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Lithium Distribution in Proterozoic Sedimentary Rocks of the Southern Urals

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Abstract:

Introduction: Lithium is currently a critically important resource for high-tech industries. However, data on the Li content in the sedimentary rocks of the Southern Urals have not been provided. The limited understanding of lithium geochemistry in the Proterozoic sedimentary rocks dictates the need for detailed geochemical studies.The objective of this study was to determine the lithium distribution in the Proterozoic sedimentary rocks on the western slope of the Southern Urals and analyze the potential causes of enrichment.

Methods: Inductively coupled plasma atomic emission spectrometry (ICP-AES) was used to analyze sandstones, shales, and carbonate rocks.

Results: Two stratigraphic intervals of lithium enrichment were identified in the Proterozoic sedimentary rocks on the western slope of the Southern Urals: the Suran and Avzyan Mesoproterozoic formations. The maximum enrichment of this alkali element occurred in carbonate rocks, where Li concentrations reached 125–268 ppm, exceeding the Clarke value by 5–12 times on average. In the Avzyan Formation, lithium showed a strong positive correlation with chlorite content. In the Suran Formation, lithium was highly correlated with fluorine (r = 0.97) and rubidium (r = 0.93), indicating its association with F-bearing phlogopite. The highest lithium concentrations, reaching industrially significant levels of up to 0.1 wt.% Li_2O, were confirmed within the fluorite ore halo of the Suran deposit. Cryolithionite was the dominant lithium-bearing mineral, accounting for 0.1–7 wt.% of the bulk composition.

Discussion: The lithium enrichment in the sedimentary rocks of the Suran and Avzyan Mesoproterozoic formations resulted from sedimentation under near-evaporitic conditions, as well as the subsequent influence of postmagmatic fluids during epigenesis caused by the intrusion of gabbrodolerite dikes. These findings are significant for both regional metallogeny and the broader pursuit of lithium resources, highlighting the substantial potential of sedimentary rocks.

Conclusion: The sedimentary rocks of the Suran and Avzyan formations on the western slope of the Southern Urals have the potential to host economically significant lithium concentrations. Of particular interest are the host rocks of the Suran Formation in the vicinity of the Suran fluorite deposit.

Keywords: Lithium, Carbonate rocks, Mesoproterozoic, Suran formation, Avzyan formation, Western slope of the Southern Urals.

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1. INTRODUCTION

In recent decades, lithium has become the focus of interdisciplinary research, including studies in geology, mining technology, and economics [1-8]. Due to the development of high-tech industries, including the production of electric vehicle batteries, portable electronics, and energy storage systems, the metal has rapidly become one of the most in-demand resources [9-11]. Global consumption of lithium in 2024 was estimated to be 220,000 tons, marking a 29% increase from 2023 [12]. Demand is projected to increase by 20–30% annually due to the global green-energy transition [13]. The majority of global lithium consumption (87%) is allocated to battery production, with the remainder used in ceramics, glass, lubricants, medicine, and other industries [12]. According to a report by the IEA [14], the global demand for lithium batteries is expected to grow thirtyfold by 2030 and more than a hundredfold by 2050 compared to 2020.

While lithium is relatively abundant in the Earth's crust (Clarke of carbonate rocks is 5 ppm, sandstones 15 ppm, shales 66 ppm [15]), mining poses significant challenges [16]. Over 90% of the Earth's total lithium resources are contained in oceans and seawater, currently unsuitable for mining. The measured and indicated global lithium reserves for 2025 are estimated to be about 115 million tons [12]. Half of these reserves, as salar brines, are contained in the so-called “Lithium Triangle” - comprising Argentina (23 million tonnes), Bolivia (23 million tonnes), and Chile (11 million tonnes) [17]. However, lithium extraction from salar brines requires large volumes of water and poses substantial environmental risks [18, 19]. The most significant deposits of lithium-bearing pegmatites [20, 21] are located in Australia and China, with reserves estimated at 8.9 million tons and 6.8 million tons, respectively [12]. Their primary advantage is the high lithium concentration, while their disadvantages include limited resource availability; only a small fraction hosts economically relevant lithium mineralization. In addition, the complexity of the lithium ore beneficiation process from these ores has ;ade scaling production more difficult [1, 22].

An important strategy for sustainable lithium supply is the development of closed-loop technologies, particularly lithium recycling from spent batteries [23-25]. Recycling is projected to meet only about 5% of global lithium demand by 2035 (25% by 2050) [13]. However, the current battery recycling capacity is insufficient to meet the projected demand [26]. Additionally, it requires the improvement and scaling of extraction technologies and the development of efficient waste collection infrastructure [27, 28].

According to the USGS [12], estimated lithium reserves in Russia stand at 1 million tons. Greisenized granites were once the major source of lithium in the world, but are now only being mined in southeastern Russia [29]. In reality, the resources in Russia are much larger; proven mineral reserves amount to at least 1.65 million tons, while predicted hydromineral resources reach 4.2 million tons at the Znamenskoye deposit alone [4, 8, 30]. Taken together, this puts Russia in 5th place worldwide, on par with China and Australia. This is crucial for strengthening Russia's resource base amid the energy transition [31]. At the same time, supply shortages, coupled with advances in mining technologies, are driving interest in untapped resources in unconventional deposit types.

In detailed studies of the Southern Urals examining the geochemical behavior of most trace elements in the Proterozoic sedimentary rocks [32-35], data on lithium content were not addressed. This is partly due to the fact that most of the studies in the region during the last century were performed using semi-quantitative spectral analysis, which underestimates lithium concentrations in rocks by 1.5–2 times compared to quantitative determination, for example, flame emission analysis [36]. Recent studies on trace element distribution in the Proterozoic rocks are based on modern analytical techniques related to inductively coupled plasma: mass spectrometry (ICP-MS) [37-40] and atomic emission spectroscopy (ICP-AES) [41-43]. A review of the results from these recent studies, conducted with contributions from one of the present article’s authors [44], showed that in the Southern Urals there are two stratigraphic intervals of lithium enrichment in sedimentary rocks, in which the Suran and Avzyan (Kuzha) Mesoproterozoic formations exceed the Clarke value by 2–8 times. At the same time, the established dependencies were based on limited data, and the poor understanding of lithium geochemistry in the Proterozoic rocks of the Southern Urals underscores the need for further geological and geochemical research in this area.

In comparison to earlier studies [41-43], the authors have obtained new geochemical data from over 350 samples of sandstones, shales, and carbonates from various Proterozoic formations on the western slope of the Southern Urals (Fig. **1**). The study focuses particularly on lithium-enriched sedimentary rocks of the Suran and Avzyan (Kuzha) formations, which account for approximately half of the analyzed samples. This article presents these new results alongside previously published data from other researchers. The study aims to determine the lithium distribution in the Proterozoic sedimentary rocks of the western slope of the Southern Urals and to explain the possible causes of lithium accumulation in the Mesoproterozoic. The authors seek to answer the question of whether the described sediments could be promising for detecting elevated lithium concentrations.

