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Tabular ground ice origin: cryolithological and isotope-geochemical study

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ABSTRACT: An integrated cryolithological-isotope-geochemical study was undertaken at five sites in the Arctic within the framework of a three-year INTAS project. The conclusion based on geochemical analyses is that at the Asian westernmost Yugorsky to the easternmost Chukotka, marine sedimentation changed to subaerial followed by permafrost and massive ice formation due to the regression of the polar basin. Burial of the surface ice was possible, mainly in the mountainous areas of the Arctic coasts, i.e. the Urals and Chukotka.

1 INTRODUCTION

Tabular ground ice (TGI) in the Russian Arctic is found north of 53°N in the mountain regions and north of 66°N in the plains. The widest distribution of TGI is linked to lowlands marked as areas of several marine transgressions in the Pleistocene: Polar Urals' piedmont, Yamal, Gydan and Yugorsky Peninsular, Yenisei-river mouth, coastal areas of Chukotka Peninsula (Streletskaya et al. 2001).

Sediments enclosing TGI in the coastal lowlands often have syngenetic ice wedges of various age at the top of the section, as a result of a change in the sedimentary and thermal regimes after the formation of the TGI.

The origin of thick ground ice layers is still under discussion. It is concluded by the present authors, and reported widely in the literature that in the Russian Arctic TGI formation in most cases is due to ground water migration under gradual freezing of the former sea floor exposed by either eustatic or isostatic fall in sea level. Some calculations and observations argue for the possibility of syngenetic submarine TGI formation. In many cases two ice layers are observed in one section (Kotov 2001, Leibman et al. 2000, Vasiliev & Rogov 2001). In some cases, though, other mechanisms such as burial of surface ice are possible as well.

An integrated cryolithological and isotope-geochemical study was undertaken to consider the origin of TGI. A total of 15 sections were characterised. 290 samples of ice (tabular, constitutional, ice-wedge, icing, snow-infiltration), snow and water, and about 70 samples of enclosing (mainly overlying) deposits were collected within the framework of a three-year INTAS project. Analyses of H, O, C, and S-isotope composition, of macro- and micro-elements, ice petrography, and cryolithological construction were used for genetic interpretations. Detailed interpretations are presented in separate papers of this volume.

2 CRYOLITHOLOGICAL CONSTRUCTION AND ICE PETROGRAPHY

Crystallographic studies were undertaken at four sites (Fig. 1, points 1, 3, 5 & 7, respectively, several sections in each):

- Shpindler, center of Yugorsky Peninsula coast,
- Marre-Sale, Western coast of Central Yamal Peninsula,
- Se-Yakha, Central Yamal,
- Cape Rogozhny, northern coast of Onemen Bay, Chukotka Peninsula.

At the Shpindler (Sh) section, two ice layers are found in the main thermocirque, an upper body with a thickness of up to 15 m, and a lower ice body with a thickness of 3 to 5 m. The ice bodies are separated by 12 m of frozen deposits consisting of alternating sand, clay and peat, probably of deltaic genesis. Cryostructural contacts with ice are conformable. The upper body is overlain by marine (glacial-marine?) clay, with low ice content, most likely thawed during the climate optimum of Holocene, having an unconformable cryostructural

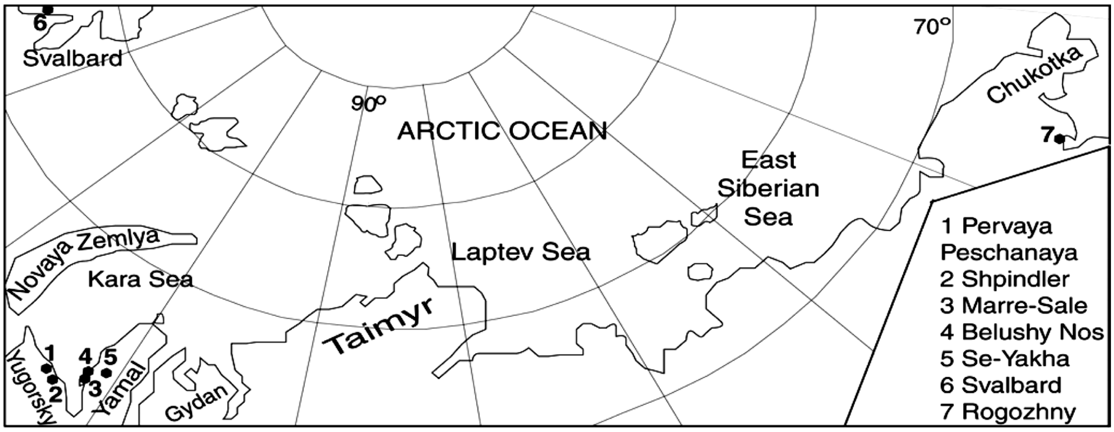

Figure 1. Study sites.

