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Carbon, Oxygen, Strontium, and Sulfur Isotopic Compositions in Late Precambrian Rocks of the Patom Complex, Central Siberia: Communication 1. Results, Isotope Stratigraphy, and Dating Problems

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Abstract—Results of the study of isotopic compositions of C, O, S, and Sr in late Precambrian sections of the Patom Complex and its analogues are presented. Total scatter in $\delta^{13}C$ values is more than 21‰ (from –13.5 to 8.1‰). The sections strongly differ in thickness, but they have similar carbon isotope curves with two dramatic drops in $\delta^{13}C$ from extremely high (>4‰) to extremely low (<–8‰) values. The lower negative excursion is associated with the glacial horizon (Dzhemkukan and Nichatka formations), while the upper excursion spans the entire Zhuya Group, which is as thick as 800–1000 m on the carbonate shelf (Nikol'skoe and Chencha formations along the Zhuya and Lena Rivers) and only 250–350 m at the carbonate platform (Torgo Formation, Chara River). Steady extremely high $\delta^{13}C$ values (from 7 to 8‰) are typical of the glacial horizon underlying the Mariinsk Formation, as well as the Barakun and Valyukhta formations and their analogues, which separate negative excursions. The minimum $^{87}Sr/^{86}Sr$ ratios in limestones of the Kumukulakh (0.70725), Barakun (0.70727), Valyukhta (0.70769), Nikol'skoe (0.707904), Chencha (0.70786) and Torgo (0.70799) formations suggest the accumulation of sediments 660–580 Ma ago. Correspondingly, glacial diamictites of the Nichatka and Dzhemkukan (Bol'shoi Patom) formations can be correlated with the early stage of the Marinoan glaciation (635–665 Ma); the Zhuya Formation, with transgression that terminates the late stage of the same glaciation or the Gaskiers glaciation (580 Ma). Problems related to the genesis of carbonate rocks with extremely high and low $\delta^{13}C$ values will be considered in the second communication.

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INTRODUCTION

Sharp variations in Sr, C, and O isotopic compositions in Neoproterozoic carbonate sequences in response to global environmental changes make them important chronostratigraphic markers. The most significant fluctuations in $\delta^{13}C$ (>20%) are one order of magnitude higher than those in Mesozoic and Cenozoic sequences. These sharp fluctuations have been the subject of much controversy (Kaufman and Knoll, 1995; Jacobsen and Kaufman, 1999; Pokrovskii, 1996; Pokrovskii et al., 1996; Pokrovskii et al., 1999; Walter et al., 2000; Des Marais, 2001; Kennedy et al., 2001; Hoffman and Schrag, 2002; Schrag et al., 2002; Godderris et al., 2003; Nedelec et al., 2005). The most interesting factors affecting these variations are those that define the CO_2 content in atmosphere and climate: volcanic activity, degree of water stratification in the sedimentation basin and World Ocean as a whole, rate of bioproductivity, conditions of burial and decomposition of hydrocarbons in sediments, and intensity and pattern of chemical weathering. An important insight into this issue can be provided by the study of Late Precambrian carbonate sequences of the Patom Complex, which has the widest $\delta^{13}C$ ranges and volumes of rocks with anomalous isotope characteristics known to date.

Thick (>500 m) horizons of Late Precambrian carbonates with extremely low $\delta^{13}C$ values (from –8 to –12‰ PDB) were found in Central Siberia more than 10 years ago (Pokrovskii and Gertsev, 1993]. Epigenesis of sediments with an extremely high content of organic matter (>30%) was considered the most probable reason for the formation of rocks sharply depleted in heavy carbon isotope relative to "normal" marine carbonates.

At present, this explanation cannot be accepted as satisfactory one. Such organic-rich rocks and signatures of extremely strong postsedimentary transformations are absent in the study region. Almost coeval carbonates with similarly low $\delta^{13}C$ values have been reported from South Australia (Calver et al., 2000; McKirdy et al., 2001), northwestern Canada (Narbonne et al., 1994), Oman (Cozzi et al., 2004; Le Guerroue, 2006), East Siberia (Semikhatov et al., 2004), and northern Norway (Melezhik et al., 2005). These facts

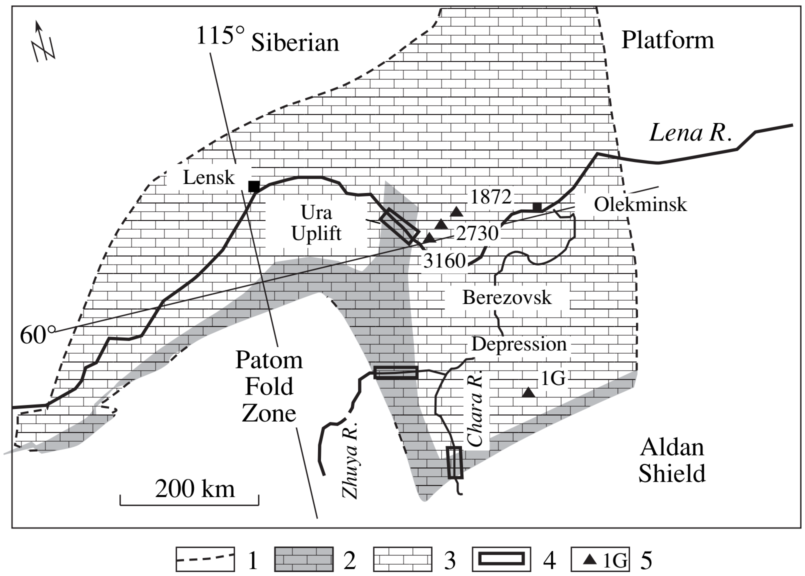

Fig. 1. Position of sampled sections of Late Precambrian rocks of the Patom Complex and its analogues. (1) Inferred boundaries of the Late Precambrian paleobasin (Bobrov, 1964, 1979); (2) margin of the Patom fold zone and Ura Uplift, where rocks of the Patom Complex are exposed; (3) southern margin of the Siberian Platform (with Berezovsk Depression), where rocks of the Patom Complex and its analogues are recovered from boreholes; (4) studied exposures; (5) studied boreholes.

suggest the abundance of basins with anomalous carbon cycle in the Neoproterozoic as a response to global changes in natural environment. To refine the chemostratigraphy of Late Precambrian rocks of the Patom Complex and decipher the nature of carbonates with anomalous carbon isotopic composition, we scrutinized the isotopic composition of rocks from surface exposures and deep boreholes that penetrated various parts of the paleobasin.

GEOLOGICAL SETTING

Rocks of the Patom Complex and its analogues occupy wide areas in the northern and eastern parts of the Patom fold system and in the southern Siberian Platform. In the late Precambrian, this territory represented a vast (no less than 250 000 km^2) basin, which accumulated a carbonate–terrigenous sequence more than 4 km thick. The Late Precambrian rocks are exposed as a narrow band bounding the Patom Highland in the northwest, north, and east within the relatively young Ura Uplift and in the Chara River valley (Fig. 1). Rocks of the Patom Complex were recovered by deep boreholes in the Berezovsk Depression east of the Ura Uplift.

The geological structure of the territory has been described in a number of papers and monographs (Chumakov, 1959; Bobrov, 1964, 1979; Dol'nik and Vorontsova, 1974; Shenfil, 1991, Ivanov et al., 1995). According to the accepted correlation scheme (Table 1), the studied sections of the Patom Complex are subdivided into the Balaganakh, Dal'nyaya Taiga, and Zhuya groups. The scheme is based on the small-scale mapping and tracing of the stratigraphic marker horizons of the Patom Complex from the Zherba River in the Ura Uplift to the Tokko River on the western slope of the Aldan Shield (Zhuravleva et al., 1961) and was later confirmed by the state geological survey (scale 1 : 200000), deep drilling, and numerous thematic works (Bobrov, 1964, 1979; *Opornye razrezy* …, 1972; Ivanov et al., 1995; Grausman, 1997). The most important regional marker units are black shales and carbonates of the Barakun Formation and characteristic aphanitic limestones of the Chencha and Torgo formations that are crosscut by numerous stylolitic sutures.

The Ura Uplift

The Ura Uplift incorporates transitional (subplatformal) and weakly dislocated sediments of the Patom Complex. Rocks of the *Balaganakh Group* are exposed here incompletely. Therefore, we did not analyze and consider them in the present paper.

The *Dal'nyaya Taiga Group* is subdivided into the Bol'shoi Patom or Dzhemkukan (~1000 m), Barakun (1000–2000 m), and Valyukhta (1000–1500 m) formations. The Bol'shoi Patom (Dzhemkukan) Formation consists of diamictites intercalating with sandstones and rare beds of black siltstones and schists. The formation is crowned by cap dolomites with an apparent thickness of 2.5 m. There is evidence for glacial origin of rocks of the Dzhemkukan (Bol'shoi Patom) Formation (Chumakov, 1993, 2004).

The Barakun Formation is subdivided into three subformations with gradual transitions. The lower subformation consists of limestones and sandy limestones.

Table 1. Stratigraphic subdivision and correlation scheme of sections of the Patom Complex and its analogues (Chumakov, 1959; Zhuravleva et al., 1959; Bobrov, 1964, 1979; Ivanov et al., 1995; Grausman, 1997)

<table>
<tr><td rowspan="2">Group, age</td><td>Ura Uplift and Patom Highland</td><td>Boreholes 2730 and 3160</td><td colspan="2">Boreholes 1G and 1872</td><td>Chara River</td></tr>
<tr><td colspan="5">Formation</td></tr>
<tr><td>Cambrian</td><td>Nokhtuisk</td><td>Nokhtuisk</td><td colspan="2">Yuedei</td><td>Yuedei</td></tr>
<tr><td rowspan="2">Vendian</td><td>Tinnaya</td><td>Tinnaya</td><td colspan="2">Tinnaya</td><td>Tinnaya</td></tr>
<tr><td>Zherba</td><td>Seralakh</td><td colspan="2">Seralakh</td><td>Seralakh</td></tr>
<tr><td rowspan="2">Zhuya, Late Riphean (?)</td><td>Chencha</td><td>Chencha</td><td rowspan="2">Torgo</td><td rowspan="2">upper
middle
lower</td><td rowspan="2">Torgo</td></tr>
<tr><td>Nikol'skoe</td><td>Nikol'skoe</td></tr>
<tr><td rowspan="6">Dal'nyaya Taiga, Middle Riphean (?)</td><td rowspan="2">Valyukhta</td><td>Kalancha</td><td colspan="2">Alekseev</td><td>Upper Sen</td></tr>
<tr><td>Ura</td><td colspan="2">Chekurdakh</td><td>Lower Sen</td></tr>
<tr><td rowspan="3">Barakun</td><td>Khalatyrbyt</td><td colspan="2">Khalatyrbyt</td><td rowspan="3">Kumukulakh</td></tr>
<tr><td>Shumikha</td><td colspan="2" rowspan="3">Crystalline basement</td></tr>
<tr><td>Moldoun</td></tr>
<tr><td>Dzhemkukan
Bol'shoi Patom</td><td rowspan="5">Unexposed</td><td>Nichatka</td></tr>
<tr><td rowspan="4">Ballaganakh, Middle Riphean (?)</td><td>Mariinsk</td><td colspan="2" rowspan="4">Unexposed</td><td rowspan="4">Ballaganakh</td></tr>
<tr><td>Kharluktakh</td></tr>
<tr><td>Khaiverga</td></tr>
<tr><td>Bugarikhta</td></tr>
</table>

The middle subformation is dominated by sandstones, schists, and carbonate sandstones. The upper subformation is again composed of limestones. The overlying Valyukhta Formation in the southern part of the Ura Uplift is mainly composed of clayey and silty schists with rare interlayers of sandstones and limestones. In the northern part along the Lena and Ura rivers, the formation is subdivided into the lower Ura Formation (300–700m) consisting of terrigenous rocks and the upper Kalancha Formation (450–550 m) consisting of carbonaceous limestones and dolomites. The formation is crowned by quartz–feldspar sandstones up to 200 m thick. It is noteworthy that limestones of the Dal'nyaya Taiga Group have high (up to 1.5%) contents of Sr, which are considered an indicator of the primary aragonite composition of limestones (Golovenok, 1985). Black and dark gray rocks of the Barakun and Valyukhta formations contain up to 3% organic matter and often have a hydrosulfuric smell.

The *Zhuya Group* is subdivided into the Nikol'skoe (300–400 m) and Chencha (400–500 m) formations. The Nikol'skoe Formation rests on the underlying rocks without visible unconformity and consists of variegated marls and silty limestones. The carbonate material gradually increases upward the section. The base of the overlying Chencha Formation is arbitrarily drawn along the line of predominance of limestones over marls and silty limestones. In most sections, the Chencha Formation consists of two (Alyancha and Khopych) units, which are often considered independent formations (Chumakov, 1959; Bobrov, 1979). The Alyancha Formation is composed of light gray and variegated platy limestones (150–180 m) grading into stromatolitic limestones (100–150 m). The Alyancha Formation (150 m thick) is dominated by oncolitic limestones intercalated with sandy and silty limestones. The stromatolitic limestone is subordinate. Aphanitic limestones of the Chencha Formation contain abundant stylolitic sutures, indicating extensive postsedimentary dissolution and removal of carbonate material.

The Zherba Formation is composed of quartzose sandstones (with a significant amount of dolomites at the base) and overlies the Chencha Formation without visible unconformity (Chumakov, 2004). The lower (carbonate) and upper (terrigenous) units of the Zherba Formation are separated by an unconformity of indefinite duration (Pelechaty, 1998; Khomentovskii et al., 2004). The study of overlying carbonate-rich rocks of the Tinnaya Formation is beyond the scope of this communication.

The Eastern Margin of the Patom Fold Zone

One of the best sections of the Patom Complex is located at lower reaches of the Zhuya River, which transects the eastern margin of the Patom Highland (Fig. 1). The base of the Patom Complex consists of the *Balaganakh Group*, which is subdivided into the Kharluktakh, Khaiverga, Bugarikhta, and Mariinsk formations. The Kharluktakh, Khaiverga, and Bugarikhta formations (total thickness ~2km) consist of metamorphosed terrigenous rocks. They are conformably overlain by the Mariinsk Formation (~650 m) composed of dark gray and black bedded carbonaceous limestones and sandy limestones with interlayers of calcareous sandstones (more rarely, siltstones) in the lower and upper parts.