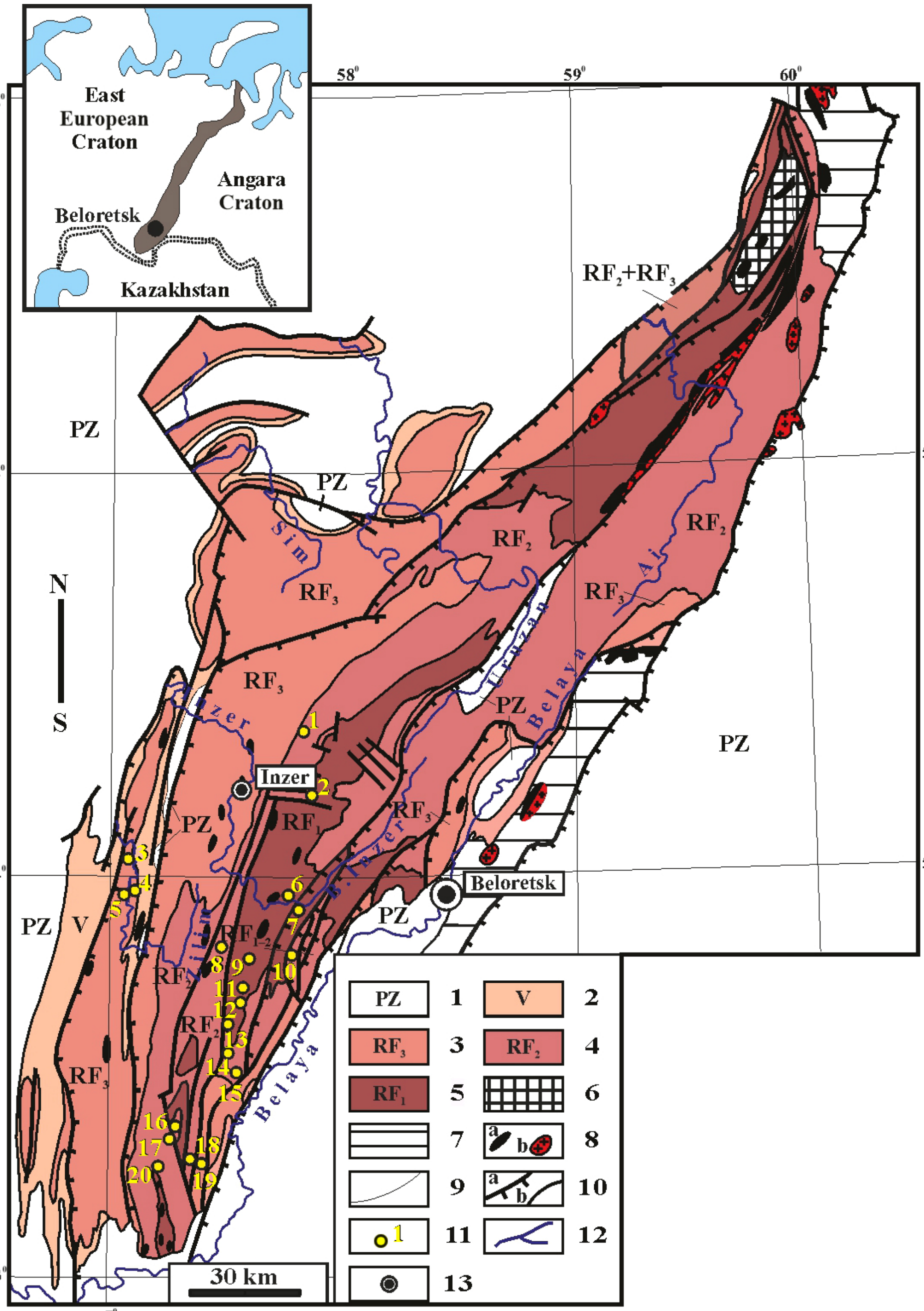

Fig. (1). Schematic geological map of the Bashkirian uplift on the western slope of the Southern Urals according to a previous study [45] (with additions), showing the locations of the studied sections.

1-5 – undivided deposits: 1 – Paleozoic (PZ), 2 – Vend (V), 3 – upper (RF_3), 4 – middle (RF_2), 5 – lower (RF_1) Riphean; 6 – Taratash metamorphic complex; 7 – Uraltau and Ufaley metamorphic complexes; 8 – igneous rocks: gabbro (a) and granites (b); 9 – geological boundaries; 10 – main tectonic disturbances: a – thrusts; b – faults; 11 – studied sections of various formations and section numbers (Neoproterozoic formations: Minyar – 3 (on the river Zilim near the Tolparovo village); Inzer – 4 (on the river Zilim); Katav – 5, 19: 5 – on the river Zilim, 19 – in the Aktash region. Mesoproterozoic formations: Avzyan – 1, 8, 15: 1 – on the river Tyulmen, 8 – near the Tukan village, 15 – near the Verkhny Avzyan village; Kuzha – 16, 17, 18, 20: 16 – on the river Tanasitkan, 17 – near the Islambaevo village, 18 – in the Aktash region, 20 – on the river Allakuyan; Zigazino-Komarovo – 14, 15: 14 – on the river Bolshoy Avzyan, 15 – near the Verkhny Avzyan village; Suran – 2, 7, 10, 13: 2 – near the Bagaryshta village, 7 – host rocks of the Suran deposit on the river Suran, 10 – on the river Kuporda, 13 – near the Ismakaevo village; Paleoproterozoic formation: Bolsheinzer – 6, 9, 11, 12, 13: 6 – on the river Bolshoy Inzer, 9 – near the Bzyak village, 11 – borehole 31, 12 – borehole 26, 13 – near the Ismakaevo village, boreholes 18 and 21); 12 – rivers; 13 – settlements.

2. STRATIGRAPHY OF THE PROTEROZOIC SEDIMENTS OF THE SOUTHERN URALS

Stratigraphy of the Proterozoic sediment of the Bashkirian uplift, located on the western slope of the Southern Urals, is shown in Fig. (**2**). The distribution area of these sediments within the Bashkirian uplift covers approximately 15,000–20,000 km^2 [34]. The total thickness of the Proterozoic sediment in the Bashkirian uplift exceeds 12 km, with sedimentation occurring from approximately 1750 to 660 Ma. According to the ISC [44-47], this age interval corresponds to the Paleoproterozoic, Mesoproterozoic, and Neoproterozoic, and according to the GSCR [48], to the Lower, Middle, and Upper Riphean (Fig. **2**). Figure **1** shows the boundaries of the Burzyanian, Yurmatinian, and Karatavian stratons in accordance with the GSS.

In the northern and central parts of the Bashkirian uplift, the Proterozoic stratotype formations include Ai (volcanogenic-sedimentary), Satka (terrigenous-carbonate), Bakal (carbonate-terrigenous), Mashak (sedimentary-volcanogenic), Zigalga (sandstone-dominated), Zigazino-Komarovo (terrigenous), Avzyan (terrigenous-carbonate), Zilmerdak (terrigenous), Katav (limestone-dominated), Inzer (terrigenous-carbonate), Minyar (carbonate-dominated), and Uk (terrigenous-carbonate). The thicknesses of these formations are shown in Fig. (**2**). In the central and southern parts of the Bashkirian uplift, stratigraphic facies analogues have been identified for the Paleo- and Mesoproterozoic Ai, Satka, Bakal, and Avzyan formations, which correspond to the Bolsheinzer, Suran, Yusha, and Kuzha formations, respectively.