contact with underlying ice. The TGI is composed by four main ice facies: vitreous, bubbly, stratified (containing thin layers of sandy to clayey material), and gravel (containing gravel inclusions). Detailed description is given in Goldfarb & Ezhova (1990); Leibman et al. (2000).

The Pervaya Peschanaya site, only 30 km off the Shpindler, has a very different appearance. Two sections, at the western (PPw) and eastern (PPe) thermocirques are found here at a distance of 1 km from each other. Due to its location close to the mountains, hard rock faces are observed several metres beneath the ice in the western thermocirque. The section is mainly sandy, with many clastic materials in the enclosing deposits and in the ice, and very thin and discontinuous clayey beds. Some common features with the Shpindler section can be observed, as the ice is deformed, there are sandy "rolls" 3–5 m in diameter protruding from overlying deposits into the ice. Such "rolls" are found not only on Yugorsky, but also at Kolguev island coast, Barents Sea (Velikotskiy 1998). The Marre-Sale site (MS), Western Yamal coast is described in detail in Kaplyanskaya & Tarnogradsky (1982), Vasiliev & Rogov (2001) and many other publications. The studied sections are at the coastal bluff of the third marine terrace. The TGI of the lower ice body is exposed at an altitude of 0–3 m above the sea level in marine clay with a sub-horizontal ice layer. The upper cryostructural contact of the ice body is conformable with the overlying marine clay. The ice is mainly vitreous, but some interbeds are bubbly.

The upper TGI body with an ice thickness of 2.5 to 3.5 m dips westward with a 30° angle and is located at the upper portion of the marine-clay bluff, 15–17 m above the sea level, at the contact clay/sand. The upper cryostructural contact of the ice is unconformable. Three ice facies are characteristic of the Upper TGI body: stratified, muddy bubbly, and muddy with clayey clods.

The Belushy Nos site (BN) at the western Yamal coast, 30 km north of Marre-Sale, shows better developed but, probably, the same TGI patterns. The dune-like sections show steeply dipping (up to 90°) sandy layers with ice interbeds, steep cryolithologically conformable contacts of sand and clay. The ice bodies in sand and those in clay are analogues of Upper and Lower ice of Marre-Sale (respectively).

The Se-Yakha site (SY) is in the middle course of Se-Yakha river at Central Yamal. The ice body has an appearance of an anticline fold with sustained layers of ice, overlain by marine, very icy clay. The clay is fully removed from the top of the section, but primary contacts of ice and clay are seen at the fold wings. As a whole, the structure of the ice body is a rhythmic alternation of ice layers with various amounts of bubbles and mineral inclusions, with a conformable cryostructural contact of the ice body and overlying clay. The cryostructure of clay next to the ice is agglomerate with transition to reticulate, and with thinning of ice lenses farther from the ice body. The ice layers and lenses are parallel to the contact. Six facies of ice are identified: vitreous, heavily or slightly bubbly, vitreous with clayey clods and bubbles, stratified, and muddy.

The Rogozhny site (Ro), at the northern coast of Onemen Bay, Bering Sea, Chukotka contains an ice body, which is overlain by laminated marine clay. Next to the contact with TGI the cryogenic structure of the clay is thick reticulate. Further from the ice body the ice lenses become thinner. At the central zone of the main thermocirque, alluvial sandy-pebble deposits interbedded with peat replace the overlying marine clay.

The ice body does not show stratification. The upper contact is sub-horizontal, the lower contact is not exposed. The zone of re-crystallization is found, about 20 cm thick, approximately parallel to the contact of ice and marine clay. In the central and the eastern zones of the exposure re-crystallization zone dips downwards, as though following an outline of alluvial deposits. Its thickness increases up to 1 m.

Bubbly ice dominates in the structure of the ice body and exceeds 70%. The remaining 30% are represented by vitreous ice, ice with clayey clods, and gravel ice.

