

Isotopic Signatures of Deposition and Transformation of Lower Cambrian Saliferous Rocks in the Irkutsk Amphitheater: Communication 3. Carbon and Oxygen Isotopic Compositions in Carbonates

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Abstract—In previous communications based on the study of sulfur and strontium, we showed that Lower Cambrian rocks of the Irkutsk Amphitheater underwent a significant epigenetic transformation. All postsedimentary alterations of rocks are related to the influence of water solutions that provoke the direct (physical) dissolution of material and its chemical transformation. In particular, an appreciable portion of anhydrites disappeared from the section due to reduction. Probably, these processes took place several times in the past and they are continuing at present. A similar conclusion was deduced from the strontium isotopic composition of carbonate rocks. Their strontium isotopic composition is usually shifted relative to the primary composition, although the prevalence of sulfate and carbonate rocks in the section promotes the stability of strontium isotopic composition with respect to secondary alterations. The carbon isotope system is even more stable due to the abundance of carbonate rocks in the section. This circumstance is probably responsible for the incapacity of isotope data to serve as obvious evidence of the epigenetic transformation of carbonates. The major elements of the evolution of carbon isotope signature could be retained since the sedimentation stage.

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INTRODUCTION

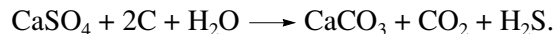
In our previous communications (Vinogradov et al., 2006a, 2006b) based on the case study of boreholes Bel'sk and Zhigalovo, we demonstrated that nearly all rocks of the 2-km-thick Early Cambrian section in the Irkutsk Amphitheater underwent secondary alterations irrespective of their types. This is particularly well seen in the sulfate section that was reduced by 100 m or more because of sulfate reduction alone. The consequent redistribution of material is reflected, for example, in the ⁸⁷Sr/⁸⁶Sr values in sulfate and carbonate portions of the section (Vinogradov et al., 2006b). Secondary alterations could also be reflected in carbon and oxygen isotopic compositions of carbonate rocks.

The impact of postsedimentary alterations on the oxygen isotopic composition of carbonate sediments is well known. This is usually related to the reaction of rocks with the meteoric water that is characterized by low δ¹⁸O values relative to the World Ocean water. The shift of oxygen isotopic composition depends on the water/rock ratio and temperature (these parameters have a negative correlation with the δ¹⁸O value in carbonates). Although the reaction of rocks with the mete-

oric water changes the oxygen isotopic composition of carbonates, this reaction may not be reflected in the carbon isotopic composition at all.

Groundwaters are commonly saturated with carbon dioxide owing to the oxidation of organic matter in rocks by sulfates (sources of oxygen).

The in-depth mechanism of sulfate reduction is rather complicated and usually unclear. Therefore, this process is usually demonstrated by initial and final products of the following reaction:



Actually, sulfates are reduced due to the oxidation of hydrocarbons, and water turns out to be one of the final products:



To our knowledge, this fact was first noted in (Worden and Smalley, 1996; Worden et al., 1996) based on study of the Permian Kuff gas-bearing formation in Abu Dhabi. The Kuff Formation (carbonate–evaporite sequences) is located at a depth of 2500–6000 m or more. Salt concentration in formation waters of this

region is close to the halite solubility limit. High temperatures of rocks fostered the active thermal reduction of sulfates and the formation of highly concentrated hydrosulfuric gases. Anhydrites are replaced by calcite.

Study of fluid inclusions showed that the concentration of solutions in inclusions has a positive correlation with the degree of anhydrite replacement by calcite. In unaltered anhydrites, the salinity of inclusions is similar to that in formation brines with the maximal salt concentration (25 wt %). The salinity drops to 5 wt % if the degree of anhydrite replacement is 50%. This implies a fivefold dilution of saline formation waters by fresh water (reaction product). The degree of brine dilution by the fresh water directly correlates with the $\delta^{18}\text{O}$ value that can decrease to 8‰ (Worden and Smalley, 1996).

It is worth mentioning that the reduction of sulfate produces an equivalent amount of carbon dioxide and water that create an aggressive medium for carbonate rocks. Influence of this medium should be recorded in the isotopic composition of carbonate carbon as shifts of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ parameters to negative values.

In the present communication, we have attempted to estimate the degree of postsedimentary alterations of carbonate rocks based on carbon and oxygen isotopic compositions.

LITHOLOGY OF LOWER CAMBRIAN CARBONATES OF THE IRKUTSK AMPHITHEATER

As was noted in (Vinogradov et al., 2006a, 2006b), lithology of the Irkutsk Amphitheater was comprehensively investigated by geologists under the supervision of Ya.K. Pisarchik (Pisarchik, 1963; Pisarchik et al., 1975). They carried out in-depth analysis of the abundant core material. They also summarized original data and numerous results of previous lithological investigations.

