

New Data on the Isotopic Composition and Evolution of Modern Ice Wedges in the Laptev Sea Region

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Summary: The first step for the application of stable isotope analyses of ice wedges for the correct paleoclimatic reconstruction supposes the study of the isotopic composition of modern ice wedges and their relationship with the isotopic composition of modern precipitation. The purpose of this research is to present, to analyze and to discuss new data on isotopic composition ($\delta^{18}\text{O}$, δD , ^3H) of modern ice wedges obtained in the Laptev Sea region in 1998-99.

Investigations were carried out at two sites: on Bykovsky Peninsula in 1998 and on Bol'shoy Lyakhovsky Island in 1999 and were based on the combined application of both tritium (^3H) and stable isotope ($\delta^{18}\text{O}$, δD) analyses.

Tritium analyses of the atmospheric precipitation collected during two field seasons show seasonal variations: high tritium concentration in snow (to a maximum of 207 TU) and low values of tritium concentration (<20 TU) in rain. High tritium concentrations are also observed in the surface water, in supra-permafrost ground waters, and in the upper part of permafrost. High tritium concentrations range between 30-40 TU and 750 TU in the studied modern ice wedges (active ice wedges), which let us believe that they are of modern growth. Such high tritium concentrations in ice wedges can not be associated with old thermonuclear tritium because of the radioactive decay. High tritium concentrations found in the snow cover in 1998/99, in the active layer and in the upper part of permafrost give evidence of modern (probably the last decade) technogenic tritium arrival from the atmosphere on to the Earth surface in the region.

The comparison of the isotopic composition ($\delta^{18}\text{O}$, δD and d-excess) of active ice wedges and modern winter precipitation in both sites shows: 1) the isotopic composition of snow correlates linearly with a slope close to 8.0 and parallel to the GMWL at both sites; 2) the mean isotopic composition of active ice wedges on Bykovsky Peninsula is in good agreement with the mean isotopic composition of modern snow; 3) the isotopic composition of active ice wedges and snow on Bol'shoy Lyakhovsky Island are considerably different. There are low values of d-excess in all studied active ice wedges (mean value is about 4.8 ‰), while in snow, the mean value of d-excess is about 9.5 ‰. Possible reasons for this gap are the following: 1) the modification of the isotopic composition in snow during the spring period; 2) changes in the isotopic composition of ice wedges due to the process of ice sublimation in open frost cracks during the cold period; 3) mixing of snowmelt water with different types of surface water during the spring period; 4) different moisture source regions.

Zusammenfassung: Die Anwendung der stabilen Isotopenanalyse von Eiskeilen für eine korrekte Paläoklima-Interpretation erfordert die Kenntnis der Isotopenzusammensetzung moderner Eiskeile und ihre Beziehung zu Rezentniederschlägen. In dieser Arbeit werden neue stabile Isotopendaten ($\delta^{18}\text{O}$, δD , ^3H) von modernen Eiskeilen, die in den Jahren 1998 und 1999 beprobt wurden, dargestellt, analysiert und diskutiert.

Die Untersuchungen wurden an zwei Lokalitäten durchgeführt: 1998 auf der Bykovski-Halbinsel und 1999 auf der Grossen Ljachow-Insel. Sie basieren auf der Kombination von Tritium- (^3H) und stabilen Isotopenanalysen ($\delta^{18}\text{O}$, δD). Tritiumanalysen der atmosphärischen Niederschläge, die während der beiden Feldaufenthalte gewonnen wurden, weisen saisonale Schwankungen

auf: hohe Tritium-Konzentrationen (von maximal 207 TU) im Schnee und niedrigere Konzentrationen (<20 TU) im Regenwasser. Erhöhte Tritiumkonzentrationen werden auch im Oberflächenwasser, im Suprapermafrost-Grundwasser und im obersten Bereich des Permafrostes gemessen.

Die Tritium-Konzentrationen sind hoch und liegen zwischen 30-40 TU und 750 TU in den untersuchten, heute aktiven Eiskeilen, und dies belegt heutiges Eiskeil-Wachstum. Die erhöhten Tritium-Konzentrationen in Eiskeilen können wegen des radioaktiven Zerfalls nicht mit altem thermonuklearen Tritium assoziiert werden. Hohe Tritium-Konzentrationen in der Schneedecke (der Jahre 1998/99), in der saisonalen Auftauschicht und im oberen Bereich des Permafrostes belegen in der Region die Ankunft von jungem (vermutlich in der letzten Dekade) technogenen Tritium aus der Atmosphäre zur Erdoberfläche.

Der Vergleich der Isotopenzusammensetzung ($\delta^{18}\text{O}$, δD und d-Exzess) von aktiven Eiskeilen und rezenten Winterniederschlägen für beide Lokalitäten zeigt: 1) die Isotopenzusammensetzung von Schnee ist für beide Lokalitäten linear korreliert und verläuft mit einer Steigung nahe 8.0 parallel zur GMWL; 2) die mittlere Isotopenzusammensetzung von aktiven Eiskeilen der Bykovski-Halbinsel stimmt mit der mittleren Isotopenzusammensetzung von rezentem Schnee überein; 3) die Isotopenzusammensetzungen von aktiven Eiskeilen und Schnee der Grossen Ljachow-Insel unterscheiden sich deutlich. Alle untersuchten aktiven Eiskeile zeigen niedrige d-Exzess-Werte (Mittelwert: 4.8 ‰), während im Schnee im Mittel ein d-Exzess von 9.5 ‰ gemessen wird.

Die möglichen Ursachen für diesen Unterschied sind: 1) die Veränderung der Isotopenzusammensetzung des Schnees im Frühjahr, 2) eine Veränderung der Isotopenzusammensetzung von Eiskeilen durch Sublimationsprozesse in der offenen Frostspalte im Winter, 3) die Mischung von Wasser aus der Schneeschmelze mit verschiedenen Oberflächenwässern im Frühjahr, 4) unterschiedliche Niederschlagsquellen.