The ice petrography at this site appears to be very important for the interpretation. In the exposure, exceptionally large ice crystals are characteristic of the crystalline structure of the ice. For example, in 4 of 6 samples of vitreous ice, crystal size exceeds 13 cm (the diameter of Polaroid glasses used in field). Large and medium-sized crystals are characteristic of bubbly ice at Rogozhny, in contrast to medium to small sized crystals at other sites.

Crystalline structure of the gravel ice of Rogozhny Cape differs significantly from that of Shpindler sections analyzed in Leibman et al. (2000). First, at Rogozhny section gravel ice contains bubbles. Second, the presence of gravel does not affect in any way its crystalline structure. The size of crystals is the same whether they include grains or not. Larger grains are located on crystal faces only, smaller grains are both entrapped within crystals or are on crystal faces. This is evidence of re-crystallization of the initial crystalline structure, during which some gravel grains were forced out of large reshaping ice crystals. An oxidized zone is traced by bright reddish-coloured ferruginous sandy-grit inclusions in TGI. This is also evidence of partial melting and re-crystallisation of ice.

Interpretation of TGI origin can be suggested based on ice petrography and cryolithological properties of ice-bearing sections. At Yugorsky Peninsula, Shpindler ice formed in two stages: the lower ice out of free water, possibly due to segregation and intrusion mechanism, while the upper ice formed either from buried glacier, or out of glacier meltwater and underwent deformations due to external stress epigenetically, possibly by glacier action. Pervaya Peschanaya, eastern and western sections more likely contain buried initially superficial ice. Deformations can be explained by ice creep along the rocky slope.

At Yamal Peninsula: Marre-Sale and Belushy Nos ice formed in two stages by syngenetic segregation in submarine conditions for the lower ice bodies and by intrusion epigenetically for the upper ones. Se-Yakha ice formed most likely due to alternating segregation/intrusion out of water from sandy aquifer at the base of clayey sediment, deformation (anticline fold) was due to intrusion.

At Chukotka Peninsula: Rogozhny ice is re-crystallised and thus lost its initial properties. That is why cryolithology of the sections and ice petrography are not confident indicators of the ice origin. Kotov (2001) assigned TGI of Rogozhny to glacier buried by marine sediments of the cold sea after ingression. But the absence of ice stratigraphy, which cannot be explained by re-crystallization only, allows intrusion mechanism as well.

Thus, at all three regions of the Arctic (Yamal, Yugorsky and Chukotka Peninsular) TGI is overlain with initially marine clay whether driven to the area by glacier or formed *in situ*. At Yugorsky peninsula cryostructural contacts of clay and ice, its cryogenic structure, landforms on the surface prove deep thaw to form cryostratigraphic unconformity between ice and clay. The clay at Yamal and Chukotka sections has initial cryogenic structure and shows a gradual transition from massive ice to icy clay. At Se-Yakha section there is no evidence of glacial activity, the ice structure is very close to that described for pingo ice (Vtyurin 1975). At the same time, Chukotka sections are in the middle of glacial till. But practically no deformations of any kind are found in the ice or covering deposits. Therefore, (a) deformations are not evidence of buried glacial ice origin; and (b) conformable cryostructural contacts of ice and overlying deposits are not evidence of interground TGI origin.

The obvious conclusion is that (a) the epoch of TGI formation in most cases is connected with marine sedimentation subject to syngenetic, or epigenetic freezing after marine regression had brought the sea floor to the surface, or even forming on top of glacial ice due to marine sedimentation in the cold-water sea; (b) there is no real opportunity to decide the TGI origin based only on stratigraphic and cryolithological data.

3 ISOTOPE-GEOCHEMICAL STUDY

This is the first time that geochemical properties of TGI based on laboratory studies of a wide range of micro- and macro-elements and 4 stable isotopes (^{18}O, D, ^{34}S, ^{13}C) have been carried out at such a scale. The main approach applied in this study is the comparison of geochemical data for TGI with that of well-defined types of ice, as well as modern water and snow. This method was tested successfully for the Shpindler sections (Leibman et al. 2001).

3.1 *Trace elements, rare earths*

The chemical elements tested are arbitrarily subdivided into two main groups: macro-elements with a concentration as a rule exceeding 1 mg/l (Fig. 2a) and microelements with a concentration never exceeding 1 mg/l (Fig. 2b).