Carbonate rocks prevail in the Cambrian section of the Irkutsk Amphitheater. They first appear in the middle Moty Subformation and gradually replace terrigenous sediments. They are mainly represented by dolomitic marls and clayey dolomites with anhydrite layers and lenses. The carbonate sequence shows a rhythmic structure, but the amount of clastic material decreases upward the section. This trend is also observed along the amphitheater margin (Borehole Bel'sk) to its center (Borehole Zhigalovo). The total content of carbonate material in the upper Moty Subformation reaches 60% in the Bel'sk section and 70% in the Zhigalovo section. Calcite accounts for only a few percents. Calcitization is probably a secondary process related to recrystallization of dolomite and increase in salinity. Secondary alteration of carbonates is also indicated by the following features: the presence of microstylolitic sutures, patchy structure and silicification of rocks, presence of fluorite and celestine crystals, and filling of cracks with

halite and anhydrite. However, secondary alterations of carbonate rocks are generally subordinate.

The Usol'e Formation is mainly composed of rock salt. Its total thickness is 500–600 m, which accounts for 60–70% of the total Usol'e section. Carbonates (dolomites) account for 20% of the section. Calcite is developed as a subordinate component in dolomite recrystallization sectors. Primary calcareous sediments are absent.

The Bel'sk Formation is largely composed of carbonates (80%) represented by dolomites and anhydrite-dolomites (~65%) and calcite (~35%) including the primary variety. These rocks show distinct signs of secondary alteration, such as the replacement of anhydrite with dolomite, formation of breccia, secondary salinization, calcitization, and dedolomitization.

METHODS

Carbonate rocks were decomposed to obtain the gaseous CO_2 for the two-stage isotopic analysis. The finely ground sample was first treated with orthophosphoric acid at room temperature for 1 h according to the routine procedure. We assumed that the gaseous CO_2 released in this process corresponds to the calcite dissolution product (Walters et al., 1972). The sample was further decomposed at 100°C for 1.5 h by sinking the reactor into a vessel with boiling water. The gaseous CO_2 released at this stage represents the dolomite breakdown product (Rosenbaum and Sheppard, 1986). The isotopic composition was measured with a MI-1201 mass spectrometer (PO Electron Co., Suma, Ukraine) with an uncertainty of $\pm 0.2\text{‰}$ in replicate runs.

CARBON AND OXYGEN ISOTOPIC COMPOSITIONS IN LOWER CAMBRIAN CARBONATES OF THE IRKUTSK AMPHITHEATER

Carbon. Sampling sites are shown in lithological columns (Fig. 1). Results of isotope analysis are also presented below (Tables 1, 2; Figs. 2, 3). We could separate carbon dioxide from the calcitic and dolomitic portions of rocks by the routine procedure. The carbon isotopic composition in them is similar and unrelated to contents of calcite and dolomite in the rock. Therefore, we use hereafter the term “carbonate” to designate carbonate rocks, in general, irrespective of their mineral composition.

Carbon isotope ratios in carbonates from boreholes Bel'sk and Zhigalovo show similar variation trends (Fig. 3). The minimal $\delta^{13}\text{C}$ value (approximately -4‰) is recorded in the middle Moty Subformation. In both boreholes, the $\delta^{13}\text{C}$ value increases upward the section and reaches the maximum ($\sim 6\text{‰}$) at the base of the Usol'e Formation. Then, the value decreases and stabi-

