe,Mn)PO ₄	9.47
Amblygonite	LiAl(PO ₄)F	10.10
Montebrasite	LiAl(PO ₄)OH	10.10
Jadarite	LiNaSiB ₃ O ₇ (OH)	7.30
Hectorite	Na _{0.3} (Mg,Li) ₃ (Si ₄ O ₁₀)(F,OH) ₂ × nH ₂ O	

* Theoretical value [5].

There are three main types of Li deposits [3]: (1) Granite–pegmatite deposits (“hard rock deposits”), which include pegmatites, hydrothermally altered and metasomatized granites, lithium–fluorine granites, ongonites and similar silica-rich igneous rocks; (2) Clay deposits where Li is hosted in hectorite and other clay minerals; (3) Brine deposits where Li occurs in continental salt-rich lakes. Li can also be extracted from geothermal and oil field brines. According to the US Geological Survey [6], the hard rock Li deposits account for about 60% of the world’s Li production but they represent only about a quarter of the global Li reserves.

2.1. Granite–Pegmatite-Related Lithium Deposits

Granites and particularly pegmatites are important sources of rare metals, including Li. Although granitic pegmatites are common, rare-metal pegmatites represent only about 0.1% of the pegmatite total, and Li-rich pegmatites are only a fraction of those [7]. In addition to pegmatites, this group of deposits also includes rare-metal Li-F granites, their subvolcanic (ongonites) and volcanic (ongorhyolites) equivalents, and greisens.

Granitic pegmatites have been the predominant source of Li for many decades. Only in recent years, their share has been reduced by production from continental brines. Compositionally, Li-rich pegmatites are similar to peraluminous rare-metal granites. These pegmatites are enriched in incompatible trace elements, including Li, Cs, Ta, Sn, Rb, Be and Nb (e.g., [8,9]). They are composed of quartz, plagioclase, potassium feldspar and micas with various amounts of garnet, tourmaline, apatite and Li-bearing minerals such as spodumene, petalite, amblygonite, lepidolite and eucryptite. Mongolian Li-rich pegmatites belong to this category. Their Li₂O content ranges mostly from 0.5% to 1.5% [10].

Rare-metal granites (RMG; [11]) are felsic, peraluminous to peralkaline rocks that contain magmatic disseminated mineralization (e.g., [12]). Among these rocks, Li mineralization is typically confined to two major types of granites [5,11]. The first are metaluminous to peraluminous low-phosphorus RMG with high contents of Nb, Ta, Sn and Li, which occur in both anorogenic and post-orogenic tectonic environments. Elevated Li concentrations are hosted by Li-F micas including lepidolite and zinnwaldite. An example is the Cínovec (Zinnwald) deposit in the Czech Republic. The second type refers to the peraluminous

high-phosphorus RMG which are enriched in Ta, Sn, Li and F and were typically emplaced in a continental collision setting. These granitic rocks have high concentrations of Li (~0.5% to 1% Li₂O), which is hosted by lepidolite and Li-rich muscovite. Examples of such granitic bodies are Beauvoir (France) and Argemela (Portugal) [5,11].

Greisens are highly fractionated granitic rocks that underwent a high-temperature transformation which led in the extreme to the generation of a porous Li–mica–quartz assemblage. In these rocks, Li is hosted in micas, in particular Li-rich muscovite, lepidolite and zinnwaldite. Greisens typically form veins or haloes around the granitic bodies, both peraluminous and metaluminous RMG. In addition to quartz and mica, they may contain subordinate feldspars, topaz, tourmaline, cassiterite and wolframite. The greisen deposits can be related to both magmatic and hydrothermal processes. In addition to Li, important co-products in these rocks are Sn and W [5].

2.2. Lithium Clay Deposits (Sedimentary Rocks Hosted Lithium Deposits)

Lithium clay deposits contain an anomalous accumulation of Li-bearing clay minerals, in particular hectorite. These clays have the potential to be a significant source of Li. Bowell et al. [3] recognized three types of these deposits. The first type includes those in which Li is within the clay mineral (hectorite or similar mixed layered clays). The second type is the case where Li is an absorbed ion into clay minerals (ion–clay deposits). These clay deposits were found in the western USA (Nevada, Oregon). Lithium-bearing clay deposits typically have a genetic and/or spatial relationship to rhyolitic rocks [3,13]. The last type of these deposits refers to the jadarite clay deposit. This world-class Li deposit, which contains 118 Mt of ore with a grade of 1.8 wt.% Li₂O and 13.1 wt.% B₂O₃, is hosted in an intermontane lacustrine evaporite basin in Serbia [4,14]. The ore is composed of jadarite-bearing Miocene siltstone and mudstone.

2.3. Lithium Brine Deposits

A brine is a watery solution with concentrations of dissolved salts higher than that of seawater (>3.5%) [3,15]. The lithium content in most brines typically ranges between 200 and 700 ppm, with some reaching more than 1000 ppm [16]. The total salinity of Li brines typically ranges from 1.7 to 24 times that of seawater. There are three categories of brines: continental Li-rich salt lakes, oilfield brines and geothermal brines. The continental brine deposits are by far the largest source. The amount of Li in the high-altitude continental brine deposits around the world is about 40 million tons. Most of this Li resource is in the “lithium triangle” of the central Andes, an area of about 400,000 km² that includes northern Chile, western Bolivia and northwestern Argentina. The continental brines/deposits are hosted in young (mostly Quaternary) enclosed, tectonically active basins that contain lacustrine evaporites. The basins occur in an arid climate, where inflowing surface and sub-surface water contains Li which has been released from surrounding felsic volcanic rocks by weathering or leaching. Lithium-rich continental brine deposits have been identified in many places [17], including Mongolia [10]. Groundwater brines are also associated with oil fields in the USA (North Dakota, Texas, Oklahoma, Arkansas, Utah) and can contain up to 700 mg/L (ppm) of lithium [17]. Geothermal brines from Reykjanes in Iceland have up to 130 mg/L of Li and Salton Sea geothermal brines of California hold up to 286 mg/L of Li [18]. Lithium-containing geothermal brines are also known from Wairakei in New Zealand. All these Li-bearing brines are concentrated by natural evaporation before extracting lithium.

3. Lithium Mineralization in Mongolia

Although all three types of Li deposits are known from Mongolia, the focus of the paper is on deposits hosted by felsic igneous rocks as there are only limited amounts of data on the Li mineralization generated by exogenic processes.

In Mongolia and an adjoining part of Russia (Transbaikalia), Li mineralization is linked to rare-metal Li-F granites and related rocks (Figure 1). These Late Paleozoic and Mesozoic

granites are associated with Sn, W, Li and Ta-Nb mineralization (e.g., [19,20]) and were the subject of discussion among Russian geologists. Initially, they were defined as “apogranites” generated by post-magmatic metasomatic processes [21] but later, after the discovery of ongonites, their subvolcanic equivalents, they were considered to be of magmatic origin [22,23]. These granites are shallow-seated, highly fractionated, peraluminous A-type granites enriched in fluorine and rare metals but low in P. They resemble the first (post-orogenic) type of granite of Gourcerol et al. [5].