One can see that a higher total concentration is characteristic of constitutional (cryostructural) ground ice (Gro), almost twice that of other types of water, snow and ice. An exception is found at Pervaya Peschanaya, both eastern and western sections, probably because of

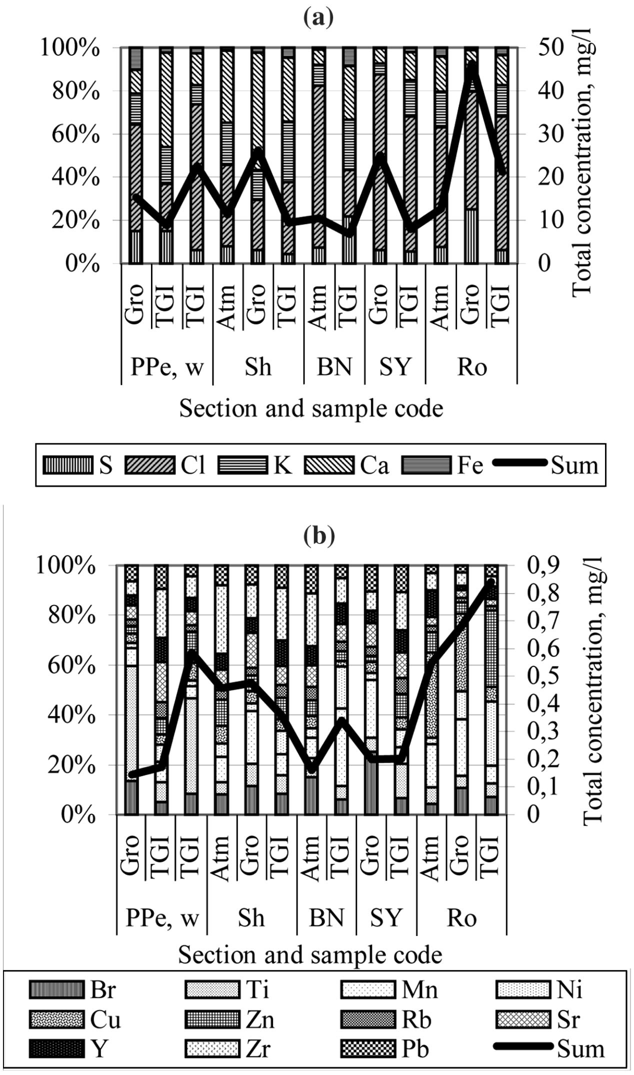

Figure 2. Structure of average concentrations of macro- (a) and micro- (b) elements in tabular ground ice (TGI) compared with atmospheric sources (Atm: rain, snow, ice-wedge ice etc.) and constitutional ground ice (Gro: out of shlieren and agglomerate cryostructure ice). PPe, w – Pervaya Peschanaya, eastern and western sections, and Sh – Shpindler sections (Yugorsky); BN – Belushy Nos, and SY – Se-Yakha sections (Yamal), Ro – Rogozhny section (Chukotka).

fewer analysed samples. TGI at Pervaya Peschanaya, Shpindler, Belushy Nos and Se-Yakha sections has a slightly lower total concentration compared with the moisture of atmospheric origin. Impressive is the fact that (1) at Pervaya Peschanaya, western and Rogozhny sections TGI is much more mineralised than shlieren (constitutional), and (2) in two sections at 1 km distance from each other (Pervaya Peschanaya, eastern and Pervaya Peschanaya, western) there is such an essential difference in geochemical properties. Structure of microelements is shown at Figure 2b. It appears that TGI contains higher or at least the same concentration of microelements compared with other types of moisture. To interpret the structure of element composition in various types of ice we use methods applied in Leibman et al. (2001).

A high concentration of S, Cl, Br, K: an association of elements rather characteristic of sea water, when prevailing in TGI, can be interpreted as ice formation under the influence of marine salinisation either of atmospheric precipitation (if ice is a buried glacier), or of groundwater (in the case of interground ice formation). This combination of elements is most conspicuous at Pervaya Peschanaya, western, Se-Yakha and Rogozhny. The most "continental" is TGI of Pervaya Peschanaya, eastern.