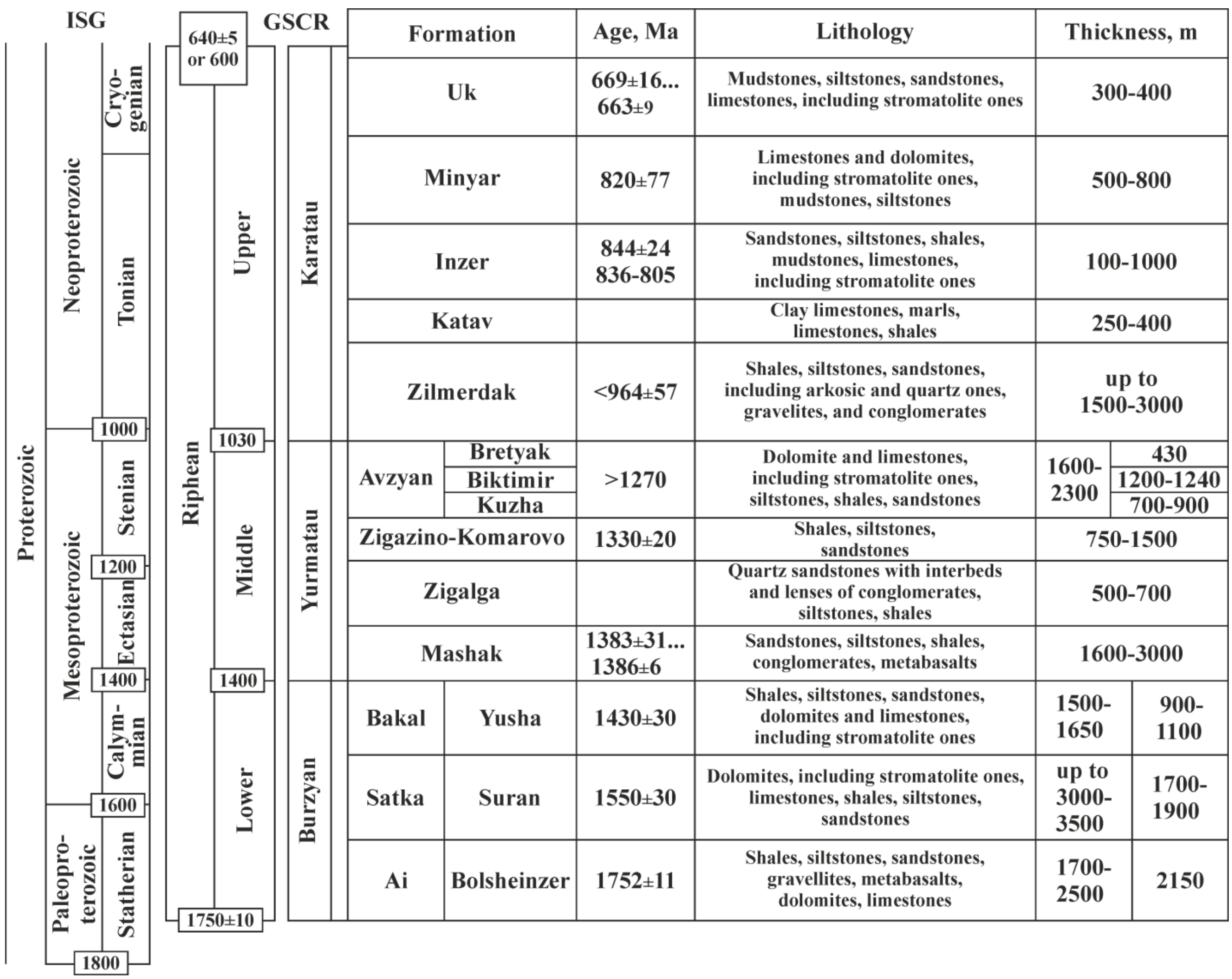

Fig. (2). The generalized Proterozoic sequence of the Bashkirian uplift on the western slope of the Southern Urals, according to a previous study [46] (with additions).
Ages are given as per recent studies [46, 49-51].

The terrigenous rocks of the Bashkirian uplift sediments are predominantly represented by sandstones, siltstones, and shales (occasionally mudstones), with rare low-thickness interlayers of gravellites and conglomerates. The carbonate sediments consist of limestones and dolomites.

3. MATERIALS AND METHODS

A total of 20 outcrops from 8 different formations were studied in the central, western, and southern parts of the Bashkirian uplift (Fig. **1**). These outcrops were found along riverbanks and were exposed during the construction of highways, including: Minyar – 1, Inzer – 1, Katav – 2, Avzyan – 3, Kuzha – 4, Zigazino-Komarovo – 2, Suran – 4, and Bolsheinzer – 5. Core samples for the study were also taken from 4 boreholes (No. 18, 21, 26, 31), which were drilled through Bolsheinzer formation sediments in 2003–2006 (Fig. **1**, numbers 11–13). Along with limited samples from our previous studies [42-44], this investigation analyzes a total of 403 samples: sandstones (66), shales (74), and carbonate rocks (263).

ICP-AES analysis for major elements (Na, Mg, Al, P, Ca, Ti, Mn, Fe) and trace elements (Li, Sc, V, Cr, Co, Ni, Cu, Zn, Sr, Y, Zr, Pb) was carried out on an ICPE-9000 (Shimadzu, Japan) spectrometer at AO INKhP (Joint-Stock Company Institute of Petroleum Refining and Petrochemistry), Ufa (analysts A.M. Karamova and Z.R. Biktimerova), following the technique of Musina and Michurin [52]. The ICP-AES method was selected for this study due to its ability to provide rapid, precise, and accurate multi-element data. The detection limits of the method are sufficient for the quantitative determination of lithium and associated elements in the studied sedimentary rocks. Compared to ICP-MS, this method is less dependent on the matrix element content in the analyzed solution (up to 1–2 vol.% or higher). It is reliable and cost-effective for analyzing large numbers of samples. Potential spectral interference was minimized through the selection of alternative analytical wavelengths and the application of background correction algorithms. Calibration curves were constructed using multi-element and single-element standard solutions produced by High-Purity Standards (USA).

To ensure measurement accuracy, CRMs of rocks were used: sandstone SA-1, carbonate-silicate loose sediments SGHM-1 and SGHM-3, carbonates SI-1, SI-2, and SI-3, produced by the A.P. Vinogradov Institute of Geochemistry of the Siberian Branch of the RAS (Russia). Both the studied rock samples and CRMs were decomposed in open Teflon vessels using a stepwise acid treatment with HF, HNO_3, $HClO_4$, and HCl. The acid treatment was carried out at temperatures of 70–150°C for 20 hours until a dry residue was obtained. The chlorides were converted to nitrates and diluted to the required volume with 15 vol.% HNO_3. The detection limit of the method was 0.1 ppm; the sample weight was 0.10–0.25 g.

4. RESULTS AND DISCUSSION

4.1. The lithium concentrations in the Proterozoic formations of the Southern Urals

The data obtained by the authors of this article on the lithium content in sedimentary rocks from the Proterozoic formations of the western slope of the Southern Urals are presented in Table **1**. The results of these data, along with previously published research [36-43], are graphically displayed in Fig. (**3**).

Table 1. The average, minimum, and maximum lithium content (in ppm) in the Proterozoic formations of the western slope of the Southern Urals.

Formations	Sandstones	Shales	Carbonates
Minyar	–	–	**2.3±2.9** 0.0-23.4 (n=27)
Inzer	–	–	**1.1±1.3** 0.0-7.6 (n=29)
Katav	–	–	**10.9±7.6** 0.0-33.6 (n=36)
Kuzha	**13.9±3.2** 9.7-16.3 (n=4)	**29.3±28.0** 8.3-103.6 (n=10)	**7.4±8.4** 0.0-38.2 (n=30)
Avzyan	–	**52.1±38.4** 12.1-221.2 (n=33)	**60.0±57.1** 0.0-267.5 (n=58)
Zigazino-Komarovo	**9.3±5.8** 4.9-19.2 (n=8)	**21.9±2.9** 20.0-25.3 (n=3)	**5.9±1.6** 4.1-7.5 (n=4)
Suran	–	**87.5±101.8** 15.4-302.5 (13)	**25.1±32.9** 0.0-125.2 (n=41)

(Table 1) contd.....

Formations	Sandstones	Shales	Carbonates
Bolsheinzer	7.6±7.2 0.0-33.0 (n=54)	43.1±14.6 5.0-65.1 (n=15)	11.4±13.9 0.0-39.0 (n=38)

Note: The numerator shows the average value and standard deviation; the denominator shows the range of values. n — the number of analyzed samples — is shown in parentheses. A dash (−) indicates no data available.