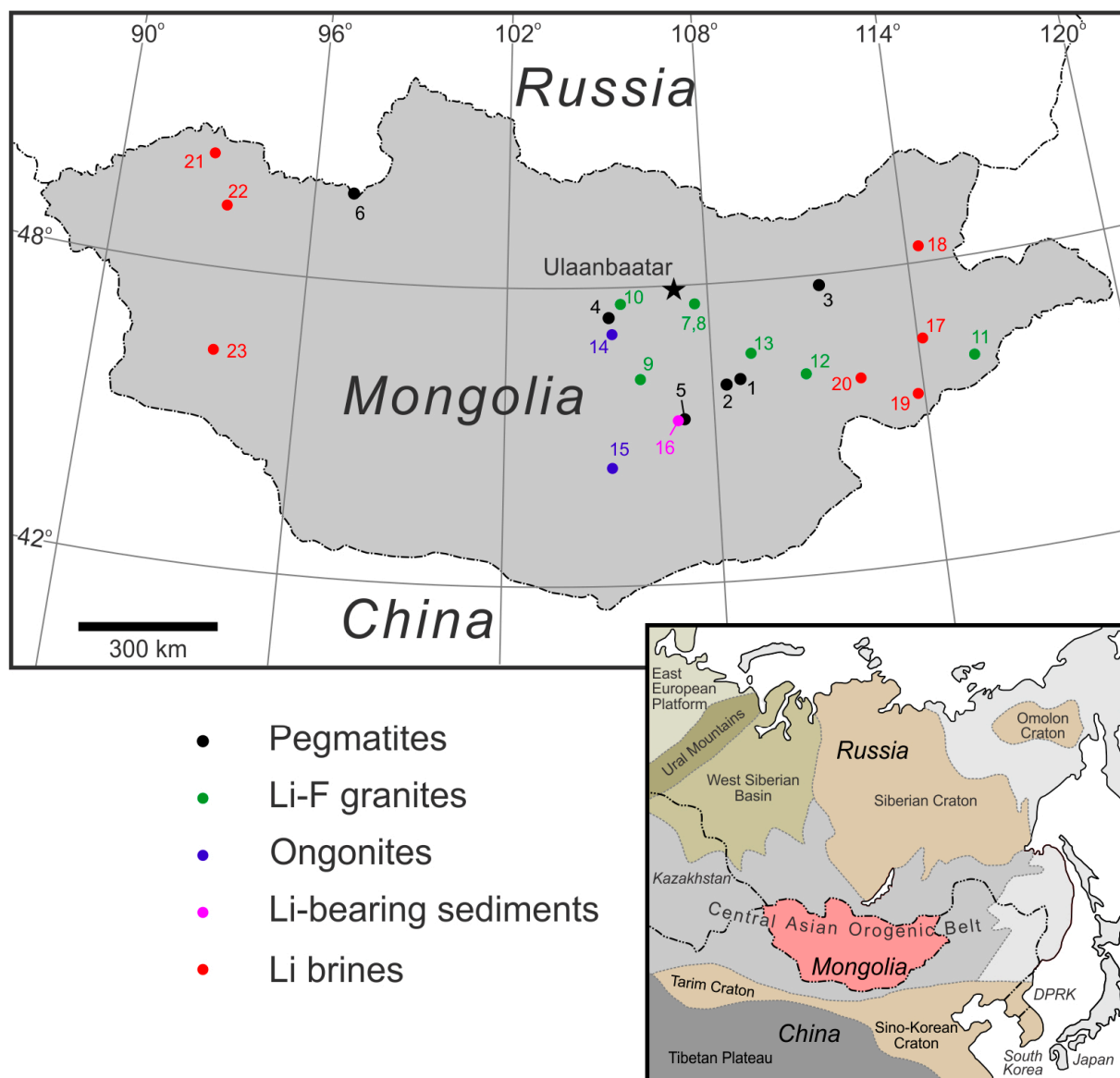


Figure 1. Map of Mongolia showing the locations of the significant Li mineralization. Locations of significant Li mineralization sites hosted by granitic pegmatite (No. 1–6), Li-F granites (No. 7–13), ongonites and ongorhyolites (No. 14–15), sedimentary rocks (No. 16) and Li salt lakes (No. 17–23) (Table 2). Inset map shows a geological sketch of northeastern Asia and the location of Mongolia. DPRK: Democratic People’s Republic of Korea (North Korea).

Table 2. Coordinates of Li mineralization sites.

Pegmatite 1–6			
1	Khukh Del Uul	N 46°00′	E 108°49′
2	Munkhiin Tsagaan Durvuljin	N 45°53′	E 108°22′
3	Berkh	N 47°46′	E 111°11′
4	Unjuul	N 47°19′	E 105°03′
5	Bayan Teeg	N 45°16′	E 107°07′
6	Baga, Ikh Yamaat	N 49°46′	E 97°06′
Granite 7–13			
7	Janchivlan	N47°35′	E 107°34′
8	Urt Gozgor	N 47°34′	E 107°32′
9	Baga Gazar	N 46°15′	E 105°56′
10	Avdar	N 47°37′	E 105°27′
11	Arbayn	N 46°03′	E 115°47′
12	Uizen	N 46°03′	E 110°38′
13	Bor Khujir	N 46°33′	E 109°14′
Ongonite 14–15			
Ongonite; Ongorhyolite			
14	Ongon Khairkhan	N 47°04′	E 105°10′
15	Teeg Uul	N 44°19′	E 105°10′
Li sediments 16			
16	Khukh Del	N 45° 07′	E 106°52′
Li brines 17–23			
Eastern Mongolia			
17	Dund Bayan nuur	N 46°26′	E 114°07′
18	Baruun Davst nuur	N 48°20′	E 114°35′
19	Baavhai Uul	N 45°17′	E 113°49′
20	Urgakh Naaran	N 45°50′	E 112°20′
Western Mongolia			
21	Uvs nuur	N 50°23′	E 92°41′
22	Khyargas nuur	N 49°11′	E 93°16′
23	Dergen nuur	N 46°13′	E 93°27′

3.1. Granite–Pegmatite-Related Lithium Deposits

Rare-metal granitic rocks that contain Li mineralization in Mongolia occur within the Mongol–Okhotsk orogenic belt (MOOB). The belt is linked to the closure of the Mongol–Okhotsk Ocean, which lasted from the Permian to the Late Jurassic. MOOB, which extends from the Khangai region in central Mongolia to the Okhotsk Sea, hosts a belt of granitoid rocks of Permian to Mesozoic ages that runs parallel to the suture zone. Some of these rocks were emplaced in post-collisional settings [10]. A significant part of the MOOB in central Mongolia is made up of the Khentii batholith of a Late Triassic to Early Jurassic age (230–180 Ma). The batholith consists of rocks ranging from granodiorites to leucogranites accompanied by minor gabbros and diorites. The last stages of magmatic activity in the batholith featured the emplacement of rare-metal granites, which constitute about 10% of granitoids in the belt. These late-stage granitoids include lithium–fluorine granites and

related rocks (Li pegmatites, ongonites, ongorhyolites and greisens) emplaced mainly along the margin of the batholith [10]. The Li-F granites are relatively rare, post-orogenic and represent either the latest, highly fractionated portions of multiphase plutons or late one- or two-phase stocks/plutons occurring along the margins of the Khentei batholith.

Gerel [10] recognized three different sub-types of granite–pegmatite-related Li deposits in Mongolia. These deposits comprise (1) Li pegmatites, (2) Li-F granites and greisens, and (3) subvolcanic (ongonites) and volcanic (ongorhyolites) equivalents of Li-F granites (Figure 1).

3.1.1. Lithium Pegmatite

In Mongolia, rare-metal pegmatites, particularly Li-bearing ones, belong to the LCT pegmatites of Černý and Ercit [9]. The Mongolian pegmatites are typically peraluminous, ferroan and alkali–calcic. Among them, the most prominent are pegmatites of Khukh Del Uul (site No. 1 in Figure 1 and Table 2) in the Middle Gobi belt (Figure 2) located about 250 km southeast of Ulaanbaatar [24]. The Late Paleozoic pegmatite swarm includes about 25 dikes which spread over an area of about 6 km² where they intruded Precambrian metamorphic rocks and Paleozoic syenites and granites [24]. The pegmatite dikes are steeply dipping, 50 to 300 m long and 1 to 10 m wide. The dominant mineral assemblage of this pegmatite swarm is quartz (25–35 vol.%), coarse-grained platy albite (cleavelandite; 20–35 vol.%), sugary albite (5–10 vol.%), lepidolite (10–30 vol.%), topaz (5–10 vol.%) and microcline (1–5 vol.%).