The *Dal'nyaya Taiga Group* is subdivided into the Dzhemkukan, Barakun, and Valyukhta formations. In the Zhuya section, the Dzhemkukan Formation (400–800 m thick) overlies the Mariinsk Formation without visible unconformity and consists of terrigenous sediments (sandstones, calcareous sandstones, and dark gray carbonaceous phyllitic and silty schists). The Dzhemkukan Formation is gradually replaced upsection by the Barakun Formation (700–800m), which is composed of dark massive limestones with interbeds of schistosed limestones, calcareous limestones, and calcareous sandstones. In the Zhuya section, the Valyukhta formation (500–600 m) conformably overlies the Barakun Formation and is mainly composed of terrigenous rocks: sandstones sandwiched between the carbonaceous quartz–sericite schists.

The *Zhuya Group* combines the Nikol'skoe and Chencha formations. The Nikol'skoe Formation overlies the Valyukhta Formation without visible unconformity. In the Zhuya section, the Nikol'skoe Formation consists of thin-bedded, usually bright cherry red, pink, lilac, and green marls and calcareous siltstones. The thickness of the Nikol'skoe Formation in most exposures is 350–400 m. The overlying Chencha Formation (700–720 m) consists of monotonous light gray aphanitic limestones in the lower part and intercalation of stromatolitic and microphytolitic limestones in the upper part (*Opornye razrezy…*, 1972).

The Northern Part of the Berezovsk Depression

We studied cores of two boreholes. Borehole 3160 "Macha" is located on the left bank of the Lena River near the mouth of the Macha River on the northwestern wall of the depression. Borehole 2730 "Bysakhtakh-Kyuel'sk" is located 35 km away in the north in the deepest part of the depression. We also studied individual core samples from borehole 1872 "Bysakhtakh" located 25 km northeast of borehole Bysakhtakh-Kyuel'sk. The Late Precambrian section recovered by boreholes is generally similar to the Ura Uplift section described above. However, there are some differences. For example, carbonate rocks in counterparts of the Barakun and Valyukhta formations in the boreholes consist of dolomites rather than limestones as in the Ura Uplift.

The deepest horizons of the section were encountered in borehole Bysakhtakh-Kyuel'sk. Near the base at a depth of 2757 m, the borehole encountered dark gray dolomites of the Moldoun Formation, the counterpart of the lower subformation of the Barakun Formation. The overlying Shumikha Formation (200 m thick) comprises shales, siltstones, dolomitic siltstones, and more rarely, pure dolomites. The amount of dolomites significantly increases in the overlying Khalatyrbyt Formation (307 m). This formation is overlain by the Ura Formation (188 m), which consists of very dense siltstones, shales, and quartzitelike sandstones, and the dolomite-rich Kalancha Formation (394 m). In the Kalancha Formation, dolomites are supplemented with abundant oncolitic (microphytolitic) dolomites. The overlying Nikol'skoe Formation (444 m) was represented by two core samples of very dense silicified calcareous cherry siltstones. The overlying Khopych (Chencha) Formation (363 m) was also poorly sampled in the borehole. We had three samples of dark gray silicified limestones that apparently differ strongly from rocks of the Chencha Formation in the Ura Uplift. Sections of boreholes Macha and Bysakhtakh were sampled with large intervals. Therefore, they are not considered in this paper. The sequences recovered by these boreholes are similar in thickness to those in borehole Bysakhtakh-Kyuel'sk. However, the Ura Formation is more than 900 m thick in borehole Macha.

The Southern Part of the Berezovsk Depression

We studied two sections on the southeastern limb of the Berezovsk Depression adjacent to the Early Precambrian Chara Block: (1) section along the Chara River and mouths of its left tributaries (Mokryi and Sukhoi Kumukulakh rivers) and (2) section recovered by borehole 1G "Verkhnii Dzhege" in the watershed of the Chara and Tokko Rivers near the sources of the Torgo River.

Although the Chara section is located at a relatively small distance (100 km) from the Zhuya section, this section is characterized by weaker metamorphism, significantly lesser thickness, and different lithology. The base of the section consists of sandstones, gritstones, and conglomerates of the *Ballaganakh Group*. The overlying Nichatka Formation (150–160 m) of diamictites and sandstones is correlated with the Bol'shoi Patom (Dzhemkukan) Formation of the Patom Highland and Ura Uplift (Chumakov, 1993).

The Kumukulakh Formation, which overlies the Nichatka Formation without visible unconformity, consists of three members. The lower member (30–35 m) is composed of thinly interbedded variegated siltstones with rare interlayers of limestones (10–15 cm). The middle member (50–60 m) consists of intercalated siltstones and limestones. The upper member (~30 m) is represented by black carbonaceous shales. The formation is dominated by rhythmic alternation of pelitic and silty beds typical of the two-member flysch accumulated in a deep-water shelf environment.

The Sen Formation conformably rests on the Kumukulakh Formation and is subdivided into two units, which are sometimes considered individual formations. The lower terrigenous unit (200 m) is identified as the Imalyk Formation, whereas the upper carbonate unit (150–180 m) is identified as the Tokko Formation. The lower unit is composed of quartz–carbonate and carbonate sandstones (calcarenites) with a bimodal “herring-bone” cross-bedding typical of basins with strong tidal currents. The upper unit is dominated by carbonate breccias, which typically fill underwater erosion channels of the hydrodynamically active slope of the carbonate platform. Carbonate rocks with abundant spherical nodules possibly developed after calcium sulfates are subordinate. These rocks are typical of the shallower-water and evaporate facies.

The overlying Torgo Formation (300–350 m) begins with a 10- to 20-m-thick bed of variegated marls (*Opornye razrezy*…, 1972), which are similar to rocks of the Nikol’skoe Formation. These rocks are replaced upsection by homogenous light gray (mainly, oncolitic and stromatolitic) limestones. Stromatolites make up giant bioherms and biostromes with the lifetime relief. Their height (a few meters) suggests a relatively deep-water part of the carbonate platform. In the upper part of the section, the height of stromatolites decreases, while the space between the buildups is filled with calcarenites with a bimodal (cross- and cross-wavy) bedding suggesting shallow-water settings affected by waves and tidal currents.

The Late Precambrian section recovered by borehole 1G Verkhnii Dzhege is no more than 1000 m thick. The 11-m-thick bed of gray dolomites encountered near the bottomhole above the crystalline basement is ascribed to the Khalatyrbyt Formation. The dolomites grade upsection into a terrigenous sequence (134 m thick), which is correlated with the Chekurdakh Formation. In the borehole, the latter formation is represented by variegated shales and siltstones with sandstone intercalations. Terrigenous rocks often contain a significant carbonate admixture (dolomite). At the boundary between the Chekurdakh Formation and the overlying Alekseev Formation (178 m), which is composed of dolomites, dolomitic siltstones, and sandstones with interlayers of gritstones, the borehole encountered a thick sill of alkaline syenites, which resemble rocks of the Malyi Murun Massif.

The overlying Torgo Formation is subdivided into three subformations. The lower subformation (84 m) is mainly composed of terrigenous rocks (siltstones, dolomite-bearing siltstones, and shales). The middle subformation (68 m) begins with a bed of dark gray dolomites (20 m), which grade upsection into characteristic bright cherry marls (~40 m) that are similar to rocks of the Nikol’skoe Formation in the Ura Uplift. The upper subformation (132 m thick) can be subdivided into two units. The lower unit is composed of aphanitic porcelainlike limestones with an insignificant dolomite admixture. The upper unit consists of low-calcareous dolomites. Dolomites in the lower unit are silicified and compact, whereas dolomites of the upper unit are porous and marked by hydrosulfuric smell. In places, carbonates of the middle and upper subformations of the Torgo Formation are crosscut by vertical anhydrite veinlets 1–2 cm thick. The core of rocks overlying the Torgo Formation is nearly absent. We had only one sample of cavernous calcareous dolomite from the Telegespin sequence, which is considered a part of the Tinnaya Formation.

The age of the rocks of the Patom Complex is equivocal. Based on the study of stromatolites, oncolites, and catagraphites, the Dal’nyaya Taiga Group was traditionally ascribed to the Middle Riphean; the Zhuya Group, to the Late Riphean; and the Zherba and Tinnaya formations, to the Vendian. (Zhuravleva et al., 1961; Dol’nik and Vorontsova, 1974; Bobrov, 1979). According to the later viewpoint, which is based on the historical–geological considerations and supported by geological correlations with distant areas, the Dal’nyaya Taiga and Zhuya groups should be ascribed to the Baikalian period with an age of 850–650 Ma (Khomentovskii et al., 2002).

The Vendian age of the Zherba Formation is substantiated by K–Ar glauconite dates within 580–620 Ma (*Opornye razrezy*…, 1972). The lower boundary of the Cambrian is commonly drawn at the base of the Nokhtuisk Formation (Zhuravleva et al., 1961; Golovenok et al., 1963; Bobrov, 1964; Kolosov, 1975). This viewpoint was recently supported by findings of the Nemakit–Daldyn and Sunnagin fauna in the upper part of the Tinnaya Formation and lower part of the Nokhtuisk Formation, respectively (Khomentovskii et al., 2004). Attempts to substantiate the Cambrian/Precambrian boundary based on carbon isotope data did not yield unambiguous results (Sochava et al., 1996; Khomentovskii et al., 2004). The remarkable $\delta^{13}C$ pre-Tommotian positive excursion (4–5‰) in typical sections of the northern and southern Siberian Platform (Pokrovskii and Missarzhevskii, 1993; Pokrovskii, 1996; Kaufman et al., 1996) is less distinct in the Ura Uplift. The position of the negative carbon isotope anomaly, which marks here the base of the Manykai (Nemakit–Daldyn) stage, is also unclear.

METHODS

To determine the carbon and oxygen isotopic compositions, samples were decomposed in 100% orthophosphoric acid at two stages: at 25°C for 1.5–2 h and then at 100°C for 1 h. The first stage fosters the decomposition nearly whole calcite and 2–3% dolomite. The complete decomposition of dolomite at the second stage promotes the separate measurement of carbon and oxygen isotopic compositions in calcite and dolomite, as well as the determination of proportions of calcite and dolomite in the carbonate phase by volumetric method with an accuracy of ±5% (Rosenbaum and Sheppard, 1986). Since the oxygen isotope fractionation is different during the acid decomposition of calcite at 25°C (10.2‰) and the decomposition of dolomite at 100°C (9.1‰), the measured $\delta^{18}O$ values in dolomite are 1.1‰ higher. To determine the sulfur isotopic composition, anhydrite was decomposed with V_2O_5 in the presence of Cu at 1100°C. The carbon, oxygen, and sulfur isotopic compositions were measured on a MI 1201B mass spectrometer. The $\delta^{13}C$ value is given in per mille (‰) relative to the PDB standard; the $\delta^{18}O$ value, in per mille relative to the SMOW standard; and the $\delta^{34}S$ value, in per mille relative to the Sikhote Alin meteorite standard. The accuracy (reproducibility) of measurement is ±0.2‰ for $\delta^{18}O$ and $\delta^{13}C$ and ±0.3‰ for $\delta^{34}S$.

The Sr isotopic composition and Rb and Sr contents were determined by isotope dilution. Measurements were performed on a MAT 260 mass spectrometer in the Geological Institute (Moscow) and a MAT-261 mass spectrometer at the Laboratoire de Mécanismes et Transfert en Géologie, Midi-Pyrenees Observatoire, Toulouse, France. The $^{87}Sr/^{86}Sr$ values were normalized to the $^{87}Sr/^{86}Sr$ ratio in the VNIIM standard (Vinogradov and Chernyshev, 1987). The $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios were measured accurate to ±1% and ±0.0002%, respectively. The Mn and Fe contents were determined by the X-ray spectral method (borehole core and rocks from the Ura Uplift) in the chemical–analytical laboratory of the Geological Institute (Moscow) and the ICP-MS method (section along the Chara River) in the Geological Survey of Norway.

RESULTS

Carbon, Oxygen, and Sulfur

The **Ura Uplift.** Variations in the carbon and oxygen isotopic compositions in the summary section of Upper Precambrian rocks of the Ura Uplift are presented in Fig. 2 and Table 2. The total scatter of $\delta^{13}C$ values is more than 21‰ (from –13.5 to 8.1‰, with sharp changes in the carbon isotopic composition confined to the boundaries between formations.

In the carbonate cement of sandstone sampled in the upper part of the Dzhemkukan Formation along the Ura River, $\delta^{13}C$ = –8.8‰. In dolomites at the top of glacial diamictites, $\delta^{13}C$ is significantly higher (from –3.9 to –4.2‰).Limestones of the Barakun Formation demonstrate a rapid upsection growth in $\delta^{13}C$ from –0.1 to 8.1‰. The thickness of this interval is no more than 100 m. The remaining part of the Barakun Formation sampled along the Ura and Bol'shoi Patom rivers demonstrate uniformly high carbon isotopic composition: $\delta^{13}C_{av}$ = 6.5 ± 1‰ (n = 13). The Valyukhta Formation is also characterized by elevated $\delta^{13}C_{av}$ = 4.5 ± 1.5‰ (n = 6) without sharp deviations but an insignificant upsection depletion in ^{13}C (Fig. 2).