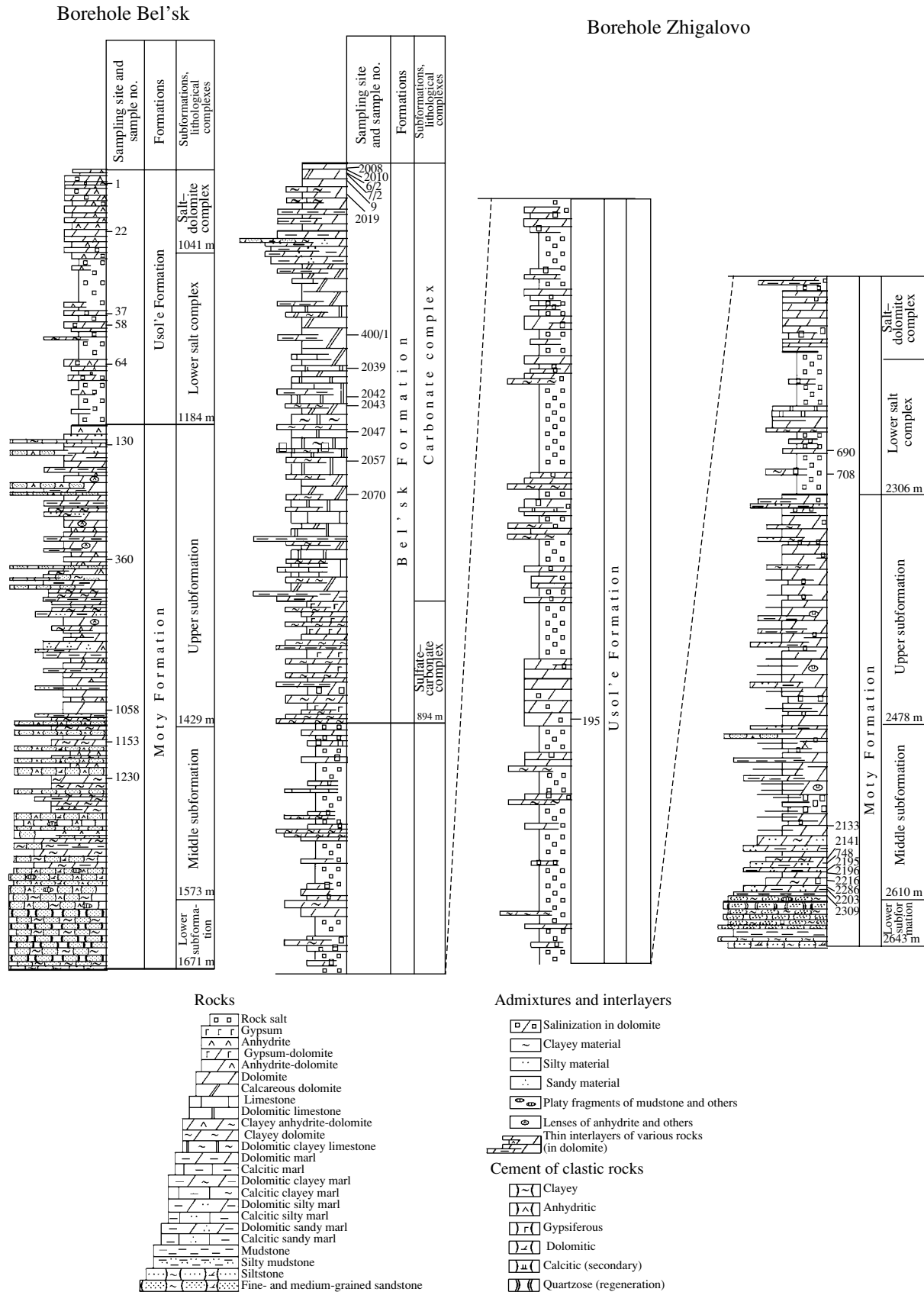


Fig. 1. Lithological columns of sampled portions of boreholes Bel'sk and Zhigalovo showing sites of sampling for the study of carbon and oxygen isotopic compositions of carbonates.

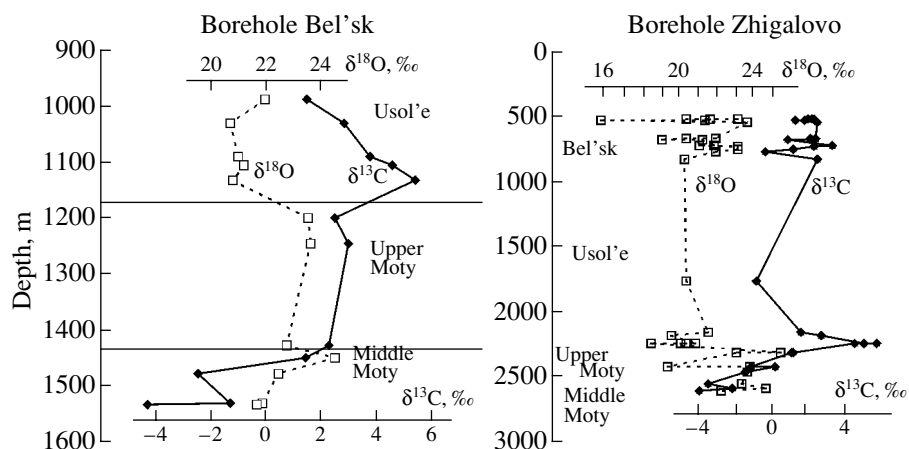


Fig. 2. Carbon and oxygen isotopic compositions of carbonates in boreholes Bel'sk and Zhigalovo.