INTRODUCTION

This paper focuses on ground ice studies carried out in the frame of the multidisciplinary research program „Paleoclimatic signals in ice-rich permafrost“ in the Laptev Sea region.

Ice wedge ice is the most abundant type of ground ice in the region. Its formation had taken place over a long period during the Pleistocene, the Holocene and at present time. Because of this, ice wedges are considered to be a unique archive of paleoenvironmental and paleoclimatic information. In the modern view the stable isotope composition of ice wedges is mainly determined by the average isotopic composition of winter precipitation and it reflects well winter climatic conditions (MACKAY 1983, KONYAKHIN 1988, VAIKMAE 1989, VASIL'CHUK 1989). In 1998-99 the isotopic composition ($\delta^{18}\text{O}$, δD , ^3H) of Pleistocene, Holocene and recent ice wedges was studied in detail on Bykovsky Peninsula and Bolshoy Lyakhovsky Island both located in the Eastern Laptev Sea region, Northern Siberia.

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We started our investigations by studying the isotopic composition of modern ice wedges and their relationship with the isotopic composition of modern winter precipitation in the region. We also used results of previous stable isotope investigations in the Taymyr region at Labaz Lake and Cape Sabler carried out between 1994 and 1996.

The purposes of this paper are (1) to discuss data on modern processes of ice wedge formation in the region based on tritium analysis and stable isotope method, (2) to compare the isotopic composition of modern ice wedges at two study sites and (3) to correlate new data of the isotopic composition of modern ice wedges and winter precipitation.

STUDY SITES

Studies of modern ice wedges were conducted at two sites (Fig. 1): on Bykovsky Peninsula at Mamontovy Khayata outcrop (71° 60' N, 129° 20' E) in 1998 and on Bol'shoy Lyakhovsky Island at both sides of the mouth of Zimov'e River (73° 20' N, 141° 30' E) in 1999. The nearest long-term weather stations are in Tiksi and at the Shalaurova polar station, respectively. The distance between these two locations is about 600 km. Modern main climatic and environmental conditions of the study areas are presented in Table 1.

Both sites belong to the coastal lowlands of Northern Siberia within the zone of continuous permafrost reaching a thickness of about 400-600 m (GEOCRYOLOGY OF THE USSR 1989). The mean annual ground temperature at the Bykovsky site is about -11 °C and at the Bol'shoy Lyakhovsky site about -12.2 °C. The thickness of the active layer varies from 0.2-0.5 m depending on landscape and ground conditions. Seasonal thawing begins in the first or second decade of June and ends in the second decade of September (GRIGOR'EV 1966).

One of the main geological and cryolithological features of the study area is the occurrence of the Ice Complex, very ice-rich Late Pleistocene sediments with huge syngenetic polygonal ice wedges. These sediments form vast accumulation plains with heights of about 36-40 m above sea level. The sedimentary part of the Ice Complex mainly consists of poorly-sorted sandy silt. According to ¹⁴C age determinations in ice wedges, the continuous formation of the Ice Complex and the growth of huge ice wedges at the Bykovsky site ended about 9.4 ka ago (MEYER et al. 2001).

According to ¹⁴C dates of enclosed sediments (SCHIRRMESTER et al. 2000) and data on tritium analyses, ice wedge formation in the region occurred widely during the Holocene and still occurs at present time. Deposits of thermokarst depressions, (so called alases), thermo-erosional valleys, (so called logs), fluvial terraces and peat bogs were formed in the Holocene. Holocene and modern ice wedge growth can be observed generally in all geologic units, such as Ice Complex, alases, logs, fluvial terraces, flood plains and peat bogs. The systems of polygons of different generations of ice wedges usually cover the surface of these geomorphologic elements and mark the processes of modern frost cracking on the surface.

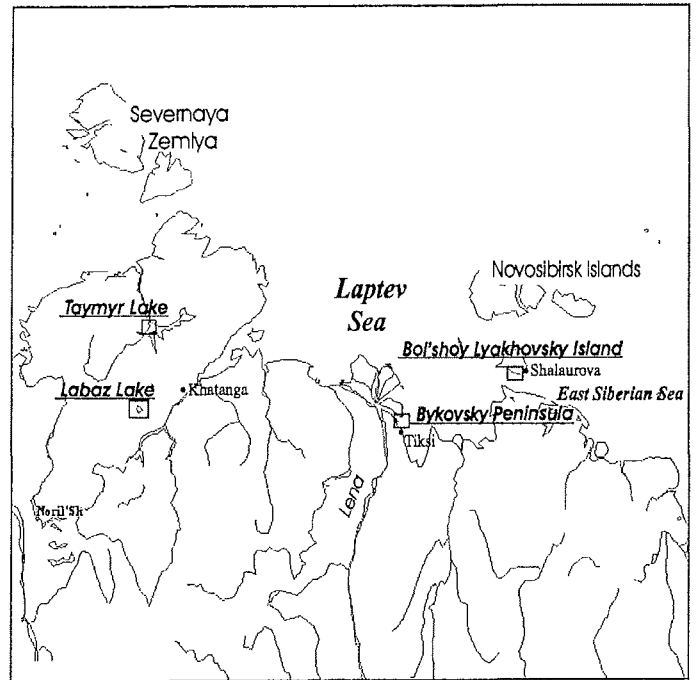


Fig. 1: Location map.

Fig. 1: Karte des Arbeitsgebietes.

STUDY SUBJECT

Frost cracking in permafrost is commonly accompanied by ice wedge growth. The general mechanism of ice wedge growth is well known and based on the ice wedge cracking theories (DOSTOVALOV 1957, LACHENBRUCH 1962, GRECHISHCHEV 1970 and others). When thermal stress is induced to frozen ground, thermal contraction takes place and a frost crack opens in the ground. In spring, snowmelt water will trickle down into open cracks where it freezes forming a subvertical wedge-shaped elementary ice vein. Further field investigations and studies of isotopic composition ($\delta^{18}\text{O}$) of modern ice wedges at different regions of Arctic support the belief that the formation of ice wedges is mostly due to freezing of snowmelt water of winter precipitation in frost cracks (MACRAY 1975, 1983, KONYAKHIN 1988, VASIL'CHUK 1989).

