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Sulfur and Carbon Isotopes within Atmospheric, Surface and Ground Water, Snow and Ice as Indicators of the Origin of Tabular Ground Ice in the Russian Arctic

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ABSTRACT

Field sampling of tabular ground ice (TGI) was undertaken at a number of geological sections along the Russian Arctic coast. ^{34}S in sulfate ion and ^{13}C in organic matter were analysed in ground ice and enclosing deposits, and in reference samples from snowpacks, atmospheric precipitation, surface waters and glaciers. The scatter in the stable isotope data obtained indicates the heterogeneity of moisture sources for TGI formation. There is a notable difference in the sulfur and carbon isotopic structure between TGI and atmospheric and continental moisture. TGI and its enclosing deposits have a heavier isotopic composition of sulfur and carbon than buried snow and glacial ice. This is considered to be evidence of an essential contribution of marine moisture and sediments to TGI formation. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: Russian Arctic; tabular ground ice; sulfur isotopes; carbon isotopes; snowpacks; glaciers

INTRODUCTION

Massive ice is ‘A comprehensive term used to describe large masses of ground ice, including ice wedges, pingo ice, buried ice and large ice lenses’ (van Everdingen, 2005). This paper deals with massive ice whose lateral extent exceeds its thickness and whose genesis is debated, sometimes referred to as tabular ground ice (TGI) (e.g. Moorman *et al.*, 1998). TGI may be useful to reconstruct palaeoclimatic and palaeoenvironmental conditions as it potentially contains significant information preserved in its chemical and isotope composition relating to its source atmospheric, surface and ground moisture (snow, ice, water and vapour), as well as entrapped gases, sediment particles and organic matter of a specific age.

TGI is classified as buried or intrasedimental in origin (Vtyurin, 1975). Buried TGI is subdivided further according to its source as (a) glacial ice, (b) snowpack, (c) icing ice or (d) lake, river or sea ice. Intrasedimental ice is subdivided further according to the mechanism of moisture mobilisation into segregated, intrusive and segregated-intrusive. Buried snowpack, icing ice and river, lake or sea ice, as well as intrasedimental intrusive (pingo) ice are fairly easy to recognise due to their specific appearances, but buried glacier and segregated or segregated-intrusive ice bodies are more difficult to distinguish visually.

In many papers, the origin of TGI is determined from the origin of the enclosing sediments, which itself may be doubtful. For example, ice covered with till (or what is assumed to be till) may be considered as evidence of buried glacier ice and hence the source of the ground ice body (e.g. Arkhangelov and Novgorodova, 1991; Belova *et al.*, 2008; Kaplyanskaya and Tarnogradsky, 1976, 1986; Kotov, 2005; Lokrantz *et al.*, 2003; Manley *et al.*, 2001; Murton, 2005; Solomatin, 1982). Other papers describe TGI resulting from buried surface ice or intrasedimental formation depending on the glacial history of the area and ice properties (e.g. Michel, 1998; French and Harry, 1990).

Few papers deal with the properties of the ice itself, mainly because obtaining these data are challenging.

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Methods available include geochemical analyses (e.g. ionic analysis which was used from the start of ground ice investigations), as well as relatively new methods that examine the isotopic and microelemental composition. Most publications dealing with the study of ice properties conclude that TGI is of intrasedimental origin (e.g. Danilov, 1989; Leibman, 1996; Leibman *et al.*, 2000, 2001, 2003; Lein *et al.*, 2003; Mackay, 1971, 1989; Moorman *et al.*, 1998; Rogov *et al.*, 2003; Streletskaya and Leibman, 2003; Shpolyanskaya, 1999; Streletskaya *et al.*, 2008). These methods help to identify whether the intrasedimental ice formed by moisture segregation, intrusion or mixed mechanisms. Even the former existence of ice sheets does not necessarily indicate the origin of the ice. The interface between till deposits and the base of the ice sheet can serve as a zone of re-freezing of moisture originating as meltwater that migrates into this weakened zone. In this case, the ground ice produced would have the properties of both atmospheric and intrasedimental water sources (Rampton, 1988; Moorman *et al.*, 1998).

Our previous publications were devoted to an analysis of the origin of TGI using a wide combination of field and laboratory methods: cryolithology, ice petrography, mineralogy, ionic, microelement and trace element geochemistry, gas and sediment inclusion geochemistry, stable isotope structure and microbiology (Leibman *et al.*, 2000, 2003; Rogov *et al.*, 2003; Vanshtein *et al.*, 2003; Lein *et al.*, 2003). Our view is that the sections studied contain TGI bodies of intrasedimental origin. Subsequently, more isotopic data were obtained from new sites in the Chukotka region in addition to those from the western Russian Arctic, as well as snow and glacial ice from Kolguev Island, Novaya Zemlya and Svalbard. Stable isotopes of sulfur and carbon allow more detailed characterisation of these ground ice bodies and contribute to a conclusion regarding the marine or continental origin of the moisture sources.

We recognise that the question of ice origin is far from being settled, but our position concerning the specific ice bodies under study is based on knowledge of permafrost principles, long-term field experience, and multiple descriptions of ice sections undertaken by ourselves and colleagues in many areas of the Arctic and sub-Arctic (Streletskaya *et al.*, 2003). The conceptual model of TGI formation for the western part of the Russian Arctic was suggested in Streletskaya and Leibman (2003) and is employed in this study. This assumes that the TGI in the Barents-Kara region was formed epigenetically from groundwater in a subsea aquifer which migrated to the freezing front after the sea floor was exposed subaerially. This concept explains the position of the TGI at the interface between two lithologic units: sandy sediments beneath and clayey ones above. Water segregation and intrusion through the deposits leave evidence of both sources of water and the aquifer properties in the resulting TGI.

In this paper, the focus is on the source water for ground ice formation which may differ from the origin of the enclosing deposits. For example, even though sediments were formed in the sea, transported and deposited on land by a glacier, the TGI can be formed through re-freezing of water-saturated sediments after glacier melt, due to segregation and intrusive mechanisms. Such a mechanism is substantiated by cryolithologic and ice-structure evidence (Leibman *et al.*, 2000; Rogov *et al.*, 2003), as well as by geochemical and microbiological data (Vanshtein e*t al.*, 2003; Lein *et al.*, 2003).

