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## Lithium Deposits of Spodumene Pegmatites in Siberia

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### Abstract

Comparative analysis of lithium deposits and ore manifestations of spodumene pegmatites of Siberia was carried out for the purpose of their development and substantiation of the investment attractiveness for nuclear, electrochemical industry and defense technologies. The characteristics of the geological structure of ore fields of spodumene pegmatites are presented, along with the mineralogical and geochemical characterization of lithium-bearing complexes contained therein. The richest in lithium spodumene ore species are those from the deposits of the Eastern Sayan, Tuva and Eastern Transbaikalia. Comparable concentrations of lithium oxide are present in the ore from the Tashelga deposit in the Shoria Highlands. The ore from the Alakha stockwork situated in the south of the Altai Highlands has the lowest lithium oxide content; however, due to the uniformity of its distribution and substantial scale of mineralization, large-scale resources are concentrated there. After ore concentrating, the concentrate consists mainly of spodumene. Iron should be mentioned as one of the most abundant admixtures. The level of concentrate enrichment with lithium oxide is determined by its concentration in spodumene. In this respect, among the studied deposits the most promising ones appear to be the pegmatites of the Eastern Sayan (Goltsovoye deposit). We emphasize that there is a necessity to perform additional geological prospecting, chemical engineering and inspection examinations for the purpose of allocating the sites with the richest lithium ore species within the Zavardino deposit (Transbaikalia), as well as at the Goltsovoye, Belorechensk and Urik deposits (Eastern Sayan), Tasty deposit (Tuva) and promising ore manifestations Tashelga (Mountain Shoria) and Alakha (Altai Highlands). It is concluded that the spodumene pegmatites of Siberia are able to become the necessary and sufficient mineral raw material basis for the development of lithium industry in Siberia.

**Key words:** lithium, spodumene, pegmatites, geological structure, mineralogy, geochemistry, Siberia

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## INTRODUCTION

Lithium represents a lithophilous element inherent in granitic magmas. Most often, it is accumulated in the late magmatic formations with a lot of volatile components such as pegmatites. In large-scale pegmatite deposits of lithium, the pegmatites usually form the “suites” of the vein bodies with a considerable extent; they represent veins or the lenses within the granite masses, with a large-grain and giant-grain structure. Among 150 lithium-bearing minerals only five of them are of industrial importance. They are spodumene  $\text{LiAl}[\text{Si}_2\text{O}_6]$ ,  $\text{K}\{(\text{Li}, \text{Al})_3[(\text{Si}, \text{Al})_4\text{O}_{10}](\text{OH}, \text{F})_2\}$ , petalite  $\text{Li}[\text{AlSi}_4\text{O}_{10}]$ , amblygonite  $\text{LiAl}[\text{PO}_4](\text{OH}, \text{F})$ , zinnwaldite  $\text{K}\{(\text{Li}, \text{Fe}, \text{Al})_3[\text{AlSi}_3\text{O}_{10}](\text{OH}, \text{F})_2\}$ . The processing of these minerals is the base of the mining branch of the Russian lithium-extractive industry. At the same time, there is another branch of the industry such as hydromineral branch, focused on the processing of mineralized solutions and the brine of alpine salt lakes (salars). A detailed analysis of the global commodity market of lithium demonstrated that today the first place is occupied by hydromineral fields, in particular the salars of South America and Tibet [1–5]. However, the lithium-containing spodumene-pegmatite mineral raw is not only far from losing its economic importance and investment attraction, but also it is being processed in ever larger scales [6].

The increasingly growing interest in the lithium-bearing spodumene-pegmatite mineral raw materials is connected with several factors. First, initially the largest producers of lithium from salars almost monopolized the world market, which caused reducing the price to 3–3.5USD/kg of lithium carbonate to put thus the ore min-

ing and processing enterprises all over the world to the brink of bankruptcy. However, in the future, these monopolist companies occupying a major sector of the market gradually raised prices above the level of the 90-ies of the last century (6–6.5USD/kg of lithium carbonate). As the result, the processing plants survived were successfully reopened. Secondly, the decision to replace uranium stems by tantalum ones in the ultra-precise guidance weapons, which was adopted in a number of countries has resulted in an abrupt rising the prices of tantalum, whereas one of main tantalum sources is presented by spodumene containing rare-metal pegmatites. It is obvious, this was the motivating factor for the development of the mining industry in all the countries. Thirdly, the use of alumina silicate materials allows one to produce promising lithium materials for the electrochemical industry directly from the spodumene concentrate.

In the lithium industry in of Russia, whose share in the world market in the early 1990s, reached 20 %, there is a different situation observed. Disadvantageous factors connected with the overall negative processes in the restructuring of the Russian economy, have resulted in the loss of positions in the domestic and foreign markets and in the stagnation of the Russian lithium-producing complex. In order to find way out of the situation, Siberian Branch of the RAS, the Rusatom State Nuclear Energy Corp. and the TVEL JSC within the framework of the protocols concerning the scientific and technical cooperation and interdisciplinary integration projects took the decision on renewing the processing of lithium pegmatite raw materials in Siberia. One of the main challenges for solving this problem was to conduct field

studies for the purpose of additional geological exploration, sampling the laboratory specimens of lithium deposits in different regions of Siberia (Eastern Transbaikalia, Eastern Sayan, Tuva, Kuznetsk Alatau, Altai Highlands), for a detailed mineralogical analysis and enriching the ore for obtaining spodumene concentrates with further certification and testing at chemical and metallurgical plants.

This paper presents a comparative overview of the deposits and ore manifestations for the case of spodumene pegmatites in Siberia as a mineral raw base for the lithium industry in Russia.

#### SUBJECTS OF INQUIRY

Figure 1 demonstrates lithium-bearing and potential ore-bearing metallogenic provinces of the Southern Siberia and the Eastern Kazakhstan. List of geological objects and their tectonic position definitely indicate that there is a high lithium-bearing potential of the Central Asian fold belt observed. The main attention is paid to investment-attractive ore objects of the Southern Siberia those are able to provide both electrochemical and nuclear power engineering, as well as the military equipment of Russia with raw materials. The geological, geochemical and mineralogical characteristics of the Eastern Kazakhstan lithium ore province are presented in [7–16] thus being out of consideration of the present article.

#### *Eastern Transbaikalia*

Within the Mongol-Okhotsk fold belt, the Transbaikalian Mesozoic province of rare metal granites and pegmatites is well known [17]. All the pegmatite fields containing lithium mineralization in this province such as the Sedlovskoye, Zavitino, Kanga, Kulinda fields are attached to the marginal parts of the Onon terrane (Agin mountain range), sandwiched between the two branches of the Mongol-Okhotsk suture zone, formed as a result of collision between the Siberian craton and the Argun microcontinent in the middle-late Jura [18, 19]. Of greatest interest is Zavitino field with a similarly named lithium deposit of spodumene peg-

matites those served as a commercial source of lithium in Russia.

**The Zavitino deposit of lithium** is controlled by the Ingoda-Shilka branch of the Mongol-Okhotsk suture zone being spatially connected with the granites of the Kukulbey complex ( $J_3-K_1$ ). According to the U–Pb isotopic dating the Zavitino granite-pegmatite system is polychronal. Its formation coincides with the period of changing the geodynamic regimes in the region at the turn of the ( $J_3-K_1$ ): the age of the early granitic components of the system corresponds to the time of completing the collision process (167–147 million years), whereas the formation of spodumene pegmatites is dated to the beginning stages of rift genesis (130 million years) [20, 21].

Figure 2 demonstrates the geological structure of the Zavitino field. Within the field, we determined four types of pegmatite units according to mineral composition and textural features. They are: 1) granite-pegmatites, 2) uneven-grained macrocrystalline (up to block), Potassium feldspar and binary feldspar pegmatites, 3) significantly albite pegmatites, and 4) severely uneven-grained spodumene-albite pegmatites often forming the vein bodies of banded textures together with the albite and spodumene-albite granite rocks of aplite and granite structure of [23].

