GEODYNAMICS & TECTONOPHYSICS
Published by the Institute of the Earth's Crust, Siberian Branch, Russian Academy of Sciences

PALEOGEODYNAMICS

2023 VOLUME 14 ISSUE 3 ARTICLE 0698

ISSN 2078-502X

DOI: 10.5800/GT-2023-14-3-0698

C- AND Sr-ISOTOPE CHEMOSTRATIGRAPHY OF THE UPPER PROTEROZOIC – LOWER CAMBRIAN TRANSITIONAL DEPOSITS IN THE LENA-ANABAR TROUGH (NORTHEASTERN SIBERIAN PLATFORM)

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ABSTRACT. Studies have been made of the carbon and strontium isotope composition in carbonate sediments of the Khorbusuonka group and Kessyusa formation corresponding to the Upper Vendian in deep Khastakhskaya-930 and Burskaya-341-0 boreholes at the northeastern margin of the Siberian Platform. The maximum $\delta^{13}C$ values in carbonates of the Turkut and Kessyusa formations in the Khastakhskaya-930 borehole are +7.0…+7.4 ‰, while the minimum $^{87}Sr/^{86}Sr$ ratios are as low as 0.7079. Such isotope-geochemical characteristics suggest that these formations are younger (Tommotian) or older (early Vendian) than it was supposed and allow for the possibility of alternatives to their regional correlation with the Burskaya-341-0 borehole and Olenek uplift sections. The deposition of sediments of the age considered, more intensive than in the adjacent regions, may be indicative of rift-related extension settings.

KEYWORDS: Vendian; Ediacaran; Lower Cambrian; C- and Sr-isotope chemostratigraphy; Siberian Platform; Lena-Anabar trough

FUNDING: Analytical studies were supported by RSF grant 20-77-10066. Data compilation was performed using RSF grant 22-77-10096. The area of research was coordinated with state assignments for scientific work FMUW-2021-0003, FMMG-2022-0002 and FWZZ-2022-0002.

RESEARCH ARTICLE

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Received: October 13, 2022
Revised: December 28, 2022
Accepted: January 11, 2023

FOR CITATION: Kochnev B.B., Pokrovsky B.G., Kuznetsov A.B., 2023. C- and Sr-Isotope Chemostratigraphy of the Upper Proterozoic – Lower Cambrian Transitional Deposits in the Lena-Anabar Trough (Northeastern Siberian Platform). Geodynamics & Tectonophysics 14 (3), 0698. doi:10.5800/GT-2023-14-3-0698

1. INTRODUCTION

The Upper Vendian deposits (550–530 Ma) in the General Stratigraphic Scale of Russia (GSSR) corresponding to the Upper Ediacaran and to the Fortunian stage of the Cambrian Terreneuvian in the International Chronostratigraphic Chart (ICC), in addition to an unprecedented increase in biodiversity (Cambrian explosion), are characterized by high-amplitude and global traceable variations of the carbon and strontium isotope composition in marine carbonate sediments [Maloof et al., 2010; Xiao et al., 2016]. In particular, positive $\delta^{13}C$ 5p and 6p (ZHUCE) excursions at the base of the Tommotian stage in the GSSR and negative BACE excursion at the base of the Fortunian stage in the ICC are widely used for intra- and interregional correlations [Kouchinsky et al., 2017; Marusin et al., 2019; Grazhdankin et al., 2020a; and others]. Global variations in $\delta^{13}C$ were complicated by alternating anoxic and oxygen environments in littoral sedimentation areas and by paleogeographic conditions in a certain sedimentary basin [Sperling et al., 2015; Wood et al., 2019; Paula-Santos et al., 2017; and others]. It is implied that the presence of such variations in the Olenek uplift section particularly affect the deposits of the Khatyspyt formation of the Late Vendian and the Vendian-to-Cambrian layers in the GSSR [Cui et al., 2016; Bykova et al., 2020; Cherry et al., 2022].

However, in spite of a large amount of the age data obtained lately for this area's sections [Bowring et al., 1993; Rogov et al., 2015; Vishnevskaya et al., 2017; Grazhdankin et al., 2020a], a detailed correlation of the Vendian sections of the Olenek uplift with the sections of other areas of the Siberian Platform is hampered by significant differences in structure and composition. One of the nearest regions for which the Vendian deposits are described is the eastern Lena-Anabar trough wherein this stratigraphic section is entirely penetrated by the Burskaya-341-0 (B-341-0) and Khastakhskaya-930 (Kh-930) boreholes drilled in the late 20th century; the upper horizons of the Vendian are also penetrated by the Charchikskaya-1 (Ch-1) and Ust'-Olenekskaya-230-0 (UO-230-0) boreholes (Fig. 1). It was initially supposed [Grausman et al., 1996] that the most detailed section of hole B-341-0 exhibits full analogues of the Riphean (Sololi group) and Vendian (Khorbusuonka group) rocks of the Olenek uplift which was confirmed by the seismic data interpretation [Kontorovich et al., 2013]. The penetrated pre-Vendian deposits were afterwards assigned to the Upper Riphean of GSSR or to the Tonian of ICC on the basis of the bio- and chemostratigrapic data [Khabarov, 2015; Nagovitsin et al., 2015], whereas the rocks within the Sololi group of the Olenek uplift, on the basis of the K-Ar and Rb-Sr dates, were assigned to the Early-Middle Riphean [Zaitseva et al., 2017]. Based on the microfossils found in hole Kh-930, an amount of stratigraphy supposedly deposited during the Vendian was reduced to its uppermost part (Nemakit-Daldyn horizon or regiostage) [Nagovitsin et al., 2015]. However, the layers which comprise the skeletal remains also yielded the complex diversity of organic-walled microfossils which were previously considered as only Early Vendian [Grazhdankin et al., 2020b].