Sulfur and carbon stable isotope data obtained through sampling and laboratory testing of TGI itself, other types of moisture for reference, as well as the enclosing ice deposits, are investigated from several key sections in the Barents-Kara and Chukotka regions (Figure 1). The sections in the Barents-Kara region were reported previously (Goldfarb and Ezhova, 1990; Leibman *et al.*, 2000, 2001, 2003; Lein *et al.*, 2003; Lokrantz *et al.*, 2003; Manley *et al.*, 2001; Vanshtein *et al.*, 2003). The Chukotka and the Arctic islands (Kolguev, Novaya Zemlya and Svalbard) are presented for the first time and allow a broader view of the range of ice isotopic properties and a comparison of ground ice with buried snow and modern glacial ice. New isotopic data concerning

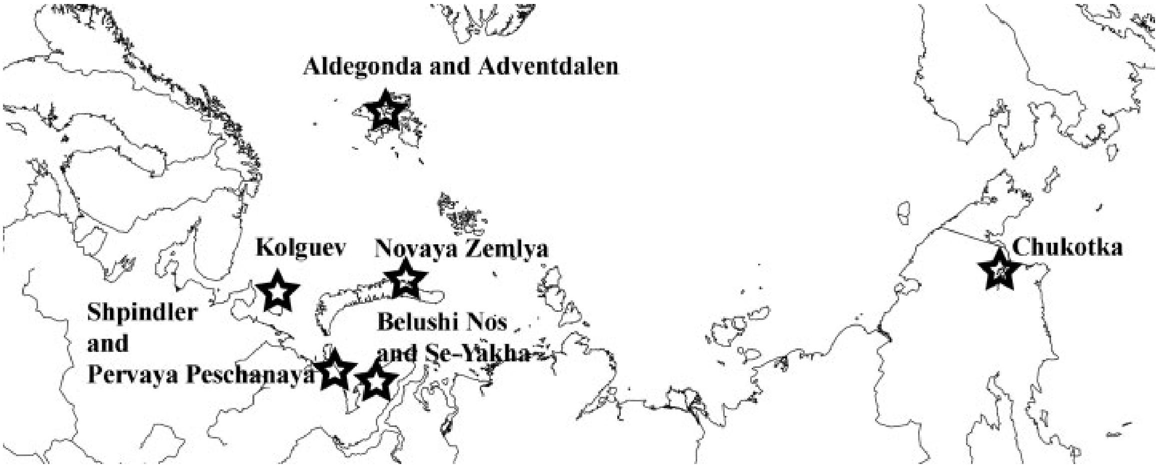

Figure 1 Key sections in the Barents-Kara region (western cluster of sites) and Chukotka region (easternmost area of Russia).

atmospheric sources of moisture provide an additional opportunity to indirectly access the impact of marine aerosols on snowpacks and glaciers as probable sources of glacial advance in the Barents-Kara region.

METHODS

The use of stable sulfur and carbon isotope structure to investigate moisture origin and fate is well developed (Galimov, 1968; Hitchon and Krouse, 1972; Krouse and Grinenko, 1991; Lein *et al.*, 1996; Fedorov, 1999). Interpretation of the isotopic composition of all sampled media is based on the range of $\delta^{34}S$ and $\delta^{13}C$ established for natural moisture sources. The main criteria referred to in this study are as follows: $\delta^{34}S$ heavier than $+5$ to $+8‰$ and $\delta^{13}C$ heavier than $25-26‰$ can be explained only by the contribution of marine moisture in the media.

The key sections were described, logged and sampled according to previously used techniques (Leibman *et al.*, 2001, 2003, 2005). Analyses were undertaken of ions and trace elements, oxygen, hydrogen, carbon and sulfur isotope composition, microbial activity in the melted ice, mineral composition and sediment inclusions in the ice, and composition of gas inclusions in the ice (Leibman *et al.*, 2001, 2003; Lein *et al.*, 2003; Vanshtein *et al.*, 2003). The Rogozhny section in Chukotka is described in detail in Kotov (2005). Here (as well as in the Yugorsky sections) two ice layers are observed, though only the lower one that is covered by marine clay is described. Visually this ice is somewhat different from that at Yugorsky. In addition to clayey inclusions (as shown on photographs in Leibman *et al.*, 2003), it contains suspended sand, but otherwise is very similar to that observed elsewhere. The Novaya Zemlya (Shokalsky glacier) section is described in detail in Leibman *et al.* (2005). The Svalbard data were obtained from two areas: glacial ice was sampled from the Aldegonda glacier, and in the Adventdalen valley, water flow was sampled from a collapsed pingo and ice formed from this water on its slopes (Figure 1; Adventdalen samples collected by Hanne Christiansen from The University Centre in Svalbard).

All samples of between 1 and 5 liters were collected from exposures using a titanium axe or sampler at depths of at least 20 cm beneath the exposed surface, to avoid sampling the weathered layer. Key section 'Shpindler' was most actively sampled in the field during the period 1998–2002, and the analytical results were published by Leibman *et al.* (2001, 2003, 2005), Lein *et al.* (2000, 2003) and Vanshtein *et al.* (2003). Other studied sections on the Yugorsky Peninsula, Yamal and Chukotka region were in part discussed in Leibman *et al.* (2005). In addition to the more than 100 samples published earlier and analysed for isotopic composition, 52 samples were tested, including TGI of Chukotka, the Rogozhny section, surface snow and ice from Arctic islands (Kolguev, Novaya Zemlya and Svalbard), and groundwater from the Svalbard pingo.