The Zavitino deposit that served as the mineral resource base for the Transbaikalia Ore-Dressing and Processing Enterprise (ZabGOK JSC) is presented by a suite of connivent veins of northwestern spread with the length of about 2.5 km and width of 1.2 km. Within its range there can be several parallel vein sets (bundles) distinguished. The suite of veins falls steeply toward the north-east, underneath the floor located above it that is rich with leucogranites, barren and moderately rare-metal (Be, Sn) pegmatites. With a great probability level, one could expect declining this vein suit toward the northwest. At the southeastern flank of the Zavitino deposit, this suite is limited by the Shamanskiy and Slyudyanka faults. In the footwall of the suite of veins there is a maximum level of saturation by pegmatites with the most rich lithium ore species revealed. The ore bodies (pegmatite veins) amount up to several hun-

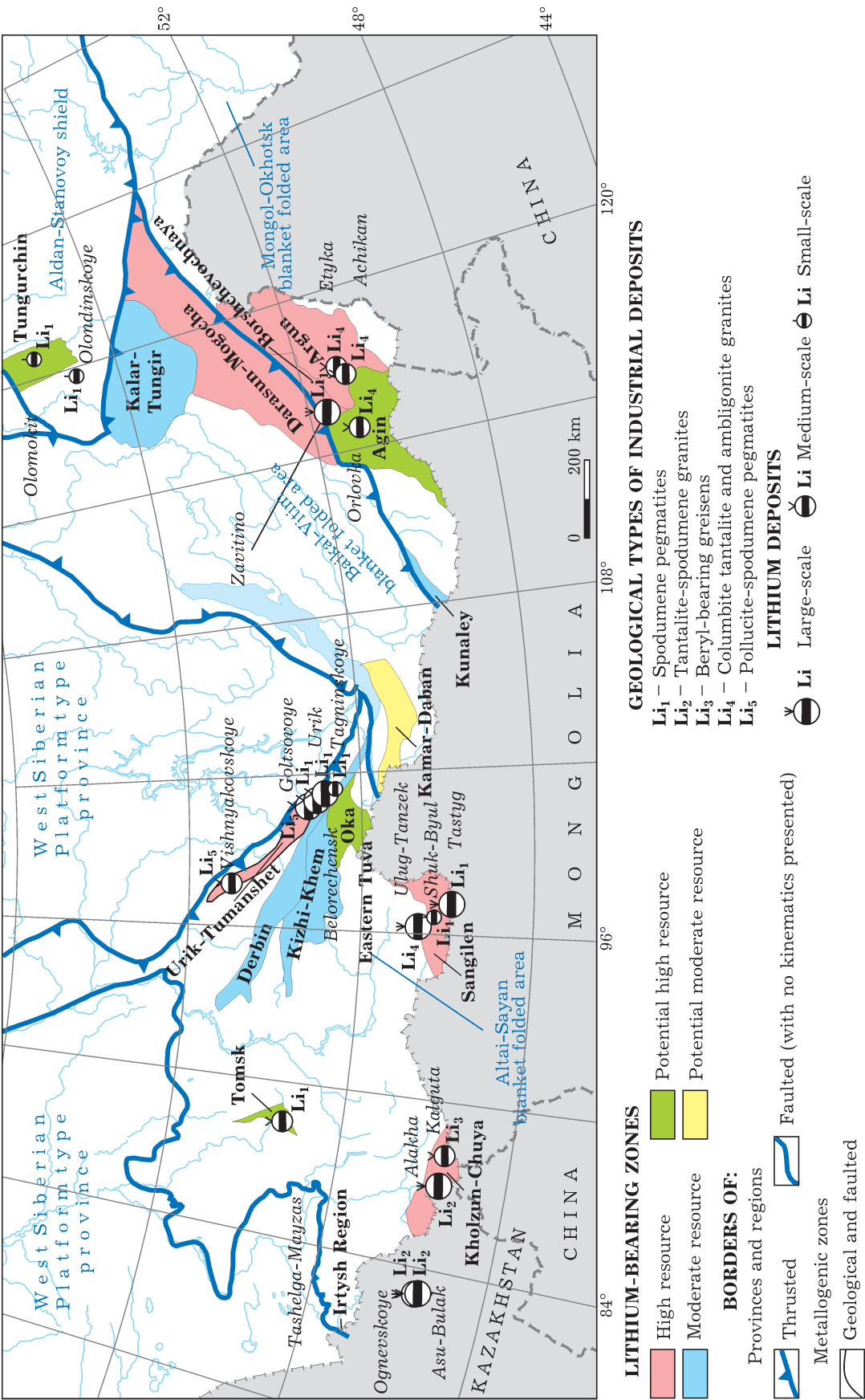


Fig. 1. Lithium-bearing and potentially mineralized metallogenic province of the Southern Siberia. The map is compiled by G. S. Gusev [3], amended and supplemented by A. G. Vladimirov, V. E. Zagorskiy, V. M. Makagon, L. G. Kuznetsova, S. Z. Smirnova, E. N. Moroz.