The lower part of the Nikol'skoe Formation, which was comprehensively sampled along the Lena River, contains transitional sequence characterized by the gradual decrease in $\delta^{13}C$ from –5.4 to –10.8‰ in the calcite (predominant) phase and from –3.8 to –5.8 in dolomite. Its middle and upper portions demonstrate uniformly low $\delta^{13}C$ values ranging from –10.2 to –12.8‰ ($\delta^{13}C$ = –11.1 ± 0.7‰ (n = 11) in the predominant calcite phase and –10.5 ± 0.8‰ (n = 11) in dolomite). The lowest $\delta^{13}C$ values (from –12.5 to –13.5‰) were found in the exposure of the Nikol'skoe Formation (presumably, in its middle part) at lower reaches of the Ura River (Table 2). In limestones of the Chencha Formation, $\delta^{13}C$ values remain extremely low and gradually increase upsection from –9.5 to –7.5 and –8.0‰. The 60-m-thick dolomitic unit, which is ascribed either to the Chencha Formation (Pelechaty, 1998) or, more often, to the Zherba Formation (Chumakov, 2004; Khomentovskii et al., 2004), demonstrates further increase in $\delta^{13}C$ from –3.5 to –4.5‰. Carbonates from the overlying Vendian and Lower Cambrian rocks (Zherba, Tinnaya, and Nokhtuisk formations) show moderately low $\delta^{13}C$ values (from 0 to –4‰). However, some relatively thin (a few meters thick) intervals have lower $\delta^{13}C$ values (from –8 to –9‰) (Sochava et al., 1996; Pelechaty, 1998; Khomentovskii et al., 2004). Of special interest is the 30-m-thick dolomitic member with extremely low $\delta^{13}C$ values (from –15 to –20‰) in the middle part of the Zherba Formation. Its geochemistry and lithology testify to diagenetic alterations (Pelechaty, 1998).

In the Late Precambrian section of the Ura Uplift, the oxygen isotopic composition of rocks shows no correlation with the carbon isotopic composition. In terms of the oxygen isotopic composition, the ^{13}C-rich Barakun ($\delta^{18}O_{av}$ = 20 ± 2‰) and Valyukhta ($\delta^{18}O_{av}$ = 19.9 ± 2.5‰) formations do not differ from the ^{13}C-depleted Nikol'skoe Formation ($\delta^{18}O_{av}$ = 19.8 ± 1.5‰). The overlying Chencha Formation shows a gradual increase in $\delta^{18}O$ from 20–22‰ in the lower part to 23–24‰ in the upper part. Rocks of the Zherba Formation are further enriched in $\delta^{18}O$ without any correlation with $\delta^{13}C$. Within individual formations, especially in the lower part of the section, variations in $\delta^{18}O$, probably correlated with postsedimentary changes, are more prominent than variations in $\delta^{13}C$.

The **eastern margin of the Patom fold zone.** This section can hold a world record for extension and amplitude of carbon isotope anomalies. The Mariinsk Formation composing the base of the section is characterized by uniform and extremely high $\delta^{13}C_{av}$ = 7.5 ± 0.5‰ (n = 20) (Table 3), with no difference between carbonaceous limestones and calcareous sandstones.

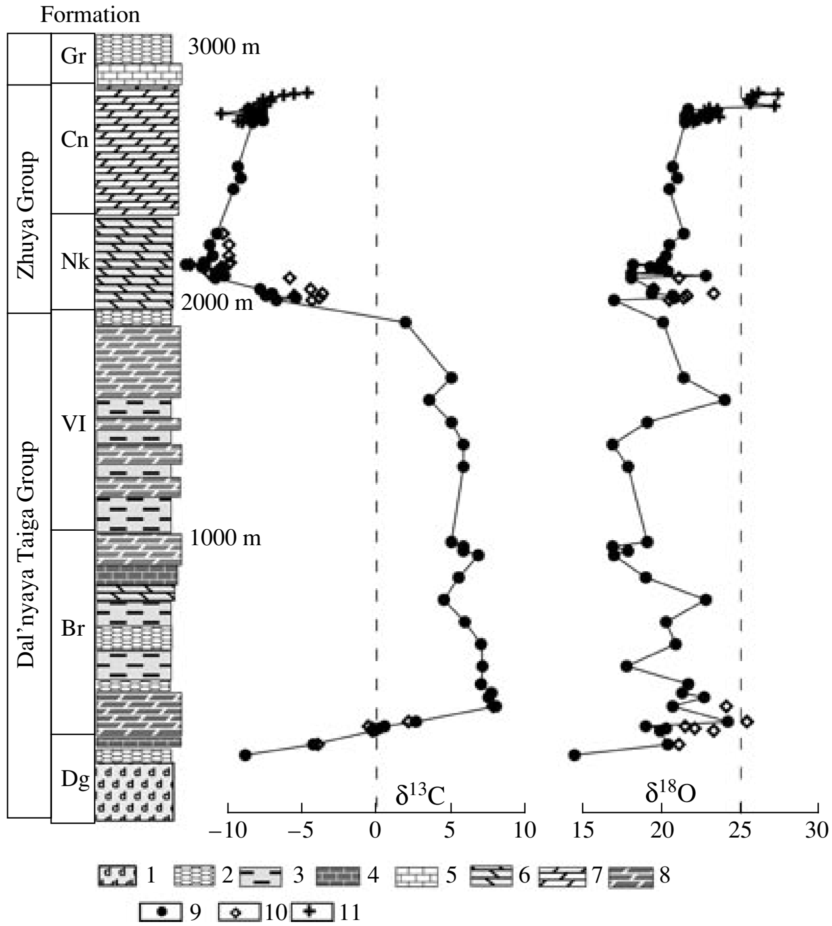

Fig. 2. Section of Late Precambrian rocks of the Ura Uplift and variations of carbon and oxygen isotopic compositions in them. Formations: (Dg) Dzhemkukan (Bol'shoi Patom); (Br) Barakun; (Vl) Valyukhta; (Nk) Nikol'skoe; (Cn) Chencha; (Gr) Zherba; (Tn) Tinnaya. (1) Diamictite; (2) sandstone and carbonate sandstone, (3) siltstone and carbonate siltstone; (4) gray and dark gray dolomites (including carbonaceous varieties) and calcareous dolomites; (5) light gray, white, and pale yellow dolomites; (6) variegated marls; (7) light gray and red limestones and dolomitic limestones, including stromatolitic and oncolitic varieties; (8) gray and dark gray limestones, including carbonaceous varieties; (9) C and O isotopic compositions in the calcite fraction; (10) the same in the dolomite fraction; (11) data from (Pelechaty, 1998). The thickness is given approximately from the roof of the Dzhemkukan (Bol'shoi Patom) Formation.

Calcareous sandstones located at the base of the Dzhemkukan Formation show drop in $\delta^{13}C$ from extremely high to very low values (Fig. 3). Boundary between the Mariinsk and Dzhemkukan formations is covered by deluvium. However, the uppermost sample of the Mariinsk Formation ($\delta^{13}C = 7.0‰$) is separated from the lowermost sample of the Dzhemkukan Formation ($\delta^{13}C = -4.2‰$) by a distance of no more than 50 m in the section. Then, within an interval of ~50 m, the $\delta^{13}C$ value in calcareous limestones, which are intercalated with carbonate-free shales, gradually decreases to –9.1‰. The middle and upper parts of the Dzhemkukan Formation, as well as its boundary with the Barakun Formation, is not exposed in the river valley. A rapid growth in $\delta^{13}C$ from –2.5 to 5.6‰ is recorded at the base of the Barakun Formation. The variation curve of carbon isotopic composition in this 100-m-thick interval is similar to the curve for the lower part of the Barakun Formation at the Ura River. The remaining part of the Barakun Formation retains steady and extremely high $\delta^{13}C$ values ranging from 4.5 to 6.9‰.

As was mentioned above, the Zhuya section of the Valyukhta Formation is mainly composed of terrigenous rocks, which were not studied by us. The Zhuya Group was sampled in two sections(on the right bank near the Sulanchin River mouth and on the left bank 2 km downstream of the Salyr River mouth). These sections differ isotopically neither from each other nor from sections of the Zhuya Group described above. The variegated marls of the Nikol'skoe Formation exhibit the lowest $\delta^{13}C_{av}$ values ($-10.4 \pm 0.6‰$, $n = 17$), which increase in the Chencha Formation to $-8.0 \pm 0.7‰$, $n = 17$) and remain at nearly the same level in the lower 100-m-thick member of the Zherba Formation. Thus, the total thickness of the rocks with extremely low $\delta^{13}C$ values in the Zhuya Section is no less than 1000 m. Sed-

Table 2. Carbon and oxygen isotopic compositions of Late Cambrian carbonates in the Ura Uplift

Sample no.	Thickness, m	Rock	Calcite (25°C)		Dolomite (100°C)	
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$
Dzhemkukan (Bol'shoi Patom) Formation						
44/93		Csa	–8.8	14.5	–	–
35/05	–2	Cd (80)	–4.2	20.4	–3.9	21.0
37/05	–1	Cd (80)	–3.9	19.5	–3.3	21.7
Barakun Formation						
45/93	10	L (10)	–0.1	19.9	–0.25	23.3
46/93	20	L (15)	0.2	20.3	–0.2	22.1
47/93	30	L (10)	0.6	19.0	–0.5	21.5
48/93	50	L (10)	2.7	24.2	2.2	25.4
50/93	70	L (15)	8.1	20.7	7.9	24.1
51/93	160	L	7.6	22.7	–	–
53/93	180	L	7.8	21.3	–	–
54/93	220	L	7.1	21.7	–	–
73/93	350	L	7.2	17.8	–	–
75/93	450	L	7.1	20.9	–	–
88/93	550	L	6.0	20.3	–	–
89/93	650	L	4.6	22.8	–	–
90/93	750	L	5.6	19.0	–	–
91/93	850	L	6.9	17.0		–
Valyukhta Formation						
18/93	1250	L	5.9	17.9	–	–
19/93	1350	L	5.9	16.9	–	–
20/93	1450	L	5.1	19.1	–	–
35/93	1550	L	3.6	24.0	–	–
36/93	1650	L	5.1	21.4	–	–
2000	1900	L	2.0	20.1	–	–
Nikol'skoe Formation						
2081	2100	M	–6.7	17.0	–4.3	20.5
2078	2110	M	–5.4	20.8	–3.8	21.4
2074	2120	M	–7.4	20.7	–5.5	21.6
2070	2130	M	–7.0	19.4	–3.6	23.3
2067	2150	M	–7.8	19.5	–4.4	19.5
2064	2200	M	–10.8	18.1	–5.8	21.1
2099	2210	M	–10.2	22.8	–10.7	20.2
2093	2220	M	–10.8	18.1	–11.2	19.8
2088	2230	M	–10.6	20.4	–10.7	20.4
2082	2240	M	–10.4	19.8	–10.5	19.5
2039	2250	M	–11.7	19.3	–10.4	19.7
2043	2260	M	–12.8	18.2	–12.5	20.8
2047	2265	M	–11.5	20.0	–9.9	23.3
2051	2270	M	–11.6	20.0	–9.8	20.6
2055	2280	M	–11.0	20.3	–9.9	20.8
2058	2290	M	–11.2	20.5	–9.9	20.6
2061	2300	M	–10.7	21.4	–10.3	20.7
10/05		L	–12.5	18.6	–	–
22/05		L	–13.3	18.5	–	–
25/05		L	–13.5	17.4	–	–
Chencha Formation						
11/93	2500	L	–9.6	20.5	–	–
1/93	2550	L	–9.1	21.0	–	–
9/93	2600	L	–9.3	20.7	–	–
2019	2800	L	–8.3	21.5	–8.1	21.4
2018	2810	L	–7.6	21.5	–8.0	22.4
2016	2820	L	–7.8	22.9	–7.7	22.7
2014	2830	L	–7.7	21.5	–7.1	23.6
2010	2840	L	–8.2	21.7	–7.7	21.5
2008	2850	L	–7.7	23.5	–8.3	25.3
2007	2860	L	–8.4	21.7	–8.4	22.6

Note: Approximate thickness is given in meters from the base of the Barakun Formation; thickness is not reported for samples taken along the strike. (L) limestone; (M) marl; (Csa) calcareous sandstone; (Cd) calcareous dolomites crowning the glacial diamictite. Numbers in parentheses is the fraction of dolomitic admixture in carbonate material. (–) isotopic composition was not determined.

iments of the Tinnaya and Pestrotsvetnaya formations, which overlie the Zherba Formation, have not been studied in detail. Separate determinations (Table 3) shows more or less normal $\delta^{13}C$ values (–1.3 and –0.1‰, respectively).

The oxygen isotopic composition in carbonates from the Zhuya section does not correlate with the carbon isotopic composition and shows only insignificant variations throughout the section. In the purely carbonate rocks from the lower part of the section, the $\delta^{18}O$ value is only 3–4‰ higher than that in rocks enriched in terrigenous material (calcareous sandstones). One can see only insignificant difference in $\delta^{18}O$ values between the Nikol'skoe (19.5 ± 0.9‰) and Chencha (21.2 ± 1‰) formations. The dolomite and calcite phases lack significant differences in both oxygen and carbon isotopic compositions.