Relatively higher concentrations of Ca, Sr, Y are characteristic of continental water origin, which means that ground ice was formed either of ground water, or of atmospheric or surface moisture, at least far from marine impact. The proportion of these elements is the largest at Pervaya Peschanaya, eastern and Shpindler (both on Yugorsky peninsula), and is rather high at Belushy Nos and Se-Yakha (both on Yamal peninsula).

Chalcogenids (Pb, Zn, Cu, Ni): the association of elements with a high migration ability in gley environments, which is characteristic of ground water, found also in shlieren ice, are indicators of the segregation (or intrusion) mechanism. The proportion of this combination of elements is the highest at the Rogozhny (more than 66% of the total concentration of microelements, Figure 2b), proving the subsurface infiltration of source water prior to TGI formation. The conclusion based on both marine and continental signals in macro- and micro-elements of the Rogozhny section, is that buried glacial origin of TGI is very unlikely.

A marine influence, connected with the subsurface infiltration of source water is observed at the Se-Yakha section. As Se-Yakha is not a coastal section, marine impact is not connected with modern conditions but is a sedimentary signal, in other words it supports the idea of interground segregation-intrusion mechanism of TGI formation. Marine impact at Pervaya Peschanaya, western shows no traces of subsurface infiltration, apparently, there was a direct seawater participation, possibly in the form of atmospheric aerosols. Shpindler, Belushy Nos and Pervaya Peschanaya, eastern show prevailing continental source water with some subsurface water infiltration. For the last two sections the source water correlates with the cryolithological data. To interpret Pervaya Peschanaya, eastern and western sections data, more samples are needed for reliable statistics.

3.2 *Isotopes*

3.2.1 *Oxygen-Deuterium analyses interpretation*

Oxygen-Deuterium analyses showed that though there is a high diversity in morphology, and perhaps, in the origin of ice-bearing sections, the isotope composition of TGI is rather uniform. Average $\delta^{18}O$ values for this ice are concentrated in narrow range between −18 and −23‰ (Fig. 3).

Constitutional (shlieren and pore) ice in total is heavier compared with TGI ($\delta^{18}O$ averages range approximately from −16‰ for Rogozhny up to −20‰ at Shpindler sections). Atmospheric water, as well as ice from such water (ice wedges, snow-patch firn and ice), when compared with TGI, show much heavier values of $\delta^{18}O$: about −13‰ at Yamal to −18,8‰ at Chukotka, and up to −8 farther northward, at the front part of Longyearbreen glacier.

In total, all ground-ice data, including constitutional ice, fit well to the meteoric water line when averages are analyzed (Fig. 3). Still, two groups of sections are subdivided: three sections of Yugorsky coincide with Mwl very closely, while Yamal and Chukotka sections are slightly below the Mwl and are closer to constitutional ice points.

The Pervaya Peschanaya, western section shows sharp distinctions from other sections, while Rogozhny section found at about 120° eastward of the Pervaya Peschanaya, western is characterized by quite the same values of $\delta^{18}O$ and δD. Thus, as in the case of element concentration structure, oxygen and hydrogen isotopic structure allows us to group sections into Yugorsky on one side and Yamal with Chukotka on the other, the first being closer to the atmospheric water source for TGI formation, and the second to ground water.

Moorman & Michel (1998) described a mechanism for formation of segregation massive ground ice out of glacier meltwater, infiltrating through deposits. Data on element and isotope composition allow such a mechanism to be applied to TGI of Yugorsky Peninsula and Chukotka. Yamal sections are most likely of interground origin with source water from a ground-water aquifer, either "marine" (Se-Yakha) or "continental" (Belushy Nos).

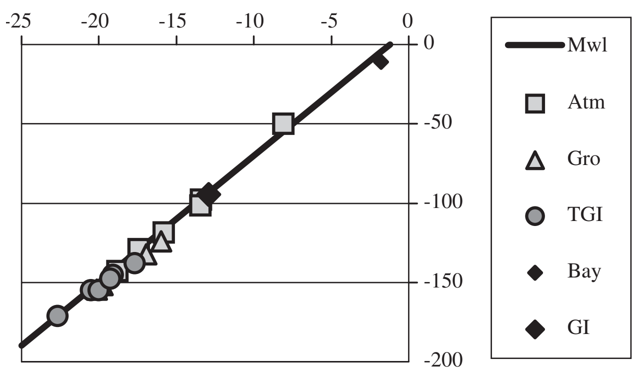

Figure 3. Excess Deuterium for various types of moisture. Mwl, meteoric water line; Atm, Gro and TGI as on Figure 2, Bay – seawater of Baydarata Bay, GI – glacier ice from the front part of Longyerbreen glacier, Svalbard.