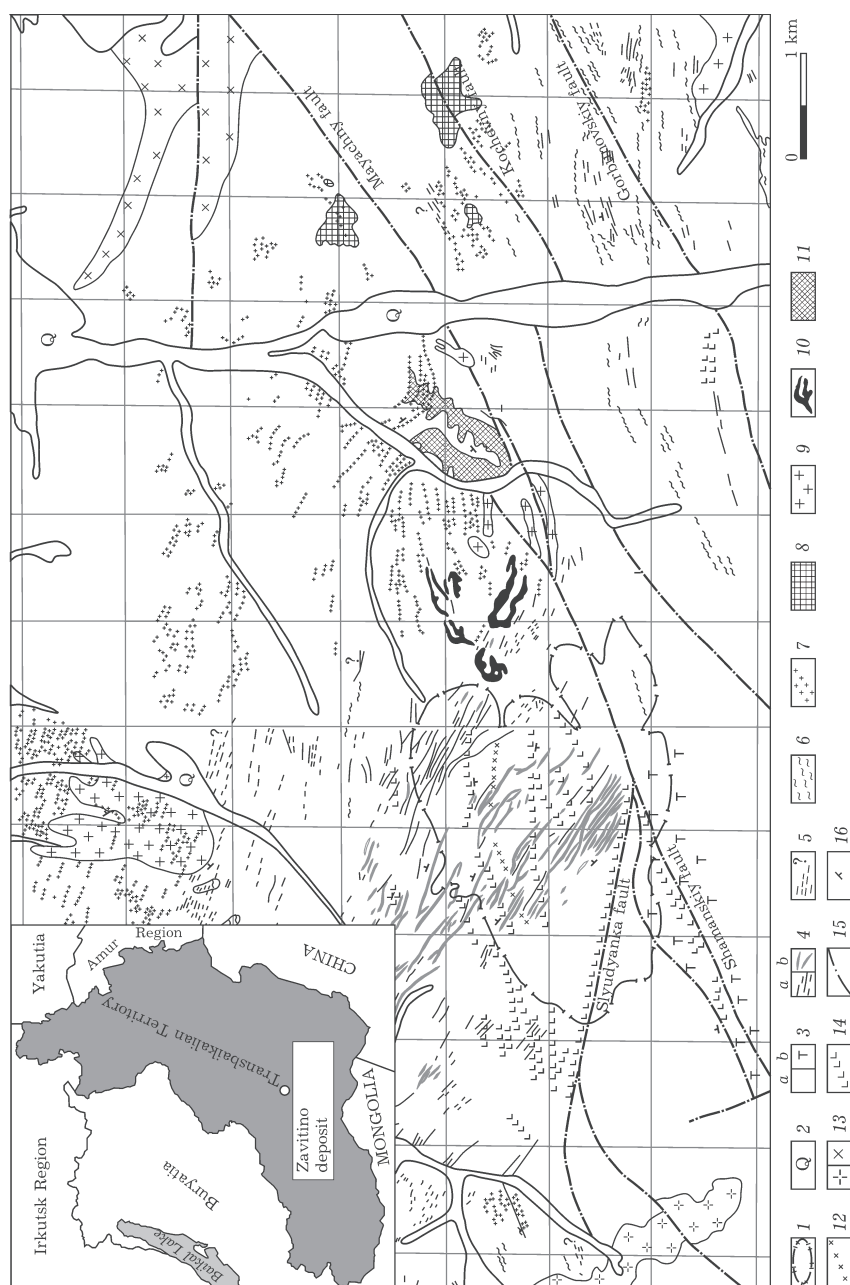


Fig. 2. Geological scheme for the location of granites and pegmatites in the western and central parts of the Zavittino pegmatite field (compiled by S. M. Beskin, V. A. Bantsekin, T. K. Prokofyeva using library materials by V. A. Grabovnikov *et al.* (1986), G. I. Petrov *et al.* (1961); the values of radiological age are presented according to [20]): 1 – outline of quarry and dumps, 2 – modern alluvium; 3 – metaterrigenous rocks of the Upper Triassic (a) and dinomometamorphic according to them (b); 4–14 – igneous rocks: 4, 5 – juvenile subalkali complex, the age of 130 million years according to spodumene-albite pegmatites (4 – albite pegmatoid granites, aplites, pegmatites III (a) and spodumene-albite pegmatoid granites, pegmatites and aplites IV (b); 5 – the same, prospective, without division into types); 6 – dikes and bodies of granite-porphyry body and albitophyry species, 7, 8 – young complex (the age of 140 million years – according to binary mica granites and binary feldspar pegmatites II); 7 – complex-shaped veins and bodies of potassium feldspar and binary feldspar pegmatite II); 8 – uniformly-medium-grained binary mica and muscovite leucogranites with garnet, often fine-pematoid (pegmatites I); 9 – intermediate complex (the age of 148 million years) and medium-grained non-uniform-grained binary mica granites, often slightly porphyry-like, undifferentiated; 10, 11 – combined formations of different complexes, undifferentiated: 10 – deposits of fine-grained binary mica granite and leucogranite, albite and spodumene-albite granite, aplite and different pegmatites (intermediate age, young and juvenile complexes); 11 – deposits of fine-grained binary mica granites and leucogranite, potassium feldspar and binary feldspar pegmatite II (intermediate age and young complexes); 12 – dikes of melanocratic micro-granites; 13 – ancient complex, melanogranites (the age of 169 million years according to biotite granites); porphyry-like biotite granite (a) and porphyry-like hornblende-biotite granites and adamellites (b); 14 – dikes of diorite porphyry species and lamprophyry; 15 – geotectonic faults; 16 – the bedding elements of mountain-rock bodies.

dred meters in length with the capacity of up to 10 m.

The ore bodies of the Zavitino field are characterized by a complex internal structure. There are the following structural-mineral complexes determined therein:

I. Fine-grained quartz-albite (“white aplite”) complex.

II. Fine-grained quartz-spodumene-albite (“gray aplite”) complex.

III. Quartz-( $\pm$ spodumene)-albite granite-like complex.

IV. Severely uneven-grained macrocrystalline spodumene-( $\pm$ potassium feldspar, muscovite)-quartz-albite complex (properly pegmatite) that sometimes contains some block sections of quartz-spodumene composition.

V. Medium-grained quartz-muscovite (“greisen”) complex.

The striking feature of the internal structure of the majority of ore bodies consists in banding conformal with respect to their contacts which banding is caused by irregular alternating the above-mentioned mineral complexes. The thickness of the bands ranges from 3.2 cm to 2.5 m. The bands can branch out, lens out and reappear. The contacts between the spodumene-containing and spodumene-free zones can be both distinct and relatively vague. Regardless of the thickness of the bands and the acutance of their contacts, the spodumene crystals are usually oriented such a way that the long side is normal with respect to spreading the bands, whose number in the cross section of the veins can reach 10–20 or more. In the large bodies, particularly in bulges, there is a disruption of the banding often observed with some cropping or crossing the bands with respect to each other (including those similar to themselves), the bends and breaks of the bands, shifts and rotations of the adjacent parts of the striate body. There are two viewpoints concerning the formation of banding in the pegmatites of the deposit: 1) a serial intrusion of melts corresponding to associations I, III, IV of “dike to dike” type; 2) the intrusion of the melt heterogeneous in composition initially graded with respect to the content of trace elements and magmatic fluid.

The average content of lithium in spodumene ( $\pm$ potassium feldspar, muscovite)-

quartz-albite complex (IV) is almost four times higher than that in the spodumene-albite-quartz “gray” aplite (III). In the areas with quartz-spodumene composition, the mass fraction of lithium amounts up to 3.9 % (Table 1). The spodumene contains 6.2–7.2 mass % of  $\text{Li}_2\text{O}$ . The lithium content in the ore species of the deposit is determined by a quantitative ratio between the major mineral complexes whose ratio varies to a considerable extent according to the dip and spread of the ore bodies, pegmatite beams and vein “suites” in general. With increasing the depth, the role of aplite and granite-like pegmatite rocks increases with respect to properly pegmatite species, but this trend exhibits a non-linear character. Furthermore, within the Zavitino deposit, the researchers of the IMGRE Institute (Moscow) determined four spatially separated blocks with the transverse dimensions from 200×200 m to 600×900 m with an increased content of lithium-bearing complexes (ore columns of arborescent shape, types III, IV) [20, 21].

Unlike the others, one of these columns (southwestern) one demonstrates the content of lithium-bearing mineral complexes to be not reduced with depth, but exhibits an increase in this parameter (see Fig. 1). On the lower horizons of the quarry, in the southeastern part, there was a large body excavated, whose base is composed of lithium-rich spodumene-albite-quartz pegmatite with some areas of a quartz-spodumene composition. These and other examples indicate that the ore potential of the Zavitino deposit is not exhausted, and the richest regions therein could be considered the investment attractive objects for high-quality spodumene raw material production, taking into account the developed infrastructure of the region and the production capacity of the ZabGOK.

### *Eastern Sayan*

The Eastern Sayan pegmatite belt extends along the southwestern margin of the Siberian Platform at a distance of over 500 km and includes the ore fields of lithium, tantalum, tin, lithium and complex (Ta–Cs–Li) pegmatites of the Riphean and Lower Proterozoic ages. This belt is divided into two parts, the southeastern

and northwestern one. The first is characterized by spodumene pegmatites those were formed under the conditions of a high initial pressure (5–3 kbar). They are attached to the Urik-Iya graben composed of Lower Proterozoic slates and amphibolites. In the northwestern part of the belt there are relatively low-pressure (3.5–2 kbar) petalite pegmatites widespread occurring in the amphibolites of Lower Proterozoic stratum of the Elashskiy graben.

In the Urik-Iya graben there are a number of intrusive mountain ranges of the Sayan complex located those are composed by a series of rocks from gabbro to granite-leucogranite and pegmatites. The available dating of the age of granitoids from the Sayan complex obtained using an U–Pb isotope method (for zircon) and an Rb–Sr isotope method (for total mica) are equal to 1858 and 1.817 billion years, respectively [26–28]. The fields of rare metal pegmatites spatially gravitate towards the mountain ranges of these granitoids. The age of spodumene pegmatites determined by means of Rb–Sr isotopic method is 1.69 billion years old, whereas that of petalite pegmatites is equal to 1490 million years. This indicates that their formation proceeded independently of the stage of granite formation. The position of pegmatite fields is controlled by the zones of deep faults [28, 29].