The **northern part of the Berezovsk Depression.** Table 4 demonstrates data on boreholes 3160, 2730, and 1872. Despite significant gaps in core sampling intervals, the carbon isotope pattern in this part of the paleobasin is characterized by a high grate of similarity (if not identity) to that in the Ura Uplift. A drastic drop in $\delta^{13}C$ values was also recorded here at the boundary

Table 3. Oxygen and carbon isotopic compositions of Late Cambrian carbonates along the Zhuya River

Sample no.	Thick-ness, m	Rock	Calcite (25°C)		Dolomite (100°C)	
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$
Mariinsk Formation						
8/04	4	Csaa	6.9	21.5	–	–
10/04	8	L	7.3	21.2	–	–
12/04	10	L (<5)	6.7	20.2	5.4	17.8
1/04	230	L (10)	6.7	17.6	6.5	16.9
18/04	280	L (10)	8.4	21.0	7.5	21.2
24/04	305	Dl (25)	8.3	21.3	8.2	20.1
26/04	340	L	7.6	19.7	–	–
27/04	390	Csa	7.9	17.7	–	–
28/04	410	L	8.0	18.4	–	–
32/04	475	L (<5)	6.5	17.9	5.9	18.8
35/04	488	L	7.4	19.7	–	–
36/04	490	Csa	7.3	19.4	–	–
37/04	512	L	7.4	19.7	–	–
38/04	518	Csa	8.0	20.1	–	–
41/04	534	L	7.2	19.5	–	–
44/04	552	L	7.6	20.8	–	–
46/04	570	L	8.0	19.8	–	–
47/04	580	L	7.4	18.7	–	–
48/04	590	L	7.0	18.4	–	–
Dzhemkukan Formation						
49/04	640	Csi	–4.2	16.5	–	–
50/04	650	Csa	–6.0	16.1	–	–
51/04	657	Csa	–7.1	16.5	–	–
52/04	675	Csi	–8.7	16.1	–	–
53/04	687	Csa	–9.2	16.1	–	–
55/04	710	Csa	–4.1	18.8	–	–
Barakun Formation						
63/04	1200	L	–2.5	21.1	–	–
57/04	1210	L (<5)	–1.1	19.9	–1.6	21.4
58/04	1215	L	–1.0	20.0	–	–
59/04	1240	L	–1.2	19.7	–	–
60/04	1260	L	–0.3	20.9	–	–
61/04	1270	L	1.3	21.3	–	–
62/04	1300	L	3.4	21.3	–	–
64/04	1460	L (<5)	5.6	16.8	6.1	18.5
65/04	1810	L	4.5	17.6	–	–
66/04	2110	L	4.7	16.9	–	–
67/04	2210	L (<5)	6.9	22.7	6.5	23.0
69/04	2220	L (<5)	6.3	22.2	–	–
24. Nikol'skoe Formation						
102/04	3150	L	–10.0	19.4	–	–
101/04	3160	L	–10.3	19.2	–	–
100/04	3170	M	–9.9	19.4	–	–
99/04	3200	M	–10.0	19.4	–	–
98/04	3220	M	–10.0	19.4	–	–
133a/04		M (25)	–10.7	18.3	–10.5	17.1
133b*/04		L	–11.8	17.4	–	–
132/04		M (40)	–10.4	18.6	–10.2	18.2
121/04		Dl	–9.4	20.7	–	–
134/04		Dl	–9.6	20.6	–10.4	18.7
97/04	3260	Dl (15)	–10.0	19.4	–9.7	19.5
96/04	3330	Dl (20)	–9.2	19.7	–9.5	21.2
95/04	3350	Dl (20)	–9.3	19.5	–9.5	19.7
94/04	3370	Dl (20)	–9.4	20.1	–9.6	18.7
92/04	3405	Dl (15)	–9.6	20.0	–9.2	20.8
89/04	3435	Dl (20)	–9.3	20.7	–9.3	20.6
Chencha Formation						
87/04	3500	Dl (20)	–9.2	19.5	–8.9	19.3
84/04	3630	Dl (20)	–8.6	20.1	–8.3	20.4
82/04	3660	Dl (20)	–9.2	19.9	–8.2	20.2
80/04	3690	Dl (20)	–8.4	20.4	–8.3	19.5
78/04	3715	Dl (20)	–7.8	20.7	–7.9	20.5
76/04	3730	Dl (20)	–8.4	20.1	–8.6	19.3
74/04	3750	Dl (20)	–7.8	20.6	–8.2	19.7
148/04	3790	L	–7.6	22.0	–	–
150/04	3808	L (10)	–7.6	21.3	–7.4	23.1
152/04	3815	L	–7.7	21.5	–	–
153/04	3835	L (10)	–7.0	22.4	–7.7	21.9
154/04	3860	L	–7.5	22.3	–	–
155/04	3880	L	–7.3	22.4	–	–
156/04	3890	L (10)	–6.9	22.9	–8.0	21.9
157/04	3900	L (10)	–8.8	21.3	–9.0	20.4
Zherba Formation						
163/04	4100	L	–9.2	20.7	–	–
159/04	4110	L	–8.7	21.7	–	–
160/04	4115	L	–9.1	21.9	–	–
161/04	4116	Csa	–9.3	21.4	–	–
162/04	4120	L	–8.9	21.4	–	–
166/04	4150	L (10)	–7.4	22.7	–8.1	23.1
Tinnaya Formation						
167/04		L	–1.3	21.1	–	–
169/04		L	–0.1	23.2	–	–

Note: Approximate thickness is given from the base of the Mariinsk Formation. (Dl) Dolomitic limestone; (Csi) calcareous siltstone. Other abbreviations as in Table 2.

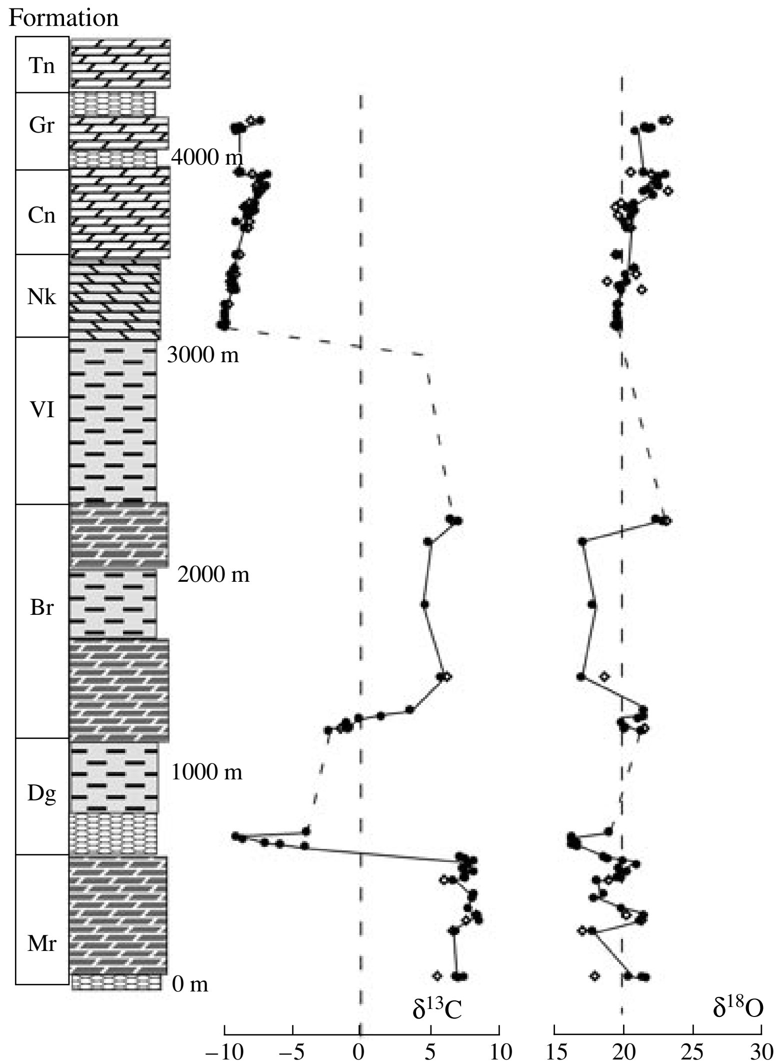

Fig. 3. The Late Precambrian section at lower reaches of the Zhuya River and variations of carbon and oxygen isotopic compositions therein. (Mr) Mariinsk Formation. Other abbreviations as in Fig. 2. The approximate thickness (in m) is measured from the base of the Mariinsk Formation.

between the Dal'nyaya Taiga and Zhuya groups. Based on available data, the thickness of ^{13}C-depleted carbonates in the northern Berezovsk Depression is no less than 500 m. Like in the Ura Uplift, the lowest $\delta^{13}C$ value (–12.0‰) is recorded here in the middle part of the Nikol'skoe Formation. The value slightly increases in the overlying Chencha (Khopych) Formation (from –9 to –10.0‰). Transitional $\delta^{13}C$ values (0.7–0.8‰) are recorded in the lower part of the Nikol'skoe Formation ~100 m above the bottom. The range of positive anomaly in borehole 2730 is narrower than that in the Ura Uplift: in the Moldoun and Khalatyrbyt formations, the $\delta^{13}C_{av} = 4.5 \pm 0.7$‰ ($n = 13$), which is ~2‰ lower than that in the Barakun Formation of the Ura Uplift. The boreholes also show differences in carbon and oxygen isotopic compositions. For example, $\delta^{13}C$ is ~2‰ lower in rocks of the Kalancha Formation in borehole 2730, in relative to boreholes 3160 and 1872 (Table 4). These differences, however, are insignificant relative to differences in $\delta^{13}C$ values between rocks of the Dal'nyaya Taiga and Zhuya Groups.

The **Chara River.** In the Kumukulakh Formation exposed near the mouth of the Mokryi Kumukulakh River, the $\delta^{13}C$ value varies from –5.9 to –6.3‰ in thin limestone horizons of the lower member and increases to –2.9‰ in the upper member (Table 5). Rocks of the Sen Formation are enriched in ^{13}C: the highest values ($\delta^{13}C = 3.9$‰) is recorded in dolomites from the upper subformation. The Torgo Formation was sampled in two exposures: the left bank of the Chara River ~1 km upstream of the Bul'dzhinei River (lower part) and the right bank of the Chara River between mouths of the Bul'dzhinei and Torgo rivers (middle and upper parts). Rocks from these exposures lack significant differences

Table 4. Oxygen and carbon isotopic compositions of Late Precambrian carbonates in boreholes drilled in the northern Berezovsk Depression

Depth, m	Rock	Calcite (25°C)		Dolomite (100°C)	
		$\delta^{13}C$, ‰	$\delta^{18}O$	$\delta^{13}C$, ‰	$\delta^{18}O$
Borehole 2730, Bysakhtakh-Kyuel'sk, Chencha Formation (831–1194 m)					
904.5	L (25)	–9.9	23.7	–	–
927.7	Dl (40)	–9.9	22.9	–10.0	24.4
1022.1	Dl (30)	–9.4	21.2	–9.0	21.8
1029	L (15)	–9.0	20.9	–9.0	22.7
Nikol'skoe Formation (1194–1638 m)					
1530	D (95)	0.8	27.6	1.1	25.1
1535.5	D (90)	0.7	25.3	1.3	25.7
Kalancha Formation (1638–2032 m)					
1737	D (90)	3.1	24.4	3.8	24.3
1747	D (85)	2.9	24.8	3.9	26.2
1748.8*	L (<5)	2.9	17.3	–	–
1748.8	D (90)	3.2	26.6	3.8	26.4
1756	D (90)	3.0	25.6	3.7	25.6
Ura Formation (2032–2527 m)					
2284.5	Ds (85)	4.0	25.5	4.5	25.3
Khalatyrbyt Formation (2032–2527 m)					
2448	D (85)	3.0	24.8	3.3	25.0
2463	D (85)	3.7	24.8	3.7	25.4
2475.3	D (90)	3.6	26.5	4.0	27.2
2487	D (90)	3.3	24.1	3.7	24.7
2490	D (85)	4.1	26.4	4.4	27.4
Shumikha Formation (2527–727 m)					
2529*	D (90)	4.1	23.4	4.9	22.5
2529	D (80)	3.9	21.0	4.8	20.9
2575	D (90)	4.2	25.7	4.7	24.3
2646.2	D (90)	–	–	5.0	23.2
2647.7	Cd (40)	2.9	18.9	3.9	19.5
2694	D (90)	4.6	25.0	5.1	24.0
2697	D (85)	5.2	23.4	4.9	22.4
Moldoun Formation (2527–2727 m)					
2748.8	Cd (50)	5.9	27.3	5.4*	25.9
2753.6	D (90)	5.4	23.8	5.8	23.7
Borehole 3160 "Macha" Nikol'skoe Formation (580–995 m)					
730	Dl (30)	–12.0	19.3	–10.0	20.2
736.3	Dl (30)	–11.8	19.2	–9.1	20.6
Kalancha Formation (995–1405 m)					
1115.6	Dl (25)	5.7	21.1	5.7	20.9
1342	Dl (30)	5.5	21.1	5.9	20.4
1348.6	Dl (30)	5.9	21.6	5.6	20.4
Ura Formation (1405–334 m)					
2010	Ds (75)	4.2	19.0	5.0	18.6
Shumikha Formation (2484–2608 m)					
2485	Csa (25)	4.5	20.8	3.4	22.3
2492.5	Csa (30)	6.0	21.2	4.1	25.8
Borehole 1872 "Bysakhtakh" Alekseev Formation (3353–3662 m)					
3450	L	7.3	22.3	–	–
3588	L	5.0	21.2	–	–
3650	L	7.3	21.1	–	–

Note: Depth is given in meters from the borehole mouth. (Cd) calcareous dolomite; (Ds) dolomitic sandstone. Other abbreviations as in Tables 2 and 3.

in the carbon isotopic composition: the $\delta^{13}C$ value in rocks of the entire Torgo Formation varies from –8.0 to –10.5‰. Only an insignificant increase is recorded upward the section (Fig. 4). In epigenetic calcite veins and crusts, the ^{13}C content is 2–4‰ higher as compared to background values (Table 5). Rocks of the Torgo Formation have a uniform oxygen isotopic composition: $\delta^{18}O_{av} = 22.4 \pm 1$‰ ($n = 26$). Significant fractionation of oxygen and carbon isotopes between calcite (the predominant phase) and dolomite phases is not observed.

Borehole 1G Verkhnii Dzhege. The pattern of carbon isotopic composition in borehole 1G (Fig. 5) is generally similar to that of the Chara section discussed above. The $\delta^{13}C$ values in the Khalatyrbyt and Chekurdakh formations (from –0.8 to –3.1‰) are comparable with those in the upper part of the Kumukulakh Formation and lower subformation of the Sen Formation. The predominant part of the Alekseev Formation is characterized by high $\delta^{13}C$ values (up to 6.1‰). Comparatively narrow ranges with lower $\delta^{13}C$ values (from –4 to –5‰) are recorded near the contact with the alkaline syenite intrusion at the base of the Alekseev Formation and in essentially terrigenous rocks near its roof (Table 6).