Modern ice wedges have been studied in Ice Complex accumulation plains (36-40 m above sea level, at Bykovsky and Lyakhovsky sites), in alases (from 3-5 to 12-15 m a.s.l. at Bykovsky and Lyakhovsky sites), in fluvial terraces (2-4 m a.s.l. at Lyakhovsky site), in thermo-erosional valleys (at Lyakhovsky site) and in peat bogs (at Bykovsky site). The identification of modern ice wedge formation was carried out both by visual observation and using the tritium analysis.

Usually, recent ice veins (modern ice wedges) can clearly be observed in the upper part of Holocene ice wedges (Fig. 2). The recent ice veins penetrate into older ice wedge down to the depth of modern frost cracks (Fig. 3). According to field observations the width of modern elementary ice veins varies from 1-4 mm, and the width of „modern growth“ from 1-5 cm. „Modern growth“ of ice wedges can be traced well inside the system of modern frost cracks, which cut through the active

| Physical geographical characteristics | Site Bykovsky | Site Lyakhovsky |
|--|--------------------------------|-----------------|
| Mean annual air temperature (°C) | -13.4 | -14.7 |
| Mean January temperature (°C) | -33.3 | -30.5 |
| Mean July temperature (°C) | 7.0 | 6.5 |
| Period with mean daily air temperature <0 °C | 260 | 275 |
| Precipitation / year (mm) | 240-260 | 70-120 |
| Precipitation / winter (mm) | 50-60 | 20-30 |
| Mean annual air humidity (%) | 79 | 88 |
| Botanical geographical zone | typical tundra / Arctic tundra | Arctic tundra |

Tab. 1: Physical geographical characteristics of the research areas.

Tab. 1: Physikalisch-geographische Charakteristika der Arbeitsgebiete.



Fig. 2: Modern ice wedge growth in the section R-32, Lyakhovsky site. For scale see length of the meter is 18 cm.

Fig. 2: Heutiges Eiskeil-Wachstum im Bereich R-32, Große Ljachow-Insel. Zollstock als Maßstab ist 18 cm lang.

layer and form polygons of different generations. The presence of „modern growth“ in the ice wedge „head“ can indicate modern evolution of the ice wedge. More detailed information on the age of modern-looking ice wedges or ice veins and their evolution results from tritium analysis.

METHODS

The investigations are based on the combined application of both tritium and stable isotope analyses. The isotopic composition (^3H , $\delta^{18}\text{O}$, δD) of „modern growth“ and „heads“ of ice wedges (recent ice veins), the upper part of permafrost and precipitation have been studied.

The tritium analysis method is applied in geocryology as a tool for the examination of processes of modern ground ice formation and determination of the age of ground ice (MICHEL 1982, CHIZHOV et. al. 1983, BURN 1990). Tritium (^3H), is a radioactive hydrogen isotope with a decay constant of 12.4 years. In nature, tritium results from the secondary interaction of cosmic rays with the nucleus of nitrogen and oxygen in the

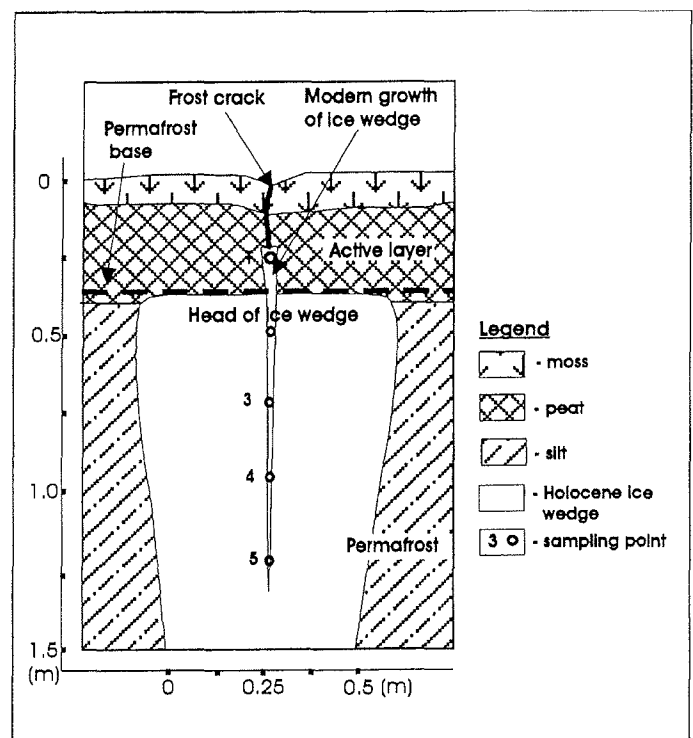


Fig. 3: Schematic sketch of modern ice wedge and sampling strategy.

Fig. 3: Schemaskizze und Probenahmeschema für rezente Eiskeile.

atmosphere. Natural cosmic ray produced tritium in precipitation is in the range of 5-20 TU (1 TU (tritium unit) = 1 ^3H atom in 10^{18} of ^1H atoms).