Carbon and sulfur stable isotopes in melted ice samples were measured in the Institute of Microbiology, Russian Academy of Sciences, Moscow, using a MI-1201B double-beam mass spectrometer (''Electron'', Ukraine). The set of laboratory calibration standards corresponded to the international reference samples PDB (Craig, 1957) and CD (Grinenko and Grinenko, 1974). Values of $\delta^{34}S-SO_4^{-2}$ and $\delta^{13}C-Corg$ were calculated as averages of five measurements for each sample. The organic carbon isotopic composition of suspension from meltwater was determined after filtration through FP-030/3 filters. Carbon from organic matter was converted into CO_2 by high-temperature burning in hermetically sealed Pyrex ampoules in the presence of CuO and $SnCl_2$ (Esikov, 1980). Pressure in the ampoules was brought to a final value of 10^{-2} mm of mercury. The samples were combusted in a muffle furnace at 500 °C for 18 h. Sulfur from meltwater sulfate ion obtained as $BaSO_4$ precipitate was converted into sulfur dioxide in a vacuum at 1150 °C in the presence of CuO and Fe (Esikov, 1980). The average error of measurement was $\pm 0.2‰$.

RESULTS AND DISCUSSION

Our approach to data analysis is based on the concept that *buried surficial ice* should initially exhibit traces of atmospheric water, and inclusions in this ice are either of aeolian origin, or, in the case of glacial ice, the subjacent strata. Initially *intrasedimental ice* should show indications of groundwater formed under submarine conditions (Danilov, 1989; Shpolyanskaya, 1999; Shpolyanskaya and Streletskaya, 2004; Shpolyanskaya *et al.*, 2007; Streletskaya and Leibman, 2003; Streletskaya *et al.*, 2008). Sediment inclusions accumulate properties of all the layers through which the water percolated, and mixed with continental and possible atmospheric moisture and sediment.

The data from the sites on Figure 1 are presented in Tables 1–5 grouped according to the study region. Generalised values of sulfur and carbon isotope structure in TGI and other types of moisture and sediment along with reference values are presented in Figures 2 and 3.

It should be noted that the range of $\delta^{34}S$ in sulfate ion in groundwater and atmospheric precipitation partially overlap (Figure 2) so that interpretation of these data is ambiguous. However, it can be stated with confidence that the presence of marine sulfate results in a relatively heavy isotopic composition, exceeding $5-8‰$ of $\delta^{34}S$ (Krouse and Grinenko, 1991; Fedorov, 1999).

The isotopic composition of organic carbon depends on the source of sediment inclusions. In surface ice it may result from organisms settling or developing on snow, such as microalgae, aerosols and sediment delivered by aeolian processes. The isotopic composition of organic carbon in a marine environment clearly differs from a continental one by $5-10‰$ (Figure 3). The data range for sea water, ice, sediment load and bottom sediment is -23 to $-26‰$, while the data range for continental and atmospheric water, snow and ice is -25 to $-30‰$. The range of values for organic carbon of marine origin is heavier than 26‰, while the range for continental surface water, atmospheric moisture and

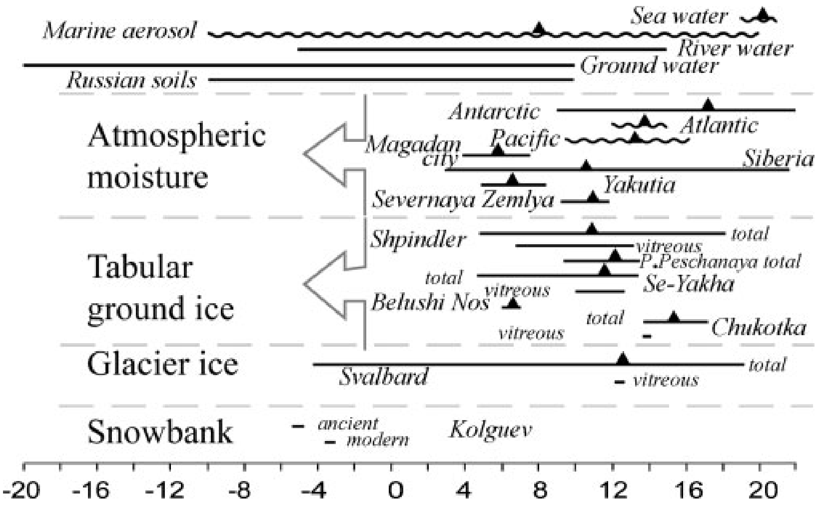

Figure 2 Stable sulfur isotope composition in various natural media as possible sources of moisture for tabular ground ice formation. Waters, aerosol, soils and atmospheric moisture are generalised from Grinenko and Grinenko (1974), Krouse and Grinenko (1991) and Lein *et al.* (1996). Spikes show the position of average values where data are available.

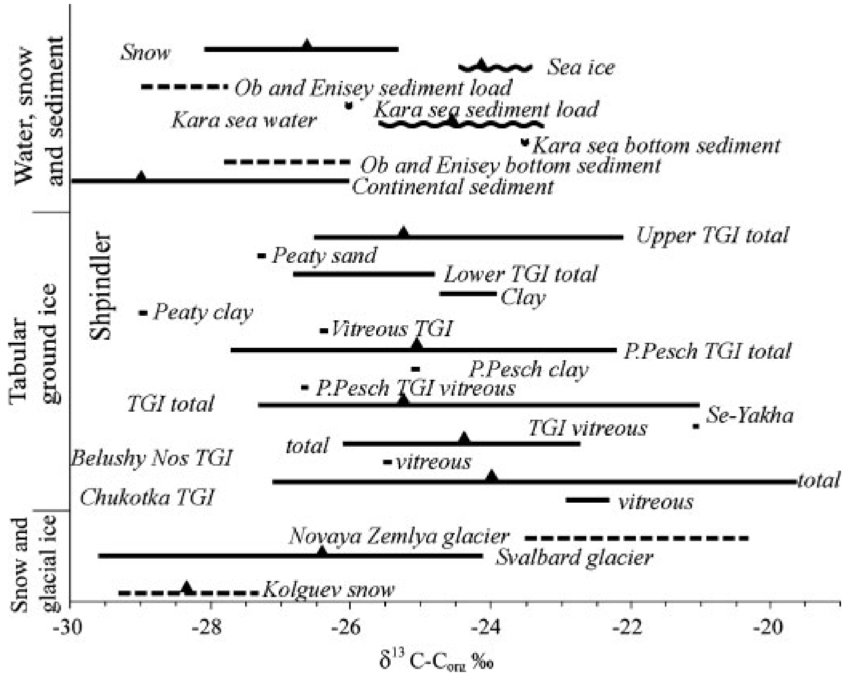

Figure 3 Stable carbon isotope composition in various natural media as possible sources of moisture for tabular ground ice TGI formation. Water, snow and sediment section at the top is based on data generalised from Galimov (1968) and Lein *et al.* (1996). Spikes show the position of average values where data are available.