The lower subformation of the Torgo Formation has a heterogeneous carbon isotopic composition. Low $\delta^{13}C$ values (0 ± 1‰) near the base and roof give way to high values (up to 5.9‰) in the middle part. It is pertinent to note that the lower subformation of the Torgo Formation more resembles the Alekseev Formation in terms of both isotopic characteristics and lithology. In contrast, the middle and upper subformations of the

Table 5. Oxygen and carbon isotopic compositions of Late Precambrian carbonates from the section along the Chara River

Sample no.	Thickness, m	Rock	Calcite (25°C)		Dolomite (100°C)		Fe, ppm	Mn, ppm	Sr, ppm	Fe/Sr	Mn/Sr
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$					
Kumukulakh Formation											
39/03	10	L (5)	–5.9	18.0	–8.1	15.8	4150	2640	436	9.52	6.06
36/03	20	L (5)	–6.0	14.9	–6.6	27.1	1810	3590	325	5.57	11.05
35/03	25	Dl (20)	–6.3	18.9	–6.3	18.5	1340	3570	198	6.77	18.03
31/03	55	Dl (20)	–5.9	18.6	–5.8	19.6	7220	2980	365	19.78	8.16
30/03	60	Dl (20)	–2.9	22	–2.5	23.5	4080	140	1928	2.12	0.07
23/03	95	Dl (25)	–2.9	22	–2.5	22.4	2160	106	1233	1.75	0.09
Lower Sen (Imalyk) Formation											
7/03	185	D (85)	–3.5	24.6	–2.2	26.2	967	198	65.4	14.79	3.03
15/03	245	D (80)	–7.6	22.2	–0.3	25.2	1160	255	39.1	29.67	6.52
18/03	255	D (80)	0.9	23.9	0.9	24.5	2100	141	73.9	28.42	1.91
Upper Sen (Tokko) Formation											
60/03	–	Dl (30)	–2.7	16.9	–3.0	16.6	116	27.8	662	0.18	0.04
59/03	–	D (90)	0.9	23.8	2.3	26.7	1170	80.1	35.9	32.59	2.23
58/03	300	D (90)	1.5	23.9	3.0	25.3	6540	779	28.6	228.67	27.24
57/03	310	D (90)	0.1	21.9	1.8	24.6	6850	666	31.5	217.46	21.14
55/03	330	Cd	2.0	27.1	2.5	29.4	5000	412	49.6	100.81	8.31
50/03	350	Cd (75)	0.1	25.5	0.4	27.3	519	197	51.5	10.08	3.83
44/03	382	Dl (40)	–0.9	20.2	2.1	22.1	58.2	53.3	118	0.49	0.45
42/03	400	Dl	2.6	21.2	–	–	110	97.1	72.7	1.51	1.34
41/03	406	Dl (40)	2.6	20.0	3.3	21.8	68.8	57.5	91.5	0.75	0.63
40/03	410	Cd	3.4	22.4	3.9	21.9	138	104	53.8	2.57	1.93
Torgo Formation											
75/03	530	Dl (25)	–9.7	21.8	–9.9	22.7	148	28.9	309	0.48	0.09
73/03	540	Dl (25)	–9.5	22	–9.2	22.2	242	21.8	191	1.27	0.11
72/03	550	Dl (20)	–9.7	21.4	–	–	222	33	225	0.99	0.15
70/03	568	Dl (25)	–9.7	21.9	–9.8	21.4	375	63	171	2.19	0.37
69/03	572	Dl (25)	–9.5	22.5	–9.9	23.2	245	32.9	167	1.47	0.20
64/03	614	Dl (25)	–9.1	21.4	–8.8	21.8	322	16.6	429	0.75	0.04
62/03	620	Dl	–10.1	19.5	–	–	117	14.7	394	0.30	0.04
100/03	637	Dl	–9.5	22.7	–	–	221	35.4	293	0.75	0.12
99/03	647	Dl (25)	–8.9	23.5	–9.4	23.3	240	29.9	301	0.80	0.10
98/03	655	Dl	–8.9	23.5	–9.4	22.8	494	35.4	147	3.36	0.24
96/03	670	Dl (20)	–9.5	22.7	–9.3	20.8	344	30.1	157	2.19	0.19
92/03	697	Dl (20)	–9.3	23.1	–9.0	21.1	384	46.1	126	3.05	0.37
90/03	711	Dl	–8.8	23.3	–8.9	21.7	516	47.5	163	3.17	0.29
87/03	719	Dl	–	–	–9.1	21.9	369	24.6	365	1.01	0.07
84/03	740	Dl (25)	–8.6	23.4	–8.8	21.4	117	20.2	307	0.38	0.07
81a/03	755.1	*L (10)	–5.6	19	–5.1	19.5	–	–	–		
81/03	755	L (10)	–8.1	23.5	–8.6	20.5	143	25.9	318	0.45	0.08
79/03	765	Dl (20)	–8.4	22.8	–8.3	20.6	688	51.4	263	2.62	0.20
78/03	775	Dl (25	–6.3	22.3	–8.6	21.4	411	50.3	308	1.33	0.16
76/03	790	Dl (25)	–8.3	23	–8.2	22.4	459	81.3	263	1.75	0.31
113/03	795	Dl (25)	–9.1	21.9	–8.9	23.4	207	41.8	373	0.55	0.11

Table 5. (Contd.)

Sample no.	Thick-ness, m	Rock	Calcite (25°C)		Dolomite (100°C)		Fe, ppm	Mn, ppm	Sr, ppm	Fe/Sr	Mn/Sr
			$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$					
112/03	800	Dl (25)	–8.8	22.8	–	–	371	45.9	387	0.96	0.12
102/03	–	Dl (20)	–8.3	22.6	–8.3	21.8	372	97.3	457	0.81	0.21
104/03	–	Dl (25)	–9.2	22.4	–8.7	24.5	388	30.9	211	1.84	0.15
119/03	–	Dl (20)	–8.9	22.8	–8.6	23.5	226	34.2	256	0.88	0.13
118/03	–	Dl (20)	–8.7	22.8	–8.1	24	440	44.0	341	1.29	0.13
117/03	–	Dl (25	–8.5	22.5	–8.2	22.2	2490	89.9	321	7.76	0.28
116/03	–	Dl (20)	–8.8	22.4	–9.2	21.5	287	47.1	486	0.59	0.10
115/03	–	Dl	–9.6	22.4	–7.6	24.6	5470	139	214	25.56	0.65
114/03	–	Dl (25)	–9.1	21.5	–9.1	22.4	392	49.7	374	1.05	0.13
484	–	Dl	–9.1	23.4	–	–	–	–	–	–	–
475	–	*L	–7.1	14.1	–	–	–	–	–	–	–
472	–	Dl	–9.6	22.9	–	–	–	–	–	–	–
468	–	Dl	–10.4	20.9	–	–	–	–	–	–	–
463	–	Dl	–9.7	21.3	–	–	–	–	–	–	–
Tinnaya Formation											
121/03	–	L	–0.8	22.1	–	–	354	50.5	164	2.16	0.31
125/03	–	L	–1.2	21.4	–	–	707	65.1	154	4.59	0.42
130/03	–	Dl	–1.1	23.4	–	–	4100	184	60.4	67.88	3.05
131/03	–	Dl	–0.1	23.2	–	–	3890	188	74.3	52.36	2.53
137/03	–	Dl	2.1	20.4	–	–	2600	107	56.9	45.69	1.88

Note: Approximate thickness is given in meters from the base of the Kumukulakh Formation; thickness is not given for blocks and samples taken along the strike of the formation. * Epigenetic veins and crusts. Other notes as in Tables 2–4.

Torgo Formation are characterized by low $\delta^{13}C$ values similar to those in the Chara section counterpart. It is noteworthy that the cherry red marls of the middle subformation of the Torgo Formation, which are similar to rocks of the Nikol'skoe Formation along the Lena and Zhuya rivers, have also similar carbon isotopic composition ($\delta^{13}C$ from –11 to –12‰), while aphanitic limestones and dolomites of the upper subformation ($\delta^{13}C$ from –8 to –10‰) can correlate accurate to 1‰ with rocks of the Chencha and Torgo formations along the Lena, Zhuya, and Chara rivers.

The oxygen isotopic composition in the core of borehole 1G shows wider variations than that in the sections considered above. The maximum depletion in ^{18}O (up to $\delta^{18}O$ = 13.8‰) occurs near the contact with intrusion at the base of the Alekseev Formation. The highest $\delta^{18}O$ values (30.0‰) were recorded in dolomites from the upper part of the Torgo Formation. Noteworthy is a sharp disturbance of equilibrium between dolomite and calcite phases in the upper subformation of the Torgo Formation. Hence, the ^{18}O-depleted calcite was undoubtedly formed during epigenesis that apparently did not affect the dolomite phase. No correlation is observed between carbon and oxygen isotopic compositions. Like in the Chara section, the ^{18}O-depleted epigenetic calcite is slightly enriched in ^{13}C (~2‰), (Fig. 5).

The ^{13}C-depleted carbonates of the Torgo Formation in borehole 1G contain anhydrite veins with an unusual sulfur isotopic composition (Table 6): the $\delta^{34}S$ value in three samples lies within the 12–20‰ interval, which is lower than the value typical of oceanic sulfates (~20‰). Only the uppermost sample has $\delta^{34}S$ = 26.2‰, which is close to the lowest values for the Late Precambrian and Lower Cambrian rocks of Siberia (Vinogradov, 1980; Vinogradov et al., 2006).

Strontium

Table 7 shows available data on the Sr isotopic composition in carbonates of the Patom Complex and its analogues. The table includes both new determinations and previous data obtained at the Geological Institute, Moscow (Pokrovskii and Vinogradov, 1990; Vinogradov et al., 1996) and the Institute of Precambrian Geology and Geochronology, St. Petersburg (Gorokhov et al., 1995). Despite some differences in experimental procedures, the results obtained show no significant

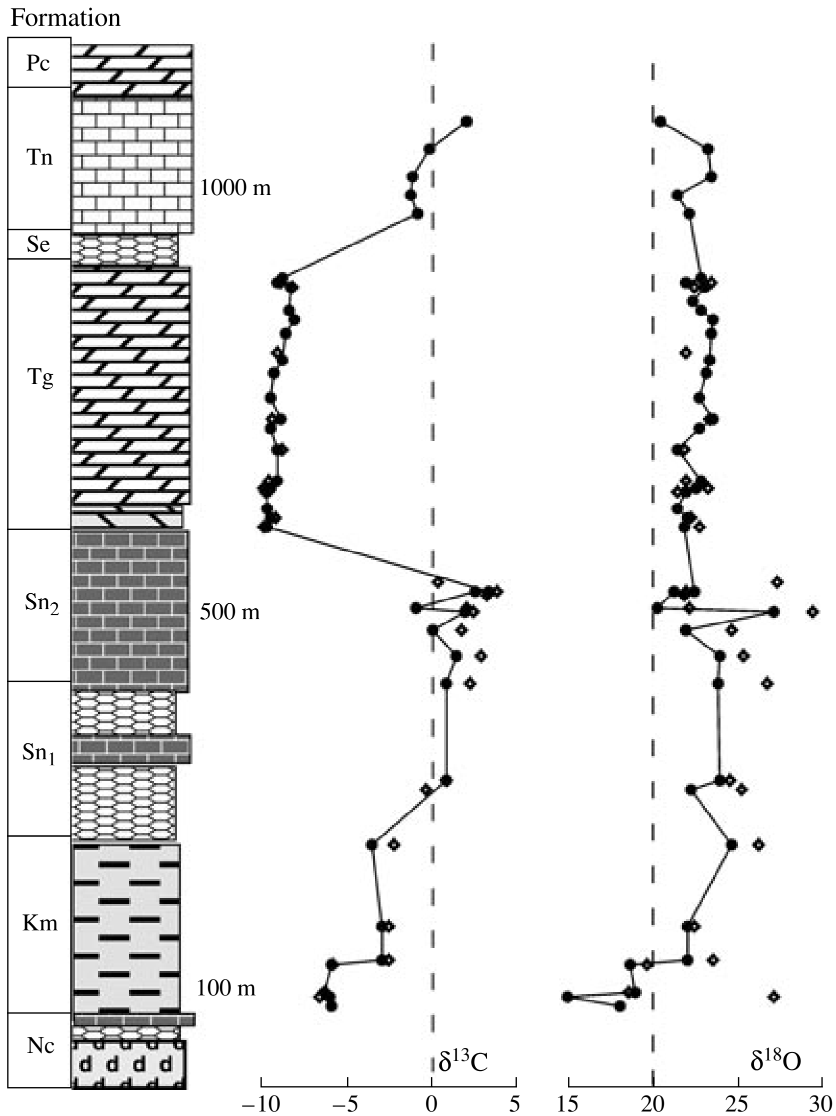

Fig. 4. The Late Precambrian section in the Chara River valley from the mouth of the Sen River to the mouth of the Torgo River and variations of carbon and oxygen isotopic compositions therein. Formations: (Nc) Nichatka; (m) Kumukulakh; (Sn_1) Sen, lower subformation (Imalyk Formation); (Sn_2) Sen, upper subformation (Tokko Formation); (Tg) Torgo; (Se) Seralakh; (Tn) Tinnaya (Turuktakh, Yudoma); (Pc) variegated (Yuedei). Symbols in the column are as in Fig. 2. The thickness is given approximately from the base of the Nichatka Formation.

discrepancies (Fig. 6a). For the Lena section of the Chencha Formation, both laboratories yielded the similar minimum value of $^{87}Sr/^{86}Sr = 0.70812$, which is slightly higher than the minimum value ($^{87}Sr/^{86}Sr = 0.70786$) obtained for the Bol'shoi Patom section of this formation at the Geological Institute (Table 7).

Table 7 presents only measured $^{87}Sr/^{86}Sr$ values. The correction for age is within the measurement error in samples with low (<0.01) $^{87}Rb/^{86}Sr$ values (only such samples are suitable for the chemostratigraphic interpretation). In samples with high $^{87}Rb/^{86}Sr$ values (>0.01), the Rb–Sr system is usually disturbed and calculation of the *initial* ratio $(^{87}Sr/^{86}Sr)_0$ is incorrect. Most analyzed samples are characterized by the low $^{87}Rb/^{86}Sr$ value (<0.01). The higher values of $^{87}Rb/^{86}Sr$ (>1) were only recorded in dolomites from borehole 1G.