The tritium concentration having regard to radioactive decay can be calculated by use of the following equation (FERRONSKY et al. 1984):

$$C_t = C_0 \exp(-\lambda t) \quad (1)$$

(where: t = age, λ = 0,056, the constant of the radioactive decay, C_0 = tritium concentration in precipitation t years ago). Being a component of the water molecule (as hydrogen and deuterium), tritium traces the „modern water“ content in permafrost and can be used as an indicator of water exchange pro-

cesses. „Modern water“ with high tritium values is being produced and precipitated from the atmosphere since 1952, when the first hydrogen bomb tests were carried out. During the 1950s and early 1960s the tritium concentration in the precipitation in Northern Siberia rose up to 4000 TU. Now, much lower tritium concentrations of 35-40 TU are measured (CHIZHOV et al. 1998). The conservation of tritium in ground ice allows to determine the availability of „modern water“ in permafrost. The application of the tritium analysis method allows to follow the processes of „modern water“ transfer between the atmosphere, the active layer and the permafrost and checks the validity of stable isotope analysis.

The stable isotope method is well known in glaciology as a useful tool for paleoclimatic reconstruction and for identification of sources of precipitation. In geocryology the stable isotope method is used both for the determination of ground ice genesis and for paleoclimatic reconstruction (of winter temperature conditions). Until the present time, the application of the stable isotope method for the study of ground ice was mainly based on the $\delta^{18}\text{O}$ -analysis (MACKAY 1983, KONYAKHIN 1988, VAIKMAE 1989, VASIL'CHUK 1989). According to the present opinion, the stable isotope composition of ice wedges is mainly determined by the average isotopic composition of winter precipitation $\delta^{18}\text{O}_s$. Investigations carried out by KONYAKHIN (1988) and VASIL'CHUK (1989) show that mean $\delta^{18}\text{O}_{\text{IW}}$ values of modern ice wedges are in good agreement with mean $\delta^{18}\text{O}_s$ values in snow. Therefore, the stable isotope composition of ice wedges is a function of the mean annual winter temperature. The correlation of $\delta^{18}\text{O}_{\text{IW}}$ and T_w (mean winter air temperature) is used for paleoclimatic reconstruction (KONYAKHIN 1988, VAIKMAE 1989, 1991, VASIL'CHUK 1989, CHIZHOV et al. 1997, DEREVIAGIN et al. 1999, MEYER et al. 2001).

The use of both $\delta^{18}\text{O}$ and δD allows to obtain a more detailed information on sources of (winter) precipitation and processes of ice wedge formation. The application of stable isotope method for the study of modern ice wedges is based on the comparison of the isotope composition ($\delta^{18}\text{O}$, δD) and the d-excess of ice and of recent precipitation. The Deuterium excess d defined by DANSGAARD (1964):

$$d = \delta\text{D} - 8 \delta^{18}\text{O} \quad (2)$$

is used to identify sources of precipitation on a global scale.

Samples of ice and snow for the tritium and stable isotope analyses were collected in parallel using a special ice screw. They were then thawed out in the field laboratory. Melt-water was collected in plastic flasks. The sampling strategy for modern ice wedges is illustrated in Figure 3. The diameter of the ice screw is equal to 15 mm. Both stratified samples of snow and bulk samples of snow were collected in July-August 1998/99 from local snow patches usually located in the relief depressions.

The tritium concentration was evaluated at the Moscow State University (Department of Radiochemistry), using a liquid-scintillation spectrometer Tricarb-1600 with an instrumental error of about 10 %. The detection limit of tritium concentration is 15 TU. Laboratory measurements of isotope ratios ($\delta^{18}\text{O}$, δD) were carried out in the Alfred Wegener Institute of

Polar and Marine Research in Potsdam using a Finnigan MAT Delta-S mass spectrometer. The stable isotopic composition is presented in ‰ vs. V-SMOW standard. The internal error is about 0.1 ‰ for $\delta^{18}\text{O}$ and about 0.8 ‰ for δD (MEYER et al. 2000).

RESULTS AND DISCUSSIONS

Tritium in modern precipitation, in the active layer and in the upper part of permafrost

Tritium analyses of the atmospheric precipitation collected during two field seasons clearly show the seasonal variation of tritium concentrations in the Laptev Sea region. Today, the modern background value of tritium concentration in the region varies between 30-40 TU (DEREVIAGIN et al. 2000). The tritium concentration in the Laptev Sea was about 36 TU in the summer period 1998/99. All samples of rain both at the Bykovsky and at the Lyakhovsky sites have a considerably lower tritium concentration than the modern background value. The mean concentration of rainwater at the Bykovsky site (in July-August of 1998) is about 20.5 TU and at the Lyakhovsky site (in August of 1999) about 17 TU.

On the other side, all snow patch samples except one from the Bykovsky site (winter 1997/98) have high tritium concentrations of more than 123 TU. One sample has a tritium concentration of about 20 TU. All stratified samples from snow patches have high tritium concentrations with the maximum values in the upper part of the snow patch. The mean value of the tritium concentration for snow is about 147 TU, the maximum value about 207 TU.

The mean value of the tritium concentration of snow samples collected at Lyakhovsky site (winter 1998/99) is about 55 TU, maximum value is 98 TU. And in this case some of the snow patch samples (three samples) also have low tritium concentration from about of 15 to 21 TU. These data show the uneven character of tritium arrival to atmospheric precipitation in winter period. The same results on the distribution of tritium content in precipitation are obtained for the Taymyr region in 1994/96: at Labaz Lake site (1994/95) to a maximum of 420 TU; at Taymyr Lake site (1996) to a maximum of 415 TU (CHIZHOV et al. 1997, DEREVIAGIN et al. 2000). The same results on the distribution of tritium content in precipitation were obtained for the Taymyr region in 1994/96 (CHIZHOV et al. 1997, DEREVIAGIN et al. 2000). The seasonal variations of tritium concentrations in precipitation with low mean tritium contents in summer and high mean tritium contents in winter correspond well with data on aerosol transportation in the Arctic, which also shows a peak in winter precipitation (SHEVCHENKO et al. 2000).

High tritium concentrations are also observed in the surface water, in the active layer, and in the upper part of permafrost at the Bykovsky site. Tritium concentrations from 107 to 186 TU are determined in surface water samples which were predominantly fed by snowmelt water such as intrapolygonal ponds, small thermokarst lakes, swamp depressions and small brooks located close to snow patches.