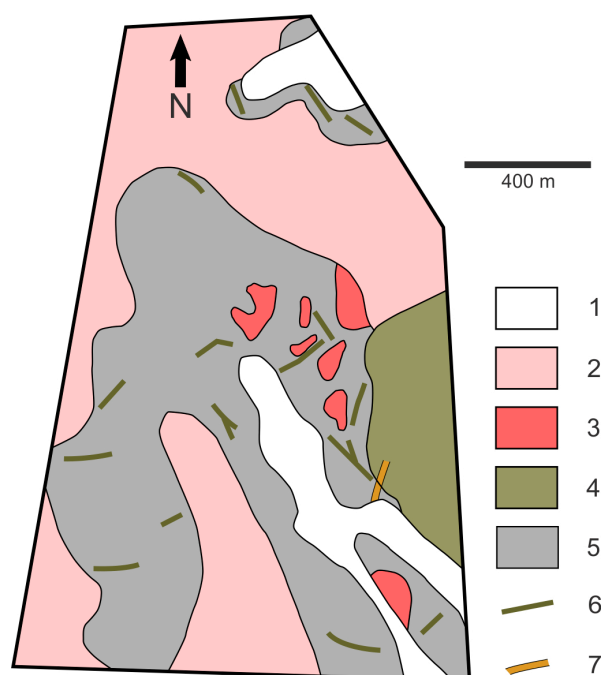


Figure 2. Generalized geological sketch map of topaz–lepidolite–albite pegmatite swarm of Khukh Del Uul (after Vladykin et al. [24]). Location: Site No. 1 in Figure 1, Table 2; coordinates N46°00′ E108°49′. 1—Quaternary cover; 2—Middle Paleozoic quartz porphyry; 3—Late Paleozoic granite; 4—post-Devonian syenite porphyry; 5—Proterozoic metamorphic rocks; 6—Pegmatite; 7—Syenite dike.

Some dikes show zoning and replacement textures where the quartz–albite–topaz–lepidolite core can be substituted by sugary metasomatic albite. Mineral assemblages are locally replaced by greisens composed of quartz and lepidolite or zinnwaldite, which in turn can be invaded by sugary albite with traces of columbite–tantalite or fluorite–quartz veinlets. According to Vladykin et al. [24], the fine-grained sugary albite is nearly pure albite ($Ab_{>0.90}$ $Or_{\sim 0.01-0.03}$), while coarse plagioclase (cleavelandite; grain size ~1–6 cm)

contains $\text{Ab}_{\sim 0.75-0.90} \text{Or}_{\sim 0.01-0.05}$. Microcline's composition is $\text{Or}_{\sim 0.50-0.70} \text{Ab}_{\sim 0.18-0.50}$ [24]. The dominant mica in the pegmatites is lepidolite, which occurs as flakes up to about 5 cm in size, but it also forms crystals ~5 mm in diameter or patches of fine-grained crystals (0.5–1 mm). Lepidolite typically contains ~3.84–5.45 wt.% Li_2O and 5.75 to 8.51 wt.% F. Fluorite is a late mineral that commonly occurs in veinlets intersecting pegmatites (Figure 3). The averages of the chemical compositions of pegmatites reported by Vladykin et al. [24] are moderately high in silica (~70 wt.%) and alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$ ~8.5 wt.%) but with $\text{Na}_2\text{O} > \text{K}_2\text{O}$.

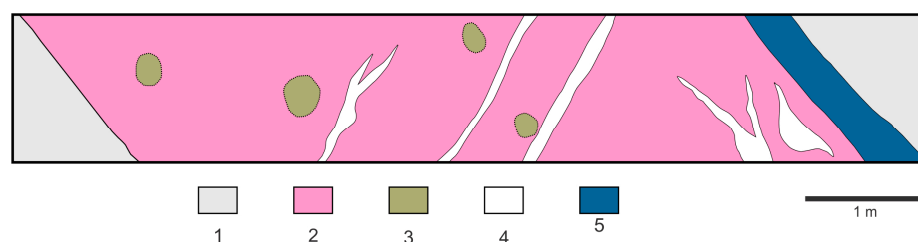


Figure 3. Generalized cross-section through a typical Khukh Del Uul pegmatite dike (modified after Vladykin et al. [24]. 1—Country rock (gneiss); 2—Pegmatite: composed of coarse-grained plagioclase (cleavelandite)—quartz—lepidolite with minor topaz; 3—Greisens: composed of quartz and lepidolite; 4—Albite veins: veins of fine-grained (sugary) albite; 5—Quartz—plagioclase: pegmatite (plagioclase + quartz) with large quartz crystals. Location: Site No. 1 in Figure 1.

Topaz–lepidolite–albite pegmatites such as those of the Khukh Del Uul deposit differ from typical spodumene pegmatites from elsewhere by having lower silica but higher contents of Fe, Na and especially F. Pegmatites have on average about 2 wt.% F, although in many samples it reaches up to 4 wt.% [24]. The high F content is also reflected by the presence of F-rich minerals such as micas, topaz, fluorite and F-rich greisens. The typical pegmatite of the swarm contains about 1.75 wt.% Li_2O [24]. In general, topaz–lepidolite–albite pegmatites of the Khukh Del Uul have high contents of F, Li, Rb, Cs, Nb, Ta and Be but are depleted in Sr, Ba and Zr. These characteristics show distinct similarities to rare-metal Li–F leucogranites and ongonites [22,23]. Compared to typical calc–alkaline granites and pegmatites, all these rocks have low abundances of B and tourmaline [24].

Munkhtiin Tsagaan Durvuljin (Figure 1; site No. 2) is another Li-rich pegmatite site in Central Mongolia [25]. Pegmatite dikes occur in an area of about 0.5 km × 0.5 km. The pegmatite swarm (Late Paleozoic to Early Mesozoic age) includes fifteen dikes which are ~200–400 m long and 1–5 m wide. The pegmatite dikes are composed of fine-grained lepidolite–quartz–feldspar leucogranitic rocks which are hosted in biotite granites. The host biotite granites are porphyritic composed of quartz (30–40%), plagioclase (oligoclase 20–25%), K–feldspar (25–35%) and biotite (9–12%). Along the contact with the pegmatite dikes, the granites are greisenized and show signs of shearing. Greisenization involves replacing biotite and feldspars by zinnwaldite. Pegmatites have a highly variable composition, in part, due to strong greisenization. Greisens are composed mainly of quartz and lepidolite/zinnwaldite, where the mica content can reach up to 40 vol.%. Accessory minerals of pegmatites are fluorite, cassiterite, columbite–tantalite and topaz. The biotite granites are peraluminous A-type granites with silica ranging from 66 to 70 wt.% while total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) vary from ~6.6 to 8 wt.%. The pegmatites are also peraluminous and contain 65–73 wt.% SiO_2 and 6.5–9 wt.% ($\text{Na}_2\text{O} + \text{K}_2\text{O}$). Compared to biotite granites, pegmatites have significantly lower contents of Fe, Mg and Ca but high concentrations of Li, Sn, W, Ta, Nb and F, typical of rare-metal Li–F granites. The pegmatites contain 0.1 to 2.4 wt.% Li_2O , whereas greisens have 1.5 to 2.4 wt.% Li_2O . In total, the Munkhtiin Tsagaan Durvuljin pegmatite hosts 2.28 Mt of ore with a grade of 0.65 wt.% Li_2O [26].