sediments is lighter than 25‰. The overlap is very limited, which allows a relatively definitive interpretation (Galimov, 1968). Marine or continental origin of the source water can also be examined through the ratio of sulfate ions to chlorine ions, which in sea water is a constant of approximately 1:14 (Horne, 1969). The closer the ratio is to this constant, the stronger is the marine signal.

Samples were grouped according to the ice types previously used to subdivide the sections (Leibman *et al.*, 2003; Rogov *et al.*, 2003): vitreous, bubbly, gravel and stratified ice. Vitreous ice, which does not contain any inclusions, is the most interesting from the point of view of source water and analyses of these samples are presented separately (Figures 2 and 3).

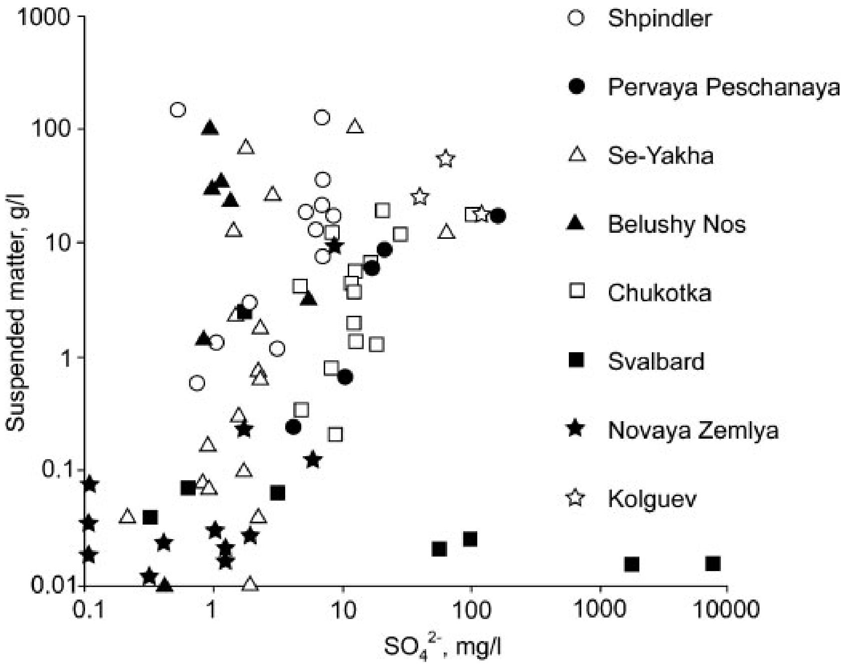

Figure 4 Relation of sulfate ion and suspended matter concentrations.

Sulfate Ion in TGI

Sulfate ion concentrations are positively related to the amount of suspended matter in the ice (Figure 4; Tables 1–5). In the glacial ice of Svalbard and Novaya Zemlya this dependency is much less apparent because of the low impact of sea water. At the same time, there is no correlation between the concentration of chlorine ion and sulfate ion in most TGI within the Barents-Kara region (Figure 5), which is evidence of the varying sources of these two ions in this area. Differences are noted in this ratio in the Se-Yakha section in central Yamal. This section is located about 80 km from the modern seashore and exhibits clear indications of intrusion (Leibman and Kizyakov, 2007), but at the same time shows traces of a marine water source. It has amongst the highest TGI concentrations of chlorine ions and the lowest proportion of sulfate ions (Figure 5). In Chukotka, a fairly high concentration of chlorine ion is accompanied by a clear dependence with sulfate ion. This indicates a higher degree of marine impact on moisture participating in TGI formation in Rogozhny Cape as compared to most TGI of the Barents-Kara region (Figure 5). The lowest proportion of chlorine ion is found in the snowpack of Kolguev Island. This is interpreted as representing a low impact of marine aerosols and spray on the snowpack even though it is located close to the shoreline.

Table 1 Isotopic composition of tabular ground ice and enclosing deposits at two sections on the Yugorsky Peninsula.

	Section	Shpindler			Pervaya Peschanaya		
	Material	Suspended matter (g/l)	$\delta^{34}S$	$\delta^{13}C$	Suspended matter (g/l)	$\delta^{34}S$	$\delta^{13}C$
Enclosing deposits	Overlying deposits	—	(−1.8 to 6.3) 1.5	(−23.9 to −28.9) 25.8	—		−25.0
	Underlying deposits	—	—	−27.2			
	Inclusions in the ice	—	(−2.9 to 1.8) −0.7	—			
Tabular ground ice	Ice with clayey inclusions (> 5 g/l of suspended matter)	(1.2 to 7.8) 4.0	(7.7 to 13.3) 11	(−22.1 to −26.0) −25.0	13.3	11	(−24.0 to −26.9) −25.0
	Ice with gravel inclusions	—	(4.8 to 10.2) 8.2	(−25.1 to −26.8) −25.8			
	Ice without inclusions (< 5 g/l of suspended matter)	2.5	6.8	(−24.8 to −26.5) −25.5	0.7	12	(−22.2 to −27.7) −25.0

Table 2 Isotopic composition of tabular ground ice and enclosing deposits at two sections on the Yamal Peninsula.