The data on samples of the active layer and of the upper part of

permafrost at Bykovsky site in 1998 also show high tritium concentrations. The tritium concentration in the active layer varies from 110-300 TU. Maximum tritium contents of up to 500-650 TU are determined in the so called „transition layer“ in the uppermost part of permafrost at a depth of about 0.4-0.7 m in segregated ice. Such high tritium concentrations observed in the active layer and in the upper part of permafrost cannot be associated with the old bomb-tritium (peak in 1963/65) because of the radioactive decay of tritium (Equation 1). In deeper horizons sampled in bore holes, we observe a considerably lower tritium content in segregated ice. This demonstrates the process of accumulation of „modern water“ in the bottom of the active layer and in the transition layer.

In summary, the high tritium concentrations found in the snow cover in different sites of the Laptev Sea region in 1994/99 give evidence of modern (the end of last decade) technogenic tritium arrival from the atmosphere to the Earth surface. Tritium input from the atmosphere on the region is mainly associated with winter precipitation. High tritium concentrations observed in the active layer and in the upper part of permafrost give evidence of modern water exchange processes between

the Earth's surface, active layer and upper part of permafrost at present time. Results on tritium analyses prove modern (the end of last decade) ground ice formation in the region including new segregated ice in the upper part of permafrost and modern ice wedge growth.

Tritium in modern ice wedges

A comparison between data on tritium concentration in modern ice wedges, in rain and snow patches for both sites Bykovsky and Lyakhovsky are presented in Figures 4a and 4b.

The availability of high tritium concentrations of more than 30-40 TU in „modern growth“ and „heads“ of some of the studied ice wedges allow to conclude on their modern (during the last 50 years) growth. Ice wedges are usually classified as active ice wedges if they crack more than once every 50 years (PÉWÉ 1966, MACKAY 1992). The occurrence of active ice wedges in the region indicates intensive modern frost cracking processes. The accumulation of modern ice in frost cracks and growth of modern ice wedges accompanies this process. Ac-

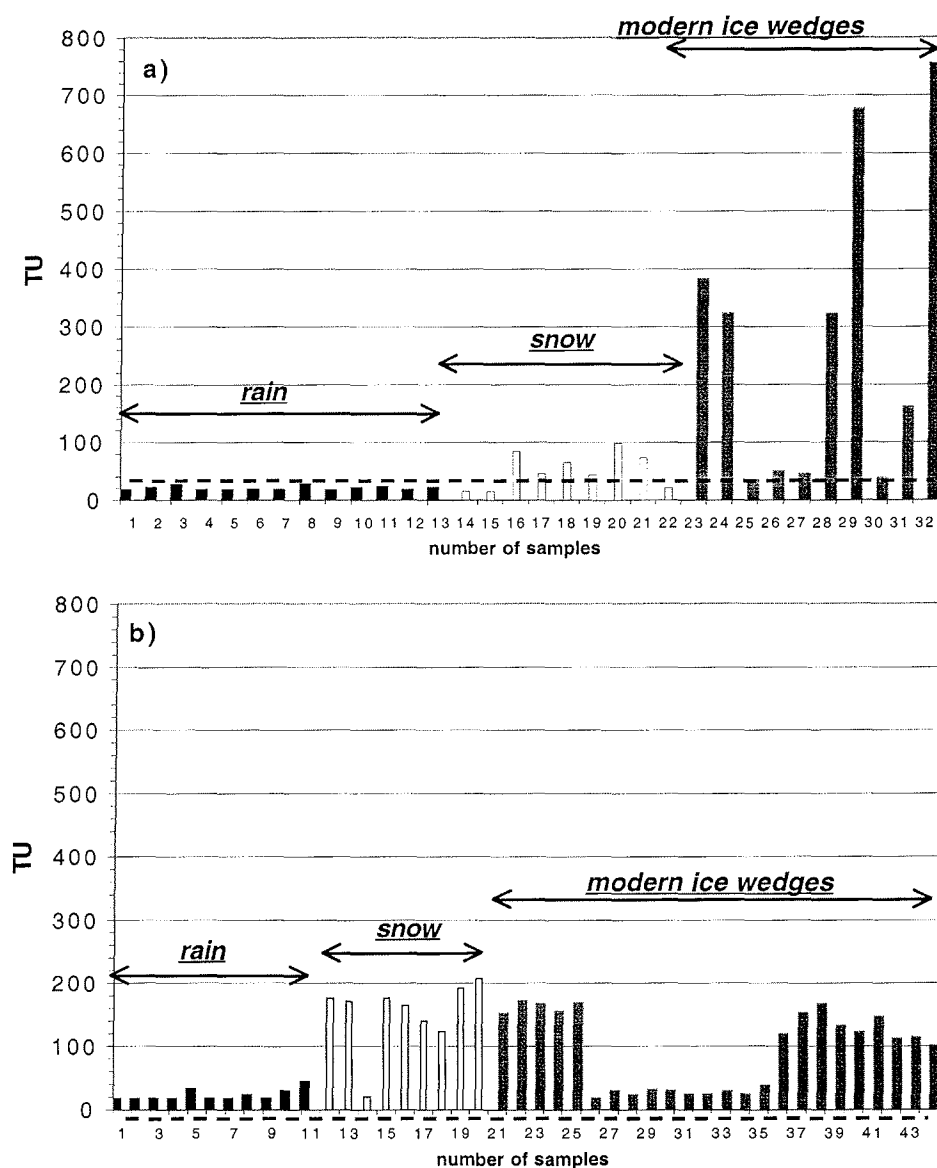


Fig. 4: Comparison between data on tritium concentration in active ice wedges, rain and snow patches: a) at site Bykovsky; b) at site Lyakhovsky. Dotted line: tritium concentration of the Laptev Sea.