The scatter of $^{87}Sr/^{86}Sr$ values in the studied samples is within 0.70725–0.71432. These variations are mainly caused by epigenetic processes, which will be considered in the second communication. Of special interest in terms of chemostratigraphy and geochronology are minimum values, which regularly increase upsection in the Ura Uplift (0.70727 in the Barakun Formation, 0.70769 in the Valyukhta Formation, 0.70790 in the Nikol'skoe Formation, 0.70786 in the Chencha Formation, and 0.70855 in the Tinnaya Formation) and along

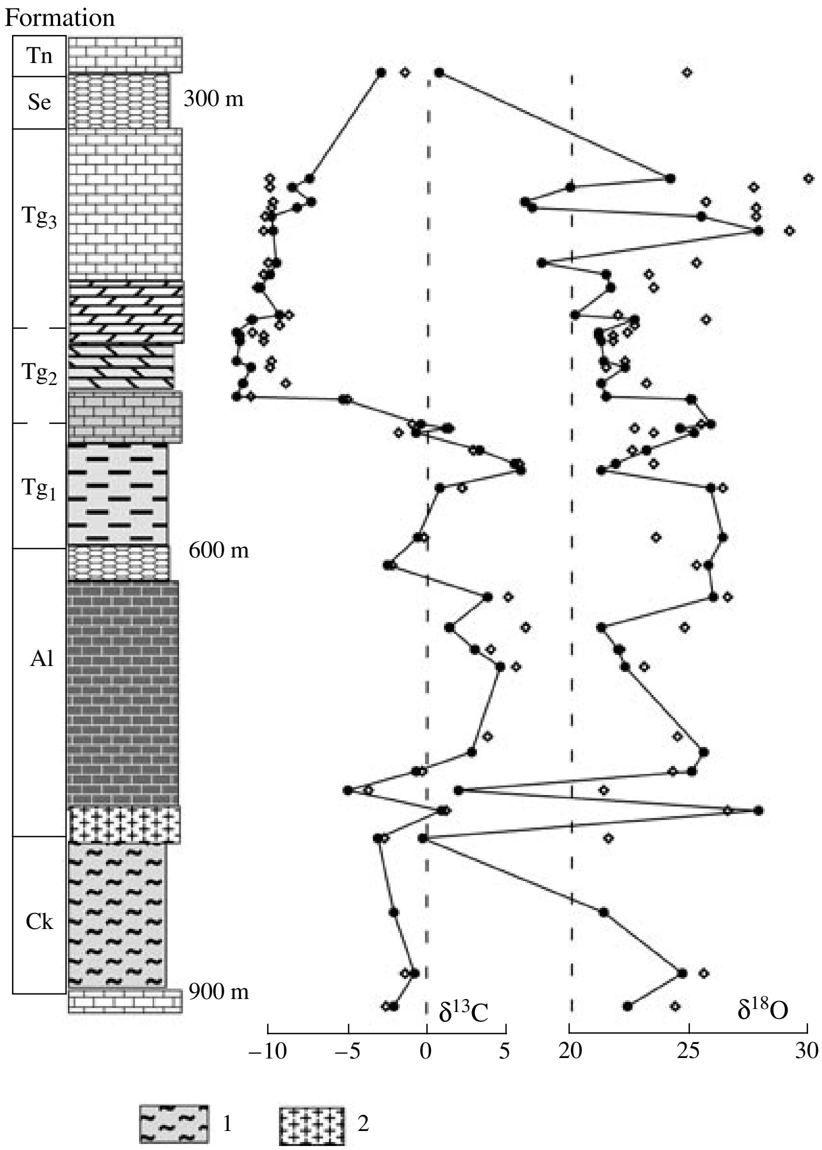

Fig. 5. The Late Precambrian section in borehole 1G "Verkhnii Dzhege" (watershed of the Chara and Tokko rivers) and variations of carbon and oxygen isotopic compositions therein. Formations: (Ck) Chekurdakh; (Al) Alekseev; (Tg) Torgo (upper, middle, and lower members); (Se) Seralakh; (Tn) Tinnaya. (1) variegated shales, including carbonate ones; (2) alkaline syenite intrusion. Other symbols are as in Fig. 2. The depth is indicated relative to the borehole mouth.

the Chara River (0.70725 in the Kumukulakh Formation, 0.70799 in the Torgo Formation, and 0.70837 in the Tinnaya Formation). Since carbonates of the Chencha and Torgo formations show a narrow scatter in Sr isotope ratios, except separate low-Sr samples (Fig. 6a), the minimum $^{87}Sr/^{86}Sr$ ratio (virtually identical to the average value) is very close to the initial value. The difference in Sr isotopic compositions between the Nikol'skoe ($^{87}Sr/^{86}Sr$ = 0.70790) and Chencha ($^{87}Sr/^{86}Sr_{min}$ = 0.70786) formations, which form the Zhuya Group, is within the measurement error. The situation in rocks of the Dal'nyaya Taiga Group is more complicated: large scatter of $^{87}Sr/^{86}Sr$ values is observed not only in the low-Sr dolomites of the Sen, Alekseev, Kalancha, Khalatyrbyt, and Moldoun formations, but also in the high-Sr limestones of the Barakun Formation (Table 7, Fig. 6b). Therefore, it is doubtful that the minimum $^{87}Sr/^{86}Sr$ ratios given above for rocks of the Barakun Formation correspond to initial ratios.

ISOTOPE STRATIGRAPHY AND PROBLEM OF THE AGE OF THE PATOM COMPLEX

Regional Correlation of Sections

Figure 7 correlates $\delta^{13}C$ variation curves and shows minimum $^{87}Sr/^{86}Sr$ values in the studied sections. The characteristic feature of the carbon isotope curve—a sharp decrease in $\delta^{13}C$ (15–20‰) in four sections

Table 6. Carbon and oxygen isotopic compositions of Late Precambrian carbonates in borehole 1G "Verkhnii Dzhege"

Depth, m	Rock	Calcite (25°C)		Dolomite (100°C)		Mn, ppm	Sr, ppm	Mn/Sr
		$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$			
Tinnaya Formation (0–280 m)								
275	Cd (80)	–2.9	14.5	–1.4	24.9	–	–	–
Torgo Formation, upper subformation (318–450 m)								
348	Cd (80)	–7.4	24.2	–9.9	30.0	67	37	1.81
354	Cd (80)	–8.5	20.0	–9.9	27.7	67	34	1.97
364	Cd (80)	–7.3	18.1	–9.7	25.7	59	130	0.45
368	Cd (80)	–8.2	18.4	–9.8	27.8	–	–	–
374	D (90)	–9.8	25.5	–10.2	27.8	55	33	1.66
384	Cd (80)	–9.7	27.9	–10.3	29.2	48	24	2.00
406	Cd (75)	–9.5	18.8	–10	25.3	230	140	1.64
414	Cd (70)	–9.9	21.5	–10.3	23.3	–	–	–
423	Cd (50)	–10.5	21.7	–10.7	23.5	–	–	–
442	Dl (15)	–9.3	20.2	–8.7	22.0	–	–	–
445	Dl (35)	–11	22.7	–11.1	25.7	210	360	0.58
449	M (30)	–	–	–9.3	22.7	–	–	–
Torgo Formation, middle subformation (450–518 m)								
454	M (20)	–12.0	21.2	–11.0	22.4	–	–	–
456	Dl (30)	–11.8	21.2	–10.3	21.8	–	–	–
460	M (30)	–11.8	21.3	–10.3	21.8	500	350	1.42
473.7	M (20)	–12.0	21.4	–9.8	22.3	540	170	3.17
478	M (25)	–11.1	22.3	–9.9	21.5	–	–	–
489	M (15)	–11.6	21.3	–8.9	23.2	–	–	–
498	Dl (15)	–12.0	21.5	–11.1	21.5	–	–	–
500	Cd (80)	–5.3	25.1	–5.0	25	–	–	–
517	D (90)	–0.4	25.9	–0.95	25.5	680	140	4.85
Torgo Formation, lower subformation (518–602 m)								
520	Cd (80)	1.2	24.6	1.4	22.7	–	–	–
523	Cd (60)	–0.7	25.2	–1.8	23.5	–	–	–
535	Ds (80)	3.3	23.2	2.9	22.6	–	–	–
544.3	Ds (80)	5.5	21.9	5.8	23.5	–	–	–
548.8	Ds	5.9	21.3	–	–	–	–	–
561	Cd (70)	0.8	25.9	2.2	26.4	–	–	–
595	Ds (80)	–0.6	26.4	–0.2	23.6	–	–	–
Alekseev Formation (602–783 m)								
614	Cd (65)	–2.5	25.8	–2.2	25.3	–	–	–
636	Cd (70)	3.8	26.0	5.1	26.6	120	64	1.87
657	Cd (70)	1.4	21.3	6.2	24.8	–	–	–
672	Cd (60)	3.0	22.0	4..0	22.1	71	230	0.30
684	Dl (40)	4.6	22.3	5.6	23.1	56	120	0.46
732	Cd (70)	–	–	3.8	24.5	82	80	1.02
742.7	Cd (60)	2.8	25.6	–	–	–	–	–
756	Cd (75)	–0.7	25.1	–0.3	24.3	–	–	–
769	Cd (70)	–5.0	15.3	–3.7	21.4	130	340	0.38
783	Cd (70)	0.9	27.9	1.2	26.6	–	–	–
Chekurdakh Formation (801–914 m)								
802	Csa (20)	–3.1	13.8	–2.7	21.6	–	–	–
853	Csi (<5)	–2.1	21.4	–	–	–	–	–
895	Csi (40)	–0.8	24.7	–1.4	25.6	–	–	–
Khalatyrbyt Formation (914–925 m)								
917.7	D (90)	–2.1	22.4	–2.6	24.4	–	–	–

Note: Depth is given in meters from the borehole mouth. The $\delta^{34}S$ values (‰ relative to the meteorite standard) in anhydrite veinlets in the core from depths of 460, 454, 449, and 386 m are 12.7, 17.4, 202. and 26.2, respectively. Other notes as in Tables 2–5.

Table 7. Strontium isotopic composition in Late Precambrian carbonate rocks from the Patom Complex and its analogues

Sample no.	Lab. no.	Formation	Rock	Fe/Sr	Mn/Sr	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Reference
Ura Uplift										
980-100	–	Tn	L	22.3	1.31	0.45	167	0.0077	0.70855	1
980-23	–	Cn	L	2.7	0.61	0.28	417	0.0019	0.70855	1
980-11	–	Cn	L	1.3	0.04	0.42	1744	0.0007	0.70826	1
980-4	–	Cn	L	1.9	0.08	0.22	1311	0.0005	0.70812	1
11/93	4099	Cn	L	–	0.09	0.17	1523	0.0003	0.70813	2
1/93	4096	Cn	L	–	0.05	0.17	1053	0.0004	0.70874	2
9/93	5190	Cn	L	–	0.06	0.26	285	0.0021	0.70812	N
90/05	5253	Cn	L			0.25	680	0.001	0.70803	*N
98/05	5254	Cn	L			0.06	2898	0.0002	0.70798	*N
104/05	5255	Cn	L			0.19	915	0.0006	0.70786	*N
982-7	–	Nk	L	9.8	1.32	0.12	340	0.0010	0.70832	1
982-5	–	Nk	L	2.0	1.37	0.14	363	0.0011	0.70932	1
982-1	–	Nk	L	2.9	2.18	0.24	330	0.0021	0.70942	1
10/05	5250	Nk	L			0.78	250	0.009	0.70829	*N
22/05	5251	Nk	L			0.06	345	0.002	0.70790	*N
25/05	5252	Nk	L			0.02	319	0.0008	0.70801	*N
18/93	4086	Vl	L	–	0.03	3.26	1824	0.0051	0.70781	2
19/93	4087	Vl	L	–	0.10	0.20	645.0	0.0008	0.70791	2
20/93	4088	Vl	L	–	0.08	0.27	1989	0.0003	0.70769	2
35/93	4089	Vl	L	–	0.09	0.13	652.5	0.0006	0.70802	2
36/93	4090	Vl	L	–	0.41	0.44	576.9	0.0022	0.70920	2
50/93	5191	Bk	L	–		0.54	1396	0.001	0.70776	N
73/93	4073	Bk	L	–	0.04	1.13	2526	0.0012	0.70790	2
75/93	4074	Bk	L	–	0.22	0.47	874.5	0.0015	0.70727	2
88/93	4076	Bk	L	–	0.30	1.10	1646	0.0019	0.70952	2
89/93	4077	Bk	L	–	0.25	18.5	1945	0.0276	0.71051	2
90/93	4078	Bk	L	–	0.07	0.08	1773	0.0005	0.70890	2
Borehole 2730 "Bysakhtakh-Kuel'sk"										
2730/90	5179	Cn	L	–	0.10	0.77	590	0.004	0.70823	N
2730/92	5178	Cn	L	–	0.64	0.77	421.1	0.005	0.70836	N
2730/17	5177	Kn	D	–	1.77	0.53	51.5	0.030	0.71031	N
2730/17	5176	Kn	D	–	1.10	0.24	59.90	0.012	0.71055	N
2730/22	5175	Hb	D	–	3.39	0.58	70.7	0.024	0.71198	N
2730/24	5174	Hb	D	–	3.16	0.46	72.71	0.018	0.71067	N
2730/27	5173	Md	D	–	1.52	2.09	62.85	0.096	0.70872	N
Chara R.										
C-490		Tn	L	–	–	–	158	–	0.70837	3
C-468		Tg	L	–	–	–	379	–	0.70822	3
C-472		Tg	CV	–	–	–	174	–	0.70917	3
110/03	5187	Tg	L	0.27	0.04	1.63	810	0.006	0.70799	N
116/03	5188	Tg	L	0.75	0.12	0.26	382	0.002	0.70810	N
99/03	5186	Tg	L	0.80	0.10	0.07	299	0.007	0.70832	N

Table 7. (Contd.)