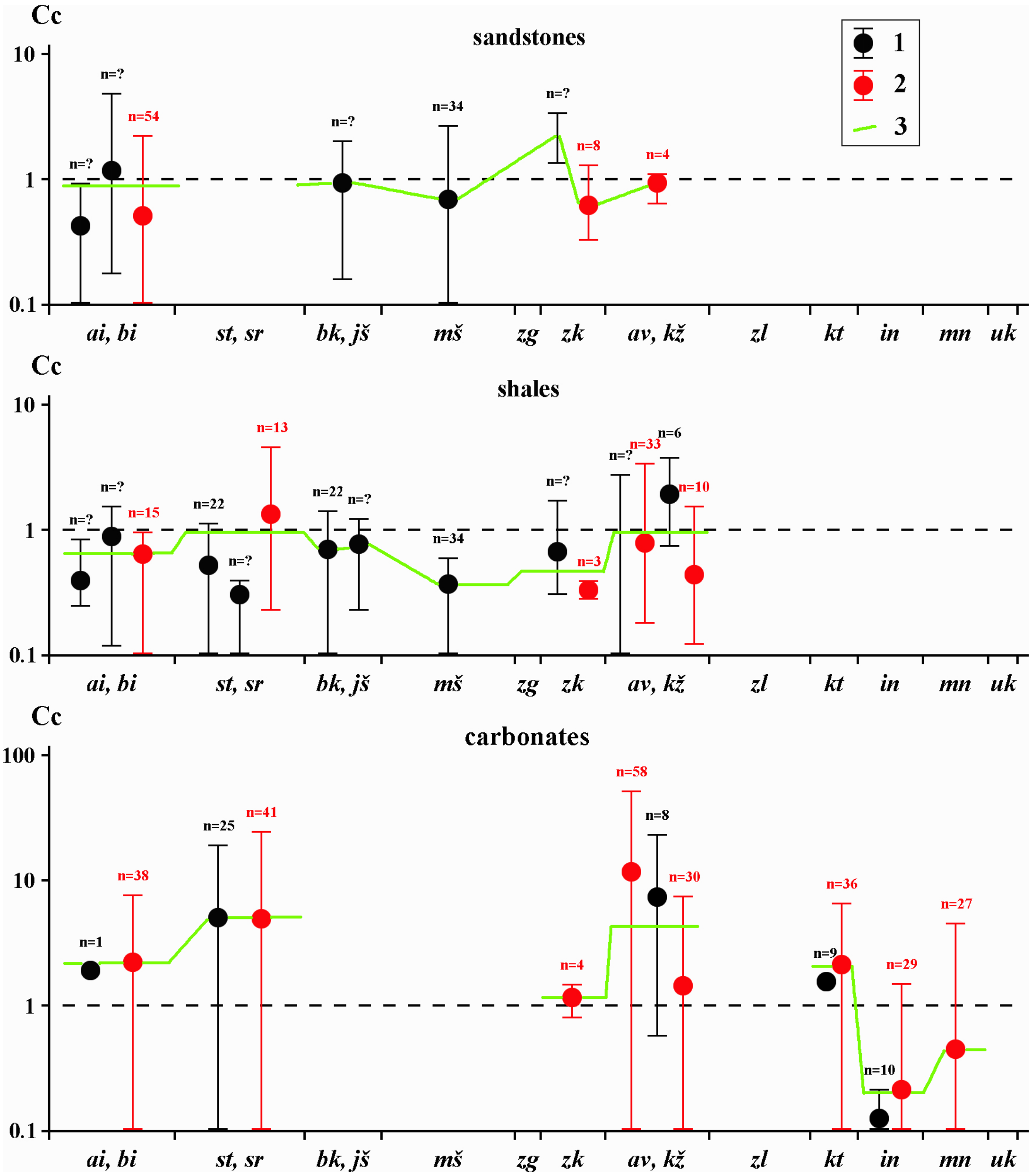

Fig. (3). Variations in lithium concentration coefficients in the Proterozoic formations of the western slope of the Southern Urals.
Cc – concentration coefficient of lithium. Cc is calculated as the ratio of the average lithium content in the lithological rock type (sandstones, shales, carbonates) to its Clarke value according to [15]. 1 – calculated Cc values based on data from the literature [36-43]; 2 – calculated Cc values based on data from the present study (see Table **1**); 3 – trend line showing the variation of average Cc values across formations. Circles show the average Cc values. The vertical range bars indicate the minimum and maximum Cc values. n – the number of analyzed samples. Abbreviations of formation names: *ai* – Ai, *bi* – Bolsheinzer, *st* – Satka, *sr* – Suran, *bk* – Bakal, *jš* – Yusha, *mš* – Mashak, *zg* – Zigalga, *zk* – Zigazino-Komarovo, *av* – Avzyan, *kž* – Kuzha, *zl* – Zilmerdak, *kt* – Katav, *in* – Inzer, *mn* – Minyar, *uk* – Uk. The differing distances on the horizontal axis correspond to the stratigraphic thickness of each geological formation (Fig. **2**). Formations *ai-bi*, *st-sr*, *bk-jš,* and *av-kž,* grouped closely together, are stratigraphic analogues.

The research results on the western slope of the Southern Urals demonstrate elevated lithium concentrations in the following Proterozoic formations: 1) Bolsheinzer ($Cc_{carbonates}$=2.3); 2) Suran (Cc_{shales}=1.3; $Cc_{carbonates}$=5.0); 3) Zigazino-Komarovo ($Cc_{sandstones}$=2.4 (?); $Cc_{carbonates}$=1.2); 4) Avzyan (Cc_{shales}=1.4; $Cc_{carbonates}$=12.0); 5) Kuzha (Cc_{shales}=1.9; $Cc_{carbonates}$=7.6); 6) Katav ($Cc_{carbonates}$=2.2). At the same time, the concentration coefficients of average lithium content in the shales of the Suran, Avzyan, and Kuzha formations range from 1.3 to 1.9, and in carbonates from 5.0 to 12.0, which indicates the maximum concentration of this element in these formations, as well as lithological control and significantly greater enrichment in carbonate rocks compared to terrigenous ones. A similar pattern is observed for the Bolsheinzer formation, where elevated lithium concentration coefficients are recorded in carbonates compared with the lower-clarke content of sandstones and shales. For sandstones of the Zigazino-Komarovo formation and shales of the Avzyan formation, the data (Fig. **3**) were sourced from [40], providing only the range of obtained values without indicating the number of analyzed samples and their average values. In this case, we compared the average value of the established variations with the clarke value, which is not entirely correct for understanding the real distribution of lithium. Consequently, the current data cannot reliably determine the enrichment levels in rocks of the Zigazino-Komarovo formation. The obtained data confirm the stratigraphic confinement of enriched intervals to the Suran and Avzyan (Kuzha) Mesoproterozoic formations.

It should be noted that a comparative analysis of lithium behavior in Mesoproterozoic sedimentary formations of various regions of the world faces certain challenges. These are primarily due to the limited amount of published geochemical data [53]. For example, a recent study [54], provided data on the average lithium content in greywackes only for Mesoproterozoic sediments of China as a whole. While in another recent review [55], focused on lithium metallogeny in Europe throughout the Earth's evolution, the time interval from 1800 to 1140 Ma was not considered. However, these researchers demonstrate in their global review that exogenous processes in Paleo- and Neoproterozoic sedimentary formations can lead to significant lithium enrichment.

4.2. Reasons for lithium enrichment in the Proterozoic formations of the Southern Ural

Possible reasons for lithium enrichment in the sedimentary rocks of the identified stratigraphic intervals are its endogenic input due to magmatic and hydrothermal activity and/or the primary enrichment of sediments of the Suran and Avzyan (to a lesser extent, possibly the Bolsheinzer and Katav) formations, which accumulated under conditions close to evaporitic sedimentation. Lithium enrichment in the host sedimentary rocks of the Avzyan and Kuzha formations, which are intruded by magmatic bodies (gabbro-dolerite dikes), supports an endogenic source. For example, in the section on the Tyulmen River (Fig. **1**, outcrop number 1), three gabbro-dolerite dikes intrude the dolomite host rocks of the upper part of the Avzyan formation [43]. In this section, the lithium concentration in carbonate rocks increases toward the contacts with the dikes, reaching peak values of 267.5 ppm, with an average content of 84.5 ± 46.4 ppm (n = 34). At the same time, changes in the geochemical and crystallochemical characteristics are observed in the dolomites due to the influence of postmagmatic fluids [56]. In contrast, lithium enrichment is typically absent in the sedimentary rocks of the Kuzha Formation where dikes are not present. For example, in the dolomite section near Islambaevo village (Fig. **1**, outcrop number 17), the average lithium concentration is 3.4 ± 2.7 ppm (n = 7), consistent with near-Clarke values.

The positive correlation between Li, F, and Mg, or between Li, F, Fe, and Mg (and possibly B), serves as evidence for a magmatic lithium source in enriched sedimentary rocks [57-59]. In the shales and carbonates of the Kuzha Formation, the observed co-enrichment of lithium and fluorine similarly indicates an endogenic source [36].