Fig. 4: Vergleich der Tritiumkonzentrationen von aktiven Eiskeilen, Regenwasser und Schneeflecken; a) Bykovski-Halbinsel, b) Große Ljachow-Insel. Gestrichelte Linie beschreibt die Tritiumkonzentration der Laptevsee.

According to the tritium analysis data of ice wedges in log and peat bog at the Bykovsky site and ice wedges in fluvial terraces and alases at the Lyakhovsky site can be described as active ice wedges.

Some of the studied ice wedges do not contain tritium in their „heads“. The absence or low values of tritium (<15 TU) in „heads“ of ice wedges signifies that during the last 50 years these ice wedges did not grow. These ice wedges are referred to as inactive ice wedges (MACKAY 1992). For example, inactive ice wedges with low tritium content (<15 TU) in their „heads“ are characteristic for the Ice Complex at both sites.

These results show that frost cracking processes for different geomorphological and geological units are not annual and furthermore not regular at present time. Considering that the modern winter temperature conditions (air temperature, amplitudes of air temperatures, amplitudes of ground surface temperatures) at both sites is approximately equal, the processes of frost cracking most likely depend on snow conditions and

frozen ground conditions (composition and cryogenic construction of the upper part of permafrost, ice content and soil water content).

Mean values of the tritium concentration in active modern ice wedges on Bykovsky Peninsula range from 98 to 160 TU. These results are in a good agreement with the mean tritium concentration of about 145 TU in the snow cover of 1997/98. The mean tritium concentration in active ice wedges of Bol'shoy Lyakhovsky Island in 1999 was about of 276 TU and thus exceeds by far the tritium concentration in modern snow. The highest tritium concentration was found in ice wedges located in alas (up to 670 TU) and in fluvial terraces (up to 752 TU). Such a high tritium concentration in ice wedges can not be associated with old thermonuclear tritium because of the radioactive decay (Equation 1). In this case, the ice wedge formation most probably occurred one or a few years ago when the tritium concentration in winter precipitation at the Lyakhovsky site must have been significantly higher. Note that this is in good agreement with the data on tritium concentrat-

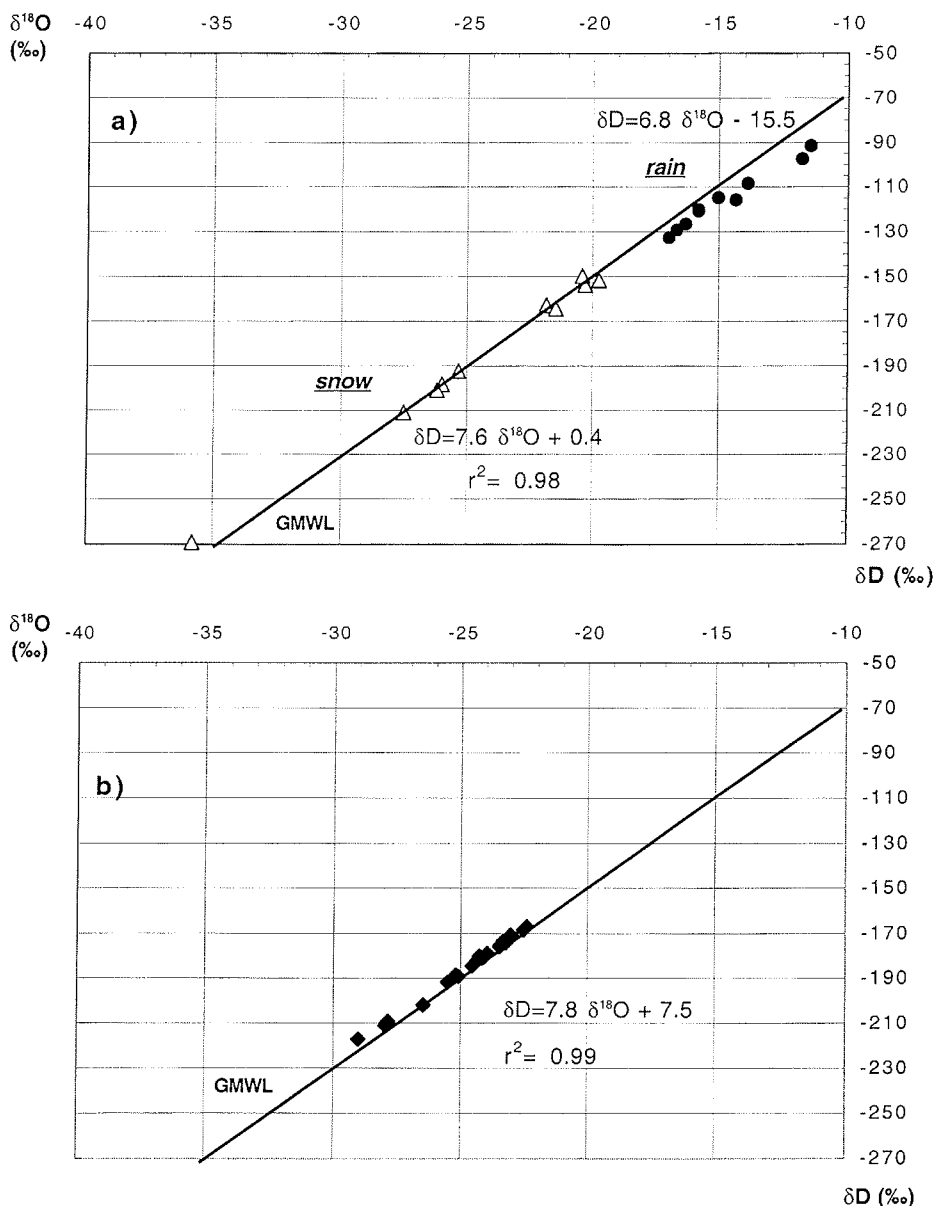


Fig. 5: $\delta^{18}\text{O}/\delta\text{D}$ diagram for a) meteoric water (rain and snow patches); b) active ice wedges. Site Bykovsky.