Sample no.	Lab. no.	Formation	Rock	Fe/Sr	Mn/Sr	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Reference
89/03	5185	Tg	L	0.22	0.04	1.47	812	0.005	0.70832	N
40/03	5183	Sn	D	2.94	2.22	0.23	46.93	0.014	0.7099	N
23/03	5180	Km	L	3.30	0.12	0.82	881	0.003	0.70734	N
27/03	5181	Km	L	3.05	0.08	0.67	2013	0.001	0.70730	N
30/03	5182	Km	L	2.05	0.07	3.68	1990	0.005	0.70725	N
C-447		Km	L	–	–	–	508	–	0.70787	3
C-419		Km	L	–	–	–	161	–	0.71354	3
Borehole 1G "Verkhnii Dzhege"										
1G/348	5172	Tg_3	D	–	2.29	6.9	29.2	0.68	0.71034	N
1G/384	5171	Tg_3	D	–	2.32	0.76	17.36	0.13	0.70836	N
1G/406	5170	Tg_3	L	–	0.82	17.4	280.9	0.18	0.71055	N
1G/445	5169	Tg_2	L	–	0.55	1.5	380.7	0.01	0.7086	N
1G/636	5168	Al	D	–	1.25	13.3	96.3	0.40	0.70975	N
1G/672	5167	Al	CD	–	0.09	3.2	818.7	0.01	0.71432	N
1G/684	5166	Al	D	–	0.58	3.0	95.8	0.09	0.71103	N

Note: Formations: (Tn) Tinnaya, (Cn) Chencha; (Nk) Nikol'skoe; (Vl) Valyukhta; (Bk) Barakun; (Kn) Kalancha; (Hb) Khalatyrbyt; (Md) Moldoun; (Tg) Torgo; (Km) Kumukulakh; (Al) Alekseev. (L) Limestone; (D) dolomite; (CV) calcite vein. Data source: (1) Gorokhov et al., 1995; (2) Vinogradov et al., 1996; (3) Pokrovskii and Vinogradov, 1990. (N) New data. * Measurements were conducted on a MAT-261 mass spectrometer in the LMTG, Toulouse, France; other determinations were made on a MAT 260 mass spectrometer at the Geological Institute, Moscow.

among the five studied sections, coincides with the boundary between the Dal'nyaya Taiga and Zhuya groups. The exception is borehole 1G, where this drastic decrease occurs between the lower and middle subformations of the Torgo Formation. However, this fact hardly testifies to asynchronism of geochemical and sedimentological events. Evidently, separation of the lower Torgo subformation from the Alekseev formation is incorrect. Isotope data confirm the correlation of the Valyukhta Formation with the Alekseev Formation and the upper subformation of the Sen Formation: all these lithostratigraphic subdivisions are characterized by high $\delta^{13}C$ values. Some differences in amplitude and short-term negative excursions in borehole 1G are presumably caused by postsedimentary changes.

The correlation is significantly weaker for the lower parts of the sections. Sections of the Barakun Formation in the Ura Uplift, Zhuya river, and boreholes from the left bank of the Lena River have high $\delta^{13}C$ values (>4‰), which are not recorded in the Kumukulakh and Khalatyrbyt formations of the Chara River and borehole 1G. Such strong changes in the carbon isotopic composition are unlikely to be caused by epigenetic alterations. The majority of the Barakun Formation is probably absent on the platformal limb of the depression and the Kumukulakh Formation corresponds to its lowermost beds adjacent to the glacial horizon. This conclusion is supported by very close minimum $^{87}Sr/^{86}Sr$ ratios in carbonates of the Barakun and Kumukulakh formations. It is impossible to decipher the evolution of initial $^{87}Sr/^{86}Sr$ ratios within individual formations.

Isotope Correlation with Remote Areas and Probable Age of the Patom Complex

Recently, the Neoproterozoic global stratigraphic scale is very often based on chemostratigraphic data, primarily variations of carbon and strontium isotopic compositions in carbonate rocks. Generally, chemostratigraphy provides only rough age estimates (~10–20 Ma at the best). However, if biostratigraphy is inefficient and reliable datings are absent, chemostratigraphy becomes the only tool for the dating of sedimentation. Preciously this type of situation is observed in the Patom Trough and Berezovsk Depression, where discrepancies in datings of Late Precambrian sediments are as high as 500 Ma.

It is well known that sedimentary rocks not universally retain initial isotope characteristics suitable for chemostratigraphic reconstructions. In order to select the least altered samples, researchers have developed a number of geochemical criteria (Gorokhov et al., 1995; Kaufman and Knoll, 1995; Semikhatov et al., 2004): low values of Mn/Sr (<1) and Fe/Mn (<10) and high $\delta^{18}O$ values (>20‰) (>–10‰ in the PDB scale). The consideration of the efficiency of these criteria is beyond the scope of this paper and postsedimentary

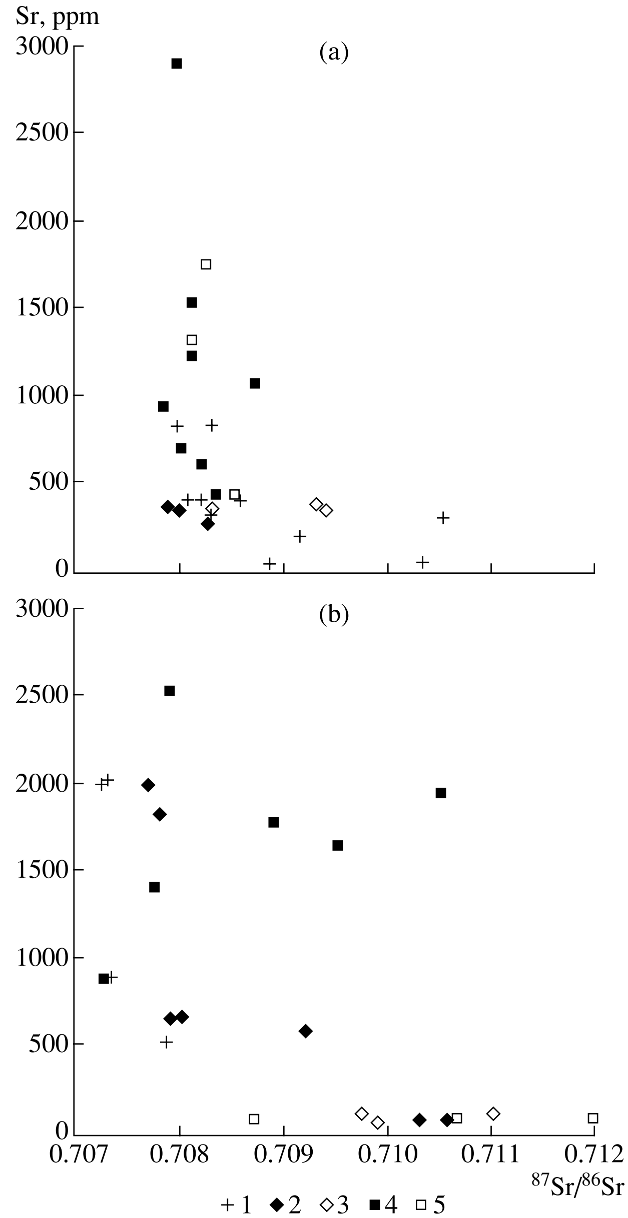

Fig. 6. Sr isotopic composition vs. Sr content in rocks of the Patom Complex and its analogues. (a) Zhuya Group: (1) Torgo Formation, new data and (Pokrovskii and Vinogradov, 1990), (2) Nikol'sk Group, new data , (3) the same (Gorokhov et al., 1995), (4) Chencha Formation, new data (Vinogradov et al., 1996), (5) the same (Gorokhov et al., 1995); (b) Dal'nyaya Taiga, new data and (Pokrovskii and Vinogradov, 1990; Vinogradov et al., 1996): (1) Kumukulakh Formation, (2) Barakun Formation, (3) Moldoun and Khalatyrbyt formations, (4) Valyukhta and Kalancha formations, (5) Alekseev and Sen formations.

transformation of isotope systems in rocks of the Patom Complex will be considered in our second communication. Before proceeding to isotope correlation between the Patom Complex and Late Precambrian sections of remote areas, it is necessary to note that the minimum $^{87}Sr/^{86}Sr$ values mentioned above were obtained for samples having moderate to high Sr contents (250–3000 g/t), low Rb/Sr values (<0.01), very low Mn and Fe contents, low Mn/Sr (<0.1) and Fe/Sr (<2) ratios, and high $\delta^{18}O$ values (>20‰) (Tables 2–7). Very high stability of these parameters over the huge heterogeneous (in terms of facies) study region is a strong evidence in favor of the fact that the minimum $^{87}Sr/^{86}Sr$ values and the main elements of the carbon isotope curve characterize the timing and sedimentation conditions of rocks of the Patom Complex comes (Fig. 7).

In recent decades, several versions of the variation of strontium and carbon isotopic compositions have been proposed for Late Precambrian sedimentary carbonate rocks. They allegedly characterize the evolution of these parameters in the World Ocean (Fig. 8). Some differences exist between these models and possible causes of the differences are discussed in (Melezhik et al., 2001). However, the following doubtless facts will hardly be refuted in future: (1) in carbonates older than 850 Ma, the $^{87}Sr/^{86}Sr$ ratio does not exceed 0.706; (2) rock sequences older than 850 Ma do not contain thick (>100 m, especially >1000 m) carbonate horizons with extremely high $\delta^{13}C$ values (>6‰) (Pokrovskii and Vinogradov, 1991; Gorokhov et al., 1995; Vinogradov et al., 1998; Semikhatov et al., 1998, 2002; Bartley et al., 2001; Des Marais, 2001, Melezhik et al., 2001; Halverson et al., 2005, 2006). These facts indicate that the Barakun and Valyukhta formations (and their counterparts) can be confidently ascribed to the Neoproterozoic. Based on the carbon isotopic composition, the Mariinsk Formation can also be ascribed to the Neoproterozoic (Sr data are so far absent for this formation).

It is more difficult to allocate accurately the Patom Complex within the Paleoproterozoic, because the reference chemostratigraphic curves are correlated to glacial horizons, the number and age of which remain controversial. The Sturtian–Rapitan (760—700 Ma) and Varangian–Marinoan (620–580 Ma) glacial stages are traditionally identified in the Neoproterozoic. The Late Riphean/Vendian boundary, the age of which was until recently accepted at 600 ± 10 Ma (Semikhatov, 2000), is drawn along the base of the Varanger (Lapland) glacial horizon. Recent U–Pb zircon datings on tuffs have complicated this issue. It was established that the Ghaub glacial rocks in Namibia (Hoffman et al., 2004) and the Doushantuo Formation in South China (Condon et al., 2005), which were ascribed to the Marinoan glaciation, formed 632–637 Ma ago. The oldest glacial deposits correlated with the Marinoan glaciation—diamictites of the Nantuo Formation in China—are estimated at 663 ± 4 Ma (Zhou et al., 2004) A similar age (665–670 Ma) was obtained for last stages of the Sturtian glaciation in China and North America (Zhou et al., 2004; Fanning and Link, 2004). Halverson et al. (2005, 2006) have substantiated the existence of Sturtian (710–735 Ma), Marinoan (635–665 Ma), and Gaskiers (~580 Ma) glaciations. However, it should be mentioned that the simultaneous accumulation of gla-

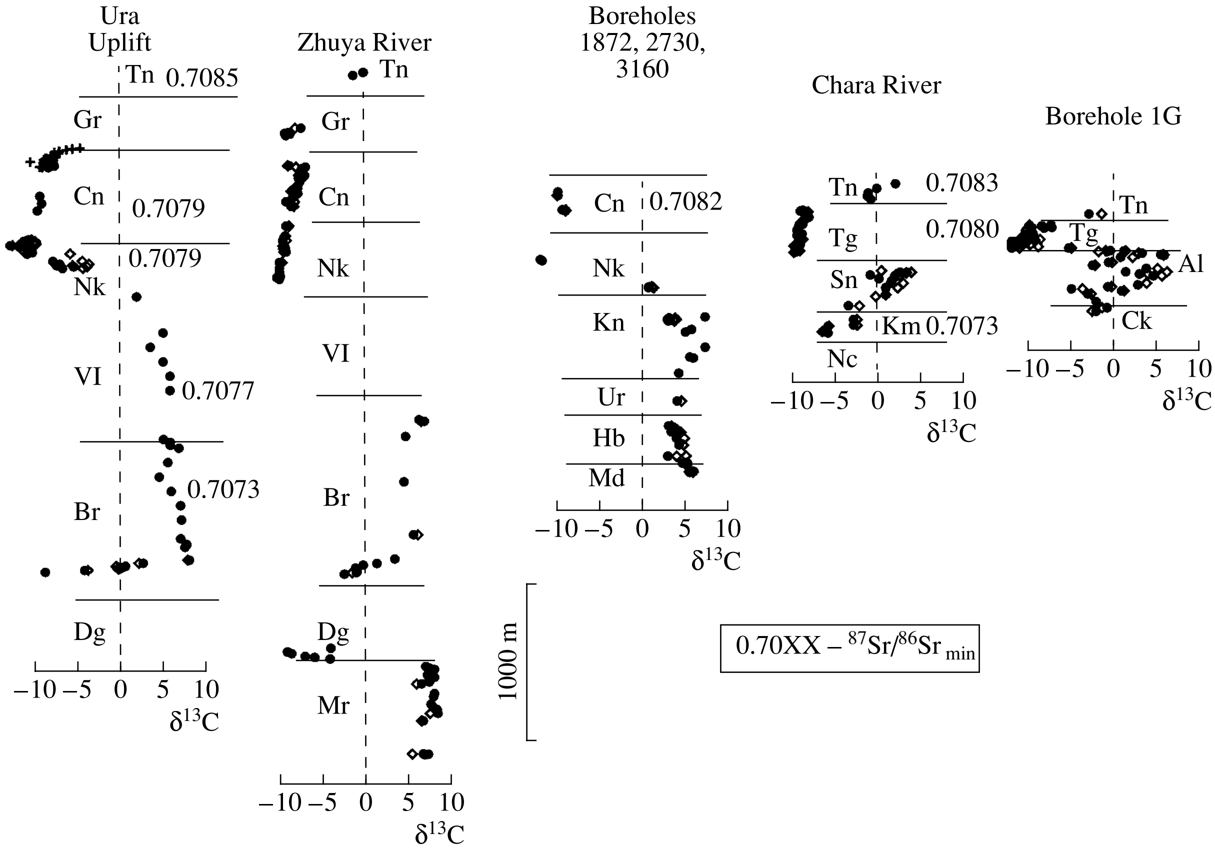

Fig. 7. Carbon isotope correlation of the studied sections and minimum $^{87}Sr/^{86}Sr$ ratios determined in separate formations. Symbols are as in Figs. 2–5.

cial deposits over various continents is only a speculation that has not been sufficiently supported by isotope datings. It is highly possible that each glaciation was divided into several stages.