It is well known that felsic igneous rocks contain significantly higher lithium concentrations compared to mafic ones [15], and large deposits of this metal are often associated with them [20, 21]. At the same time, only dikes of mafic igneous rocks have been found in the studied sedimentary rock sections on the western slope of the Southern Urals. Recent studies have provided substantial evidence that mafic and intermediate igneous rocks in modern volcanic eruptions can also exhibit significant lithium enrichment [60-64]. However, it is currently difficult to unequivocally determine whether the lithium enrichment in the sedimentary rocks of the Suran and Avzyan formations is related to magmatic influence, given the limited available data on lithium content in magmatic complexes of various ages on the western slope of the Southern Urals [44, 65].

An alternative explanation is the primary lithium enrichment in the carbonate rocks of the Suran and Avzyan formations, possibly related to evaporitic sedimentation. Lithium compounds in evaporite basins precipitate during the late stages of evaporation. Host sediments contain 30–1500 ppm Li in closed-type basins and 20–150 ppm Li in open-type basins [66]. Large lithium deposits are known to occur in evaporites [17]. The most noteworthy of several lithium brine systems in China is Zabuye Lake in Tibet [58]. It is an evaporite basin where a lithium salt (Li_2CO_3) precipitates as part of the evaporite mineral sequence, and where there is no volcanism or hydrothermal activity [17].

The sedimentary carbonates of the Satka, Suran, Avzyan, and Kuzha formations are characterized by indicators of the former presence of evaporites [67-72]. Evaporitic sedimentation conditions during the Satka–Suran period are evidenced by the presence of gypsum crystals in the carbonate sediments of the Suran Formation [67], and by collapse breccias in the Satka

Formation, located at the same stratigraphic levels and formed through the dissolution of interbeds and nests of evaporite minerals [71]. In the fluorites of the Suran deposit, localized within the Suran Formation, high-salinity fluid inclusions and the correspondence of ore-forming brines to the evaporite trend have been established [72]. The study of various geochemical features of the fluorites showed that earlier generations of gray and violet fluorites precipitated from fluorine-enriched evaporitic brines, whereas green fluorites, formed through metasomatic replacement of earlier generations, had another fluorine source likely associated with granitoids [34, 72]. Gypsum pseudomorphs have been found in the dolomites of the Avzyan Formation [68], and large gypsum crystals with sulfur isotope characteristics of sedimentary origin have been found in the dolomites of the Kuzha Formation [70]. Thus, lithological and isotopic data confirm that sedimentation conditions during the Satka–Suran and Avzyan–Kuzha periods were close to evaporitic.

In general, it can be assumed that in the established stratigraphic intervals of the Southern Urals, the Li enrichment of sedimentary rocks was caused by two combined factors: sedimentation under near-evaporitic conditions, as well as the subsequent influence of postmagmatic fluids on sedimentary rocks due to the intruding of gabbrodolerite dikes. Lithium in deposits associated with evaporites is redistributed to varying degrees by hydrothermal activity, superimposed on primarily enriched sedimentary rocks in this metal [17, 55, 73].

4.3. Lithium-bearing minerals in the Proterozoic rocks of the Southern Urals

In the carbonate rocks of the Avzyan formation section on the river Tyulmen and near the Tukan village (Fig. **1**, outcrops numbers 1 and 8, respectively), and the intruding igneous rocks, lithium shows a direct correlation with chlorite content [43, 65]. It is known that lithium can replace Mg and Fe in chlorite to some extent [74], and most likely, lithium in the rocks on the River Tyulmen is associated with chlorite.

In carbonate rocks of the Suran formation near Bagaryshta village (Fig. **1**, outcrop number 2), lithium is most likely contained in phlogopite [41]. This is indicated by the significant presence of F-bearing phlogopite and strong positive geochemical correlations between F and Li (r=0.97) and between F and Rb (r=0.93). According to Shirobokova [36], lithium in rocks of the Kuzha ore field occurs in micas. As proof, the author of this study also demonstrates a high positive correlation between F and Li.

Elevated lithium concentrations have been established in carbonate-terrigenous sediments of the Suran formation, which hosts the Suran fluorite deposit [75]. Fluorides of the cryolite group, including ussingite ($Ba_2MgAl_2F_{12}$), pachnolite ($NaCaAlF_6 \cdot H_2O$), and particularly cryolithionite ($NaLi_3[AlF_6]_2$), play an important role in the structure of the near-ore halo. Diffraction studies have confirmed the presence of lithium-bearing minerals in 11 boreholes [75]. According to spectral analysis, the lithium oxide content reaches industrial values of 0.1 wt. %. Cryolithionite is the dominant lithium-containing mineral, accounting for 0.1-7 wt. % of the bulk composition.

4.4. Prospects for finding industrial lithium concentrations in the Proterozoic formations of the Southern Urals

The study shows that lithium-enriched sedimentary rocks of the Suran and Avzyan formations have prerequisites for hosting industrial concentrations of this alkali metal. From this perspective, the host rocks of the Suran formation and ores from the Suran deposit are of particular interest, as they contain independent lithium minerals and almost economic concentrations. Moreover, the patterns of lithium distribution in the rocks of the deposit have not yet been identified [75], and this issue requires focused attention in future studies.

The sediments of the Avzyan Formation, probably enriched during sedimentogenesis, may exhibit very high lithium concentrations in areas that were intensively exposed to magmatic fluids during epigenesis. Our studies show that lithium concentrations in the carbonate rocks of this stratigraphic level, where they are intruded by gabbro-dolerite dikes, exceed the Clarke value by 53.5 times.

5. STUDY LIMITATIONS

This study provides new insights into lithium enrichment in Proterozoic sedimentary rocks on the western slope of the Southern Urals. However, certain limitations should be considered. First, the interpretation of a magmatic source for lithium-rich fluids remains hypothetical due to incomplete geochemical data on magmatic complexes of various ages in the region. Second, evidence for evaporitic sedimentation conditions, which is crucial for the proposed primary enrichment model, is based on local lithological indicators, such as gypsum pseudomorphs and collapse breccias. Variability in the preservation and distribution of these indicators across the studied sections introduces uncertainty into the precise reconstruction of paleofacies and limits the universal applicability of this model to all formations.

Future research should focus on the quantitative assessment of the proposed genetic model of postmagmatic fluid interaction with evaporite-bearing sediments, which would test the hypothesis of lithium leaching and redistribution. In addition, isotopic data (*e.g.*, lithium, strontium, and magnesium) could serve as robust indicators to distinguish between the contributions of evaporitic brines and postmagmatic hydrothermal fluids, as well as to better constrain the lithium source and sedimentation conditions.

Finally, direct geochemical comparisons with other similar lithium-enriched Proterozoic sedimentary rocks worldwide are limited due to the scarcity of detailed published geochemical data. This limitation restricts the ability to fully compare our results with global conditions and to determine universal mechanisms for lithium enrichment in sedimentary rocks.

CONCLUSION

Two stratigraphic intervals of lithium enrichment have been identified in the Proterozoic sedimentary rocks of the western slope of the Southern Urals: the Suran and Avzyan Mesoproterozoic formations. The maximum enrichment of this alkali element occurs in carbonate rocks, where the average lithium concentration exceeds the Clarke value by 5–12 times, compared to terrigenous rocks, in which it exceeds the Clarke value by 1.3–1.9 times.

On the western slope of the Southern Urals, the identified stratigraphic intervals of lithium-enriched carbonate rocks in the Suran and Avzyan formations are characterized by indicators of evaporitic sedimentation, which may explain the presence of elevated lithium concentrations. However, the same studied sections clearly demonstrate the influence of postmagmatic fluids on lithium enrichment in the sedimentary rocks. Overall, our analysis suggests that lithium enrichment in the Satka–Suran and Avzyan–Kuzha intervals likely resulted from two combined factors: sedimentation under near-evaporitic conditions, and the subsequent influence of postmagmatic fluids on the sedimentary rocks due to the intrusion of gabbro-dolerite dikes. The combination of both factors likely makes the sediments of these formations particularly prospective for further exploration of lithium occurrences.

The presented data demonstrate that the Suran and Avzyan Mesoproterozoic formations on the western slope of the Southern Urals have the potential to host economically significant lithium concentrations. Of particular interest are the host rocks of the Suran Formation in the vicinity of the Suran fluorite deposit.