Fig. 5: $\delta^{18}\text{O}/\delta\text{D}$ -Diagramm von a) meteorischem Wasser (Regen und Schneeflecken) und b) aktiven Eiskeilen der Bykovski-Halbinsel.

ion in the Bykovsky site in 1998. The reasons for the occurrence of this new regional tritium mark are not yet known.

Stable isotope analysis of modern ice wedges

Figure 5a shows the relationship between $\delta^{18}\text{O}$ and δD of meteoric water (rain and snow patches). Figure 5b depicts the relationship between $\delta^{18}\text{O}$ and δD of active ice wedges at the Bykovsky site. In the $\delta^{18}\text{O}/\delta\text{D}$ diagram the isotopic composition of snow patches correlates linearly with a slope close to 8.0 and parallel to the GMWL. CRAIG (1961) defined the linear relationship between $\delta^{18}\text{O}$ and δD in precipitation named the Global Meteoric Water Line: $\delta\text{D} = 8 \delta^{18}\text{O} + d = 10 \pm 10$. Mean values of the isotopic composition and d-excess of rain and snow of the years 1997/98 and modern ice wedges are presented in Table 2.

All points of average isotopic composition of active ice wedges (Fig. 5b) also lie on a straight line more or less parallel to the GMWL, with a minor shift of about 1-2 ‰ towards higher d-excess values. The diagram shows that during the formation of active ice wedges most data of the isotopic composition (for $\delta^{18}\text{O}$) of winter precipitation range between -22.5 ‰ to -29 ‰. Note that the mean values of $\delta^{18}\text{O}$, δD and d-excess of ice in ice wedges are very close to the relevant mean values of modern snow. These results support the view that ice wedges are predominantly fed by snowmelt water.

A somewhat different situation is obtained in the isotopic composition of active ice wedges at the Lyakhovsky site (Figs. 6a and 6b). Points of the isotopic composition of snow (Fig. 5a) also lie on a straight line in the $\delta^{18}\text{O}/\delta\text{D}$ diagram with a slope of about 7.2, close to the slope of the Bykovsky site. Points of an average isotopic composition of active ice wedges (Fig. 5b) lie on a straight line with a shift towards lower d-excess values of about 4-6 ‰. The variation of the average isoto-

pic composition of active ice wedges is about 4 ‰ (for $\delta^{18}\text{O}$). There are low average values of d-excess (mean value is about 4.8 ‰, with the range from 3.3-6.7 ‰) in all studied active ice wedges, while in snow, the mean value of d-excess is about 9.5 ‰, with a range from 5.1-12.4 ‰. The same effect was described for the Cape Sabler region on the Taymyr Peninsula where the shift in d-excess values between modern snow and active ice wedges was about 4.5 ‰ (DEREVIAGIN et al. 1999). The gap between values of d-excess in snow and in modern ice wedges at the Lyakhovsky site needs further consideration.

These results clearly show that in some cases the original isotopic composition ($\delta^{18}\text{O}$, δD) of modern winter precipitation is distorted during ice wedge formation. Here we consider the processes, which can occur in snow and ice during ice wedge formation and may produce changes in the isotopic signal of the precipitation.

First, there are possibly intensive processes of modification in isotopic composition in snow during the spring period. Two main processes can modify the stable isotope distribution in the melting snow cover during storage and thawing during spring. One is sublimation and vapour exchange within the snow cover. The other is the exchange between snow and melt water as it infiltrates from the melting surface down to the base of the snow cover (CLARK & FRITZ 1997). The values of isotopic enrichment of evaporating snow surface are similar to those of evaporating water (MOSER & STICHLER 1975). But in this case high values of d-excess in snow patches at the Lyakhovsky site cannot be explained with low values of d-excess in modern ice wedges. And we do not observe similar processes in snow at the Bykovsky site at present.

The second possible process producing the changes in the isotopic composition of ice wedges is the sublimation of ice in an open frost crack during the cold period. GASANOV (1977) described this possibility and some features of this process. The

| Site | Author | Isotopic composition | | | | | | Modern mean winter temperature °C |
|---------------------|------------------------|---------------------------|---------------|-------|---------------------------|---------------|------|-----------------------------------|
| | | Ice wedges | | | Snow | | | |
| | | $\delta^{18}\text{O}$ (‰) | d-excess (‰) | | $\delta^{18}\text{O}$ (‰) | d-excess (‰) | | |
| mean | range | mean | mean | range | mean | | | |
| Tiksi | VASIL'CHUK 1992 | -22.8 | -21.8...-24.6 | | | | | -21.2 |
| Yana River mouth | KONYAKHIN 1988 | -21.3 | -19.7...-23.2 | | | | | -21.8 |
| Novaya Sibir Island | KONYAKHIN 1988 | -18.3 | -15.0...-21.8 | | | | | -18.5 |
| Taymyr, Labaz Lake | CHIZHOV et al. 1997 | -23.0 | -19.8...-25.5 | 11.8 | -23.9 | -23.4...-26.0 | 11.5 | -23.5 |
| Taymyr, Cape Sabler | DEREVIAGIN et al. 1999 | -20.4 | -20.1...-20.6 | 7.8 | -24.8 | -21.1...-28.4 | 12.3 | -20.8 |
| Bykovsky site | this study | -25.4 | -22.5...-26.5 | 12.5 | -23.2 | -19.7...-27.5 | 9.3 | -22.9 |
| Lyakhovsky site | this study | -21.0 | -19.2...-22.5 | 4.8 | -26.9 | -17.9...-31.4 | 11.2 | -20.6 |

Tab. 2: Isotopic composition of modern ice wedges and winter precipitation in the Laptev Sea region.

Tab. 2: Isotopenzusammensetzung rezenter Eiskeile und der Winterniederschläge in der Lapteewsee-Region.