The Goltsovoye, the Urik and the Belorechensk lithium deposits in Urik-Iya graben are located at a distance of 20–30 km from each other, forming a single ore block. They are represented by lots of the veins or series of spodumene pegmatites. The major mineral complexes composing the vein bodies are presented in Table 1. Of greatest interest is the Goltsovoye deposit in the northeastern side of the Urik-Iya graben.

**Goltsovoye deposit.** The geological structural scheme of the deposit is demonstrated in Fig. 3. The length of the field is equal to about 20 km, the area being of about 30 km<sup>2</sup>. The main structural elements those control the placement of the spodumene pegmatites are presented by large-scale geotectonic faults, of trust-fold and shear type with the northwestern spread and dip to the south-west at angles of 35–60° [27–30]. The pegmatites fill obliquely cutting and interstratal cracks therein. One of the major faults, wherealong vein bodies and vein series

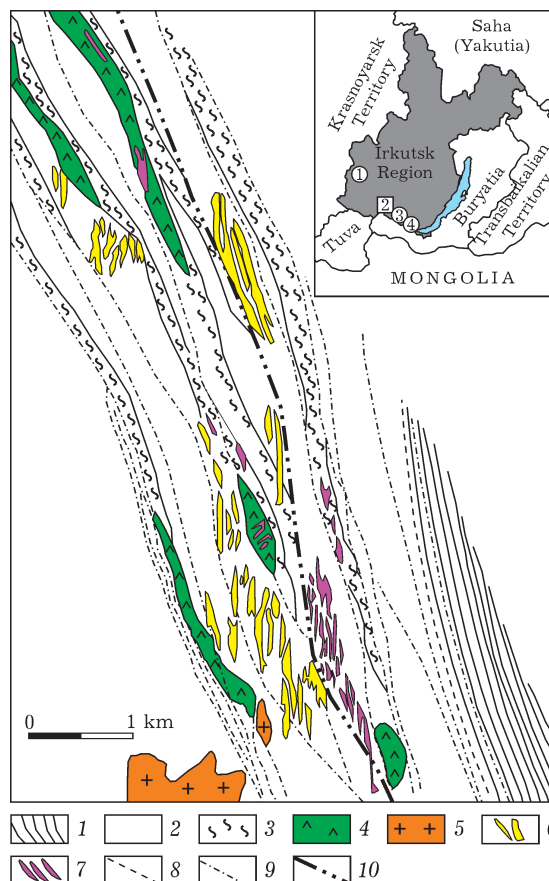


Fig. 3. Geological scheme of the southern part of the Goltsovoye rare-metal pegmatite field of the Eastern Sayan (compiled by A. G. Teremetskoy, V. E. Ryabenko, F. P. Chernukha *et al.* [30], amended and supplemented by V. M. Makagon [27]): 1 – Archean gneisses, 2 – biotite, muscovite-biotite, biotite-chlorite shale of Proterozoic age; 3 – amphibole shale, 4 – amphibolized gabbroids, 5 – granites and granodiorites, 6 – lithium pegmatites, 7 – cesium-tantalum-lithium (complex) pegmatites, 8 – regional fault, 9 – geotectonic faults, 10 – “The Main” fault, the inset demonstrates the geographical scheme of arranging the main lithium deposits of the Irkutsk Region: 1 – Vishnyakovskoye deposit, 2 – Goltsovoye deposit, 3 – Belorechensk deposit, 4 – Urik deposit.

are arranged forming a narrow band, is divided by a pegmatite field into the Eastern and Western geotectonic structural blocks.

In the Western block, there are separately located pegmatite veins, with a plate-like, lens-like beads-like shape explored, whose length amounts up to 1.5 km with the thickness up to 30 m in bulges. The Eastern block is characterized by the series of many vein bodies with complicated shape; those are repeatedly connecting and branching, with bulges and numerous apophyses. The total thickness of the pegmatite vein series amounts up to 100–140 m, the length of those ranges within 2–2.5 km. The

TABLE 1

Mineral complexes of spodumene-pegmatite deposits in Siberia

Deposits	Mineral complexes	Li <sub>2</sub> O content, mass %
<i>Eastern Transbaikalia</i>		
Zavitino	Fine-grained quartz-albite («white aplite»)	0.04–0.06
	Fine-grained quartz-spodumene-albite («gray aplite»)	0.38–2.21
	Uneven-grained spodumene-(±potassium feldspar, muscovite)-quartz-albite (properly pegmatite)	1.10–2.78
	Quartz-spodumene	up to 3.90
<i>Eastern Sayan</i>		
Goltsovoye	Coarse-grained albite-quartz-spodumene-microcline	0.81–2.66
	Fine-grained microcline-spodumene-quartz-albite	0.97–2.26
Urik	Coarse-grained albite-quartz-spodumene-microcline	1.24–2.69
	Coarse-grained quartz-albite-spodumene with tourmaline	up to 3.62
Belorechensk	Small-block microcline with tourmaline-quartz-spodumene-albite with muscovite	1.65–1.94
	Large-block quartz-albite-spodumene microcline	2.44–2.58
	Small-block petalite with microcline	up to 4.28
<i>Sangilen Highland (Tuva)</i>		
Tastyg	Small-medium-grained potassium feldspar-quartz-spodumene-plagioclase	1.2–2.5
	Fine-grained plagioclase-quartz-spodumene	2.5–4.3
Sutlug	Small-medium-grained potassium feldspar-quartz-spodumene-plagioclase	1.4–3.0
Shuk-Byul	Medium-grained potassium feldspar-quartz-spodumene-plagioclase	1.3–2.3
	Fine-grained plagioclase-quartz-spodumene	2.3–3.8
	Fine-grained quartz-albite-lepidolite with tourmaline	up to 1.7
<i>Altai Highlands and Mountain Shoria</i>		
Marmara	Aplite quartz-feldspar complex	0.08–0.39
(Tashelga)	Coarse-grained quartz-spodumene-potassium feldspar-albite with muscovite	0.022–2.24
Alakha*	Porphyry-like muscovite-spodumene-albite	0.24–1.46

\*Average content is presented.

explored sites with industrial mineralization level exhibit the area amounting to about 5 km<sup>2</sup> [27–31]. The characteristics of the mineral complexes are demonstrated in Table 1. The content of Li<sub>2</sub>O in spodumene amounts to 6.5–7.7 mass %. The Goltsovoye deposit is complex one, since contains in the industrial scale the reserves of tantalum, cesium and other trace elements.

**The Urik deposit** is located in the southeastern part of the Urik-Iya graben in the immediate vicinity of the Main Sayan fault. The length of the deposit is equal to 2 km, the width of that amounts to 500 m. The spodumene containing pegmatite veins exhibit a steep dip towards the south-west [27–31]. The characteristics of lithium-bearing structural-and-mineralogical complexes are presented in Table 1. The content of Li<sub>2</sub>O in spodumene ranges within 7.1–7.5 mass %.

**The Belorechensk deposit** is attached to the southwestern side of the Urik-Iya graben; it is divided into two sections such as the Belorechensk one, with lithium pegmatites, and the Belsk one containing veins of lithium and tantalum-tin-lithium pegmatites. The Belorechensk deposit is attached to the submeridional zone of the fracture and collapse of metamorphic rocks. The length of the pegmatite veins is within the range of dozens to hundreds meters, in this case large veins are separate, whereas small veins form vein series. The largest lithium pegmatite vein of the Belorechensk site exhibits a northeastern spread and steep angles of incidence, the shape being irregular, plate-like with sharp knee-like bends. The vein exhibits a zonal structure, whereas the thickest zone is of small-block quartz-spodumene microcline albite composition amounts to about 75 % of



the total vein bulk, reaching the thickness of 40–50 m. In one of the veins of the site area there is the zone of petalite block pegmatite with microcline observed, whose the side is occupied by spodumene and eucryptite. The characteristics of lithium-bearing structural mineral complexes are presented in Table 1. The content of  $\text{Li}_2\text{O}$  in the spodumene of the Belorechensk deposit ranges within 6.7–7.0 mass %.