AUTHORS' CONTRIBUTIONS

The authors confirm their contributions to the paper as follows: S.V.M. and G.M.K.: Study conception and design; S.V.M. and Z.R.B.: Data collection; S.V.M., Z.R.B., and G.M.K.: Analysis and interpretation of results; S.V.M.: Draft manuscript;. All authors reviewed the results and approved the final version of the manuscript.

LIST OF ABBREVIATIONS

IEA	=	International Energy Agency
USGS	=	United States Geological Survey
ICP-MS	=	Inductively Coupled Plasma Mass Spectrometry
ICP-AES	=	Inductively Coupled Atomic Emission Spectroscopy
CRMs	=	Certified Reference Materials
ISC	=	International Stratigraphic Chart
GSCR	=	General Stratigraphic (Geochronological) Chart of Russia
GSS	=	General Stratigraphic (Geochronological) Scale

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data and supportive information are available within the article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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REFERENCES

[1] P.W. Gruber, P.A. Medina, G.A. Keoleian, S.E. Kesler, M.P. Everson, and T.J. Wallington, "Global lithium availability", *J. Ind. Ecol.,* vol. 15, no. 5, pp. 760-775, 2011. [http://dx.doi.org/10.1111/j.1530-9290.2011.00359.x]

[2] P.G. Kudryavtsev, and N.P. Kudryavtsev, "Lithium: resources, production and prospects of world market development", *Alternative Energ. Ecology (ISJAEE),* vol. 10-12, no. 10-12, pp. 70-81, 2018. [http://dx.doi.org/10.15518/isjaee.2018.10-12.070-081]

[3] A.V. Tkachev, D.V. Rundkvist, and N.A. Vishnevskaya, "Evolutional aspects of the lithium metallogeny: Productive epochs, mineral deposit types and their specific features", *Prospect. Protect. Min. Resource.,* vol. 9, pp. 10-18, 2018.

[4] G.Yu. Boyarko, V.Yu. Khatkov, and E.V. Tkacheva, "Lithium raw potential in Russia, Bulletin of the Tomsk Polytechnic University", *Geo Assets Engineering,* vol. 333, no. 12, pp. 27-16, 2022. [http://dx.doi.org/10.18799/24131830/2022/12/3975]

[5] Y.B. Mironov, A.M. Karpunin, and V.Z. Fuks, "Ages of formation and types of lithium deposits in foreign countries", *Regional Geolog. Metallog.,* vol. 92, no. 92, pp. 105-116, 2022. [http://dx.doi.org/10.52349/0869-7892_2022_92_105-116]

[6] J. Szlugaj, and B. Radwanek-Bąk, "Lithium sources and their current use", *Min. Res. Manag.,* vol. 38, no. 1, pp. 61-87, 2022. [http://dx.doi.org/10.24425/gsm.2022.140613]

[7] P. Lindagato, Y. Li, J. Macháček, G. Yang, I. Mungwarakarama, A. Ndahimana, and H.P.K. Ntwali, "Lithium metal: The key to green transportation", *Appl. Sci.* , vol. 13, no. 1, p. 405, 2022. [http://dx.doi.org/10.3390/app13010405]

[8] A.Y. Tsivadze, A.A. Bezdomnikov, and G.V. Kostikova, "The lithium boom: lithium sources and prospects for the russian lithium industry", *Geol. Ore Deposits,* vol. 65, no. 5, pp. 463-468, 2023. [http://dx.doi.org/10.1134/S1075701523050094]

[9] J. Sheets, "New lithium market", *Ceram. Eng. Sci. Proc.,* vol. 21, no. 5, pp. 97-99, 2000.

[10] M.G. Ktalkherman, V.A. Emelkin, and B.A. Pozdnyakov, "Production of lithium oxide by decompostion lithium carbonate in the flow of a heat carrier", *Theor. Found. Chem. Eng.,* vol. 43, no. 1, pp. 88-93, 2009. [http://dx.doi.org/10.1134/S0040579509010114]

[11] P. Christmann, E. Gloaguen, J-F. Labbé, J. Melleton, and P. Piantone, *Global lithium resources and sustainability issues in Lithium process chemistry: Resources, extraction, batteries and recycling.,* Elsevier, 2015, pp. 1-40. [http://dx.doi.org/10.1016/B978-0-12-801417-2.00001-3]

[12] B.W. Jaskula, "Geological Survey (USGS, 2025). Mineral commodity summaries: Lithium", Available from: https://pubs.usgs.gov/periodicals/mcs2025/mcs2025-lithium.pdf

[13] "Global EV Outlook", Available from: www.iea.org

[14] S. Bouckaert, "Net zero by 2050: A roadmap for the global energy sector",

[15] K.K. Turekian, and K.H. Wedepohl, "Distribution of the nlms in some major units of the Earth’s crust", *Geol. Soc. Am. Bull.,* vol. 72, no. 2, pp. 175-192, 1961. [http://dx.doi.org/10.1130/0016-7606(1961)72[175:DOTEIS]2.0.CO;2]

[16] S.E. Kesler, P.W. Gruber, P.A. Medina, G.A. Keoleian, M.P. Everson, and T.J. Wallington, "Global lithium resources: Relative importance of pegmatite, brine and other deposits", *Ore Geol. Rev.,* vol. 48, pp. 55-69, 2012. [http://dx.doi.org/10.1016/j.oregeorev.2012.05.006]

[17] L.A. Munk, S.A. Hynek, D.C. Bradley, D.F. Boutt, K. Labay, and H. Jochens, "Lithium brines: A global perspective", In: *Rare Earth and Critical nlms in Ore Deposits,* vol. 18. Society of Economic Geologists, 2016, pp. 339-365.Ed.14 [http://dx.doi.org/10.5382/Rev.18.14]

[18] D.C. Bradley, L.L. Stillings, B.W. Jaskula, L. Munk, and A.D. McCauley, "Lithium brines −A global perspective", In: *Reviews in Economic Geology,* Society of Economic Geologists, Inc., 2017, pp. 1-24. [http://dx.doi.org/10.5382/SP.18.01]

[19] V. Flexer, C.F. Baspineiro, and C.I. Galli, "Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing", *Sci. Total Environ.,* vol. 639, pp. 1188-1204, 2018. [http://dx.doi.org/10.1016/j.scitotenv.2018.05.223] [PMID: 29929287]

[20] R.L. Linnen, M. Van Lichtervelde, and P. Černý, "Granitic pegmatites as sources of strategic metals", *nlms (Quebec),* vol. 8, no. 4, pp. 275-280, 2012. [http://dx.doi.org/10.2113/gsnlms.8.4.275]

[21] D. London, "Ore-forming processes within granitic pegmatites", *Ore Geol. Rev.,* vol. 101, pp. 349-383, 2018. [http://dx.doi.org/10.1016/j.oregeorev.2018.04.020]

[22] J. Zhou, Q. Wang, H. Wang, J. Ma, G. Zhu, and L. Zhang, "Pegmatite lithium deposits formed within low-temperature country rocks", *Nat. Commun.,* vol. 16, no. 1, p. 447, 2025. [http://dx.doi.org/10.1038/s41467-024-55793-8] [PMID: 39779665]

[23] Z. Chen, T. Wang, H. Yu, J. Guo, H. Zhong, C. Hu, R. Zhao, and H. Chen, "Closed-loop utilization of molten salts in layered material preparation for lithium-ion batteries", *Front. Energy Res.,* vol. 8, p. 587449, 2021. [http://dx.doi.org/10.3389/fenrg.2020.587449]

[24] R. Liu, Y. Liu, J. Li, Y. Chen, Y. Zhu, K. Zhang, S. Zhao, L. Du, X. Zhu, and L. Zhang, "Closed-loop process for rapid and selective lithium extraction and resynthesis from spent LiFePO4 batteries", *Molecules,* vol. 30, no. 12, p. 2587, 2025. [http://dx.doi.org/10.3390/molecules30122587] [PMID: 40572549]

[25] Y. Xie, B. Ai, L. Yi, H. Hu, S. Yan, B. Mahara, L. Yang, X. Peng, and X. Chen, "Closed-loop process towards upcycling spent lithium-ion batteries via mechanochemical activated deep eutectic solvent extraction system", *ssrn,* 2025. [http://dx.doi.org/10.2139/ssrn.5319627]

[26] T.Y. Kim, "The role of critical minerals in clean energy transitions", Available from: www.iea.org

[27] J.B. Dunn, L. Gaines, J.C. Kelly, C. James, and K.G. Gallagher, "The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling’s role in its reduction", *Energy Environ. Sci.,* vol. 8, no. 1, pp. 158-168, 2015. [http://dx.doi.org/10.1039/C4EE03029J]

[28] E.A. Olivetti, G. Ceder, G.G. Gaustad, and X. Fu, "Lithium-ion battery supply chain considerations: Analysis of potential bottlenecks in critical metals", *Joule,* vol. 1, no. 2, pp. 229-243, 2017. [http://dx.doi.org/10.1016/j.joule.2017.08.019]

[29] G.J. Bell, and B.A. Beck, "Thompson Valley Lithium Project", Available from: https://ameriwestlithium.com/wp-content/uploads/2023/05/THOMPSON_VALLEY_43-101_Jan_2023.pdf

[30] E.A. Tolkushkina, M.V. Torikova, and M.F. Komin, "Lithium mineral resources: Development and use problems", *Explor. Raw Material. Base. Miner. Resur. Ross. Ekon. Manag.,* vol. 2, pp. 2-9, 2012.