To obtain additional information on the age and formation conditions of the Vendian deposits in the eastern

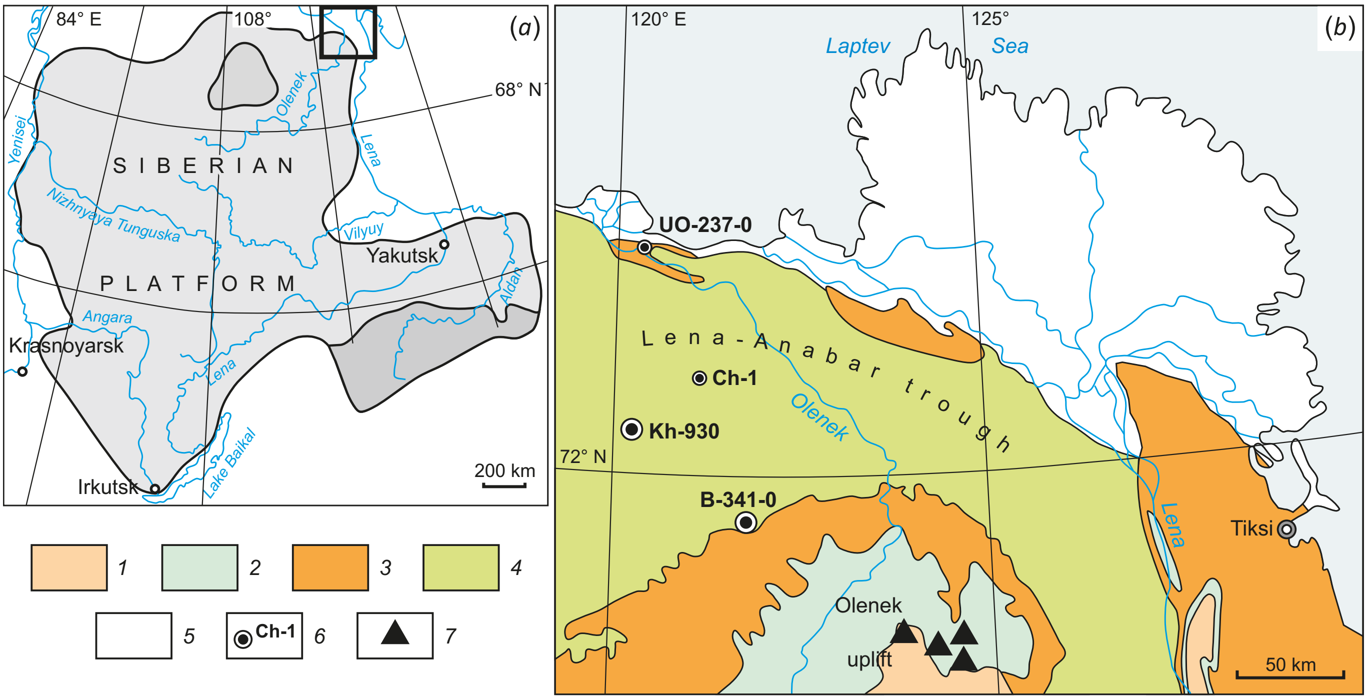

Fig. 1. An overview map (*a*) and a geological scheme of the northeastern margin of Siberian Platform (*б*).
(*1–5*) – sequences: *1* – Precambrian, *2* – Cambrian, *3* – Late Paleozoic, *4* – Mesozoic, *5* – Cenozoic; *6* – deep boreholes: UO-237-0 – Ust'-Olenekskaya-237-0, Ch-1 – Charchikskaya-1, Kh-930 – Khastakhskaya-930, B-341-0 – Burskaya-341-0; *7* – major sections of the Vendian strata of Olenek uplift.

Lena-Anabar trough, we conducted the isotope-geochemical studies of the Vendian interval of the Burskaya-341-0 and Khastakhskaya-930 borehole sections. The results obtained call into question the stratification of deposits and their correlation with the reference section of the Olenek uplift, as well as the existing ideas of the evolution of the sedimentary basin on the northeastern margin of the Siberian Craton at the Vendian-Cambrian boundary.

2. STRATIGRAPHY

The Vendian and Vendian-Cambrian transitional deposits of the Olenek uplift and the eastern Lena-Anabar trough are represented by marine epicontinental terrigenous-carbonate strata accumulated in different parts of the shelf. They are characterized by a relatively small (a few hundred meters) total thickness decreasing from margin to center of the craton, widespread occurrence of sedimentation gaps, and manifestation of bimodal rifting magmatism in the Vendian-Cambrian boundary interval [Shpunt et al., 1979; Rogov et al., 2015; Nagovitsin et al., 2015; Kiselev et al., 2016]. The age of deposits is based on the biostratigraphical [Grazhdankin et al., 2008; Rogov et al., 2012, 2015; Nagovitsin et al., 2015], isotope-geochemical [Knoll et al., 1995; Vishnevskaya et al., 2017], and geochronological [Bowring et al., 1993; Grazhdankin et al., 2020a] data. Because of the lack of the core samples, stratification of the Vendian deposits in deep-borehole sections is mostly based on the logging data [Kontorovich et al., 2013]. Stratification of deep-borehole sections used in this paper, except for the Khastakhskaya-930 borehole, corresponds to that previously published [Grausman, 1995; Nagovitsin et al., 2015] (Fig. 2).