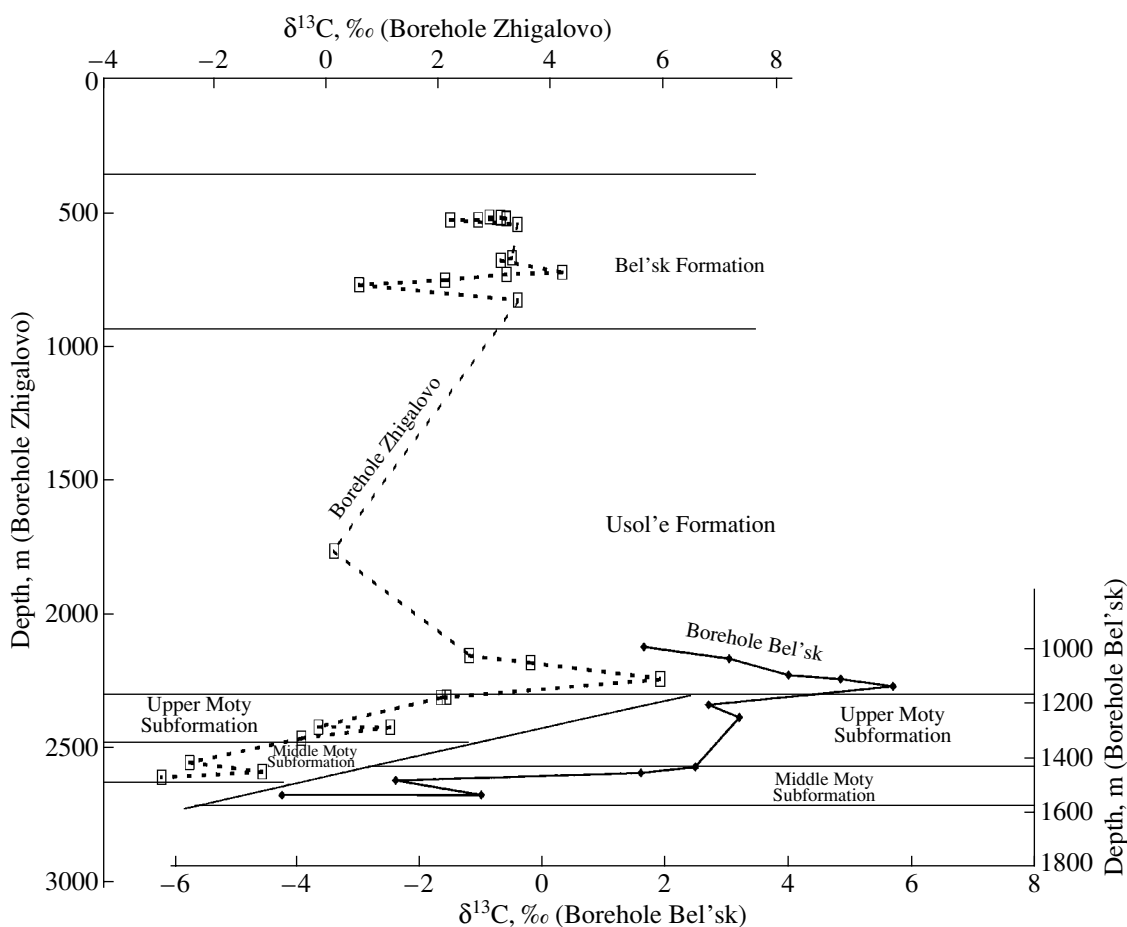


Fig. 3. Comparison of carbon isotopic composition of carbonates in stratigraphically correlated sections of boreholes Bel'sk and Zhigalovo.

lizes at $\sim 1.8 \pm 1\%$ within the Usol'e and Bel'sk formations in Borehole Zhigalovo.

Oxygen. The $\delta^{18}\text{O}$ variation range ($\sim 5\%$) in the studied sections is typical of Early Paleozoic carbonates. Therefore, one can state that carbonates of the

Usol'e Formation are generally characterized by lower $\delta^{18}\text{O}$ values ($\sim 21\%$), relative to the overlying carbonates of the Moty Formation ($22\text{--}24\%$). Relative to carbonate rocks in Borehole Bel'sk, their counterparts in Borehole Zhigalovo are usually characterized by lower

Table 1. Carbon and oxygen isotopic systems in carbonate rocks of Borehole Bel'sk

Sample no.	Depth, m	Formation	Rock composition	$\delta^{13}\text{C}, \text{‰}$	$\delta^{18}\text{O}, \text{‰}$
1	985	Usol'e	Pelitomorphically recrystallized dolomite with halite and anhydrite	1.7	22.1
22	1028	–	Inequigranular recrystallized dolomite	3.0	20.8
37	1088	–	Low-clayey micro- and fine-grained dolomite	4.0	21.1
58	1103	–	Vague-lumpy salinated dolomite with anhydrite	4.8	21.3
64	1130	–	Vague-lumpy micro- and fine-grained dolomite. Fissures and cavities are filled with halite	5.7	20.9
130	1197	Upper Moty	Clayey sandy silty dolomite with lenticles of primary anhydrite	2.7	23.7
360	1243	–	Vague-lumpy fine-grained dolomite	3.2	23.8
1058	1425	–	Low-clayey micrograined dolomite with pyrite inclusions and rare anhydrite crystals	2.5	22.9
1153	1447	Middle Moty	Low-clayey dolomite with secondary anhydrite inclusions	1.6	24.7
1230	1475	–	Clayey-silty dolomite with an insignificant admixture of primary anhydrite and pyrite	-2.4	22.6
1379‡	1528	–	Micrograined clayey-silty dolomite with anhydrite	-1.0	22.0
1393	1530	–	Silty dolomite	-4.3	21.8