Bayan Teeg pegmatite of Central Mongolia (site No. 5, Figure 1, Table 2) is another Li-rich pegmatite [27]. Its body, which is about 140 m long and up to 1.3 m thick, intruded Neoproterozoic metasedimentary rocks. In addition to quartz, plagioclase and

K-feldspar, the pegmatite also contains lepidolite, muscovite, secondary albite and accessory amblygonite, cassiterite, topaz, columbite–tantalite, monazite, zircon and fluorite. The pegmatite carries 1.48–2.15 wt.% Li_2O , 0.1 wt.% BeO , ~200 ppm Ta_2O_5 and ~100 ppm Nb_2O_5 . Bolorchimegh et al. [27] obtained the U–Pb cassiterite age of ~135 Ma and Ar/Ar lepidolite plateau age of ~131 Ma and argued that the pegmatite was formed by melting of crustal basement during the post-collisional extension after the Mongol–Okhotsk Ocean closure. Dashtseren et al. [28] also reported Li-bearing pegmatites dated at ~500 Ma from this part of Central Mongolia.

3.1.2. Lithium–Fluorine Granites

Li–F granites [10,19,20] are highly fractionated alkali-rich peraluminous RMG granites associated with Sn, W, Li, Ta and Nb mineralization. In Mongolia and the neighboring part of Russia (Transbaikalia), these post-orogenic subalkaline rocks occur either as a part of large differentiated multistage granitic complexes or as small single-stage intrusions. Typical Li–F granites are composed of albite, quartz, K-feldspar, mica and minor topaz but their modal composition is variable. They are mostly porphyritic with phenocrysts of quartz set in fine-grained groundmass dominated by albite. Li mineralization is mainly associated with lepidolite–albite assemblage, which forms minor bodies in apical or marginal parts of the granitic intrusions. These lepidolite–albite granites are made up of quartz, albite (55–60 vol.%), K-feldspar (~15 vol.%), lepidolite (~4 vol.%) and topaz (2–2.5 vol.%), although they may contain up to 10 vol.% topaz and up to 20 vol.% lepidolite [10,29]. Locally, the granites were affected by post-magmatic processes and converted to greisens composed mainly of quartz and Li-rich mica (zinnwaldite, lepidolite). One of the prominent occurrences of Li–F granites is the Janchivlan pluton (Figure 4), located about 90 km southeast of Ulaanbaatar (Site No. 7 in Figure 1; Table 2). The pluton occurs in the outer part of the Early Mesozoic Khentei batholith, which is composed of numerous intermediate to felsic granitoid complexes.

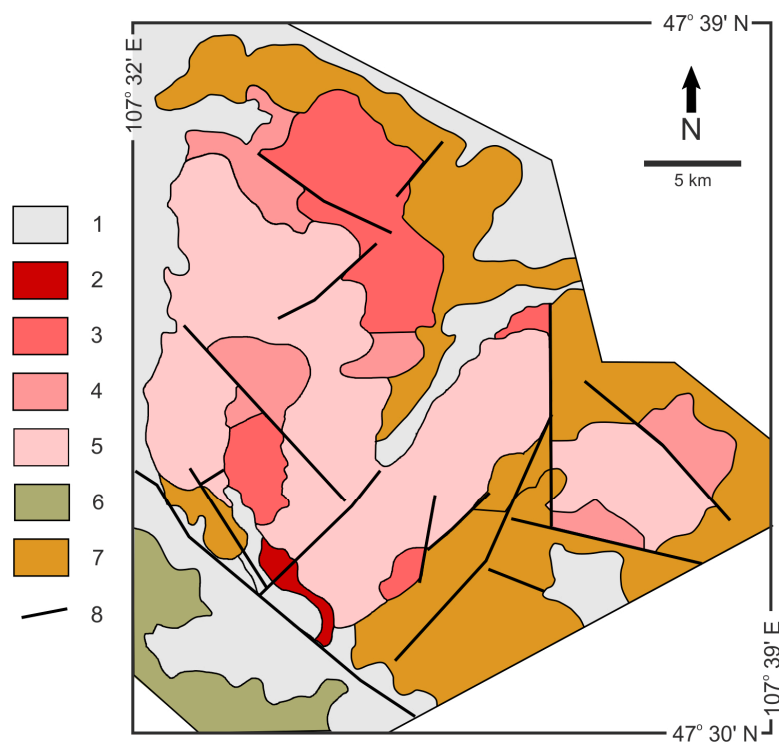


Figure 4. Generalized geological map of the Janchivlan complex modified after Kovalenko et al. [19], Antipin et al. [30] and Dostal and Gerel [31]. Location: Site No. 7 in Figure 1; Table 2. 1—Quaternary sediments; 2—Li–F leucogranite; 3—Phase III leucogranite; 4—Phase II granite; 5—Phase I granite; 6—Precambrian basement; 7—Paleozoic clastic sediments; 8—Faults.

The Janchivlan pluton dated at $\sim 190 \pm 2.1$ Ma [31–33] is composed of four distinct phases of peraluminous granites. The first phase includes porphyritic coarse-grained biotite granites with miarolitic pegmatites, while the second phase is made up of medium-grained two mica granites that locally host Sn-bearing greisens. The third phase is minor, composed of K-feldspar granite. These three phases constitute the bulk of the pluton. In the southern part, the pluton includes the minor fourth phase, Li-F leucogranite. This rock type (Table 3; [31]) is compositionally similar to two adjoining but separate minor bodies—Urt Gozgor and Buural Khangai stocks. Each of these bodies includes three distinct phases: microcline–albite, amazonite–albite and lepidolite–albite. Li contents of amazonite–albite and microcline–albite vary from ~ 290 to 430 ppm while the lepidolite–albite granite contains on average 878 ppm Li [10]. Accessory minerals of lepidolite–albite granites are fluorite, zircon, monazite, columbite–tantalite, microlite and cassiterite. The greisenized part of these rocks contains up to 1315 ppm Li [10].

Table 3. Major and trace element composition of the Li-F granitic rocks from Mongolia.

wt. %	JA-1	JA-4	JA-7	JA-9	ONG	Avdar-1	Avdar-2	Baga-1	Baga-2	Baga-Gr
SiO ₂	73.04	76.1	75.8	70.9	70.84	72.33	75.84	76.03	77.02	80.23
TiO ₂	0.215	0.061	0.014	0.004	0.02	0.22	0.02	0.12	0.10	0.11
Al ₂ O ₃	13.52	12.22	12.78	17.65	16.65	13.48	12.76	12.58	9.75	9.58
Fe ₂ O ₃ (t)	1.61	1.03	0.79	0.12	0.24	2.82	1.73	1.42	1.85	4.66
MnO	0.044	0.033	0.024	0.034	0.17	0.04	0.04	0.03	0.03	0.10
MgO	0.27	0.03	0.01	0.01	0.03	0.64	0.13	0.04	0.30	0.05
CaO	0.97	0.44	0.26	0.12	0.17	1.28	0.32	0.55	0.40	0.88
Na ₂ O	3.23	3.49	4.29	5.85	5.90	4.21	4.46	3.39	3.28	0.10
K ₂ O	4.90	4.60	4.03	3.22	3.14	4.97	4.14	4.81	4.63	2.03
P ₂ O ₅	0.10	0.01	0.01	0.01	0.03	0.07	0.05	0.03	0.04	0.04
LOI	0.77	0.52	0.49	0.86	1.40	0.46	0.43	0.65	0.64	1.57
Total	98.669	98.534	98.498	98.778	98.59	100.52	99.92	99.65	98.04	99.34
ppm										
Li	165	352	859	389	1950	338	396	156	158	856
Cs	12.7	24.5	15.2	10.1	104	12	20	15	15	36
Rb	265	627	751	1250	2404	730	753	429	525	556
Ba	384	61	1	5	15.5	3	2.5	78	27	53.4
Sr	115	15	2	6	12.7	17.9	13.6	31	23	24.7
Ta	2.97	6.17	5.93	22.6	71.1	2.0	17.1	5.4	6.8	8.9
Nb	8.8	35.6	22	56.8	83.8	15	78	40	47	93.5