The oldest Vendian deposits in the region are represented by the Maastakh formation subdivided into two sub-formations. The lower sub-formation up to 30 m in thickness, cropped out along the Khorbusuonka River and opened by hole B-341-0, is composed of red sands, clayey coarse-grained in the lower part and characterized by thickly bedded multidirectional cross stratification in the upper. The sandstones of the lower sub-formation are pinching out in the northern Olenek uplift. The upper sub-formation about 50 m thick has exposures of clayey and siliceous biolaminite intraclast and phytolithic dolomites formed in the shallow water environment. Near the top of the formation, there is a distinguished quartz dolomitic sandstone horizon. Examining the stratotypical section of the Olenek uplift has yielded information on the minimum detrital zircon ages of about 600 Ma in the upper part of the formation and the results of carbon and strontium chemostratigraphy [Knoll et al., 1995; Vishnevskaya et al., 2017], which allow (somewhat conventionally) constraining the maximum age of the formation as the Early Vendian (570–600 Ma).

The Khatyspyt formation, up to 180 m in thickness in the Khorbusuonka River basin, with a gap in the basement-sedimentary cover system, overlies either the Maastakh formation or Riphean deposits and is represented by the alternation of finely stratified, less often intraclast or biogerm layers of limestones with different clay content. In hole B-341-0, in the interval assigned to the Khatyspyt formation, there were opened gray micrite dolomites. The formation is considered to be of the Late Vendian age (no older than 550-560 Ma) in accordance with the macrofossil remains [Grazhdankin et al., 2008; Nagovitsin et al., 2015] and ichnofossils [Rogov et al., 2012] found, which is in agreement with the data on C- and Sr-isotope chemostratigraphy [Knoll et al., 1995; Cui et al., 2016; Vishnevskaya et al., 2017] and U-Pb age of detrital zircons [Cherry et al., 2022].

The Turkut formation up to 100-110 m in thickness on the Olenek uplift is composed of various (detrital, brecciated, biogerm) dolomites. In holes B-341-0, Ch-1 and Kh-930, in the intervals assigned to the Turkut formation, limestones are also found [Grausman et al., 1996; Nagovitsin et al., 2015]. The Turkut formation overlies the Khatyspyt formation with a short-term gap in sedimentation [Rogov et al., 2015]. In accordance with the small-shelly fossil finds and geochronological data on the overlying deposits, the formation can be constrained to between 550 and 544 Ma [Bowring et al., 1993; Rogov et al., 2015].

The Kessyusa formation overlies the Turkut formation with a gap in sedimentation. In recent years, however, it has been proposed to rank the Kessyusa formation as the series in which the Syargalakh, Mattaia and Chuskuna formations would be distinguished, and to recognize the Oppokun formation as an analogue of the Syargalakh formation in deep boreholes [Nagovitsin et al., 2015; Rogov et al., 2015]. Nevertheless, further in the text we use the traditional nomenclature of subdivisions and relate the names of the newly distinguished formations to the members (sub-formations) within the Kessyusa formation until their approval. In the basement of the Kessyusa formation, somewhere in the Olenek uplift sections, there occur tuffaceous breccias of the Tas-Yuryakh volcanic complex [Rogov et al., 2015]. The Kessyusa formation alone, in its bottom part is composed of sandstones, often calcareous (Syargalakh formation/member). The middle part of the Kessyusa formation is composed of aleurolites and argillites, changing to sandstones with limestone horizons (Mattaia formation/member) in the upper part. The uppermost part of the Kessyusa formation, distinguished as the Chuskuna member (formation), is composed of sandstones and aleurolites. The thickness of the Kessyusa formation on the Olenek uplift reaches 130–140 m.

The deep boreholes, in the intervals assigned to the Kessyusa formation, are dominated by fine detritus material whereas the upper part of the formation is usually composed of sandstones and gravelites (Oppokun and Mattaia formations after [Nagovitsin et al., 2015]). The thickness of the formation increases therein and reaches 420 m in hole Kh-930. The accumulation time of the Kessyusa formation is determined based on U-Pb ages of zircons from tuff interlayres, disruptive tuffaceous breccias and detrital zircons in the basement (543 Ma) and the upper part (529 Ma) of the formation [Bowring et al., 1993; Vishnevskaya et al., 2017; Grazhdankin et al., 2020a] and confirmed