Table 2. Carbon and oxygen isotopic systems in carbonate rocks of Borehole Zhigalovo

Sample no.	Depth, m	Formation	Rock composition	$\delta^{13}\text{C}, \text{‰}$	$\delta^{18}\text{O}, \text{‰}$
2008	511	Bel'sk	Clayey pelitomorphically dolomite	1.9	23.1
2010	513	–	Calcareous dolomite with clayey coating	2.1	20.3
6/2	517	–	Dolomitic limestone with OM coating	2.2	21.6
7/2	521	–	Recrystallized limestone with sutures	1.7	21.3
9	522	–	Dolomitic calcitized marl	1.2	15.7
2019	539	–	Dolomitic marl	2.4	23.6
400/12	663	–	Intensely recrystallized limestone	2.3	21.9
		–		2.0	20.3
2039	672	–	Dolomitic calcareous marl	2.1	19.0
		–		0.8	21.2
2042	717	–	Dolomitic limestone (partly replaced by dolomite)	3.2	21.8
		–		3.2	21.0
2043	724	–	Dolomitic marl	2.2	23.1
2047	746	–	Clayey-silty dolomite	1.1	23.1
2057	765	–	Dolomitic marl	-0.4	21.9
2070	822	–	Dolomitic marl with gypsum	2.4	20.2
195	1758	Usol'e	Clayey salinated dolomite	-0.9	20.3
690	2151	–	Clayey-silty dolomite	1.5	21.5
708	2177	–	Dolomite (replacement of anhydrite?)	2.6	19.5
720	2237	–	Dolomitic salinated limestone with anhydrite	4.9	20.8
		–		5.6	20.0
2133	2239	–	Dolomitic limestone with halite	4.9	20.3
		–		4.9	18.4
2141	2307	Upper Moty	Dolomitic marl with anhydrite	1.1	25.4
748	2308	–	Dolomite with halite	1.0	23.0
2195	2417	–	Dolomite with anhydrite inclusions	-1.2	19.3
2196	2418	–	Dolomitic marl with pyrite	0.1	23.7
2216(b)	2459	–	Dolomitic hydromicaceous marl with pyrite	-1.5	23.6
2286	2547	Middle Moty	Anhydritic-dolomitic marl	-3.5	23.3
2203	2583	–	Dolomitic marl	-2.2	24.6
2309	2602	–	Clayey dolomite	-4.0	22.2

values and more irregular distribution of $\delta^{18}\text{O}$ values in the section. In addition, carbonates of the Bel'sk and Moty formations show significant variations in $\delta^{18}\text{O}$ values toward both positive and negative sides. Values of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ usually lack any correlation.

Thus, the results obtained do not show explicit signs of secondary alteration of the carbon and oxygen isotopic signatures of carbonates, although lithological data and isotopic characteristics of sulfur and strontium obviously indicate the generation of isotopically light organic carbon dioxide in the section and the recrystallization of carbonates. This contradiction requires a special discussion.

DISCUSSION

When elucidating reasons for variations in carbon and oxygen isotopic compositions, one should first investigate the following specific feature: the distribution of $\delta^{13}\text{C}$ values is identical in carbonates of both the Moty section and the basal Usol'e Formation in the studied boreholes. Figure 3 clearly shows the gradual increase in $\delta^{13}\text{C}$ values from -4‰ at the base of the middle Moty Subformation to $+6\text{‰}$ at the base of the Usol'e Formation. This stratigraphic interval is marked by changes in sedimentation environment (gradual aridization of climate and grading of the terrigenous setting into the chemogenic evaporitic sedimentation). This circumstance can testify to regional (climatic) factors of variation trend of the carbon isotopic composition.

High $\delta^{13}\text{C}$ values (up to $+6$ and even $+10\text{‰}$) are typical of carbonates in evaporite basins. For example, Upper Permian marine sedimentary carbonates in the Paleotethys (sections in Yugoslavia, Armenia, Iran, Turkey, Pakistan, Nepal, and China) are characterized by high $\delta^{13}\text{C}$ values ranging from $+4$ to $+7\text{‰}$ (Baud et al., 1989, 1996; Holster et al., 1989).

A similar concentration of heavy carbon isotope is noted in carbonates of shallow-water facies (in particular, supralittoral and sebkha dolomites of evaporite and reef facies) and sediments of carbonate platforms (Chafetz et al., 1999; Lu and Meyers, 1998; Wheeler et al., 1999). These basins are commonly characterized by high bioproductivity that is responsible for the accumulation of $\delta^{13}\text{C}$ in carbonate ion.