	Section	Belushy Nos			Se-Yakha		
	Material	Suspended matter (g/l)	δ^{34}S	δ^{13}C	Suspended matter (g/l)	δ^{34}S	δ^{13}C
Enclosing deposits	Underlying deposits						
	Inclusions in the ice			−25.2			
Tabular ground ice	Ice with clayey inclusions (> 5 g/l of suspended matter)	(30.6 to 107) 57.9	(6.7 to 7.1) 6.8	(−22.7 to −26.1) −24.0	(12.4 to 107) 50.62	(4.7 to 13.4) 10.3	(−25.5 to −27.3) −26.2
	Ice without inclusions (< 5 g/l of suspended matter)	3.27	6.1	(−24.7 to −25.4) −25.0	(0.005 to 1.83) 0.56	(9.2 to 12.7) 10.9	(−21.0 to −27.0) −25.2

Table 3 Isotopic composition of tabular ground ice and sediment inclusions at the Cape Rogozhny section, Chukotka.

	Material	Suspended matter (g/l)	δ^{34}S	δ^{13}C
Tabular ground ice	Inclusions in the ice			
	Ice with clayey inclusions (> 5 g of suspended matter)	(4.2 to 19.6) 11.6	(15.8 to 17.3) 16.6	(−19.6 to −26.3) −24.1
	Ice without inclusions (< 5 g/l of suspended matter)	(0.2 to 3.9) 1.8	(13.7 to 16.0) 14.9	(−22.3 to −27.1) −24.7

Table 4 Isotopic composition of ice and snow on the Arctic islands.

	Section	Kolguev Island			Novaya Zemlya		
		Sauchikha			Shokalsky glacier		
	Material	Suspended matter (g/l)	δ^{34}S	δ^{13}C	Suspended matter (g/l)	δ^{34}S	δ^{13}C
Surface moisture	Modern snow	18	−3.5				
	Ancient (buried) snow	(26 to 55) 40.5	(−4.7 to −5.4) −5.1	(−27.3 to −29.4) −28.4			
	Glacier ice (no inclusions)				(0.003 to 0.070) 0.020		(−20.1 to −23.5) −21.3

Table 5 Isotopic composition of glacier ice and pingo ice and water on Svalbard.

	Section	Aldegonda glacier			Adventdalen pingo		
	Material	Suspended matter (g/l)	δ^{34}S	δ^{13}C	Suspended matter (g/l)	δ^{34}S	δ^{13}C
Surface moisture	Glacier ice (no inclusions)	(0.04 to 0.07) 0.035	(4.2 to 12.5) 9.6	(−26.7 to −29.6) −28.2			
	Glacier ice (with inclusions)	2.0	7.3	−24.1			
Ground-water	Pingo water				0.015	19.2	(−26.0 to −26.4) −26.2
	Pingo water icing				(0.02 to 0.025) 0.023	−4.2	(−25.8 to −26.3) −26.1

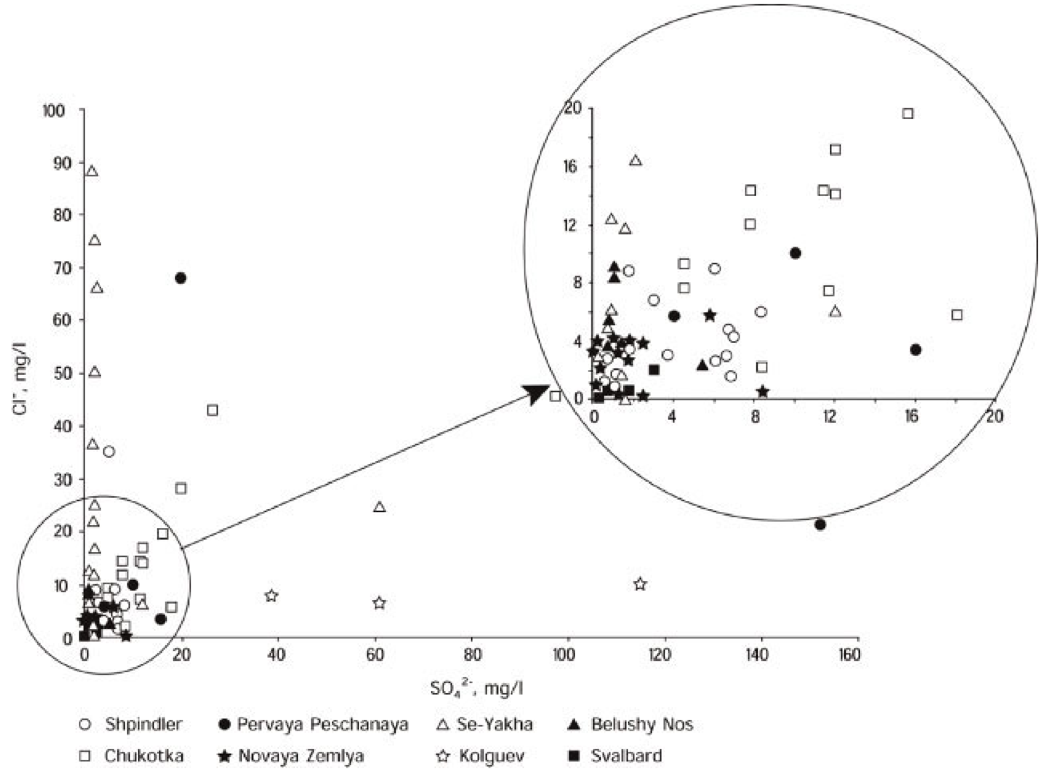

Figure 5 Relation of sulfate ion and chlorine ion concentrations.

Summarising the data in Tables 1–5, it emerges that the isotopic composition of sulfate ion in TGI in the Kara region does not exceed 13.4‰, while only in Chukotka does this value reach 17.3‰. The Kolguev snow and Svalbard glacier ice are characterised by a lighter isotopic composition of sulfate ion (negative values in snow and up to 12.5‰ in ice). Higher concentration and heavier isotopic composition of sulfate ion at Chukotka's Rogozhny section, especially near the interface of tabular ice with the overlying clay, as well as within ice lenses inside the clay ($\delta^{34}\mathrm{S} = 17.3$‰), favour marine origin of both the overlying deposits and tabular ice bodies. This is supported by the average concentration of chlorine ions in this section which is higher than elsewhere. This inference contradicts the conclusion of Kotov (2005) that TGI in the Rogozhny sections originates from the burial of glacier ice.