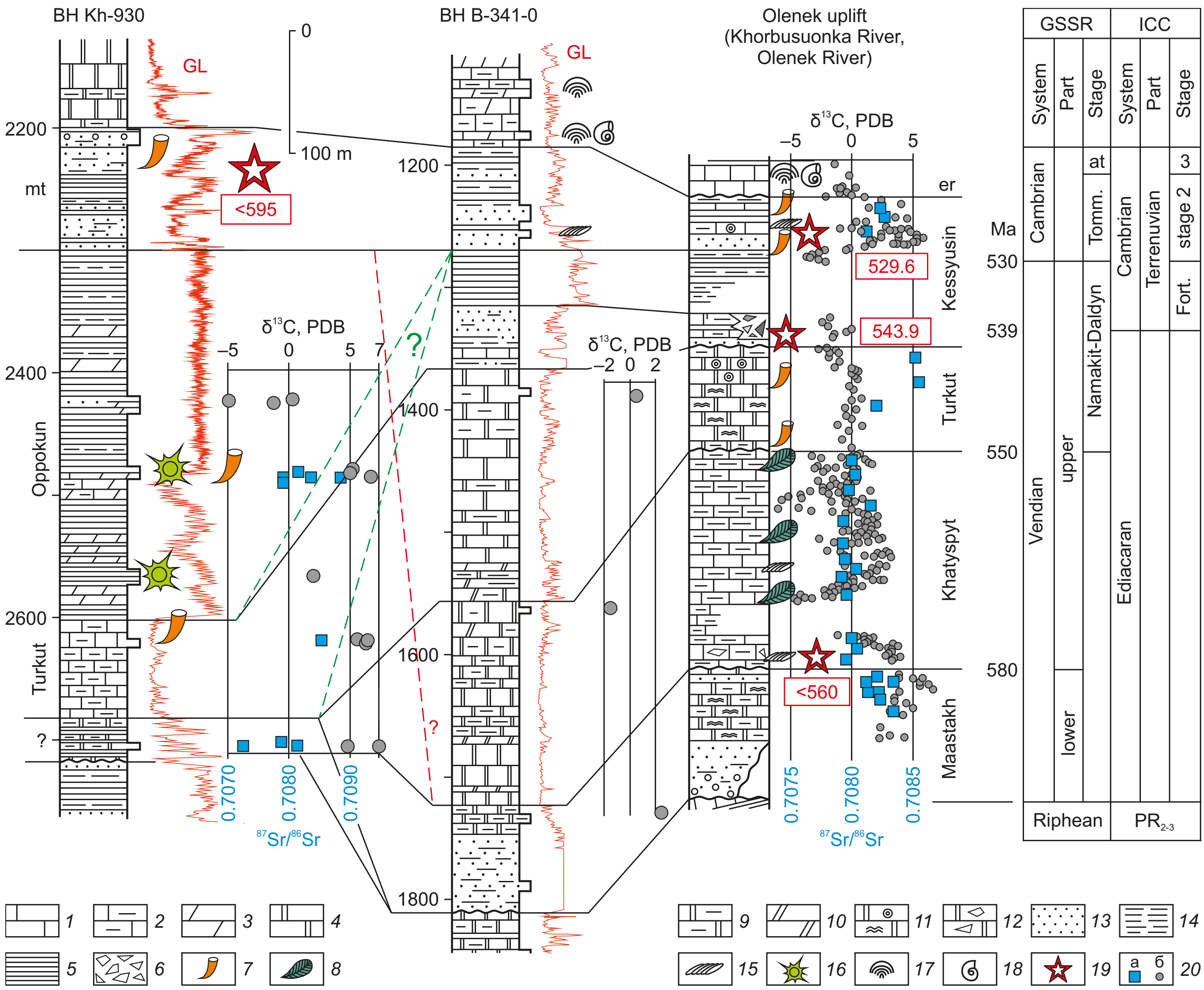

Fig. 2. Isotope and geochemical data and correlation between the Vendian deposits opened by boreholes in the eastern Lena-Anabar trough and viewed in the Olenek uplift section.

1 – limestones; *2* – clayey limestones; *3* – marls; *4* – dolostones; *5* – clayey dolostones; *6* – dolomite marls; *7* – biolaminite and oolite dolostones; *8* – dolostone breccias; *9* – sandstones; *10* – siltstones; *11* – claystones; *12* – tuff breccias; *13–18* – fossils [Grausman et al., 1996; Nagovitsin et al., 2015; Rogov et al., 2015; Grazhdankin et al., 2008, 2020a, 2020b]: *13* – small-shelly fossils, *14* – ediacara biota, *15* – ichnofossils, *16* – acantomorphous organic-walled microfossils, *17* – trilobites, *18* – gastropods; *19* – U-Pb ages of volcanic ashes [Bowring et al., 1993; Grazhdankin et al., 2020a] and maximum sedimentation ages of detrital zircons [Khudoley et al., 2015; Vishnevskaya et al., 2017]; *20*: а – $^{87}Sr/^{86}Sr$ ratios after [Vishnevskaya et al., 2017; Grazhdankin et al., 2020a; and in the present paper], б – $\delta^{13}C$ values after [Knoll et al., 1995; Vishnevskaya et al., 2017; Grazhdankin et al., 2020a; and in the present paper]. Abbreviations: GL – gamma-logging; mt – Mattaia formation; er – Erkeket formation; at – Atdabanian stage; Tomm. – Tommotian stage; Fort. – Fortunian stage. Alternative variants of correlations are marked by colored dashed lines (see text for explanation).

by numerous different organic remains [Grazhdankin et al., 2020a; Rogov et al., 2015; and references therein]. The Vendian-Cambrian boundary GSSR runs 25–40 m below the top of the formation and is identified from the emergence of the Early Tommotian small-shelly fossils and from the chemostratigraphic data [Grazhdankin et al., 2020a].

3. MATERIALS AND METHODS

Geochemical and isotopic studies were made on the 20 lowest-clay and silicified carbonate rock core samples from holes Kh-930 (17 samples) and B-341-0 (three samples) (see Fig. 1; Table 1). The core fragments were sawed, and the most homogeneous sample parts were bored with a small drill bit to extract a powder sample for further analysis. The Ca, Mg, Fe, Mn and Sr contents of carbonate fraction in 11 samples from hole Kh-930 were studied by method of atomic emission spectroscopy using hydrochloric acid extract at the Recourse Center for Methods of Compositional Analysis, SPbU, Saint Petersburg, through the procedure described in [Kochnev et al., 2018].