The assumption of climate aridization is supported to a certain extent by data on the oxygen isotopic composition. Carbonates of the Usol'e Formation at the base of the lower salt complex are generally marked by lower $\delta^{18}\text{O}$ values ($2\text{--}3\text{‰}$ lower than those in the underlying upper Moty Subformation), probably, due to temperature rise by $8\text{--}12^\circ\text{C}$ in the course of the salt sequence formation.

It should be noted that the $\delta^{18}\text{O}$ values obtained for the studied rocks are generally markedly lower than those for evaporitic rocks. For example, the $\delta^{18}\text{O}$ value

is $24\text{--}37\text{‰}$ (average $\sim 28\text{--}34\text{‰}$) in Zechstein carbonates of Poland and Germany (Botz and Muller, 1987; Peryt and Magaritz, 1990). At the same time, upper Kazanian (upper Permian) carbonate rocks of the Volga-Ural region are characterized by decrease in $\delta^{18}\text{O}$ values to $22\text{--}24\text{‰}$ (Kuleshov and Sedaeva, 2004; Kuleshov et al., 2003). Therefore, low $\delta^{18}\text{O}$ values in Lower Cambrian carbonates of the study region do not contradict the notion of their primary sedimentary nature. Variations in carbon and oxygen isotopic compositions can be caused by regional and even global paleoecological environments.

This statement is supported to a certain extent by the coincidence of our carbon data with results obtained for coeval rocks from the adjacent regions.

The Usol'e Formation is relatively depleted in bios-tratigraphic markers. Nevertheless, the available organic remains, lithology, and position in the Lower Cambrian section make it possible to confidently correlate the entire Usol'e Formation (or its basal part) with the Tommotian Variegated Formation in the southern and southeastern Siberian Craton. Correspondingly, the Moty Formation can be correlated with the Ust'yudom Formation currently referred to the Nemakitian-Daldynian (Manykai) Stage (Semikhatov et al., 2004). The Nemakitian-Daldynian (Manykai) and Tommotian sequences with reliable faunal determinations are located in the western Anabar and Aldan river regions. Curves of carbon isotope evolution (CIE) in these sections are surprisingly similar with each other. They are also similar with the CIE curve obtained for rocks of the Irkutsk Amphitheater. The CIE curves have a typical shape. The base of the Nemakitian-Daldynian (Manykai) Stage includes a negative $\delta^{13}\text{C}$ anomaly (-5‰) that coincides in the western area with the appearance of skeletal fauna marking the Vendian/Cambrian boundary. The gradual upsection increase in $\delta^{13}\text{C}$ is complicated by fluctuations of the second order. In sections with abundant small shells, these fluctuations can be attributed to zonal stratigraphy and correlated with distal areas. The $\delta^{13}\text{C}$ value decreases after reaching the maximum near the Nemakitian-Daldynian (Manykai)/Tommotian boundary. Anomalies comparable (in amplitude) to those at the Vendian/Cambrian boundary are absent in the entire Cambrian (and even Phanerozoic) section.

The in-depth isotopic investigation of Early Cambrian rocks has been carried out not only in the Siberian Craton, but also in Namibia, Morocco, Australia, South America, North America, India, and other regions (Kaufmann and Noll, 1995). The trend of $\delta^{13}\text{C}$ variation is everywhere nearly similar to that in the Siberian Craton except for minor variations in amplitude.

The carbon isotope anomaly at the Vendian/Cambrian boundary could originate as early as the sedimentation stage, reflecting a certain planetary-scale event accompanied by variation in the major parameters of the global carbon cycle. The negative anomaly at the

Vendian/Cambrian boundary could be related to emission of a large volume of gaseous carbon dioxide (product of the oxidation of organic matter accumulated in sediments during the preceding epochs) into atmosphere and hydrosphere (Pokrovskii, 1996; Pokrovskii et al., 1999).

The appearance of rocks with low $\delta^{13}\text{C}$ values could also be provoked by secondary (epigenetic) transformations. Materials reported in (Vinogradov et al., 2006a, 2006b) suggest that the entire Early Cambrian sequence of the Irkutsk Amphitheater was subjected to postdiagenetic alterations. Therefore, we can assume that the positive shift of the CIE curve matches the primary $\delta^{13}\text{C}$ signature of carbonates. Correspondingly, all lower values testify to secondary transformations.

In this model, variation in the carbon isotopic composition can be accompanied by variation in the oxygen isotopic composition. The secondary (epigenetic) transformation of carbonates is usually followed by decrease of the $\delta^{18}\text{O}$ value, i.e., enrichment in ^{16}O . The synchronous and consistent mode of such variations in carbon and oxygen isotopic compositions has been recorded in many cases. Discordance observed in the behavior of carbon and oxygen variation plots in the studied boreholes (Figs. 2, 4) is easily explained from the point of view of the retention of isotope systems of carbonates since the moment of sedimentation. However, results of lithological investigations are still inconsistent with sulfur and strontium isotope data that indicate an extensive manifestation of epigenetic transformation of Lower Cambrian rocks in the Irkutsk Amphitheater. Resolution of this contradiction is a task for future investigations.