3.2.2 *Sulfur and Carbon analyses interpretation*

The isotopic composition of sulfur from sulfate-ion ($\delta^{34}S$–SO_4^{2-}) in ice melts, the isotopic composition of total sulfur ($\delta^{34}S$) in sediments and suspended in ice material were analyzed, as well as the content of ^{13}C in C_{org} out of suspended matter from ice melts.

Close values of $\delta^{34}S$ were obtained for SO_4^{2-} from all samples of ice melts at Pervaya Peschanaya, eastern, Shpindler, Belushy Nos and Se-Yakha sections, ranging between 7 and 12‰. There are a limited number of $\delta^{34}S$ tests known from publications. For example, the range of $\delta^{34}S$ for ground water straddle the range of this value for atmospheric precipitation (Lein et al. 2000) and in part overlap the range for sea water. For this reason, data on constitutional (Gro) and atmospheric-derived (Atm) ice at the Pervaya Peschanaya, eastern section are used as benchmarks for initially surface or interground ice formation (Fig. 4a). The major difference is noted between the atmospheric and constitutional ice types (average $\delta^{34}S$ is about 5 and 13‰, respectively). So, the closer the TGI average is to one of the benchmarks, the more definite is the source water origin,

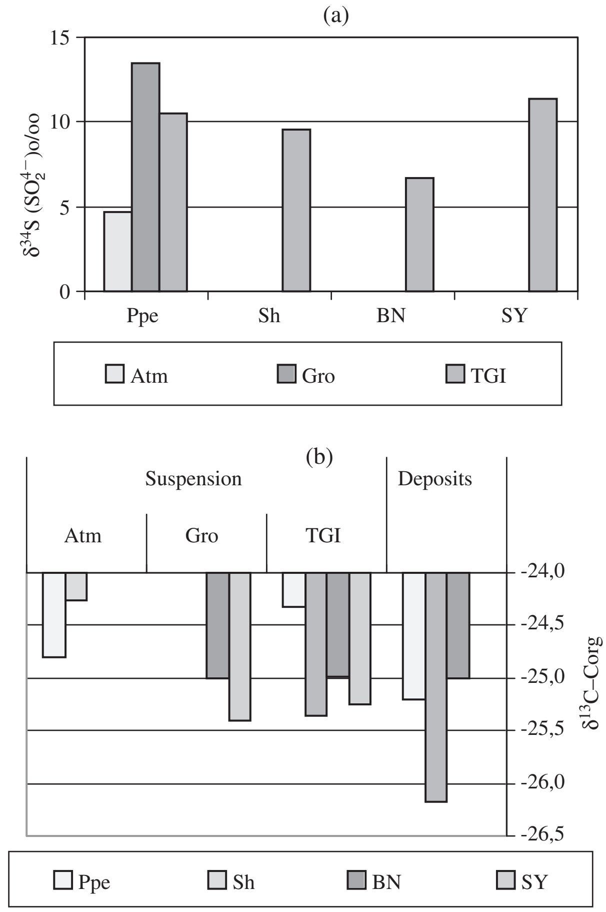

Figure 4. Averages of $\delta^{34}S$ in sulfates of ice melts (a), and $\delta^{13}C$ in organic matter of ice melts, suspended matter and enclosing deposits (b); sample and section codes are as on Figure 2.

either atmospheric, or interground. The Belushy Nos section shows $\delta^{34}S$ values closest to atmospheric, while the Se-Yakha site values are closest to interground ones, other sections being in the middle of the range.

Organic carbon provides a more definite indicator of origin, with $\delta^{13}C$ up to −23‰ for marine organic and −28‰ for continental. The data presented at Figure 4b lies within the range −24 and −25.5‰, in other words, in between the definitely marine and continental origin. The isotopic composition of ice of atmospheric origin is generally heavier than that of tabular or constitutional ice types or enclosing deposits. But specific sections do not show a consistent pattern.