Isotopic composition of carbon and oxygen was determined using Thermoelectron Delta V Advantage (GIN RAS)

Table 1. Chemical and isotope composition of carbonate sediments from the Khastakhskaya-930 and Burskaya-341-0 borehole sections

Depth, m	Formation	% carb.	Ca, mcg/g	Mg, mcg/g	Fe, mcg/g	Mn, mcg/g	Sr, mcg/g	Rb, mcg/g	Mg/Ca	Fe/Sr	Mn/Sr	$\delta^{13}C$, V-PDB, ‰	$\delta^{18}O$, V-SMOW, ‰	$^{87}Sr/^{86}Sr$
							Khastakhskaya BH-930							
2419.1+3.2	ks	–	–	–	–	–	–	–	–	–	–	0.5	23.6	–
2419.1+4.25	ks	–	–	–	–	–	–	–	–	–	–	–4.9	23.2	–
2419.1+5.4	ks	–	–	–	–	–	–	–	–	–	–	–1.3	19.9	–
2477.6+0.15	ks	**91.97**	**526000**	**10000**	**4072**	**2206**	**542**	**0.89**	**0.02**	**7.51**	**4.07**	**5.1**	**28.3**	**0.7081**
2477.6+4.3	ks	82.30	511000	9400	10742	2422	323	1.48	0.02	33.3	7.50	–	–	0.7088
2482.1+0.1	ks	75.92	527000	10200	14023	2892	638	1.89	0.02	22.0	4.53	5.0	23.7	0.7083
2482.1+1.1	ks	**90.80**	**561000**	**4600**	**6393**	**1176**	**1202**	**0.97**	**0.01**	**5.32**	**0.98**	–	–	**0.7079**
2482.1+1.35	ks	**92.38**	**550000**	**4700**	**6313**	**643**	**1406**	**0.92**	**0.01**	**4.49**	**0.45**	–	–	**0.7079**
2482.1+2.8	ks	–	–	–	–	–	–	–	–	–	–	7.0	23.2	–
2482.1+3.55	ks	**82.55**	**545000**	**7400**	**782**	**10367**	**1654**	**1.47**	**0.01**	**0.47**	**6.27**	–	–	**0.7079**
2567.9+0.3	ks	–	–	–	–	–	–	–	–	–	–	2.1	24.0	–
2618	tr	–	–	–	–	–	–	–	–	–	–	5.6	25.3	–
2618+1.9	tr	74.93	321000	143000	1539	1581	130	1.39	0.45	11.83	12.16	6.3	25.8	–
2618+3.1	tr	86.34	326000	148000	1939	1699	126	0.62	0.45	15.39	13.48	6.2	23.1	0.7085
2702+0.1	?tr	81.36	324000	147000	7812	1153	129	0.66	0.45	60.56	8.93	7.4	28.7	0.7074
2702+1.2	?tr	90.74	324000	139000	12833	6298	105	0.25	0.43	122.2	59.99	4.9	28.8	0.7076
2702+1.7	?tr	93.79	323000	146000	11030	1945	127	0.55	0.45	86.85	15.31	–	–	0.7072
							Burskaya BH-341-0							
1382+1.0	tr	–	–	–	–	–	–	–	–	–	–	0.5	26.0	–
1561+0.1	ht	–	–	–	–	–	–	–	–	–	–	–1.6	30.4	–
1730.3+0.6	ms	–	–	–	–	–	–	–	–	–	–	2.2	24.4	–

Note. Dash – not defined. Formation indexes: ks – Kessyusa, tr – Turkut, ht – Khatyspyt, ms – Maastakh. Samples with the least altered isotopic systems are marked in bold.

and Finnigan MAT-253 (IGM SB RAS) spectrometers and Gas Bench II device. Decomposition of samples and standards KH-2, C-O-1 and NBS-19 was performed using H_3PO_4 at 50 °C. The $\delta^{13}C$ values are measured in promille (‰) relative to standard V-PDB, $\delta^{18}O$ values – in promille relative to standard V-SMOW. The $\delta^{18}O$ and $\delta^{13}C$ measurement accuracy is ±0.2 and ±0.1 ‰, respectively.

Isotopic composition of strontium in carbonate rocks was determined using Triton TI mass spectrometer (IPGG RAS). Rb-Sr systematics of carbonate rocks was based on pre-leaching weighed quantity (50 mg) for enriching a sample with the primary carbonate material [Kuznetsov et al., 2005]. The mean $^{87}Sr/^{86}Sr$ values in standard samples SRM 987 and EN-1, normalized to $^{86}Sr/^{88}Sr$ 0.1194, were 0.710282±0.000006 ($2s_{mean}$, n=35) and 0.709209±0.000008 ($2\sigma_{mean}$, n=27), respectively.

4. RESULTS OF IOTOPIC-GEOCHEMICAL STUDY OF CARBONATE ROCKS

A study was made of the chemical composition of hole Kh-930 samples which were then used for determining isotope composition of strontium: Kessyusa formation, 2477.6–2487.6 m depth interval, and Turkut formation, 2618–2624.8, 2702–2708 m depth intervals (Table 1). The studied rocks of the Kessyusa formation are represented by limestones (Mg/Ca=0.01–0.02) with different clay contents (insoluble residue content 8–18 %). The manganese contents of limestones vary from 643 to 2892 mcg/g, the iron and strontium contents – from 6300 to 14 000 mcg/g and from 323 to 1654 mcg/g, respectively. The rubidium contents vary in the range from 0.89–1.89 mcg/g. Four of six samples are suitable for estimating the primary carbon isotopic composition according to their geochemical criteria (Mn/Sr<5 and Fe/Sr<10) [Podkovyrov et al., 1998; Semikhatov et al., 2004], whereas the $^{87}Sr/^{86}Sr$ ratio in at least three of six samples should be considered to be overestimated relative to that in the paleobasin water.