The available data concerning the geology of the lithium deposits of spodumene pegmatites and their technical and economic parameters distinctly indicate that the Eastern Sayan belt is promising for industrial development, whereas the field Goltsovoye is the best among the objects of geological and industrial type with respect to the geological and economic parameters. In Eastern Sayan, this field is situated in relatively favourable geographical conditions, thus it is almost ready for commercial development.

#### *Sangilen Highland (Tuva)*

**Southern Sangilen spodumene belt** of pegmatites exhibits a length of over 120 km, it is sublatitudinal oriented and clearly controlled by the getotectonic suture (Fig. 4). The belt involves several fields including the Khusun-Gol, Burcha, Tserigiin-Gol, Kachik ones. In these fields there are more than two dozen of the vein series of lithium-bearing rare metal pegmatites of all sizes. They are often located near large granite mountain ranges of the KysTarys complex of the early Paleozoic age [32]. The enclosing rocks represent Vendian-Cambrian carbonate and terrigenous carbonate. All the lithium-bearing pegmatites of the Southern Sangilen belt are of spodumene type. Along with a high lithium content (the first percentage), they tend to have a higher content of Ta, Nb, Sn, Be. The largest deposit of lithium pegmatites in this belt, the Tastyg deposit, involves several dozens of veins with the thickness ranging within 2–25 m surveyed to a depth of 700 m, with the length of its ore zone amounting up to 1000 m. The Kachik field involves two large-scale lithium pegmatite ore manifestations such as the Sutlug and Hartyn. The age of spodumene pegmatite from Tastyg deposit and of the Sutlug ore manifestation is equal to 483 and 494 million years old, respectively; this value

is close to the age of the granites of the KysTarys complex [32, 33].

In the central part of the Sangilen Highland there is the Solbelder field of rare-metal pegmatites located, attached to the system of deep faults (thrusts) of the Northwestern spread (see Fig. 4). There were revealed a number of the vein series of spodumene pegmatite with lithium specialization containing an increased amount of Li, Nb, Ta, Sn, Be, the largest of which is presented by the Shuk-Byul and Kara-Adyr deposits [32, 33]. The Shuk-Byul deposit involves more than ten veins forming a bulge with a Li-Cs-Ta-Sn-Be rare metal type mineralization in the apical part. Besides spodumene pegmatites, in the Solbelder field there are two vein series of albite-lepidolite-type rare-metal pegmatites enriched with B, F, Be, Li, Ta. This ore field has always been considered the northern branch of the Early Paleozoic Southern Sangilen pegmatite belt, however, according to new data; the Solbelder spodumene pegmatite field is much younger: the age of the Shuk-Byul and Kara-Adyr deposits is equal to 272 and 292 million years, respectively [32].

The most part of the spodumene pegmatites of the Sangilen Highland are attached to the delamination cracks in the enclosing rocks feathering the linear steeply dipping faults. They exhibit all the signs of intrusive origin and are grouped into the series of connivent subvertical tabular and (or) curved dikes with the length up to several hundred meters, with the thickness ranging from 1 to 25 m. A slightly pronounced zoning of their internal structure is caused by a prevailing development (up to 80 % by volume) of the quartz-spodumene-feldspar mineral complex, the ratio between minerals wherein is variable to a great extent. The only mineral that concentrates lithium in these rocks is presented by spodumene containing from 6.5 to 7.6 mass % of  $\text{Li}_2\text{O}$ .

With a fairly monotonous mineral composition of the rocks they are characterized by the texture heterogeneity that is manifested in the combination of fine-grained granite-aplite coarse-grained pegmatite varieties, among those the former are prevailing. According to the world practice, it is believed that the rich lithium mineralization is usually concentrated ex-



Fig. 4. Geological scheme of the distribution of Early Paleozoic granitic complexes and connected lithium pegmatites in the Eastern Sangilen (compiled by L. G. Kuznetsova and S. P. Shokalskiy basing on multiscale geological survey maps and predictive prospecting work [32]): 1, 2 – monometamorphic Naryn complex of the Tuva-Mongolia Mountain range (V-G<sub>1</sub>): 1 – carbonate and terrigenous carbonate strata; 2 – metaterigenous strata; 3–6 – intrusion fields of Early Paleozoic age: 3 – Tannuolskiy complex (C<sub>2</sub>); 4 – Argoliksiy, Sarkhoyskiy and Kys-Tarys complexes (O); 5 – Brenskiy complex (D<sub>1</sub>); 6 – Sangilen complex (D<sub>1</sub>); 7 – fault zones; 8 – areas of lithium pegmatite distribution, numerals on the scheme: 1–7 – largest manifestations of lithium pegmatite: Tastyg (1), Peachy-Tastyg (2), Burcha group (3), Sutlug (4), Hartyn (5), Kara-Adyr (6), Shuk-Byul (7); I–III – granite mountain ranges: Dzoz-Husun-Gol (I), Tumenchulu (II), Solbelder (III); the inset demonstrates the geographical arrangement of spodumene-pegmatite ore fields in territory of the Tyva Republic.

clusively in pegmatite mineral complexes, combined with the “empty” quartz-feldspar aplite. However, in the veins of pegmatite belts of the Sangilen there are just lithium-rich spodumene granite-like aplites and fine-grained mineral complexes widespread those are connected with a significant part of the reserves of lithium, whereas quartz-feldspar rocks without spodumene are either absent, or their fraction the total bulk of veins is negligible [34, 35]. The processes of autometasomatism therein are manifested to a very weak extent.

The results of petrological studies allowed us to explain these features. It was revealed that all of the spodumene granitoids of the Sangilen form an evolutionary series directed to a significant enrichment of rocks with lithium (up to 4.3 mass %), which could be caused by the specificity of the fluid regime such as the increased reduction level at a low activity of F, B, H<sub>2</sub>O [34, 35]. At the same time, the spodumene pegmatites of the Solbelderskoye field, unlike the spodumene pegmatites of the Southern Sangilen belt were formed at a higher flu-

id pressure (up to 5.8 kbar) being much stronger contaminated with a lime-carbonate material, especially in the vein series intruded into limestones [33].

Among the main factors determining the high lithium productivity of the spodumene pegmatites of the Sangilen Highland there are the following features: a) the veins are poor with a spodumene-free quartz-feldspar complex, and almost in the entire bulk they are composed of ore-bearing rocks; b) the veins do not exhibit the processes of autometasomatism (greisenization, albitization) those promote reducing the levels of lithium; c) the signs of exocontact changes in the enclosing limestone is expressed to a minimum extent, which indicates the absence of lithium carry-over from the veins; d) even in the indigenous outcrops the rocks are affected by weathering processes to an insignificant extent.

New data obtained concerning the geochemical features and different ages of the rare-metal-containing pegmatites of the Sangilen Highland are rather important for revealing the genetic links of rare-metal deposits widespread in this region, as well as for further economic developing them in the future. Particular attention should be paid to the Tastyg lithium spodumene pegmatite deposit comparable in scale, ore quality and reserves with the deposits of the Eastern Sayan rare-metal pegmatite belt. However, the transportation of ore species of the Tastyg is possible only through the territory of Mongolia, and solving the question would require for special intergovernmental agreements.

### *Mountain Shoria, Altai Highlands*

The lithium deposits and manifestations are attached here to the geological structures of the Altai accretion-collision system that was formed within the Devonian-Carboniferous periods within [36–38], and then experienced the effects of the plume in the Permian-Triassic periods [39–41]. The formation of rare-metal spodumene-pegmatite fields is dated both to the Devonian-Carboniferous events of collision of nature, and to the superimposed events of the plume nature. The composition of the Altai lith-

ium-bearing polychronal province involves pegmatite deposits of the Kalba-Narym zone of the Eastern Kazakhstan, as well as the ore manifestations of the Altai Highlands and the Mountain Shoria in Russia. The most abundant deposits are ones of the Eastern Kazakhstan; however they have been worked out to a considerable extent by now [7–10]. The ore-forming potential of the Mountain Shoria and the Altai Highlands is not demanded yet. The lithium deposits in the region (Marmara and Alakha deposits) are given by special attention in this article. The near Teletskoye Lake spodumene pegmatite belt [42] is located nowadays within the conservation area being not available for investigation.