Table 3. Cont.

wt.%	JA-1	JA-4	JA-7	JA-9	ONG	Avdar-1	Avdar-2	Baga-1	Baga-2	Baga-Gr
Hf	3.2	7.1	8.9	6.4	9.0	8.3	22	8	9	7.6
Zr	111	143	83	18	33.0	230	140	163	165	160
Y	18.4	94.7	164	1	15.4	21.8	67.4	82	130	87.3
Th	15.1	49	30.5	20.8	15.0	38.4	36.4	40	56	38
U	6.95	4.94	4.41	4.13	5.48	2.7	5.1	9.7	4.8	8.36
La	23.6	57.3	22.6	2.43	6.59	10.3	10.3	31.27	33	36.84
Ce	49.2	106	68.2	7.61	25.47	27.7	25.5	73.97	79	86.59
Pr	5.68	11.6	9.77	1.13	3.51	7.8	2.9	9.39	10	10.85
Nd	21.1	38.0	39.0	2.67	16.7	28.5	9.0	35.18	37	40.29
Sm	4.30	8.64	14.4	0.73	4.86	5.9	3.1	9.27	10.7	10.14
Eu	0.52	0.207	0.007	0.025	0.03	0.46	0.01	0.17	0.10	0.20
Gd	3.55	7.95	14.9	0.32	2.93	5.4	3.6	9.91	12.1	10.4
Tb	0.58	1.72	3.55	0.10	0.57	0.86	0.75	1.93	2.51	2.02
Dy	3.42	12.9	26.5	0.77	3.16	6.5	6.7	13.74	18.7	14.36
Ho	0.62	2.88	5.74	0.16	0.45	1.21	1.43	3.03	4.27	3.15
Er	1.9	9.73	19.3	0.59	1.32	4.4	6.0	10.26	14.8	10.54
Tm	0.276	1.64	3.43	0.173	0.26	0.82	1.2	1.66	2.52	1.72
Yb	1.86	11.9	24.4	1.64	1.73	13.8	13.7	11.58	18.0	11.9
Lu	0.287	1.81	3.69	0.288	0.23	1.08	1.62	1.73	2.69	1.80
F					8400	2800	3100	3900	4300	24,739

Baga-1 and Baga-2: averages of the biotite granite (core) and leucogranite of the Baga Gazar intrusion [33]; Avdar-1 and Avdar-2: averages of the core and rim of the Avdar intrusion [33]; Baga-Gr: average of greisens, zwitter and metasomatized granite of the Baga Gazar intrusion [34]; JA: Janchivlan intrusion; JA-1: phase 1 biotite granite; JA-4: phase 3 leucogranite; JA-7: Li-F granite, lepidolite–albite; JA-9: Li-F granite, amazonite–albite; ONG: average of 21 ongonites from the type locality.

Another composite pluton containing Li-F granites is the Baga–Gazar in Central Mongolia, located about 220 km SSW of Ulaanbaatar (Figure 5). The pluton spreads over an area of about 120 km² and is dome-shaped. This ~200 Ma old [32] ovoidal zoned body is composed of the dominant core made up of coarse- to medium-grained biotite granite surrounded by fine-grained Li-F leucogranite of a younger second phase containing Li-biotite and topaz. Both phases are crosscut by greisens (zwitter) and microcline–albite–fluorite dikes which could be over 1 km long, up to 50 m thick and occur mainly around the periphery of the pluton. Zwitter are dark Li–mica-bearing greisens containing topaz.

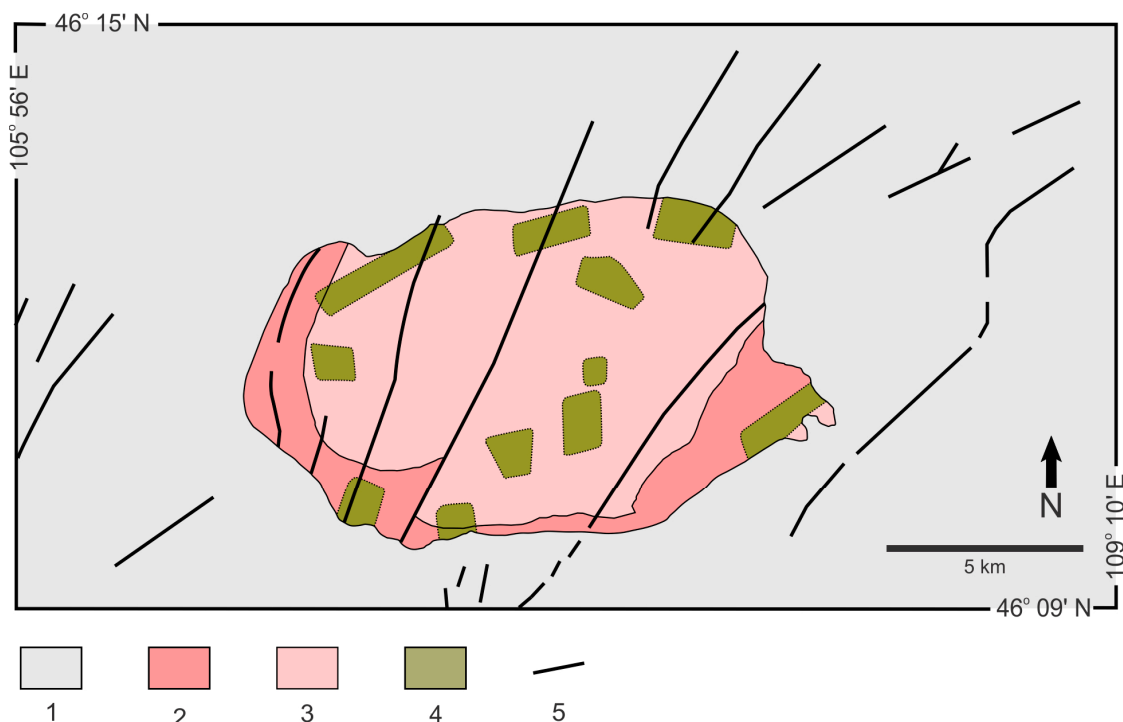


Figure 5. Generalized geological map of Baga–Gazar intrusive complex (after Antipin et al. [34]). 1—Country rock: metasedimentary rocks intercalated with Permian volcanic rocks; 2—Fine-grained leucogranites: the late–second phase; 3—Coarse- to medium-grained biotite granite: the early–first phase; 4—Zones of greisenization and veins of greisens (zwitter); 5—Faults. Location: Site No. 9 in Figure 1; Table 2.

Both main phases of the pluton have similar chemical compositions. They are peraluminous highly fractionated high silica (~75–77 wt.%) and alkali (~8–9 wt.%) rocks that are enriched in Li, Rb, Na, Ta, Th and U but depleted in Ba, Sr and Eu (Table 3; Supplementary Text S1). They are compositionally like those of the Janchivlan pluton (Figure 6). The granites have elevated contents of F (0.3–0.4 wt.% [30]) and Li (~160 ppm [33,34]), which are mainly hosted in fluorite and Li-bearing biotite, respectively. The rocks were modified by post-magmatic processes which produced both greisens and microcline–albite–fluorite dikes. Greisens have typically 0.8–1.7 wt.% F and 550–1520 ppm Li whereas the microcline–albite–fluorite dikes contain ~1600–4300 ppm Li. Greisenization led to a decrease in Al, Na and K and an increase in Fe, Li and Cs. The average of pegmatite dikes in the Baga–Gazar pluton has 1,4400 ppm F and 630 ppm Li [33,34].