The rocks assigned to the Turkut formation are represented by clayey and siliceous (insoluble residue content 6–25 %) slightly calcareous (Mg/Ca=0.43–0.46) dolomites (Table 1). Fe contents (1540–12830 mcg/g) of dolomites are comparable to those of the Kessyusa formation limestones whereas their Mn contents (1150–6300 mcg/g) are many times higher and their strontium concentrations (105–130 mcg/g) are much lower. Even according to less strict geochemical criteria for dolomites (Mn/Sr<10 and Fe/Sr<40) [Podkovyrov et al., 1998; Semikhatov et al., 2004], these samples cannot be considered responsible for the isotopic composition of the paleobasin water. However, as shown below, the $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ values from this interval are also important for chemostratigraphic reconstructions.

The $\delta^{13}C$ values in hole Kh-930, in the Kessyusa formation, vary widely, from 4.9 to 0.5‰ in the interval of 2419.1–2425 m (three samples), where calcareous aleurolites and aleurosandstones were penetrated. Lower in the section (in the interval of 2477.6–2487.6 m), the $\delta^{13}C$ values of the three samples are much higher making +5… +7 ‰. Except for one sample of the calcareous aleurolite from a depth of 2568.2 m, where $\delta^{13}C$=2.1 ‰ (Fig. 2), all the underlying deposits assigned to the Turkut formation [Nagovitsin et al., 2015] are characterized by rather high positive (4.9…7.4 ‰) $\delta^{13}C$ values (Table 1). Besides the section of hole Kh-930, we studied three samples from B-341-0 borehole, which, according to currently available classifications, are assigned to the Turkut, Khatyspyt and Maastakh formations (Fig. 2) whose $\delta^{13}C$ values are +0.5, –1.6 and +2.2 ‰, respectively (Table 1). In spite of a small amount of these data caused by extremely poorly preserved core samples, their importance lies in the fact that they are very close to the values earlier obtained from these formation outcrops. As regards the oxygen isotopic composition, the $\delta^{18}O$ values in all the collection studied, except for one sample, are within the range of 23.1…30.4‰ V-SMOW (–7.5… –1.0 ‰ V-PDB) and slightly (R=0.22) correlated with the $\delta^{13}C$ values.

The $^{87}Sr/^{86}Sr$ ratio for the sedimentary rocks of the Kessyusa formation is studied in the interval of 2477.6–2487.6 m in hole Kh-930, which penetrated relatively pure limestones. In five of six samples, it lies within the range of 0.7079…0.7083. The dolomites assigned to the Turkut formation according to the previous classifications [Nagovitsin et al., 2015], in the interval of 2618–2624.8 in one sample showed the $^{87}Sr/^{86}Sr$ ratio equal to 0.7085, whereas in three samples of dolomite from the interval of 2702–2708 m it varies from 0.7072 to 0.7076 (Fig. 2; Table. 1).

5. RESULTS AND DISCUSSION

When the isotopic-geochemical characteristics of the Vendian carbonate rocks in the Khastakhskaya-930 borehole are compared with those of the coeval deposits of the Olenek uplift, it is apparent that they considerably differ from each other. In particular, the Kessyusa formation in the section of the Olenek uplift exhibit $\delta^{13}C$ values higher than +5 ‰ only in its upper part (an analogue of excursion 5p or ZHUCE) [Grazhdankin et al., 2020a]. In deep boreholes of the Lena-Anabar trough, this stratigraphic level, in accordance with the earlier adopted correlation, is primarily composed of sandstones and gravelites (Fig. 2), because the limestones of the upper Kessyusa formation (Suordakh layer), wherein this excursion was found, have a limited lateral distribution on the Olenek uplift [Grazhdankin et al., 2020a]. In the limestone interlayres within the underlying thin terrigenous deposits of the Mattaia formation, there is a rapid decrease in $\delta^{13}C$ values to –3.4 ‰, which is also observed in the upper Oppokun formation in hole Kh-930 (Fig. 2, interval 2419.1–2425.1 m). However, high positive (up to +7 ‰) values obtained for the limestone interlayers within the middle Oppokun formation are not observed in the lower and middle parts of the Kessyusa formation or in the Tommotian-underlying deposits of other areas of the Siberian Platform dominated by near-zero or negative $\delta^{13}C$ values [Marusin et al., 2019; Grazhdankin et al., 2020a].

Besides the carbon isotopic composition, not typical of this stratigraphic level, the limestones in hole Kh-930, in the interval of 2477.6–2487.6 m, have the minimum $^{87}Sr/^{86}Sr$ ratios equal to 0.7079, which are significantly lower than those earlier obtained for the Kessyusa Formation outcrops. That is, in the section of the Olenek uplift in the upper formation, the minimum $^{87}Sr/^{86}Sr$ ratios are 0.70815 [Grazhdankin et al., 2020a]. In other sections of the Vendian – Cambrian boundary layers in the Siberian Platform, these values do not go lower than 0.7082–0.7083 [Vinogradov et al., 1994; Kochnev et al., 2018]. Nevertheless, $^{87}Sr/^{86}Sr$=0.70806, minimum in this interval in some sections, are known for the Lower Tommotian limestones of the variegated formation in the middle flow of the Lena River [Derry et al., 1994], and 0.70802 – for the Olekma River [Pokrovsky et al., 2020], which is much closer to our obtained minimum values for the Kessyusa formation.