Organic Carbon in Sediment Enclosed in TGI

The isotopic composition of organic carbon enclosed in TGI of the Barents-Kara region is fairly consistent and on the diagram of carbon isotope composition occupies the range which is characteristic of sea water and sediment rather than those of surface snow and ice (Figure 3; Tables 1 and 2). The farthest from surface sources of moisture is Chukotka ice and the organic carbon contained in its TGI is the richest in heavy isotope $^{13}\mathrm{C}$ ($\delta^{13}\mathrm{C}$ up to -19.6‰). The vitreous ice has minimal sediment enclosures and a composition of $\delta^{13}\mathrm{C} = -24.1$‰ (Table 3), which indicates the connection between the ice and the overlying marine clay, and that this organic carbon has a marine origin (Figure 3).

Surficial Snow and Ice

Modern and ancient buried snowpacks on Kolguev Island, Shokalsky glacier ice on the northern island of the Novaya Zemlya archipelago (Leibman *et al.*, 2005), ice from the Aldegonda glacier on Svalbard and water from a pingo on Svalbard (collected by Hanne Christiansen) were all studied. All three regions are within the continental rim, built of continental-type geological structures. Kolguev Island is closest to the continent with sandy-clayey Quaternary deposits, and it differs from Novaya Zemlya and Svalbard which are mountainous areas. Kolguev and Novaya Zemlya are within the southern region of the European Arctic basin with intensive cyclone activity, while Svalbard belongs to the northern part of this basin. Two main cyclone streams deliver moisture to Svalbard in winter from the Norwegian and Barents Seas. On Kolguev Island, winter winds come from the northwest of European Russia including the Kola Peninsula with its mining plants (Treshnikov and Salnikov, 1985). Sediment inclusions in the snow and glacier ice contain both mineral and organic matter.

Snowpacks of Kolguev Island.

Ancient snowpacks, buried by slope materials, were sampled, as well as the modern snowpack. Ice from metamorphosed snow of the ancient snowpack contains twice as much sediment as the modern snowpack (33 g/l and 18 g/l, respectively). At the same time, modern snow contains much more sulfate ion (114.8 mg/l) than the buried snowpack (38.7 – 60.9 mg/l), and both have much more sulfate than TGI (Figure 4). Sulfur from sulfate ion contains very low concentrations of heavy isotope ^{34}S (Table 4): −3.5‰ in the modern snowpack to −5.4‰ in the ancient buried one (Table 4). This unusual isotopic composition is explained by a high concentration of isotopically light pyrite (Figure 4) which occurs in Shpindler TGI as suspended sediment in the ice and enclosing deposits (Lein *et al.*, 2003). It can be interpreted as due to the oxidation of pyrite towards sulfate ion within aerosols transported to the snowpack. This process results in the enrichment of aerosols, and consequently the snowpack, with sulfate ion and the abnormally light isotope composition of sulfur in the sulfate ion. We infer that the higher concentration of sulfate in the modern snowpack compared to the ancient one is due to aerosol sulfates originating from mining and ore production on the Kola Peninsula. Such an anthropogenic sulfate is characterised by a sulfur isotopic composition averaging close to 0‰ (tests by A. Yu. Lein). Its participation in the isotopic structure of modern snowpack increases δ^{34}S by at least 1‰.

There is much less organic carbon in the modern snowpack compared to the ancient one. In the ancient snowpack, the concentration of carbonate ion is 10 – 40 times higher than in the TGI at the Shpindler section. Organic carbon in the suspended sediment of the snowpack (Figure 3) has a relatively light isotope composition, characteristic of organic matter delivered to the snowpack by continental aerosols. This property of buried snow allows this kind of ground ice to be distinguished from intrasedimental TGI.

Glaciers of Novaya Zemlya.

The content of suspended sediment in both snowpacks and glacier ice of Shokalsky glacier is less than 0.1 g/l of meltwater. The only exception is sediment-rich stratified glacier ice which has the highest concentration of sulfate (Figure 4), close to that of TGI at Shpindler. The proportion of organic carbon δ^{13}C in the suspended sediment ranges from −21.1 to −23.5‰, which indicates minimal participation of continental carbon in aerosol transportation. This is explained by a very limited biomass (the source of organic carbon in atmosphere over the land) in this highly glaciated area.

Glaciers of Svalbard. .

All but one sample from dead ice of the Aldegonda glacier contained very little sediment (Table 5). One sample contained 2.5 g/l and had a visible clay fraction, a feature that has been observed in iceberg ice in the Arctic seas (Shevchenko *et al.*, 2004). Vitreous ice contained only 0.014–0.07 g/l of suspended matter and the isotope composition of organic carbon δ^{13}C from this ice facies is −26.7 to −29.6‰, indicating the continental source of the suspended matter (Figure 3; Table 5). The concentration of ^{13}C is higher in samples with inclusions exceeding 2.5 g/l. This organic material must have been derived from adjacent non-glaciated slopes.

CONCLUSIONS

There is a notable difference in the sulfur and carbon isotopic structure of TGI, compared to that of glacial ice and buried snow. Heavier isotopes of sulfur and carbon occur in TGI and the enclosing deposits than in snow and ice of atmospheric origin. This is considered to be evidence of marine moisture and sediments participating in TGI formation.

The complete data-sets show that the range of results for TGI is quite large: 23‰ for δ^{34}S in sulfate ion (between −5.4‰ and + 19.0‰) and 10‰ for δ^{13}C in organic carbon of suspended sediment (between −19.6‰ and −29.6‰). This indicates heterogeneous sources of sulfur and carbon in the ice which does not contradict the concept of TGI formation through epigenetic freezing of marine deposits during regression of the sea in the Barents-Kara region (Streletskaya and Leibman, 2003).