Thus, data on carbon and oxygen isotopic compositions in carbonates suggest the following scenario. In the course of intense postsedimentary (epigenetic) transformations of Lower Cambrian sedimentary rocks in the Irkutsk Amphitheater, carbonate rocks probably retained the memory of primary sedimentation environment. Of course, one cannot affirm that the rocks represented a completely closed system, relative to aggressive epigenetic solutions. Probably, only stratigraphic positions of the major elements of isotope curves (bends, maximums, and minimums) were unaltered.

The specific features discussed above—weak alterations of rocks, retention of the primary isotopic composition, and preservation of the initial sedimentation environment—are not unique. For example, one can easily identify signs of the existence of saliferous rocks in Paleoproterozoic carbonates of the southwestern Pamirs (Litsarev et al., 1977).

CONCLUSIONS

Materials considered in this and previous communications make it possible to draw the following conclusions.

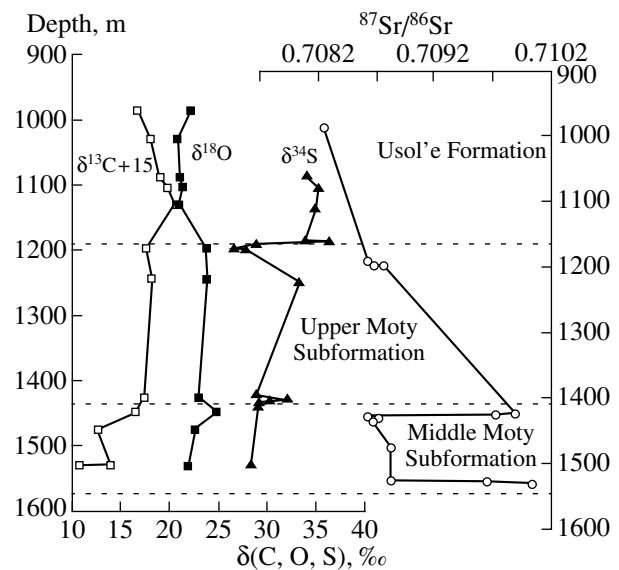


Fig. 4. Comparison of isotope ratios of carbon, oxygen, sulfur, and strontium in Lower Cambrian sulfate-carbonate rocks from Borehole Bel'sk. The $\delta^{13}\text{C}$ scale is exaggerated by 15‰ for the sake of clearness.

Sedimentary rocks are subjected to alterations during their whole life period. Their mode, rate, and intensity vary and depend on many conditions. This sufficiently trivial affirmation per se hardly needs additional confirmations. However, we believe that scales of these processes and their significance in the geochemical cycle of terrestrial material represent fundamental properties of our planet related to the presence of hydrosphere, atmosphere, and biosphere. We attempted to substantiate this statement based on the case study of Lower Cambrian saliferous rocks of the Irkutsk Amphitheater, because the saliferous rocks are likely to be most altered by secondary processes.

In any case, all postsedimentary alterations of rocks occur under the influence of water solutions that provoke the direct physical dissolution of substance and its chemical transformation. Salts (primarily, chloride and sulfate varieties) are the compounds that are most readily dissolved. In addition, the well-known natural salt-oil paragenesis (Kapchenko, 1974) offers scope for the active interaction between an ordinary member of evaporitic series (anhydrite) as oxidizer and organic matter of the oil series as reducer, resulting in the production of geochemically active gases, such as H_2S and CO_2 . At low temperatures (up to 100°C), the chemical reaction is very slow and dominated by bacterial sulfate reduction. Beginning from approximately $120\text{--}130^\circ\text{C}$, sulfates are rapidly subjected to chemical (abiogenic) reduction by organic matter. The sulfate reduction, probably, represents one of the most interesting and significant (global-scale) geochemical processes in the Earth's sedimentary cover. In our first communication (Vinogradov et al., 2006a), we showed that sulfate reduction alone was responsible for the disappearance