**The Marmara (Tashelga) pegmatite field** is located in the Mountain Shoria 40 km south from the city of Mezhdurechensk (Kemerovo Region). This manifestation of pegmatites is located to most closely with respect to the cities of Krasnoyarsk and Novosibirsk and to the processing enterprises of lithium industry thereat. There are several factors those favour the organization of ore mining, such as the availability of roads suitable for heavy traffic, the proximity of the railway station. All this determines the urgency of the further detailed study of geology, mineral and chemical composition of the spodumene-pegmatite veins of the Tashelga District.

The pegmatite field is a part of the Tashelga-Mayzas ore cluster attached to the zone of the Kuznetsk-Alatau deep fault which dissects metamorphic rocks of the Tomsk ledge [43, 44]. The basic structural unit of the Tashelga-Mayzas ore cluster which includes the spodumene-pegmatite field is presented by the fragment of the zone of the Kuznetsk-Alatau deep fault (Fig. 5). It consists of the rocks of the Tashelga polymetamorphic complex those are presented to a considerable extent by the amphibolite and carbonate strata. The metamorphic rocks are intruded by small intrusions of basic and acidic composition. The granitic intrusions are considered the youngest geological formations of the region. The largest of their engresses are located to the east of the zone of the Kuznetsk-Alatau fault. There are the mountain range of granite-gneiss species and the granite-gneiss species of the Tomsk Permian-Tri-

assic age complex, as well as the mountain ranges of sub-alkaline granite and leucogranite species of the Porozhinskiy Triassic age complex distinguished. The age of spodumene pegmatites has been determined using an U–Pb method (SHRIMP II) from magmatic zircon of the Yurievsk vein to be equal to  $(407 \pm 13)$  million years [45]. Thus, the young granite species with the age of 211 million years [43, 46] cannot pretend to play a role of pegmatite generating bodies.

The composition of the pegmatite field involves oligoclase-microcline pegmatites with biotite, microcline-albite pegmatites with muscovite and microcline-albite pegmatites with spodumene. Figure 5 demonstrates that the most part of the pegmatite bodies is attached to the «carbonate» block of the Tashelga metamorphic complex. The «amphibolite» block breaks out only by biotite pegmatites, whereas the muscovite and spodumene pegmatites are completely localized in the carbonate rocks.

In the course of prospecting and exploration, five veins in the bedrock, and a great number of boulders on the slopes and in stream beds were found. There is a possibility of revealing and other bodies within the Marmara (Tashelga) field of spodumene pegmatites, too.

The bodies of spodumene pegmatite represent veins with the size greater than 200 m in spread, with a capacity of no more than 1.5 m. They exhibit structural and mineral zonation. The near-casing parts of veins exhibit an aplite structure; in the direction towards the axial part of the veins the aplite pegmatite is replaced by coarse-grained pegmatite which in the axial part of the vein enters into the zone of block feldspar or block quartz. Within the exocontact of veins, there is developed an intermittent zone of muscovite-quartz-biotite-plagioclase composition. Within one of the veins there is a facies transition from the muscovite pegmatite in the main part of the vein to the spodumene pegmatite in the bulges.

The main minerals of spodumene pegmatite are presented by nepertite potassium feldspar, plagioclase, quartz, muscovite and spodumene. The structural-and-textural features of the pegmatite mineral complexes indicate an extensive impact of dinamometamorphism. Quartz forms elongated grains with serrated

edges due to the cataclasis process. Feldspars are destroyed at the edges and rounded. In pegmatites there are garnet, apatite, columbite-tantalite, struverit, pyrochlore, cassiterite, uraninite, zircon present in the accessory amounts.

The compositions of lithium-bearing pegmatite mineral complexes of the Marmara (Tashelga) field are presented in Table 1. Most promising as Li-bearing ore one considers a coarse-grained spodumene-albite-quartz-microcline complex containing secondary muscovite. This complex composes the most of the bulk of pegmatite veins. The ore species of spodumene pegmatites contain 1.8 mass % of  $\text{Li}_2\text{O}$  on average. In the complexes of veins different in mineral composition, the content of lithium can vary from 0.02 to 2.2 mass %. The spodumene of the pegmatites studied exhibits a reduced content of  $\text{Li}_2\text{O}$  (5.9 mass %).

**The Alakha deposit** represents a specific geological object which is crucially different from the classic spodumene pegmatites of Siberia [47–49]. This deposit is presented by the Alakha stockwork of spodumene granite-porphyry species located in the south of the Altai Highlands (Figs. 6, 7). The age of the granite porphyry species established with the help of U–Pb and Rb–Sr isotope technique amounted to  $(201 \pm 1.5)$  million years [47]. The spodumene granite-porphyry species compose two intrusive bodies with a total area equal to  $0.4 \text{ km}^2$  at the southeastern flank of the Rakhmanovskiy granite mountain range ( $375 \pm 11$  million years [44]). Both bodies are most likely to represent a part of a single mountain range, whose bulk is located below the contemporary erosion shear. The main types of the rocks of the mountain range are presented by muscovite-spodumene-albite granite-porphyry species, muscovite-albite granite-porphyry species and albitites. The main bulk of the Alakha stockwork is composed of small- and medium-grained muscovite-spodumene-albite granite-porphyry species. The albitites are attached to the top of the apical part of the stem, wherein they are spatially aligned with the greisenized rocks of the frame. There are gradual transitions between the spodumene granite-porphyry species and albitites.

The ore species are of porphyry-like structure. Porphyry phenocrysts are presented by quartz (~30 %), albite (~35 %), potassium feldspar (~10 %),