The Turkut formation in the Khastakhskaya-930 borehole also has isotopic characteristics which are distinct from those known for sections of the Olenek uplift [Knoll et al., 1995; Pelechaty et al., 1996; Vishnevskaya et al., 2017]. The $\delta^{13}C$ values in the interval of 4.9…7.4 ‰ in hole Kh-930 are much higher than those obtained for the Turkut formation outcrops where they usually lie in the interval from –1 to +1 ‰, increasing to +3.2 ‰ in only some of the samples [Knoll et al., 1995; Vishnevskaya et al., 2017]. As regards the strontium isotopic composition, the $^{87}Sr/^{86}Sr$ values yielded by most of the samples from the Turkut formation in sections along the Khorbusuonka River are high compared with the initial ones due to obvious post-sedimentation changes (dolomitization, recrystallization and others) [Vishnevskaya et al., 2017]. Nevertheless, the minimum value for one sample from the lower part of the formation is 0.70825, which can be considered as the most approximate for the initial carbonate isotopic composition because the strontium composition usually shifts toward higher $^{87}Sr/^{86}Sr$ values with post-sedimentation changes [Kuznetsov et al., 2014; and references therein]. The above value is relatively close to $^{87}Sr/^{86}Sr$ 0.7085, obtained for dolomites of the upper Turkut formation in hole Kh-930 (int. 2618–2624 m). However, lower in the section, in the interval of 2702–2708, the $^{87}Sr/^{86}Sr$ values decrease to 0.7072…0.7076, which is much lower than those known for the Late Vendian and more typical of the Neoproterozoic normal marine deposits no younger than 580–600 Ma [Kuznetsov et al., 2014; Xiao et al., 2016; Chen et al., 2022]. Accordingly, the lower clayey-dolomitic section of the Turkut formation in the Kh-930 borehole in the interval of 2680–2720 m could not be assigned thereto and is of an older (Early Vendian or even Late Riphean) age because the $^{87}Sr/^{86}Sr$ values in marine carbonates do not go lower than 0.7075 from the Late Vendian up to the Late Paleozoic [Kuznetsov et al., 2014].

In the context of isotopic chemostratigraphy, the atypically low $^{87}Sr/^{86}Sr$ and atypically high $\delta^{13}C$ for the Late Vendian carbonates of the Kessyusa and Turkut formations in hole Kh-930 can be attributed to either a wrong estimate of the age of deposits or an isolated character of the sedimentary basin. An example of the Late Ediacaran (Late Vendian) sedimentary basin with abnormal isotopic-geochemical characteristics of carbonate sediments due to the isolation from the open sea is the Bambui group of the São Francisco Craton in South America [Paula-Santos et al., 2017]. It is supposed that difficult water exchange between the intracontinental basin and the open sea resulted in anoxic conditions, unoxidized organic matter accumulation by sediments, and ^{13}C enrichment of water. An abnormal isotopic composition of strontium in carbon sediments is explained by the prevalence of low $^{87}Sr/^{86}Sr$ ratios in the eroded areas [Caetano-Filho et al., 2019].

The available geological data do not allow the more or less reasonable use of the isolated basin model for the Upper Vendian – Lower Cambrian deposits of the Lena-Anabar trough. In the inner part of the craton in the Late Vendian – Early Cambrian, there was a vast area of epicontinental, primarily small shallow-water basins and their-separating barrier reefs [Shabanov, 2016], and carbon and strontium isotope composition of carbonate sediments deposited therein is close to typical values of the cumulative curves [Kochnev et al., 2018]. There are presently no data that would imply the existence of sediment barrier which was lying north of the Lena-Anabar trough and separating it from the open sea. After the refinement of deposit ages based on the minimum detrital zircon ages, it became obvious that the Kessyusa formation analogues in the section of the Ust'-Olenekskaya borehole 237-0 on the Laptev Sea coast have the same structure as in other deep boreholes of the eastern Lena-Anabar trough [Priyatkina et al., 2017]. There is evidence that the epiconitental sedimentary basin in the Early Paleozoic time could extend far beyond the present-day Arctic zone of the Siberian Platform [Danukalova et al., 2014]. Thus, nothing indicates that there existed large landmasses which could separate this part of the sedimentary basin from both inner parts of the craton and the open sea in the northeast (present-day coordinates).

A combination of abnormally low $^{87}Sr/^{86}Sr$ ratios in the Vendian – Cambrian boundary layers and high $\delta^{13}C$ values of carbonates could imply that the considered strata originated at an earlier time, particularly during the Early Vendian. However, besides their position in the upper part of the section, the Oppokun formation and its underlying limestones of the Turkut formation can also be dated based on new finds of skeletal fossils such as anabaritids which emerged only at the end of the Ediacaran of ICC or in the Late Vendian of GSSR [Nagovitsin et al., 2015]. The assumption that these skeletal fossils emerged in the Early Vendian seems to be less probable than the hypothesis about large, profusely ornamented organic-walled microfossils, found in hole Kh-930 in the Kessyusa formation, which did not disappear in the Middle Vendian/Ediacaran but continued to survive in specific environments [Grazhdankin et al., 2020b; and references therein]. If the Oppokun and Turkut formations, penetrated by the Khastakhskaya borehole, are dated to the Early Vendian by independent methods, then one will have to admit the existence of a large gap in the top of the Oppokun formation due to which the Upper Vendian deposits are entirely missing in the section and to suggest that anabaritids as one of the first groups of skeletal fossils emerged not in the Late Vendian but at least 40–50 Ma earlier, in the deposits comparable with the Dalnetaiga group of the Patom upland at the southern Siberian Platform, and dated to be no younger than 575 Ma [Rud'ko et al., 2021].