The Avdar pluton is characteristic of the small Li–F granitic intrusions in Central Mongolia. The pluton occurs about 150 km southwest of Ulaanbaatar (Figure 1; site No. 10), where it intrudes Devonian clastic metasedimentary rocks. This elliptical-shaped body is about 6 km long and spreads over an area of about 10 km² [33]. Several age determinations range from about 202 to 212 Ma [33,35]. The intrusion is composed of a dominant core made up of medium-grained biotite leucogranite surrounded by a rim of amazonite–albite leucogranite. The contact between these two units is gradational (Figure 7). The biotite leucogranite contains plagioclase (An_{4–18}), quartz, microcline and minor Li–biotite (2–3 vol.%) whereas the amazonite–albite leucogranites contain albite (An_{2–7}) (~30 vol.%), quartz (~45 vol.%), microcline (amazonite ~20 vol.%) and Li-rich mica. Accessory minerals of both phases include Fe–Ti oxides, zircon, fluorite, cassiterite and columbite–tantalite. Both granitic rock types are rich in silica (72–77 wt.%) and alkalis (8–10 wt.%) but are low in Ca, Mg, and Fe. Their trace element composition is typical of Li–F granites (Table 3). The average content of F and Li in the biotite leucogranites is F ~1300 ppm and Li ~38 ppm, whereas amazonite–albite leucogranite has F ~2600 ppm and Li ~507 ppm Li [35].

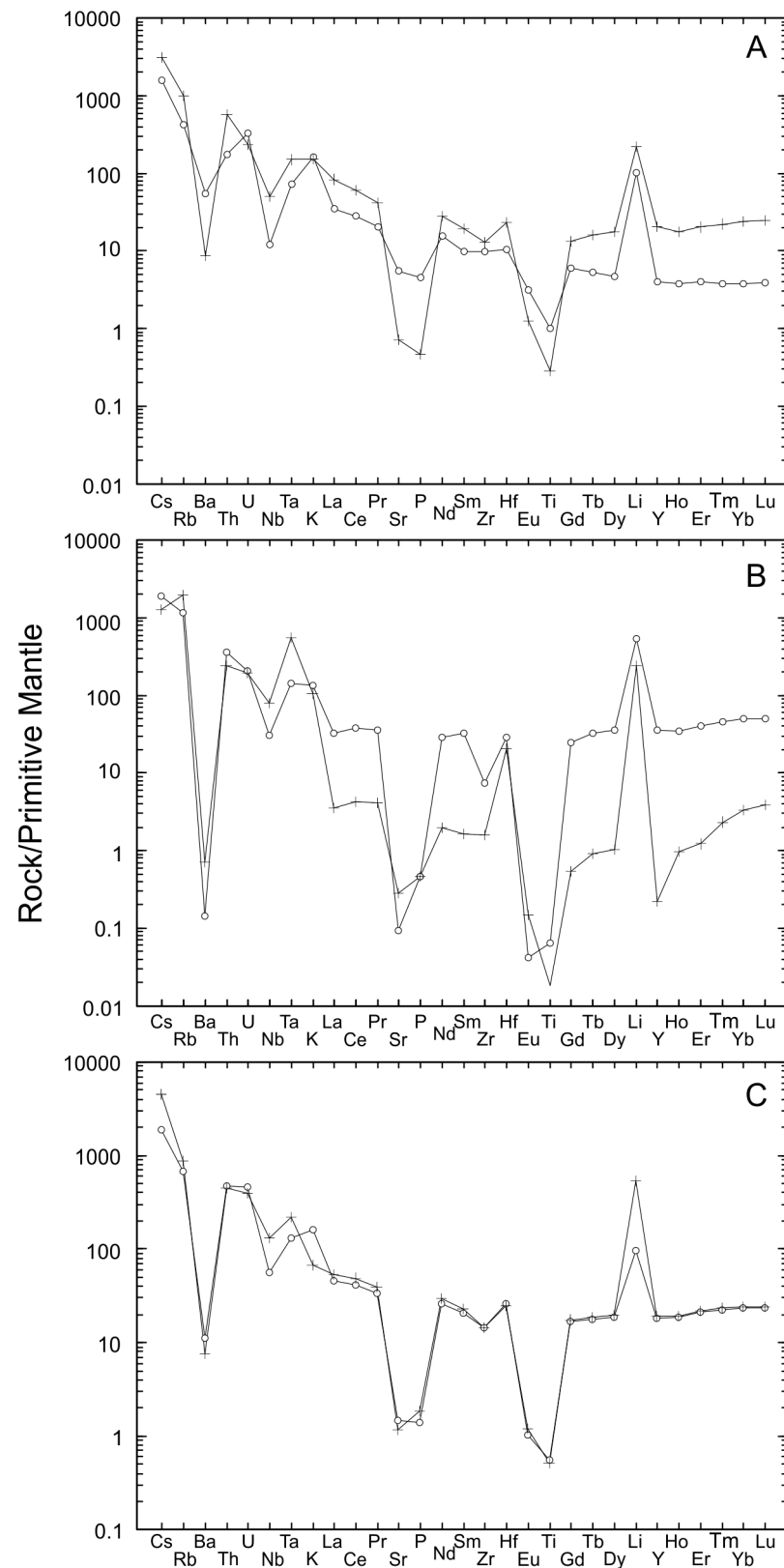


Figure 6. Primitive mantle-normalized incompatible element abundances of RMG granites and related rocks. (A) Janchivlan, phase 1 granite: JA-1 (o); phase 3: leucogranite (+). (B) Janchivlan, Li-F granite, lepidolite-albite: JA-7 (o), amazonite-albite: JA-9 (+). (C) Baga-Gazar: average of phase 1 (o), average of greisens (+). Normalizing values after McDonough and Sun [36]. Data are from Table 3; data of Baga-Gazar are from Antipin et al. [33].

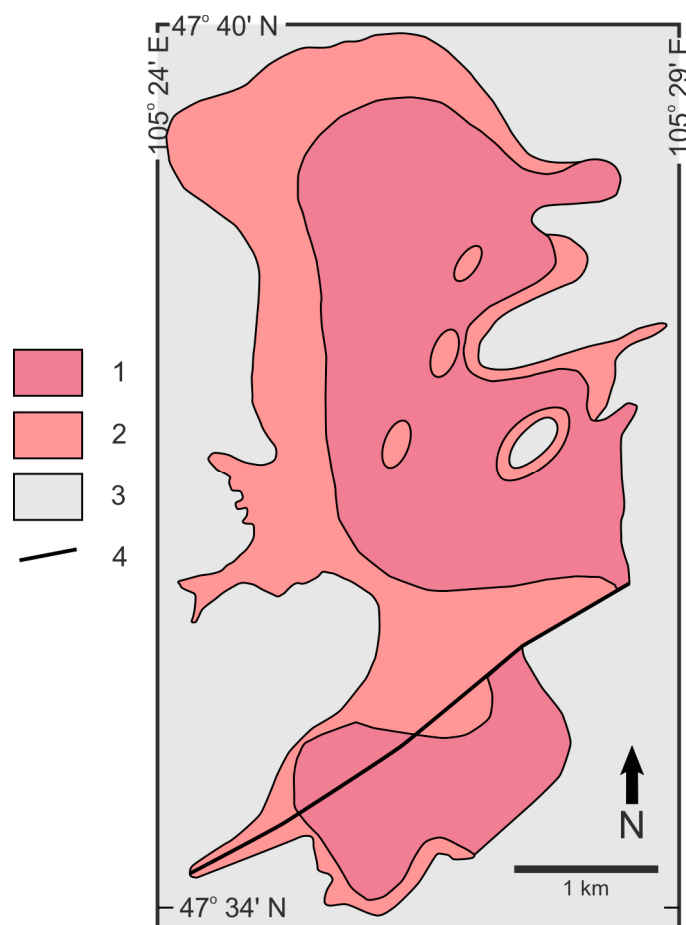


Figure 7. Generalized geological map of Avdar pluton modified after Antipin et al. [30] and Dostal and Gerel [31]. Location: Site No. 10 in Figure 1; Table 2. 1—Biotite leucogranite; 2—Amazonite–albite leucogranite; 3—Country rock; 4—Faults.