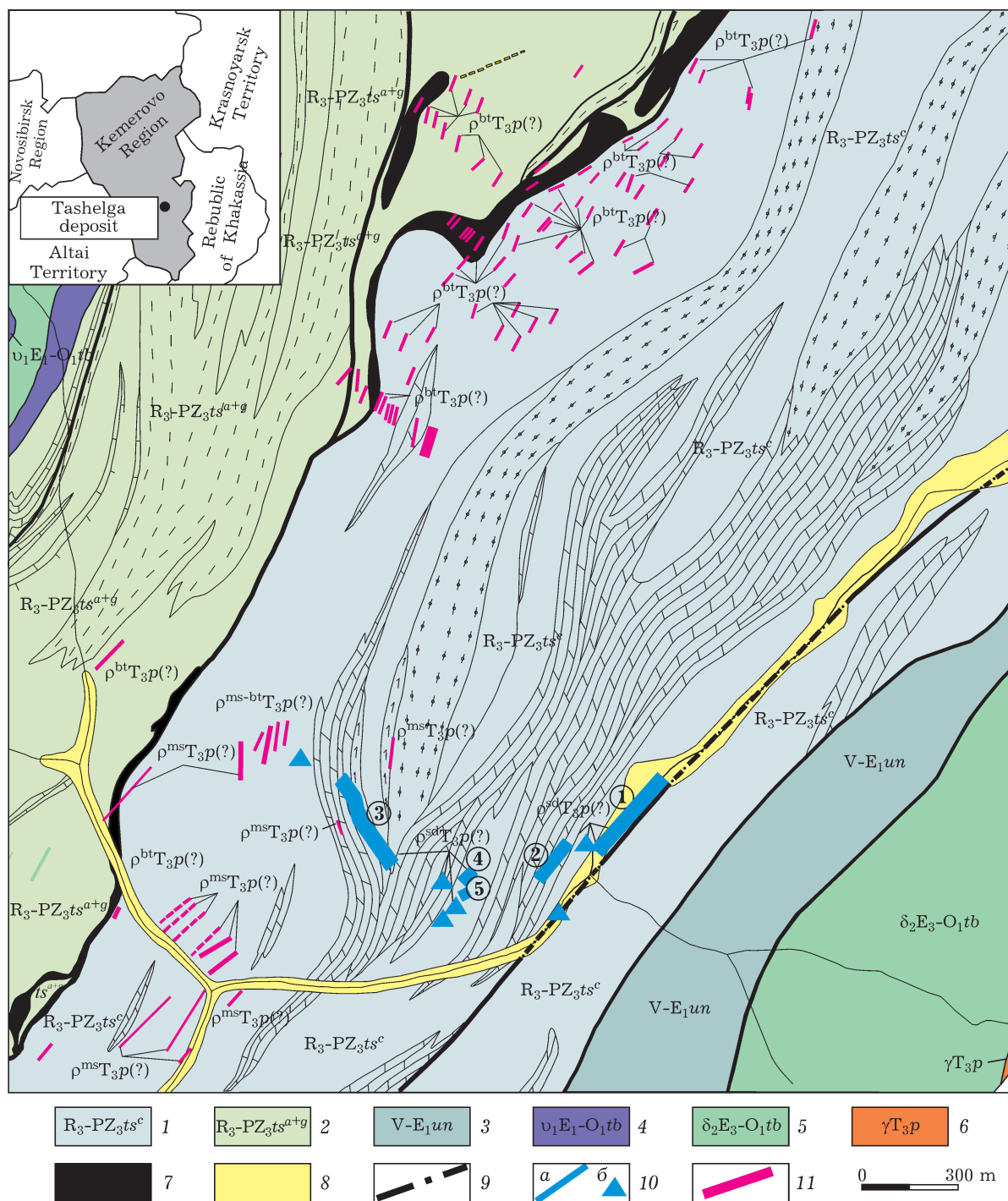


Fig. 5. Geological scheme of the Marmara (Tashelga) spodumene-pegmatite ore field in the Shoria Highlands (compiled by A. N. Uvarov, I. A. Lyapunov, A. A. Yuriev *et al.* [45] with amendments and supplements by S. Z. Smirnov, A. G. Vladimirov, P. D. Kotler, E. I. Mikheev, O. A. Gavryushkina [22]): 1 – carbonate subcomplex of the Tashelga polymetamorphic complex; 2 – amphibolite and migmatite-gneiss subcomplexes of the Tashelga polymetamorphic complex; 3 – Ust-Anzas trachyte-trachybasalt-basalt complex; 4 – gabbroids of the Teba gabbro-diorite complex; 5 – diorites of the Teba gabbro-diorite complex; 6 – granitoids of the Porozhinskiy subalkali granite-leucogranite complex; 7 – iron ore skarns; 8 – Quaternary alluvial deposits; 9 – the disjunctive faults of the Kuznetsk zone of the Alatau deep fault; 10 – the manifestations of spodumene-microcline-albite pegmatites (*a* – vein bodies opened by exploratory excavations, *b* – spodumene pegmatite boulders in dealluvial piles and river alluvium); 11 – the veins of spodumene-free of quartz-albite-microcline pegmatites with muscovite and biotite, numerals 1–5 in the figure indicate the following veins: Yurievskaya (1), Yubileynaya (2), Nikolayevskaya (3), Lyapunovskaya (4), Rodchenkovskaya (5); the inset demonstrates the geographical layout of the Marmara (Tashelga) ore field of spodumene pegmatites in the Kemerovo Region.

muscovite (~10 %) and spodumene (0–20 %). The bulk is composed of the blades of albite, xenomorphic quartz secretions, potassium feldspar and mica flakes. The spodumene in these rocks is developed unevenly. Its content varies within a very wide range from 3–4 to 18–20 %; in some cases, it is completely absent. Among the accessory and

secondary minerals there occur petalite, pollucite, apatite, pyrite, manganotantalite, manganokolumbite, bismuthine, much more seldom one can observe zircon, tourmaline, orthite, *etc.*

The main types of lithium ore at the Alakha deposit are presented by muscovite-spodumene-albite and muscovite-spodumene gran-