The isotope-geochemical properties of Chukotka TGI show major differences from the Barents-Kara TGI. A heavy isotopic composition of sulfate ion ($\delta^{34}S = 17.3‰$) together with other properties indicate a higher level of participation of marine moisture in the formation of this ice. Organic carbon in suspended matter in this TGI also suggests its marine origin.

On Kolguev Island, buried ancient snowpack is affected by continental atmospheric transport only: sulfur from sulfate ion in snow is formed as a result of oxidation of isotopically light pyrite yielded by sediment. Organic matter in the suspension also has a continental origin.

In the glaciers of Svalbard, sulfate ion is poor in the ^{34}S isotope formed through the oxidation of sulfide minerals, most likely pyrite from local coal mines. Organic carbon in the glaciers, likely originating from summer growth of microalgae, is enriched by the ^{13}C isotope. So surface snow and ice do not exhibit perceptible traces of marine impact even in the coastal zone. It is therefore inferred that a marine signal in the ice bodies is evidence of an intrasedimental origin of TGI.

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REFERENCES

Arkhangelov AA, Novgorodova EV. 1991. Genesis of massive ice at Ice Mountain, Yenisei River, Western Siberia, according to results of gas analyses. *Permafrost and Periglacial Processes* **2**(2): 167–170.

Belova NG, Solomatin VI, Romanenko FA. 2008. Massive ground ice on the Ural coast of Baydaratskaya Bay, Kara Sea, Russia. In *Proceedings of Ninth International Conference on Permafrost*, 1. Kane DL and Hinkel KM (eds.). University of Alaska Fairbanks: 107–112.

Craig H. 1957. Isotope standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. *Geochimica et Cosmochimica Acta* **12**(1-2): 133–149.

Danilov ID. 1989. Massive ice in the glacial-marine sediments as a result of cryogenic diagenesis. *Reports of Academy of Sciences of the USSR* **306**(5): 1201–1203 (in Russian).

Esikov AD. 1980. *Mass Spectrometry of Natural Waters*. Nauka: Moscow; (in Russian).

Fedorov YuA. 1999. *Stable Isotopes and evolution of hydrosphere*. Istina Publisher: Moscow; (in Russian).

French HM, Harry DG. 1990. Observations on buried glacier ice and massive segregated ice, Western Arctic Coast, Canada. *Permafrost and Periglacial Processes* **1**: 31–43.

Galimov EM. 1968. *Geochemistry of stable isotopes of carbon*. Nedra Publisher: Moscow; (in Russian).

Goldfarb JI, Ezhova AB. 1990. Fossil tabular ice on Yugorsky Peninsula. In *Questions of Evolution and Development of Permafrost*. Permafrost Institute AS USSR Press: Yakutsk; 22–31 (in Russian).

Grinenko VA, Grinenko LN. 1974. *Sulphur isotope geochemistry.* Nauka: Moscow; (in Russian).

Hitchon B, Krouse HR. 1972. Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada: stable isotopes of oxygen, carbon, and sulphur. *Geochimica et Cosmochimica Acta* **36**(12): 1337–1357.

Horne RA. 1969. *Marine chemistry (The structure of water and the chemistry of the hydrosphere)*. John Wiley & Sons: New York, London, Sydney, Toronto.

Kaplyanskaya FA, Tarnogradsky VD. 1976. Relic glacial ice at the north of West Siberia and their role in geological construction of the regions with Pleistocene glaciation of cryolithozone. *Reports of Academy of Sciences of the USSR* **231**(8470): 1185–1187 (in Russian).

Kaplyanskaya FA, Tarnogradsky VD. 1986. Remnants of the Pleistocene ice sheets in the permafrost zone as object for paleoglaciological research. *Polar Geography and Geology* **10**: 257–265.

Kotov AN. 2005. Comparative analysis of the composition and structure of the Chukotka tabular ice fields. In *Materials of the III Conference of Russian geocryologists*, 1. Moscow University Press: Moscow; 168–175.

Krouse HR, Grinenko VA (eds). 1991. *Stable isotopes: natural and anthropogenic sulphur in the environment. SCOPE 43*. John Wiley & Sons: Chichester, New York, Brisbane, Toronto, Singapore.

Leibman MO. 1996. Results of chemical testing for various types of water and ice, Yamal Peninsula, Russia. *Permafrost and Periglacial Processes* **7**(3): 287–296.

Leibman MO, Vasiliev AA, Rogov VV, Ingolfsson O. 2000. Study of massive ground ice of Yugorsky peninsula with crystallographic methods. *Kriosfera Zemli* **2**: 31–40 (in Russian).

Leibman MO, Lein AYu, Hubberten HW, Vanshtein BG, Goncharov GN. 2001. Isotope-geochemical characteristics of tabular ground ice at Yugorsky peninsula and reconstruction of conditions for its formation. In *Materials of Glaciological Studies. Chronicles, discussion* **90**: 30–39.

Leibman MO, Hubberten HW, Lein AYu, Sterletskaya ID, Vanshtein BG. 2003. Tabular ground ice origin in the Arctic coastal zone: cryolythological and isotope-geochemical reconstruction of conditions for its formation. In *Proceedings of the Eighth International Conference on Permafrost*, 1. Phillips M, Springman SM, Arenson LU (eds.). Balkema: Lisse; 645–650.

Leibman MO, Arkhipov SM, Perednya DD, Savvichev AS, Vanshtein BG, Hubberten HW. 2005. Geochemical properties of the water-snow-ice complexes in the area of Shokalsky glacier, Novaya Zemlya in relation to the tabular ground ice formation. *Annals of Glaciology* **42**(1): 249–254.

Leibman MO, Kizyakov AI. 2007. *Cryogenic landslides of the Yamal and Yugorsky peninsulas*. Earth Cryosphere Institute Publisher: Moscow-Tyumen.

Lein AYu, Rusanov II, Savvichev AS, Pimenov NV, Miller YuM, Pavlova GA, Ivanov MV. 1996. Biogeochemical processes on the sulphur and carbon cycles in the Kara sea. *Geochemistry International* **34**(11): 925–941.