[31] J.D. Graham, J.A. Rupp, and E. Brungard, "Lithium in the green energy transition: The quest for both sustainability and security", *Sustainability,* vol. 13, no. 20, p. 11274, 2021. [http://dx.doi.org/10.3390/su132011274]

[32] E.Z. Gareev, "*Geochemistry of sedimentary rocks of the stratotypic Riphean section: Abstract of Cand*", Geol.-Miner. Sci. (Rus.) Dissertation. – Moscow, 1989.

[33] L.V. Anfimov, *Lithogenesis in the Riphean sedimentary strata of the Bashkir meganticlinorium (Southern Urals)].,* UrO RAN: Ekaterinburg, 1997.

[34] A.V. Maslov, M.T. Krupenin, E.Z. Gareev, and L.V. Anfimov, *Riphean of the western slope of the Southern Urals (classical sections, sedimentation and lithogenesis, minerageny, geological natural monuments).,* IGG UrO RAN: Ekaterinburg, 2001.

[35] A.V. Maslov, A.D. Nozhkin, V.N. Podkovyrov, E.F. Letnikova, O.M. Turkina, D.V. Grazhdankin, N.V. Dmitrieva, M.V. Isherskaja, and M.T. Krupenin, *Geochemistry of finegrained terrigenous rocks of the Upper Precambrian of Northern Eurasia.,* UrO RAN: Ekaterinburg, 2008.

[36] T.I. Shirobokova, *Stratiform polymetallic and barite mineralization of the Urals.,* UrO AN SSSR: Sverdlovsk, 1992.

[37] A.V. Maslov, E.Z. Gareev, M.T. Krupenin, and S.G. Kovalev, "Kovalev. Lithogeochemical features of shales from Lower Riphean Bakal Formation (Bashkirian meganticlinorium): New data, Proceedings of higher educational establishments", *Geol. Explorat,* vol. 2, pp. 21-29, 2013.

[38] A.V. Maslov, E.Z. Gareev, M.T. Krupenin, and S.G. Kovalev, "Lithogeochemical features of shales from Lower Riphean Satka Formation (Bashkirian Anticlinorium): New data, Bulletin of Perm University", *Geology,* vol. 1, pp. 9-19, 2013.

[39] A.V. Maslov, E.Z. Gareev, V.N. Podkovyrov, and S.G. Kovalev, "Lithogeochemistry of clastic rocks of the Mashak Formation (western slope of the South Urals): In search of «camouflaged» pyroclastics, Vestnik of Saint Petersburg University", *Earth Sci. (Paris),* vol. 65, no. 1, pp. 121-145, 2020. [http://dx.doi.org/10.21638/spbu07.2020.107]

[40] S.G. Kovalev, I.V. Vysotsky, V.N. Puchkov, A.V. Maslov, and E.Z. Gareev, *Geochemical specialization of structural-material complexes of the Bashkirian meganticlinorium.,* DizainPress: Ufa, 2013.

[41] S.V. Michurin, A.G. Sultanova, G.M. Kazbulatova, A.A. Sharipova, D.E. Saveliev, V.M. Gorozhanin, A.M. Karamova, and Z.A. Voikina, "Fluorine and chlorine in carbonate rocks of the Lapyshta Subformation of the Suran Formation of the Lower Riphean (Bagaryshtinsky section, South Ural)", *Geologicheskii vestnik,* no. 3, pp. 3-26, 2020. [http://dx.doi.org/10.31084/2619-0087/2020-3-1]

[42] S.V. Michurin, Z.R. Biktimerova, G.M. Kazbulatova, V.M. Gorozhanin, A.G. Sultanova, A.M. Karamova, Z.A. Voikina, and A.A. Sharipova, "Mineralogical and geochemical features of carbonate rocks of the lower subformation of Inzer Formation of the Upper Riphean in the area of Tolparovo village (South Urals)", *Geologicheskii vestnik,* vol. 1, no. 1, pp. 80-97, 2021. [http://dx.doi.org/10.31084/2619-0087/2021-1-8]

[43] S.V. Michurin, A.A. Sharipova, G.M. Kazbulatov, and V.F. Yuldashbayeva, "Mineralogical and geochemical features of

limestones of the Katav Formation of the Aktash area (Yamantau anticlinorium, Southern Ural)", *Geologicheskii vestnik,* vol. 1, no. 1, pp. 83-93, 2022. [http://dx.doi.org/10.31084/2619-0087/2022-1-7]

[44] A.G. Sultanova, and S.V. Michurin, "Some issues of lithium geochemistry and its distribution in Rifhean rocks of the Southern Urals", *Geologicheskii vestnik,* vol. 2, pp. 65-80, 2024. [http://dx.doi.org/10.31084/2619-0087/2024-2-6]

[45] N.D. Sergeeva, "Deposits of the Lower Karatau Subseries of the Karatau Series of the Alatau Anticlinorium in the section along the Zilim River near the Tolparovo village (Southern Urals)", *Geologicheskii vestnik,* vol. 1, no. 1, pp. 4-?:?, 2021. [http://dx.doi.org/10.31084/2619-0087/2021-1-1]

[46] A.V. Maslov, A.B. Kuznetsov, A.Y. Kramchaninov, L.V. Shpakovich, E.Z. Gareev, V.N. Podkovyrov, and S.G. Kovalev, "Provenances of the Upper Precambrian clay rocks in the Southern Urals: Results of geochemical and Sm–Nd isotope geochemical investigations", *Stratigr. Geol. Correl.,* vol. 30, no. 1, pp. 30-51, 2022. [http://dx.doi.org/10.1134/S0869593822010038]

[47] "International Stratigraphic Chart, ver. v2020/03", Available from: www.stratigraphy.org

[48] G. Stratigraphic, "General Stratigraphic (Geochronological) Chart of Russia as of 2019", Available from: http://www.vsegei.com/ru/info/stratigraphy/stratigraphic_scale/

[49] A.A. Krasnobaev, V.N. Puchkov, V.I. Kozlov, N.D. Sergeeva, S.V. Busharina, and E.N. Lepekhina, "Zirconology of Navysh volcanic rocks of the Ai Suite and the problem of the age of the Lower Riphean boundary in the Southern Urals", *Dokl. Earth Sci.,* vol. 448, no. 2, pp. 185-190, 2013. [http://dx.doi.org/10.1134/S1028334X13020050]

[50] A.A. Krasnobaev, V.I. Kozlov, V.N. Puchkov, S.V. Busharina, N.D. Sergeeva, and I.P. Paderin, "Zircon geochronology of the Mashak volcanic rocks and the problem of the age of the lower-middle Riphean boundary (Southern Urals)", *Stratigr. Geol. Correl.,* vol. 21, no. 5, pp. 465-481, 2013. [http://dx.doi.org/10.1134/S0869593813050055]

[51] M.A. Semikhatov, A.B. Kuznetsov, and N.M. Chumakov, "Isotope age of boundaries between the general stratigraphic subdivisions of the Upper Proterozoic (Riphean and Vendian) in Russia: The evolution of opinions and the current estimate", *Stratigr. Geol. Correl.,* vol. 23, no. 6, pp. 568-579, 2015. [http://dx.doi.org/10.1134/S0869593815060088]

[52] A.M. Musina, and S.V. Michurin, "ICP AES determination of elemental composition during the open-pit rock digestion in Materials of the IV All-Russian Youth Conference", *"Geology, geoecology and resource potential of the Urals and adjacent territories"* 2016, pp. 39-44

[53] N.A. Grigoriev, *Chemical nlm distribution in the upper continental crust.,* UB RAS: Ekaterinburg, 2009.