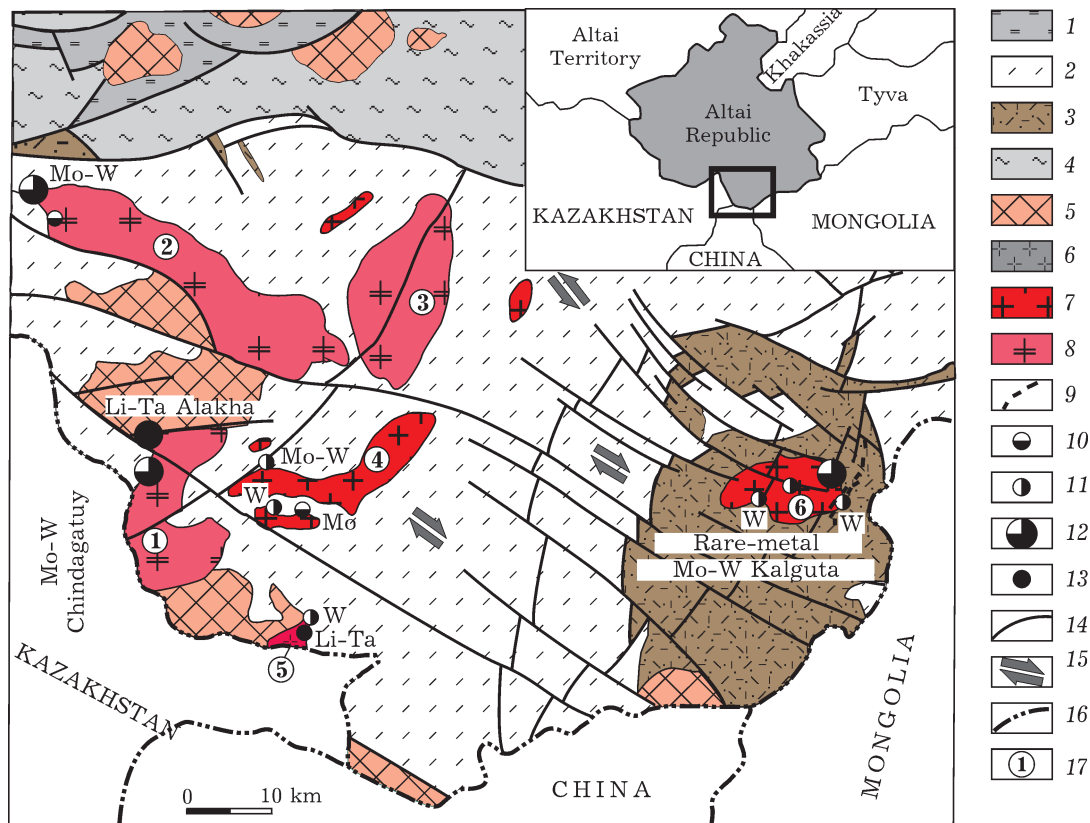


Fig. 6. Geological scheme of arranging the Early Mesozoic rare-metal granites, ongonites, elvans, spodumene granite-porphyry species and connected ore deposits in the southern part of the Altai Highlands (compiled by A. G. Vladimirov, V. I. Krupchatnikov, I. Yu. Annikova basing on multiscale geological survey maps and predictive prospecting work [50]): 1 – structural material complexes of the Vendian-Early Cambrian accretionary prism of the Altai Highlands; 2–4 – Holzun-Chuya terrane in the structure of the Altai-Mongolian microcontinent: 2 – a lower structural level presented by the turbidite strata of Early Paleozoic age; 3 – upper structural level presented by sedimentary-volcanogenic strata of the Middle Paleozoic age; 4 – collisional suture presented by the southern Chuya metamorphic complex ( $PZ_1$ :  $PZ_2$ ); 5 – Middle Paleozoic collisional granitoids with calc-alkaline composition within Holzun-Chuya terrane being monzonitoid within the Southern Chuya collisional suture; 6–10 – Early Mesozoic igneous complexes dated to the stage of intraplate orogeny: 6 – granite-leucogranites of the Kungur-Dzharin complex ( $T_2kg$ ); 7 – granite-leucogranites of the Kalguta complex ( $T_3-J_1kl$ ); 8 – granite-leucogranites of the Chindagatuy complex ( $J_1vk$ ); 9 – granite-porphyry species, elvans and ongonites of the Eastern Kalguta complex ( $J_1vk$ ); 10–13 – rare-metal hydrothermal and magmatogene ore manifestations and deposits: 10 – significantly molybdenum; 11 – significantly tungsten; 12 – molybdenum-tungsten; 13 – lithium-tantalum; 14 – Early Mesozoic faults of fault-overthrust nature; 15 – dominant kinematics of shears in various geoblocks; 16 – frontiers; 17 – mountain range numbers: 1 – Chindagatuy, 2 – Orochagan, 3 – Ak-Alakha, 4 – Tekekundeyskiy, 5 – Kungur-Dzharin, 6 – Kalguta; the inset demonstrates the location of the area under investigation.

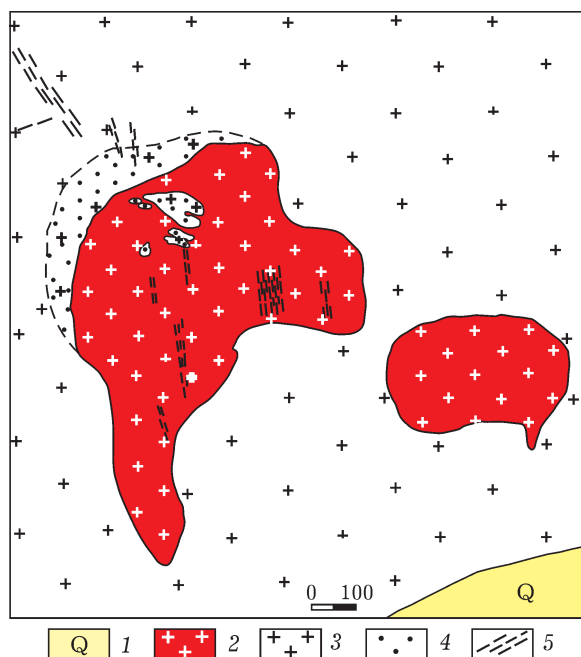


Fig. 7. Geological scheme of the Alakha deposit of spodumene granite-porphyry species, located in the southern part of the Altai Highlands (compiled by V. I. Timkin, V. S. Kudrin, O. D. Stavrov, T. N. Schuriga [48], amended and supplemented by A. G. Vladimirov and N. N. Kruk [49]): 1 – Quaternary sediments; 2 – spodumene granite-porphyry species of the Alakha stem,  $T = 201.5$  million years; 3 – enclosing quartzdiorite-granodiorite rocks of the Rakhmanovskiy complex,  $T = (375 \pm 11)$  million years; 4 – zones of greisenization; 5 – linear cataclase zones; for the geographical position of the Alakha deposit see Fig. 6.

ite-porphyry species (see Table 1). The content of  $\text{Li}_2\text{O}$  therein ranges within 0.24–1.46 mass % with the average value of  $\text{Li}_2\text{O}$  content equal to 0.98 mass %. In the muscovite-albite granite-porphyry species the  $\text{Li}_2\text{O}$  content ranges within 0.02–0.04 mass %. In albitites the  $\text{Li}_2\text{O}$  content is equal to 0.02 mass %.

The spodumene species of the Alakha stockwork demonstrates wide variations in the content of  $\text{Li}_2\text{O}$ , in a similar manner as the spodumene from the Tashelga pegmatite deposit, demonstrates decreased concentrations  $\text{Li}_2\text{O}$  (5.7–6.6 mass %). The highest content of  $\text{Li}_2\text{O}$  (6.2–6.6 mass %) is inherent in muscovite-spodumene varieties those compose the main bulk of the intrusive bodies.

The ore-forming potential of the Altai lithium-bearing province is still undervalued. It is necessary to continue the studies and to perform a comparative techno-economic analysis

concerning the geological data available and the quality of spodumene concentrates.

#### LITHIUM IN ELECTROCHEMICAL ENERGY ENGINEERING

Lithium metal and its compounds (cobaltite, ferrophosphate, etc.) are widely used in lithium electrochemical cells as cathode and anode materials, as well as in lithium ion conductors. Another promising area of lithium compounds application is connected with electrochemical generators (ECG) based on fuel cells with molten carbonate electrolyte (FECE) [51]. In such cells the anode and the cathode are separated by a space filled with an eutectic melt  $\text{Li}_2\text{CO}_3$ – $\text{K}_2\text{CO}_3$ , thickened with finely suspended gamma-lithium monoaluminate  $\gamma\text{-LiAlO}_2$ . The melt based on such a composition is called a matrix electrolyte cannot already leak. Another important function of the matrix electrolyte is connected with the fact that it does not allow “flooding” or “draining” the anode and the cathode, thereby providing the electsteme filling level with the melt electsteme within the range of 50 % of thickness. The second half of the porous electstememes should be filled with electroactive gases.

An electrochemical generator with 100 kW power requires for loading of about 100 kg of fine-dispersed gamma-lithium monoaluminate with the specific surface area greater than  $10 \text{ m}^2/\text{g}$ . The today's world need for highly dispersed  $\gamma\text{-LiAlO}_2$ , required for the operation of electrochemical generators based on FECE amounts to dozens tons per year. In the case of a widespread commercialization of such generators, the need for a highly dispersed gamma-lithium monoaluminate could increase by several orders of magnitude. Taking into account that in the electrochemical generators there is a significant amount of lithium carbonate besides lithium monoaluminate additionally used, the mentioned branch of the electrochemical energy engineering represents an attractive investment area for the application of lithium-containing compounds and materials in the long term.

These materials could be successfully produced at the processing enterprises located in Siberia.

The experimental studies have demonstrated that spodumene concentrates from pegmatite deposits of the Southern Siberia could be successfully used in order to produce double Li hydroxide and  $\text{Al}[\text{LiAl}_2(\text{OH})_6](\text{OH}) \cdot 2\text{H}_2\text{O}$  with the use of the technique presented in [52]. Using the double Li and Al hydroxide, employing the methods described in [53?55] one could perform the synthesis of single-phase gamma-lithium monoaluminate, whose dispersion level is acceptable for use as a matrix electrolyte in carbonate melt based fuel cells. The experiments have demonstrated that for the production of double lithium and aluminum hydroxide one could efficiently use spodumene concentrates from all known fields Southern Siberia as a raw material.

## CONCLUSION

1. The deposits of spodumene pegmatite in the Southern Siberia possess large-scale reserves of lithium raw materials; they could be characterized by a high quality of ore, which allows one consider them to be necessary and sufficient mineral raw material base in order to develop of the lithium industry in Russia (nuclear, electrochemical energy engineering, defense technology and other industries).

2. The ore species of the spodumene pegmatites of the Southern Siberia represent a promising raw material that could be used as a basis for the creation of new domestic technologies for obtaining lithium-containing materials, which, in turn, would promote the development of economically viable technologies for the electrochemical energy engineering.

3. The choice of investment-attractive ore objects depends on the economic and geological assessment, taking into account the geographical location of fields and deposits, the infrastructure, ore quality, novel technologies for processing the raw materials. The desirability of additional exploration, chemical engineering and audit work seems to be obvious in order to determine the areas with the richest lithium ore species in the Eastern Transbaikalia, the Eastern Sayan, Tyva, Mountain Shoria and the Altai Highlands. The most promising are the Goltsovoye, Belorechensk and Urik deposits of

spodumene pegmatite almost ready for the commercial development.

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