The isotopic composition at the Pervaya Peschanaya, eastern section has TGI much heavier than atmospheric (marine signal in TGI), while isotopic composition of enclosing (overlying) deposits is lighter. This may indicate genetic links between TGI and the underlying deposits rather than with overlying deposits. At the Shpindler section, both TGI and enclosing deposits have the strongest continental signal in organic matter (Fig. 4b). Two Yamal sections (Belushy Nos and Se-Yakha) are in the middle of the range. It is worth noting, that at Belushy Nos TGI is in harmony with enclosing deposits ($\delta^{13}C$ in this type of ice is the same as in constitutional ice and deposits).

Different isotopic composition of sulfate ion, as well as the presence of organics of both marine and continental origin in one and the same section, suggest the polygenetic origin of TGI, i.e. involvement of various sources of water in the formation of the ice bodies.

4 CONCLUSION

The epoch of TGI formation corresponds to a specific geological sedimentary stage in the Quaternary. The sedimentation (marine, riverine, glacial-marine) was followed by continental or shallow-water freezing/re-freezing.

It is suggested that in the study areas from the Asian westernmost Yugorsky peninsula to the easternmost Chukotka there was an epoch in the Late Pleistocene when freezing was accompanied by tabular ground ice formation. Parallel to this event, burial of surface ice bodies was possible as well, mainly in the mountainous areas of the Arctic coasts: Urals (Pai Khoi) and Chukotka.

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REFERENCES

Goldfarb, Yu.I. & Ezhova A.B. 1990. Relic TGI on Yugorsky Peninsula. In *Questions of evolution and development of permafrost*: 22–31. Yakutsk.

Kaplyanskaya, F.A. & Tarnogradsky, V.D. 1982. Glacial formation at the area of settlement Marre-Sale, Yamal Peninsula. In *Transactions of VSEGEI, New series 319:* 77–84. Leningrad.

Kotov, A.N. 2001. Peculiarities of occurrence, composition and structure of TGI layers at the northern coast of Onemen Bay (Chukotka). In *Materials of the Second Conference of Russian Geocryologists, MSU 6–8 June 2001*1. Moscow: Moscow University Press.

Leibman, M.O., Lein A.Yu., Hubberten H.-W., Vanshtein B.G. & Goncharov G.N. 2001. Isotope-geochemical characteristics of TGI at Yugorsky peninsula and reconstruction of conditions for its formation. *Data of glaciological studies* 90: 30–39.

Leibman, M.O., Vasiliev, A.A., Rogov, V.V. & Ingolfsson O. 2000. Study of massive ground ice of Yugorsky peninsula with crystallographic methods. *Earth Cryosphere* IV(2): 31–40.

Lein, A.Yu., Leibman M.O., Pimenov N.V. & Ivanov M.V. 2000. The isotope composition of sulphur and organic carbon in melted massive ground ice from Yugorsky peninsula. *Doklady Academii Nauk* 374 (7): 1142–1144.

Moorman, B.J., Michel F.A. & Wilson A.T. 1998. The development of tabular massive ground ice at Peninsula Point, N.T.W. Canada. In A.G. Lewkowicz & M. Allard (eds), *Permafrost. Proceedings of the Seventh International Conference, Yellowknife, Canada, June 23–27, 1998*. Universite Laval, Centre d'etudes nordiques, Collection Nordicana 57.

Siegert, C., Derevyagin, A.Y., Shilova, G.N., Hermichen, W.-D. & Hiller A. 1999. Paleoclimatic indicators from permafrost sequences in the Eastern Taymyr lowland. In *Land-Ocean Systems in the Siberian Arctic: dynamics and history: 477–499. Berlin: Springer-Verlag.*

Streletskaya, I.D., Ukraintseva N.G., Drozdov I.D., Streletsky D.A. & Leibman M.O. 2001. Distribution of massive ground ice in the Arctic and review of views on its origin. In *Abstracts. First European Permafrost Conference, Rome, Italy, March 26–28, 2001. Rome.*

Vasiliev, A.A. & Rogov, V.V. 2001. TGI in the area of Marre-Sale, Western Yamal. In *Materials of the Second Conference of Russian Geocryologists, MSU 6–8 June 2001*1. Moscow: Moscow University Press.

Velikotskiy, M.A. 1998. Modern shore dynamics of Kolguev island. In *V.I.Solomatin,* V.A. Sovershaev & I.I. Mazur (eds), *Dynamics of the Arctic coasts of Russia:* 93–101. Moscow: Faculty of Geography MSU.

Vtyurin, B.I. 1975. *Ground ice of the USSR*. Moscow: Nauka (in Russian).