3.1.3. Li-F Subvolcanic and Volcanic Felsic Rocks (Ongonites and Ongorhyolites)

Ongonites were discovered and defined by Kovalenko et al. [22] and Kovalenko and Kovalenko [23] in the Ongon Khairkhan Mountains, Central Mongolia, as topaz-bearing albite–quartz keratophyres, containing phenocrysts of albite, K-feldspar, quartz, mica and topaz hosted in a groundmass composed of the same minerals. It was named after the Ongon Khairkhan pluton and associated tungsten deposit. These rocks are strongly enriched in several incompatible elements, particularly Li, Rb, Cs and Ta but depleted in Mg, Ba, Sr and Eu (Table 3) and are frequently associated with Sn–W–Ta–Nb mineralization. Compositionally, they resemble glassy volcanic rocks—macusonites from Peru (e.g., [37–39]).

In Mongolia, there are two types of ongonites: subvolcanic, which typically occur as dikes, and the volcanic variety. As the subvolcanic ongonites are better known in Mongolia, the emphasis here is on this type. In Central Mongolia, the Cretaceous ongonite dikes crop out in the Mesozoic Kharkhorin rift zone, in a string of the SW–NE-trending grabens. The ongonite dikes (~120 Ma old; [40]) at the type locality—the Ongon Khairkhan—are shallow-seated [41] and hosted by the Devonian–Carboniferous clastic sedimentary rocks (Figure 8).

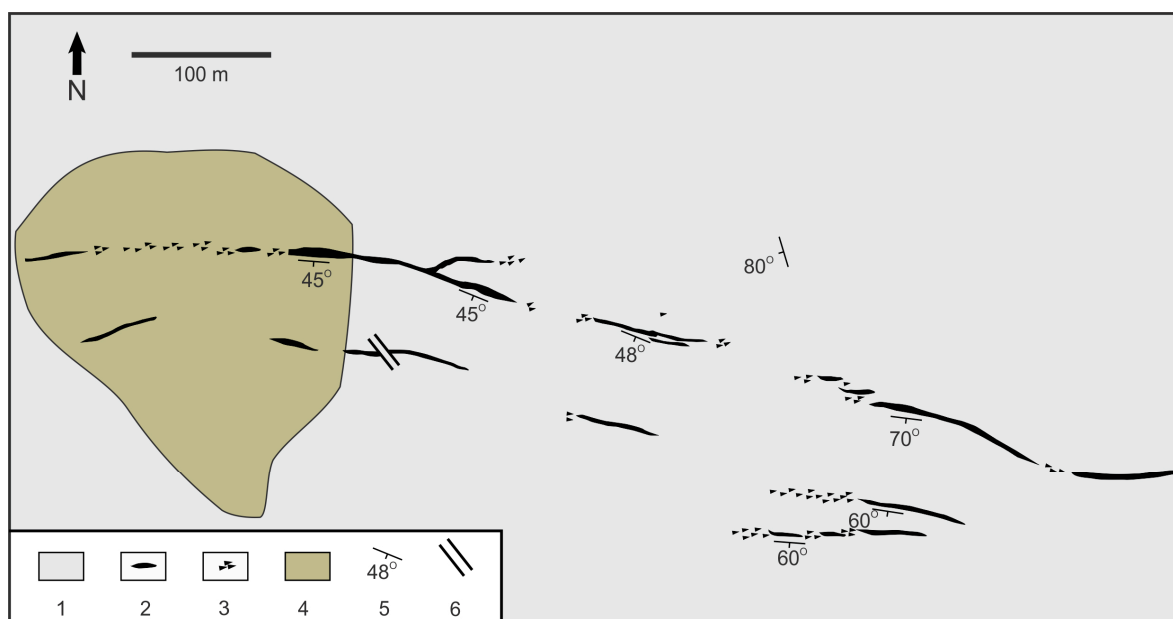


Figure 8. Generalized geological map of ongonite dike from Ongon Khairhan; modified after Dostal et al. [40]. Location: Site No. 14 in Figure 1; Table 2. 1—Sedimentary rocks; 2—Ongonite; 3—Ongonite regolith; 4—Stockwork; 5—Strike/Dip; 6—Faults.

The ongonites form a dike swarm about 2 km long with the thickness of individual dikes ranging from several cm to about 5 m. The dikes have chilled margins. The content of Li_2O is variable, ranging typically from about 0.1 wt % in porphyritic ongonites to 0.56 wt.% in aphyric types [41]. Kovalenko and Kovalenko [23] reported the average Li contents of the main ongonite dike as 1950 ppm. The dominant Li mineral is Li-rich mica, which occurs both as microphenocrysts and in the groundmass. The mica microphenocrysts are rare (<0.1 to 2 vol.%) whereas the groundmass contains up to 7 vol.% mica [40]. The mica is zinnwaldite. The primary mica usually contains about 2.5 wt.% Li_2O although it can reach up to ~8 wt.%. The secondary mica has slightly lower concentrations of Li_2O (~2 wt.%; [40]).

The ongonites are rich in SiO_2 (70–74 wt.%), Al_2O_3 (16–18 wt.%) and alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$; 8.5–10 wt.%) but have low contents of MgO , TiO_2 , CaO (<0.4 wt.%) and P_2O_5 (< 0.06 wt.%) (Table 3). These leucocratic granitic rocks are strongly peraluminous and have high contents of F (~2 wt.%; [23]). The primitive mantle-normalized incompatible element patterns for the ongonites feature large negative anomalies for Ba, Sr, Eu and Ti (Figure 9) and are in general similar to those of RMG [11] and Li-F granites [30]. The ongonites have unusually low ratios of several incompatible elements including K/Rb (<20), Zr/Hf (2–5) and Nb/Ta (0.6–2.2) versus typical crustal values of K/Rb ~250, Zr/Hf ~35–40 and Nb/Ta ~11. The low values of these ratios are indicative of the role of hydrothermal fluids [42–44] and suggest the involvement of both crystal and fluid fractionation in the evolving ongonitic melt. Li-F granites and related rocks were generated through prolonged fractional crystallization which involved fluids, including F. However, recent experimental data [45] suggest that the distinctive geochemical features of these rocks require not only such a fractionation process but also mica dehydration melting and probably a distinct source.