Lein AYu, Leibman MO, Pimenov NV, Ivanov MV. 2000. The isotope composition of sulphur and organic carbon in massive melted ground ice from Yugorsky Peninsula. *Doklady Academii Nauk* **374**(7): 1142–1144.

Lein AYu, Savvichev AS, Leibman MO, Miller YuM, Pimenov NV. 2003. Isotopic-biogeochemical peculiarities of tabular ground ice of Yugorsky and Yamal peninsular. In *Proceedings of the Eighth International Conference on Permafrost*, 2. Phillips M, Springman SM, Arenson LU (eds.). Balkema: Lisse; 661–666.

Lokrantz H, Ingylfsson O, Forman SL. 2003. Glaciotectonised Quaternary sediments at Cape Shpindler, Yugorski Peninsula, Arctic Russia: implications for glacial history, ice movements and Kara Sea Ice Sheet configuration. *Journal of Quaternary Science* **18**(6): 527–543. DOI: 10.1002/jqs.771.

Mackay JR. 1971. The origin of massive icy beds in permafrost, western Arctic Coast, Canada. *Canadian Journal of Earth Science* **8**(4): 397–422.

Mackay JR. 1989. Massive ice: some field criteria for the identification of ice types. In Current Research, Part G, Geological Survey of Canada, Paper 89-1G, 5–11.

Manley WF, Lokrantz H, Gataullin V, Ingolfsson O, Andersson T. 2001. Late-Quaternary stratigraphy, radiocarbon chronology, and glacial history at Cape Shpindler, Southern Kara Sea, Arctic Russia. *Global and Planetary Change* **31**: 239–254.

Michel FA. 1998. The relationship of massive ground ice and the Late Pleistocene history of northwest Siberia. *Quaternary International* **45/46**: 43–48.

Moorman BJ, Michel FA, Wilson AT. 1998. The development of tabular massive ground ice at Peninsula Point, N.T.W. Canada. In *Proceedings of the Seventh International Conference on Permafrost*. Lewkowicz AG and Allard M (eds.). Universite Laval: Quebec. Collection Nordicana; 57, 757–761.

Murton JB. 2005. Ground-ice stratigraphy and formation at North Head, Tuktoyaktuk Coastlands, western Arctic Canada: a product of glacier-permafrost interactions. *Permafrost and Periglacial Processes* **16**(1): 31–50. DOI: 10.1002/ppp.513.

Rampton VN. 1988. Origin of massive ground ice on Tuktoyaktuk Peninsula, Northwest Territories, Canada: a review of stratigraphic and geomorphic evidence. In *Proceedings of the Fifth International Conference*, 1. Kaare Senneset (ed.). Tapir Publishers: Trondheim; 850–855.

Rogov VV, Kizyakov AI, Leibman MO, Perednya DD, Vasiliev AA. 2003. Tabular ground ice: cryolithological construction and crystalline structure. In *Proceedings of the Eighth International Conference on Permafrost*, 2. Phillips M, Springman SM, Arenson LU (eds.). Balkema: Lisse; 977–982.

Shevchenko VP, Lisitsyn AP, Vinogradov AA, et al. 2004. New view on the impact of aeolian transport on modern marine sedimentation and environment in the Arctic. Results of aerosols and snow cover study. In *New Ideas in Oceanology*, 2. Vinogradov ME, Lappo SS (eds.). Nauka Publisher: Moscow; 168-214; (In Russian).

Shpolyanskaya NA. 1999. Cryogenic structure of dislocated deposits with massive ice beds as indicator of their genesis. *Kriosfera Zemli* **4**: 61–70 (in Russian).

Shpolyanskaya NA, Streletskaya ID. 2004. Genetic types of massive ground ices and peculiarities of their distribution in Russian Subarctic. *Kriosfera Zemli* **4**: 56–71 (in Russian).

Shpolyanskaya NA, Streletskaya ID, Surkov AV. 2007. Comparative genetic analysis of tabular massive ice and adjacent Pleistocene sediments of the northern part of West Siberia. *Geoecology. Engineering Geology. Hydrogeology. Geocryology* **3**: 212–224 (in Russian).

Solomatin VI. 1982. Buried relicts of glacial ice at the north of West Siberia. *Materials of Glaciological Studies. Chronicles, Discussion* **29**: 233–240 (in Russian).

Streletskaya ID, Leibman MO. 2003. Cryogeochemical model of tabular ground ice and cryopegs formation at central Yamal, Russia. In *Proceedings of the Eighth International Conference on Permafrost*, 2. Phillips M, Springman SM, Arenson LU (eds.). Balkema: Lisse; 1111–1115.

Streletskaya ID, Ukraintseva NG, Drozdov ID. 2003. A digital database on tabular ground ice in the Arctic. In *Proceedings of the Eighth International Conference on Permafrost*, 2. Phillips M, Springman SM, Arenson LU (eds.). Balkema: Lisse; 1107–1110.

Streletskaya ID, Vasiliev AA, Kanevskiy MZ. 2008. Freezing of marine sediments and formation of continental permafrost at the coasts of Yenisey Gulf. In *Proceedings of Ninth International Conference on Permafrost*, 2. Kane DL and Hinkel KM (eds). Institute of Northern Engineering, University of Alaska Fairbanks: Fairbanks;1722-1726.

Treshnikov AF, Salnikov SS (eds). 1985. *Polar and Southern oceans*. Nauka: Leningrad; (in Russian).

Van Everdingen R (ed). 1998. revised May 2005. *Multi-language glossary of permafrost and related ground-ice terms*. National Snow and Ice Data Center/World Data Center for Glaciology: Boulder, CO.

Vanshtein BG, Cherkashev GA, Leibman MO, Piven PI. 2003. Geochemical properties of the water-snow-ice complexes in the area of Shokalsky glacier, Novaya Zemlya in relation to the tabular ground ice formation. In *Proceedings of the Eighth International Conference on Permafrost*, 2. Phillips M, Springman SM, Arenson LU (eds.). Balkema: Lisse; 1155–1160.

Vtyurin BI. 1975. *Underground ice of the USSR*. Nauka: Moscow; (in Russian).