Figure 8a demonstrates the three most known schemes of strontium isotope evolution in the Neoproterozoic oceanic water based on different data: (1) materials related to Greenland, Spitsbergen, and Namibia (Jacobsen and Kaufman, 1999); (2) the Late Riphean Uralian stratotype and other areas (Kuznetsov et al., 2003); and (3) Neoproterozoic sections of Australia and Canada with the consideration of data on other territories (Walter et al., 2000). Correlation of these schemes with our data on the Patom Complex (Fig. 8a) showed that the rocks of the Zhuya Group were formed in the Early Vendian at the end or immediately after the Varangerian–Marinoan glaciation 580–600 Ma ago, whereas the Dal'nyaya Taiga Group is not older than 630–650 Ma (the end of Late Riphean or Early Vendian) if the Vendian boundary is drawn at 635 Ma (Condon et al., 2005).

The residence time of carbon in the World Ocean (10^3–10^4 yr) is two to three orders of magnitude lower that that of strontium (5×10^6 yr). This allows one to develop a more detailed chemostratigraphic scale based on the carbon isotopic composition, on the one hand, and brings about additional problems related to regional fluctuations of the carbon isotopic composition in seawater, on the other hand (Veizer et al., 1998). The carbon isotope variation pattern typical of Neoproterozoic carbonate sections represents an alternation of extended (hundreds of meters) segments with extremely high $\delta^{13}C$ values (from 4 to 10‰) and relatively short (up to a few tens of meters) segments with low $\delta^{13}C$ values (from –6 to –4‰). Since the cap carbonates with low $\delta^{13}C$ values often overlie glacial diamictites, the negative isotope–carbon anomaly was applied as a marker of glacial stages even in areas not associated with diamictites.

The generalized scheme of carbon isotope variation in the Neoproterozoic proposed in (Jacobsen and Kaufman, 1999) includes five negative $\delta^{13}C$ excursions, which correspond to five glacial periods (two stages of the Sturtian–Rapitan glaciation, two stages of the Varangerian–Marinoan glaciation, and one glaciation at the Vendian/Cambrian boundary) separated by positive excursions of different durations and amplitudes (Fig. 8b). The largest "plateau" of extremely high $\delta^{13}C$ values is observed between the Sturtian–Rapitan and Varangerian–Marinoan epochs (presumably, at the

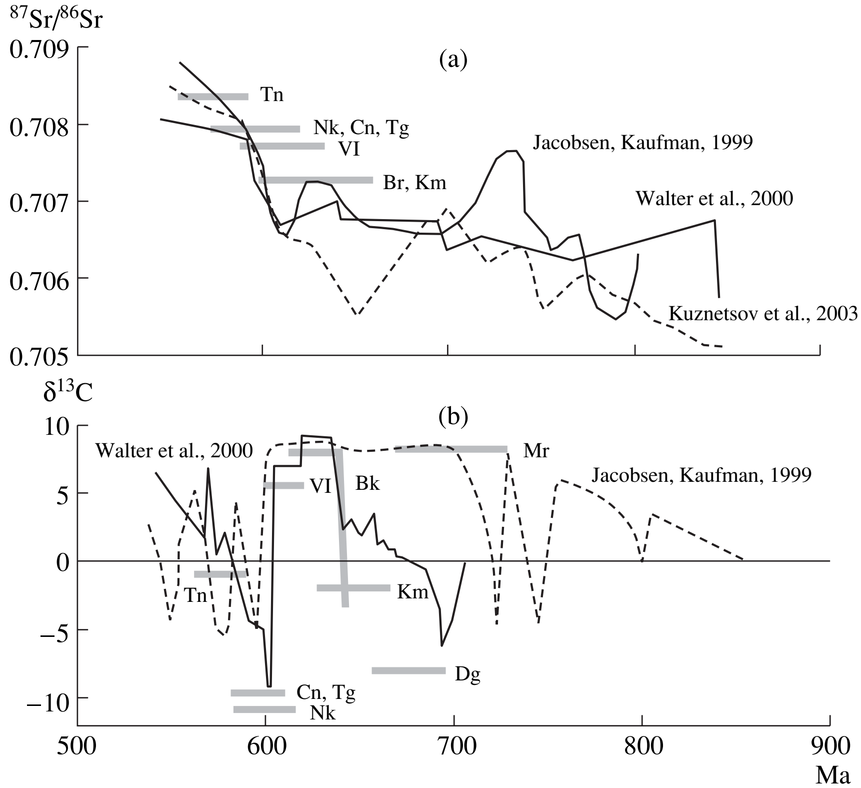

Fig. 8. Isotopic composition of (a) strontium and (b) carbon in Late Precambrian carbonates of the Patom Complex and its analogues as compared to evolution curves of $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ in the Neoproterozoic ocean published before 2003 (Jacobsen and Kaufman, 1999; Walter et al., 2000; Kuznetsov et al., 2003).

interval from 600–620 to 700–720 Ma). A similar (in duration and amplitude) positive plateau was found at this level in the majority of known Neoproterozoic sections, and they usually do not contain more than two negative excursions. Therefore, some researchers concluded that only two glacial periods existed in the Neoproterozoic (Kennedy et al., 1998).

The curve based on the Australian data (Walter et al., 2000) is characterized by extremely high $\delta^{13}C$ values (from 6 to 9‰) within the interval of 630–635 Ma, gradual growth in $\delta^{13}C$ from 0 to 9‰ within 690–635 Ma, and three negative excursions at 690–700, 595–605, and 560–580 Ma. The negative excursions at 595–605 and 560–580 Ma (Trezona and Wonoka formations) are comparable in thickness (100–150 m) and $\delta^{13}C$ amplitude (from –8 to –10‰) with the negative excursion in the Zhuya Group. Unfortunately, no reliable geochronological datings are available for the Trezona and Wonoka formations, and their age is estimated from the inferred sedimentation rate. Moreover, the Wonoka anomaly with no analogues in the adjacent territories is considered a local event (Calver et al., 2000; Walter et al., 2000).

No exact age determinations are also available for units comparable to the Zhuya horizons in amplitude and thickness, e.g., the Tokur Subformation of the Yukanda Formation in the Uchur–Maya region (Semikhatov et al., 2004), as well as the Shuram and Buah formations in Oman (Cozzi et al., 2004; Le Guerroue, 2006), which perhaps mark independent Vendian event(s). The Tokur subformation is correlated with the Late Varangerian glaciation (Semikhatov et al., 2004). However, this estimation is mainly based on its correlation with the Shuram and Buah formations in Oman. Based on new U/Pb datings (Le Guerroue, 2006), the age of the latter formations is estimated at 600–550 Ma, i.e., virtually the entire Vendian.

The latest evolution schemes of strontium and carbon isotopic compositions in the Neoproterozoic ocean based on new dates and more detailed study of carbon and strontium isotope variations in sections of Spitsbergen, Canada, Oman, and Namibia (Halverson et al., 2005, 2006) significantly differ from the previous schemes. According to the new schemes, the Marinoan glaciation began ~665 Ma ago and terminated ~635 Ma ago, with an independent short-term Gaskiers glaciation 580 Ma ago (Fig. 9). The Sr isotope curve in the last schemes has smoother outlines without sharp short-term excursions. In (Halverson et al., 2005, 2006), the nature of negative $\delta^{13}C$ anomalies is not discussed. They are considered as initial and global anomalies. Moreover, the Trezona Formation is correlated with the beginning of the Marinoan glaciation 665 Ma ago; the

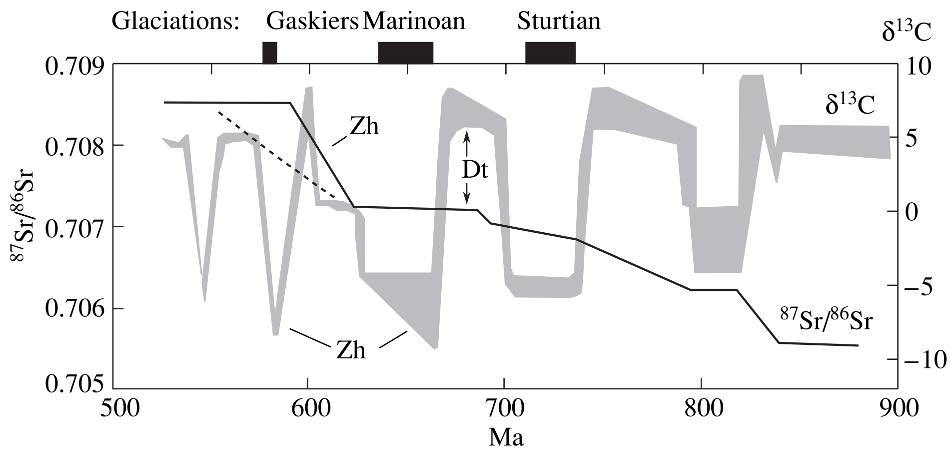

Fig. 9. The $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ secular trends revised on the basis of new isotope data and recent U–Pb zircon datings of Neoproterozoic glaciations (Halverson et al., 2005, 2006). (Dt) Dal'nyaya Taiga Group; (Zh) Zhuya Group. Dashed line shows the possible evolution of Sr isotopic composition in the Neoproterozoic ocean, assuming that the Zhuya Group is nearly coeval to the Wonoka Formation in Australia (~580 Ma).

anomalous Wonoka Formation, with the Gaskiers glaciation ~580 Ma ago.

Comparison of data on the Patom Complex with the last schemes (Fig. 9) confirms the young age of the Patom Complex. However, some principle issues, in particular, the age of the Dzhemkukan (Bol'shoi Patom) glacial horizon, remain open. The carbon and strontium isotopic compositions of the Barakun Formation, which overlies the Dzhemkukan Formation, is similar to those of the carbonates that underlie diamictites correlated with the Marinoan glaciation, such as the Keele Formation (northwestern Canada), Etina Formation (South Australia), and Ombaatjie Formation (northern Namibia). According to the latest data, deposits younger than the Marinoan glaciation lack carbonate horizons comparable (in thickness) with those in the Dal'nyaya Taiga Group that are characterized by ultrahigh $\delta^{13}C$ values and $^{87}Sr/^{86}Sr$ ratios (<0.7075). All these facts make it impossible to ascribe the Dal'nyaya Taiga Group to the Vendian. However, the Bol'shoi Patom glacial horizon cannot also be unequivocally correlated with the Sturtian glaciation, because the $^{87}Sr/^{86}Sr$ ratio during the Sturtian time was significantly lower than that in the Dal'nyaya Taiga Group (Fig. 9).

The position of the Zhuya Group also remains unclear. As was mentioned above, its closest analogues (in terms of the carbon isotopic composition) are the Trezona and Wonoka formations in South Australia. However, the Trezona Formation has significantly lower $^{87}Sr/^{86}Sr$ values, while the Wonoka Formation has higher values, relative to the Zhuya Group. In the Shuram and Buah formations (Oman), the negative anomaly range is similar to that in the Zhuya Group in duration and amplitude, but differs in higher $^{87}Sr/^{86}Sr$ values (~0.7085) (Le Guerroue, 2006).

Differences in the strontium isotopic composition between the Zhuya Group and rocks of Oman and South Australia mentioned above can probably be related to a shift of the $^{87}Sr/^{86}Sr$ ratio in the latter two regions owing to postsedimentary processes. However, most of these discrepancies can be resolved if Sr and C isotope curves will not be strictly correlated with glacial horizons. The age of glacial horizons is not always unambiguous and their simultaneous accumulation at different continents is only a speculation. One can suppose, in particular, that glacial diamictites of the Nichatka and Dzhemkukan formations deposited at the early stage of the Marinoan glaciation; the Barakun and Valyukhta formations, between the early and late stages of this glaciation; and the Zhuya Formation, during the transgression that completed the long-term and prominent Early Vendian glacial stage.

CONCLUSIONS

(1) Similar variations in the carbon isotopic composition with a total $\delta^{13}C$ amplitude of more than 21‰ (from –13.5 to 8.1‰) are established in five sections localized at similar stratigraphic levels in various parts of the Patom Trough and adjacent areas. Alternation of intervals with extremely high and extremely low $\delta^{13}C$ values typical of the majority of Late Neoproterozoic sections indicates a very young (<750 Ma) age of the Patom Complex, including the Balaganakh and Dal'nyaya Taiga groups ascribed by some geologists to the Middle Riphean. The Patom Complex is distinguished from other Neoproterozoic sections by a unique in thickness (up to 1000 m) and amplitude (up to –13.5‰) negative carbon isotope anomaly that virtually spans the entire Zhuya Group.

(2) Minimum $^{87}Sr/^{86}Sr$ values in limestones of the Kumukulakh (0.70725), Barakun (0.70727) Valyukhta (0.70769), Nikol'skoe (0.70790), Chencha (0.70786) and Torgo (0.70799) formations indicate their accumu-

lation 660–680 Ma ago. Glacial diamictites of the Nichatka and Dzhemkukan formations can preliminarily be correlated with the early stage of the Marinoan glaciation (635–665 Ma); the Barakun and Valyukhta Formations, with the interval between its early and late stages; and the Zhuya Formation, with transgression completing its late stage.

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