Another possible explanation for high $\delta^{13}C$ values in the limestone interlayers within the Oppokun formation in hole Kh-930 could be their confinedness to large positive $\delta^{13}C$ excursions at the base of Tommotian stage of the Lower Cambrian GSSR. The lowest of these excursions (5p) is identified in the upper Kessyusa formation where the maximum $\delta^{13}C$ values reach +5 ‰ [Grazhdankin et al., 2020a]. In the Oman sections, which are well characterized by the geochgronological dates, these values go even higher and reach +6...+7 ‰ [Maloof et al., 2010]. In this case, the earlier adopted correlation between the deep-hole and outcrop sections also changes significantly: the Oppokun formation would correspond not to the middle Pre-Tommotian thin terrigenous part of the Kessyusa formation but to its upper part (Fig. 2). If such comparison is correct, then most of the upper part of primarily thin terrigenous Oppokun formation could accumulate within a relatively short period of time which took no longer than 10 Ma. It turns out to be limited to the Tommotian stage base age of 530 Ma [Grazhdankin et al., 2020a] and the age of carbonate deposits of the Erkeket formation analogues which contain trilobites of the Atdabanian stage (<521 Ma). High sedimentation rates in combination with a marked predominance of thin terrigenous rocks in the Oppokun formation could be attributed to rifting-related local extension settings in this part of the Siberian Platform during the Vendian-Cambrian transition [Pokrovskii et al., 2006]. But they do not explain the appearance of high $\delta^{13}C$ values to +6.3 ‰ in the lower section, in the limestones of the Turkut formation analogues. If these limestones, penetrated by hole Kh-930 in the interval of 2618–2624 m, are also of the Tommotian age, than all the overlying deposits will also be of the Early Cambrian (Tommotian and younger) age in the context of GSSR. Considering that the dolomite sequence underlying the Turkut limestones has the minimum $^{87}Sr/^{86}Sr$ 0.7072, not known for the deposits younger than the very beginning of the Vendian/Ediacaran [Xiao et al., 2016], this may imply there is a practical absence of the Late and partially Early Vendian deposits at such a correlation.

In spite of the fact that the two above correlations of the Khastakhskaya borehole-930 sections are mutually exclusive, both of them are in good agreement with the available data on the strontium isotopic composition. In the Lower Vendian of Siberia, the minimum $^{87}Sr/^{86}Sr$ ratios are about 0.7074 [Pokrovskii et al., 2006] but can be much higher with post-sedimentation changes or capture of radiogenic strontium from the terrigenous rock fraction. In the Vendian-Cambrian boundary interval, the minimum known $^{87}Sr/^{86}Sr$ ratios are about 0.7080…0.7081 (see above), which is rather close to the minimum value of 0.7079 for the limestones of the Oppokun formation.

The most important geodynamic consequence of the data obtained is a conclusion about rather high rates of sedimentary sequence accumulation near the present-day northeastern margin of the Siberian Platform in the Vendian and/or Early Cambrian. Intensive subsidence was most likely caused by the rift-related crustal extension whose features in the form of major or bimodal magnetic force accompanied by on-land and subaqueous volcanism in an age interval of 544–526 Ma are known both for the Olenek and Kharaulakh uplifts [Kiselev et al., 2015; Prokopiev et al., 2016]. Besides the northeastern Siberian Platform, similarly aged rifting events are also known for other paleocontinents, Laurentia in particular [Golonka, Gaweda, 2012; Brueseke et al., 2016], which allows relating them to the opening of the Iapetus Ocean [Vishnevskaya et al., 2017].

6. CONCLUSIONS

The isotopic-geochemical characteristics ($\delta^{13}C$ to +7 ‰; 87Sr/86Sr=0.7079) obtained for the carbonate deposits assigned to the Upper Vendian in the eastern Lena-Anabar trough (Khastakhskaya-930 borehole) are in obvious contradiction with other geological data, primarily biostratigraphic. The proposed alternative dating and correlation of hole Kh-930 section with the sections of the Burskaya 341-0 borehole and Olenek uplift allow for significant differences in sequence thickness and composition at the comparable stratigraphic levels which are even more pronounced as compared to the previous correlations [Grausman et al., 1996; Kontorovich et al., 2013; Nagovitsin et al., 2015]. One of the ways to solve this contradiction could be revision of the ideas of global evolution of the carbon and strontium isotopic compositions, reflected in the available reference curves. Because of the lack of the additional data on the deposit ages that can hardly be obtained without drilling additional deep boreholes, the viewpoint on the assignment of the Oppokun formation and Turka formation in hole Kh-930 to the Upper Vendian still remains disputable which should be taken into account when drawing regional stratigraphic and paleotectonic schemes.

7. CONTRIBUTION OF THE AUTHORS

All authors made an equivalent contribution to this article, read and approved the final manuscript.

8. DISCLOSURE

The authors declare that they have no conflicts of interest relevant to this manuscript.

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