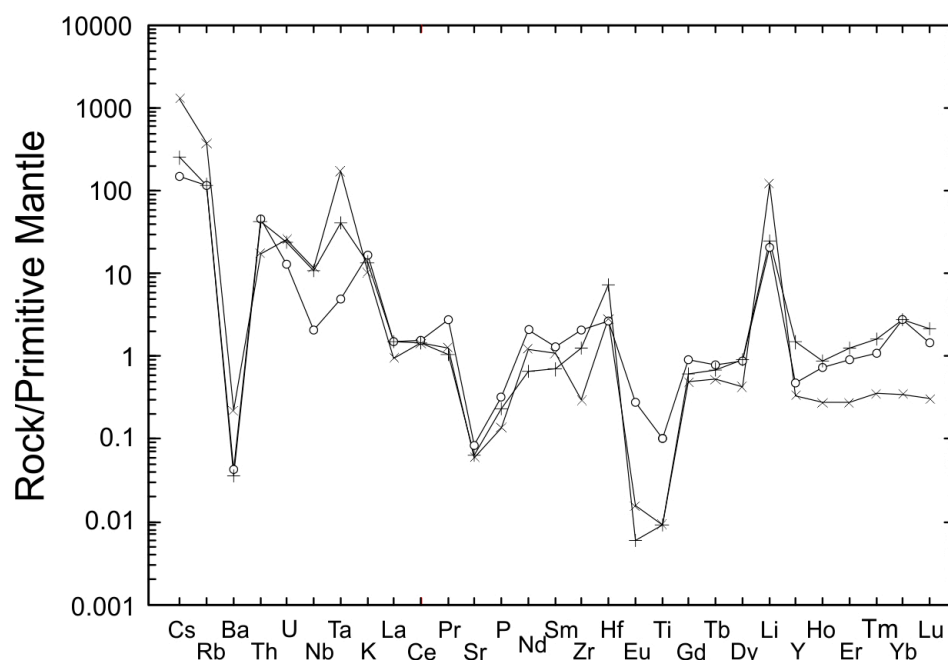


Figure 9. Primitive mantle-normalized abundances of incompatible elements of granitic rocks from the Avdar intrusion and ongonites. Avdar: biotite leucogranite (o) and amazonite–albite leucogranite (+); ongonite from Ongon Khairkhan (x). Normalizing values after McDonough and Sun [36]. Data are from Table 3.

The ongonites are the product of protracted fractional crystallization mainly due to high contents of fluorine which allows the melts to crystallize over a range from a liquidus temperature that exceeded 800 °C to an anomalously low solidus temperature of around 600 °C. This is also supported by the saturation temperatures for apatite (814 ± 27 °C), monazite (747 ± 13 °C) and zircon (615 ± 15 °C) (Supplementary Text S2). The ongonites probably represent melt from the apical part of an underlying granitic pluton and correspond to the last stage of fractionation of a highly evolved F-rich granitic magma.

Similar occurrences of subvolcanic ongonites (dikes) occur, for example, at Baga–Gazar and Janchivlan (Figure 1; sites No. 7 and No. 9) in Central Mongolia. Their average Li content was reported to be about 2780 ppm while the average of Rb was 2380 ppm and Ta was 88 ppm [10]. Volcanic analogs of ongonites occur in southern Mongolia and are called ongorhyolites [10,22]. They form volcanic necks and sheets. Compared to subvolcanic types, the volcanic ongonites have lower contents of Li and rare metals such as Ta, Nb and Be but are much more voluminous. Some of these mineralized units expand over > 1 km² and are 10–20 m thick. The main occurrence of volcanic ongonites (ongorhyolite) is Teeg Uul (Figure 1; site No. 15).

3.2. Sedimentary Rocks Hosted Lithium Deposits

The Mongol–Okhotsk orogenic belt that runs across Mongolia was affected during the Jurassic and Cretaceous by extension probably accompanied by gravitational collapse leading to the formation of a series of extensional basins in eastern and central Mongolia [46]. Sedimentary successions of the basins are typically 3–4 km thick. The bounding faults are mostly shallow dipping. Individual basins are composed internally of various-scale sub-basins. The extensional basins are frequently elongated, roughly parallel to the Mongol–Okhotsk suture zone and spread over the China–Mongolia border region [46]. Some of these basins host uranium and lithium mineralization [10].

The most prominent Mongolian deposit of this type is the Khukh Del deposit (Figure 1, site No. 16) situated in the middle of the Gobi Desert, about 550 km southwest of Ulaanbaatar [47]. The deposit is hosted in a basin (Tugrug Valley) filled by middle–upper

Jurassic clastic sediments including siltstones and clays. The deposit is 6 km long and 5 km wide. The ore horizon, which is ~1.1 m thick, is clay-bearing siltstone containing reserves of 37.7 thousand tons of ore with 0.153 wt.% Li [10,26].

3.3. Lithium-Bearing Brines

The Gobi Desert is dry with very low rainfall and high evaporation rates, resulting in the development of saline lakes. The host basins are endorheic, closed drainage basins that do not have an outlet and retain water. Such watersheds are needed for the formation of saline lakes that have elevated Li from inflow during weathering, leaching and erosion of surrounding rocks and the subsequent concentrations of Li through evaporation.

Mongolia hosts several promising sites of Li-bearing salt lake brines [10], but the information is rather limited. Ariunbileg et al. [48] reported elevated concentrations of Li in lake waters from Eastern Mongolia, particularly at Dund Bayan nuur and Baruun Davst nuur (Figure 1; Table 2). They concluded that the closed saline lakes in the Gobi Desert have significant Li potential. Another promising site, the Baavhai Uul solar in southeastern Mongolia (Figure 1; Table 2), is close to the border with China. The site is in the Gobi Desert, within the subsiding basin filled, in part, with Cretaceous volcanic and sedimentary rocks and Quaternary sediments that form a favorable aquifer for Li brine (the average content of Li in brines is 426 ppm with the maximum of 811 ppm Li [49]). Another similar site is the Urgakh Naaran Li brine [49] located in the South Gobi Desert, about 450 km southeast of Ulaanbaatar (Figure 1; Table 2). Some of these lakes in the Gobi of Eastern Mongolia have also high concentrations of U [50]. Similar salt lakes with elevated concentrations of Li in water are present in Western Mongolia. Isupov et al. [51] reported Li concentrations up to 600 ppm in lakes of the West Mongolian Great Lake Valley (Uvs nuur, Khyargas nuur and Dergen; Figure 1). Ariunbileg et al. [52] also noted that the Valley of Lakes in the Gobi Desert in Southern Mongolia hosts promising sites such as a Cretaceous Zunbayan basin.

4. Conclusions

Mongolia hosts several promising sites of Li mineralization, which can be of economic importance. However, there is insufficient knowledge of most of these occurrences, in part, due to a relative lack of interest in this commodity in the past. The prospective deposits include both endogenic (Mesozoic hard rocks: Li-rich pegmatites, rare-metal Li-F granites, ongonites, ongorhyolites and greisens) and exogenous (Li-bearing clays and Li salt lake brines) mineralization.

The lithium in hard rocks is contained mainly in Li-bearing micas, particularly lepidolite and zinnwaldite, unlike the world-class Li-bearing pegmatite deposits such as those in Australia (Greenbushes) and Canada (Whabouchi) where the bulk of Li is in spodumene. This is likely due to the high contents of F in the Mongolian rocks, indicating different fluxing fluids (F vs. B and P). Compared to pegmatites, the rare-metal Li-F granites and volcanic equivalents form large kilometer-scale bodies.

A favorable geodynamic environment for Mongolian Li accumulation in hard (igneous) and sedimentary rocks is a post-orogenic extensional setting. Li-F granites and related rocks from an area around the margin of the Khentei batholith are particularly prospective for Li mineralization. Likewise noteworthy are Li salt lake brines in the Gobi Desert with an arid environment, high evaporation rates and low precipitation. They occur in evaporite-bearing endorheic basins without outflow to an external water reservoir and with shallow aquifers occurring in vicinities of felsic igneous rocks including Cretaceous felsic volcanic rocks.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min14100960/s1>, Text S1. Analytical methods; Text S2. Saturation temperatures [42,53–56].

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