[54] F.Z. Teng, W.F. McDonough, R.L. Rudnick, C. Dalpé, P.B. Tomascak, B.W. Chappell, and S. Gao, "Lithium isotopic composition and concentration of the upper continental crust", *Geochim. Cosmochim. Acta,* vol. 68, no. 20, pp. 4167-4178, 2004. [http://dx.doi.org/10.1016/j.gca.2004.03.031]

[55] B. Gourcerol, E. Gloaguen, J. Melleton, J. Tuduri, and X. Galiegue, "Re-assessing the European lithium resource potential: A review of hard-rock resources and metallogeny", *Ore Geol. Rev.,* vol. 109, pp. 494-519, 2019. [http://dx.doi.org/10.1016/j.oregeorev.2019.04.015]

[56] R.R. Akhmedova, S.V. Michurin, E.O. Shiyanova, N.D. Sergeeva, and A.A. Sharipova, "Crystal chemical, mineralogical and geochemical features of dolomites of the Middle Riphean Avzyan formation (Southern Urals)", *Lithol. Miner. Resour.,* vol. 59, no. 6, pp. 691-705, 2024. [http://dx.doi.org/10.1134/S0024490224700706]

[57] L.L. Stillings, and C.L. Morissette, "Lithium clays in sediments from closed-basin, evaporative lakes in the Southwestern United States: Abstracts with Programs", *Geol. Soc. Am.,* vol. 44, no. 7, p. 210, 2012.

[58] D.C. Bradley, L.L. Stillings, B.W. Jaskula, L.A. Munk, and A.D. McCauley, "Lithium, chapter K of *Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply", *U. S. Geological Survey Professional Paper 1802-K,* pp. K1-K21, 2017. [http://dx.doi.org/10.3133/pp1802K]

[59] A. Pesquera, E. Roda-Robles, P.P. Gil-Crespo, D. Valls, and J.T. Ruiz, "The metasomatic enrichment of Li in psammopelitic units at San José-Valdeflórez, Central Iberian Zone, Spain: A new type of lithium deposit", *Sci. Rep.,* vol. 10, no. 1, p. 10828, 2020. [http://dx.doi.org/10.1038/s41598-020-67520-6] [PMID: 32616753]

[60] K. Berlo, J. Blundy, S. Turner, K. Cashman, C. Hawkesworth, and S. Black, "Geochemical precursors to volcanic activity at Mount St. Helens, USA", *Science,* vol. 306, no. 5699, pp. 1167-1169, 2004. [http://dx.doi.org/10.1126/science.1103869] [PMID: 15486253]

[61] A.J.R. Kent, J. Blundy, K.V. Cashman, K.M. Cooper, C. Donnelly, J.S. Pallister, M. Reagan, M.C. Rowe, and C.R. Thornber, "Vapor transfer prior to the October 2004 eruption of Mount St. Helens, Washington", *Geology,* vol. 35, no. 3, pp. 231-234, 2007. [http://dx.doi.org/10.1130/G22809A.1]

[62] M.C. Rowe, A.J.R. Kent, and C.R. Thornber, "Using amphibole phenocrysts to track vapor transfer during magma crystallization and transport: An example from Mount St. Helens, Washington", *J. Volcanol. Geotherm. Res.,* vol. 178, no. 4, pp. 593-607, 2008. [http://dx.doi.org/10.1016/j.jvolgeores.2008.01.012]

[63] M.V. Portnyagin, V.B. Naumov, N.L. Mironov, I.A. Belousov, and N.N. Kononkova, "Composition and evolution of the melts erupted in 1996 at Karymskoe Lake, Eastern Kamchatka: Evidence from inclusions in minerals", *Geochem. Int.,* vol. 49, no. 11, pp. 1085-1110, 2011. [http://dx.doi.org/10.1134/S0016702911110085]

[64] M.L. Tolstykh, V.B. Naumov, M.G. Gavrilenko, A.Y. Ozerov, and N.N. Kononkova, "Chemical composition, volatile components, and trace nlms in the melts of the Gorely volcanic center, southern Kamchatka: Evidence from inclusions in minerals", *Geochem. Int.,* vol. 50, no. 6, pp. 522-550, 2012. [http://dx.doi.org/10.1134/S0016702912060079]

[65] S.V. Michurin, "Petrological and geochemical features of the gabbrodolerites of the Paleozoic Yurmatau complex (Southern Urals)", *Geologicheskii vestnik,* vol. 2, no. 2, pp. 84-103, 2025. [http://dx.doi.org/10.31084/2619-0087/2025-2-6]

[66] H.L. Cannon, T.F. Harms, and J.C. Hamilton, *Lithium in unconsolidated sediments and plants of the basin and range province, Southern California and Nevada.,* US Department of Interior: Washington: United States, 1975.

[67] V.A. Filippov, "Formation complexes of the Bashkirian meganticlinorium and their metallogeny", *Doklady AN SSSR,* vol. 271, no. 4, pp. 935-938, 1983.

[68] J.K. Bartley, L.C. Kah, J.L. McWilliams, and A.F. Stagner, "Carbon isotope chemostratigraphy of the Middle Riphean type section (Avzyan Formation, Southern Urals, Russia): Signal recovery in a fold-and-thrust belt", *Chem. Geol.,* vol. 237, no. 1-2, pp. 211-232, 2007. [http://dx.doi.org/10.1016/j.chemgeo.2006.06.018]

[69] S.V. Michurin, S.G. Kovalev, and V.M. Gorozhanin, "Genesis of sulfides and sulfates from Lower Riphean sediments of the Kama-Belaya aulacogen and Bashkirian meganticlinorium. – Ufa: Design Polygraph Service",

[70] S.V. Michurin, and V.M. Gorozhanin, "Gypsum from Middle Riphean carbonate deposits of the Bashkir anticlinorium (Southern Urals) in XI Congress of the Russian mineralogical society", *Modern mineral.,* pp. 47-49, 2010.

[71] M.T. Krupenin, "*Magnesian-ferruginous carbonate ores in Riphean sediments of the Bashkirian meganticlinorium (sources of matter, stages and formation mechanisms: Abstract of Doct*", Geol.-Miner. Sci. (Rus.) Dissertation. – Novosibirsk, 2025.

[72] M.T. Krupenin, W. Prochaska, and Yu.L. Ronkin, "Multiple formation of the Suran fluorite deposit (Bashkirian meganyticlinorium): Evidence from study of REE, fluid inclusions,

and Sr–Nd systematics", *Litosfera,* no. 5, pp. 126-144, 2012.

[73] A. Meixner, R.N. Alonso, F. Lucassen, L. Korte, and S.A. Kasemann, "Lithium and Sr isotopic composition of salar deposits in the Central Andes across space and time: The Salar de Pozuelos, Argentina", *Miner. Depos.,* vol. 57, no. 2, pp. 255-278, 2022. [http://dx.doi.org/10.1007/s00126-021-01062-3]

[74] C. Li, Z. Li, T. Wu, Y. Luo, J. Zhao, X. Li, W. Yang, and X. Chen, "Metallogenic characteristics and formation mechanism of Naomugeng clay-type lithium deposit in Central Inner Mongolia, China", *Minerals,* vol. 11, no. 3, p. 238, 2021. [http://dx.doi.org/10.3390/min11030238]

[75] P.M. Bignov, A.A. Makushin, I.I. Kazakov, and S.G. Cheban, "The role of the deep structure in the placement of oil and gas, ore deposits and new promising zones of the Republic of Bashkortostan in Materials of the IV Respubl", *Geol. Conf.,* pp. 3-26, 2001.