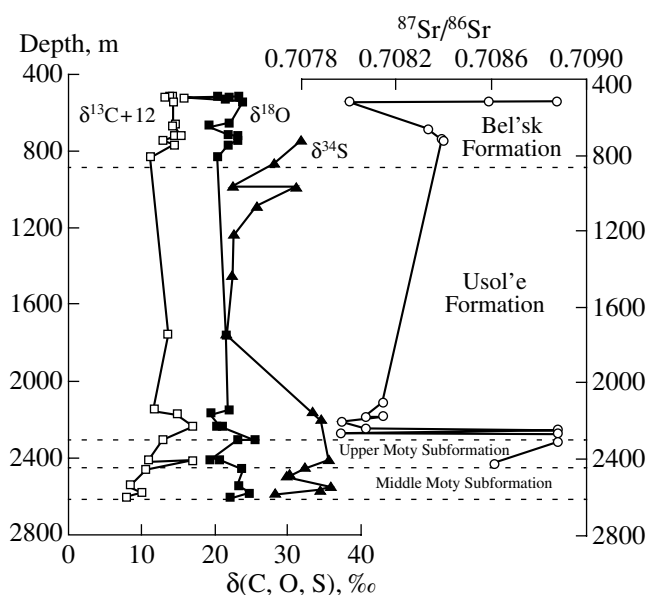


Fig. 5. Comparison of isotope ratios of carbon, oxygen, sulfur, and strontium in Lower Cambrian sulfate-carbonate rocks from Borehole Zhigalovo. The $\delta^{13}\text{C}$ scale is exaggerated by 12‰ for the sake of clearness.

of no less than 30% of anhydrite sediments from the section. Hence, an equivalent amount of organic matter was oxidized. Judging from the well-known isotope data, this redox pattern is typical of all Cambrian evaporites that are widespread in virtually all continents.

One additional essential conclusion can be deduced from the isotope data. In our first communication, we analyzed the well-known “principle of exhaustion” as applied to isotope fractionation in the course of sulfate reduction. According to this principle, the more mobile light isotope ^{32}S is involved in chemical reactions more often than the heavy isotope ^{34}S . Consequently, the hydrosulfuric sulfur turns out to be isotopically lighter in the reaction product than in the residual sulfate. Thus, the sulfate is progressively enriched in the heavy isotope. However, realization of this scenario needs the involvement of the whole sulfate volume in the process of reduction; i.e., the sulfate material should pass through the solution in a regime of constant mixing. This option is apparently essential for the whole volume of sulfates that are present in the present-day section. This mechanism requires a thorough analysis and, probably, special investigation. However, the participation of this mechanism is indisputable.

This inference is sometimes difficult to perceive or is not perceived at all, because the low-porous anhydrites are considered an impermeable medium. However, stratal carbonatization of anhydrites is a well-known process that can proceed only with the participation of solutions. It is noteworthy that the replacement of anhydrite with carbonates leads to nearly 20% reduction of volume and autocatalytic acceleration of the anhydrite-methane interaction (Worden et al., 1996).

Dissolution and removal of salt also fosters the acceleration of water-anhydrite interaction and the expansion of rocks. The formation of cavities provokes the brecciation and fracturing of overlying rocks and the consequent increase of their permeability. Scales of the underground dissolution of salt are discussed in our previous paper (Vinogradov et al., 2006a). The Irkutsk Amphitheater is not an exception in this respect. For example, Kapchenko (1974) has noted that leaching zones in the West Canada Basin, up to 1500–2000 km long, include as much as five cycles of salt dissolution embracing the Devonian-Cretaceous interval.

In any case, the previously known and recently obtained data on the sulfur isotopic composition show that virtually all Lower Cambrian anhydrites of the Irkutsk Amphitheater were probably subjected to recurrent processes of epigenetic dissolution, recrystallization, and sulfate reduction. These processes are likely to continue at present. Perception of this fact provides new insights into scales of the epigenetic transformation of rocks.

Data on the strontium isotopic composition of carbonate rocks also lead to the same conclusion. The Sr isotopic signature is shifted in the majority of carbonate rocks. As was mentioned above, the strontium isotope system is relatively stable in specific regional conditions, because carbonate and sulfate rocks that prevail in the section turn out to be Sr-carriers. The Sr isotopic composition is shifted by the input of ^{87}Sr from the subordinate silicate component of rocks. Therefore, the shift of Sr isotope ratio is also insignificant (Vinogradov et al., 2006b). It is obvious that carbonates could only be contaminated with the radiogenic Sr via the solutions. Hence, all Lower Cambrian carbonate sequences of the Irkutsk Amphitheater were altered by the solutions.

The carbon isotope system is even more stable, because carbonate rocks prevail in the section and the amount of carbon dioxide—product of organic matter oxidation by sulfates—is relatively small. Therefore, isotope data do not provide explicit evidence of the involvement of carbon dioxide in the recrystallization of carbonates. The major elements of the CIE curve were probably conserved after the sedimentation stage.

Figures 4 and 5 compare sulfur, carbon, oxygen, and strontium isotope data on the Lower Cambrian section in boreholes Bel'sk and Zhigalovo. Isotopic compositions of these elements are characterized by significant variations, and correlation between them is absent or insignificant. The isotopic scatter of each element was governed by its geochemical properties and specific conditions of rock formation or transformation. This fact once more demonstrates that the notion of “united stratigraphic level” is rather conditional. Its precise definition is a very complicated stratigraphic, geological, and geochemical issue.

We intend to continue the investigation of isotopic systems in the Middle Cambrian section of the Siberian

Craton characterized by a unique sulfur isotopic composition (Pisarchik et al., 1981).

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