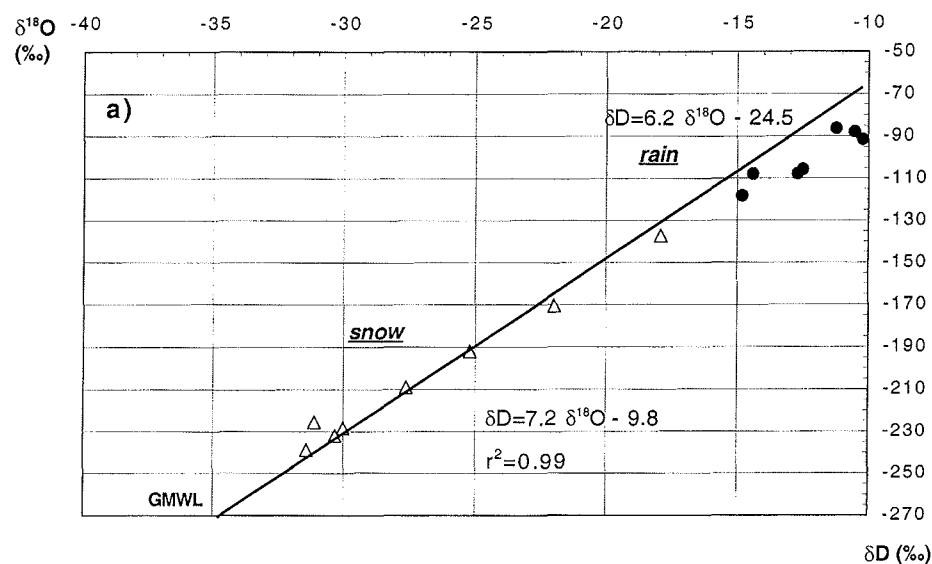
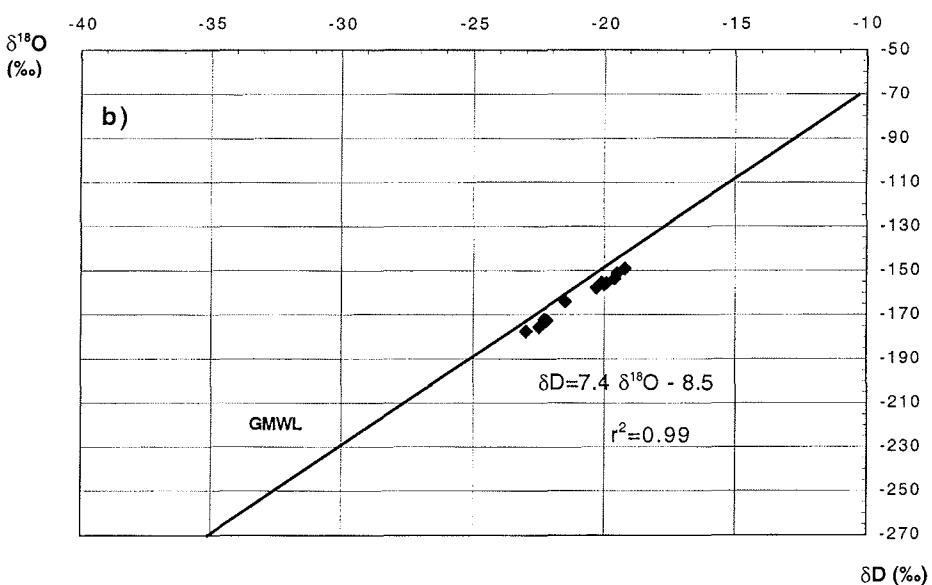


Fig. 6: $\delta^{18}\text{O}/\delta\text{D}$ diagram for a) meteoric water (rain and snow patches); b) active ice wedges. Site Lyakhovsky.

Fig. 6: $\delta^{18}\text{O}/\delta\text{D}$ -Diagramm von a) meteorischem Wasser (Regen und Schneeflecken) und b) aktiven Eiskeilen der Großen Ljachow-Insel.



process of ice sublimation in open frost cracks is based on the hypothesis of the presence of a quasi-liquid film on the ice surface. The process of ice sublimation is meant to be the process of evaporation of this film (YERSHOV 1998). The experimental data obtained by YERSHOV (1998) show that an increase in the sublimation intensity is possible with increasing air flux velocity. Hence, the process of sublimation of ice in an open frost crack during the cold period theoretically can produce the observed gap in d-excess values between snow and ice. Air temperature conditions and the duration of the period without snow cover (or with thin snow cover) and with open cracks during winter possibly control this process.

Third, mixing of snowmelt water with different types of surface water cannot be ruled out. In this case, the initial isotopic composition of snowmelt water can also change considerably. The possibility of this process was discussed in literature (ROMANOVSKY 1977, KONYAKHIN 1988, VASIL'CHUK 1989). D-excess values considerably lower than in snow are measured in modern ice wedges located both in fluvial terraces of the Zimov'e River and in alas. The process of mixing of snowmelt water and surface water is possible for ice wedges located in

fluvial terraces in spring during the overflow. But it is unlikely for ice wedges located in alas because of their high position and good drainage conditions.

A fourth possible process, which might be responsible for the difference between the d-excess in snow and in recent ice wedges on Bol'shoy Lyakhovsky Island is the participation of an isotopically depleted moisture source. Moisture originating from the Pacific Ocean, which is characterised by low d-excess (CLARK & FRITZ 1997), or from the polynya, an ice-free zone in the Laptev Sea shelf could both be such a (local) source (MEYER et al. submitted).

The analysis of the isotopic composition of modern ice wedges shows that in one case the isotopic composition of ice is similar to the isotopic composition of modern snow (Bykovsky Peninsula, Labaz Lake region). Whereas in the other cases, the isotopic composition of modern ice wedges can considerably be modified during the winter or spring period (Bol'shoy Lyakhovsky Island, Cape Sabler). Distinctions in isotopic composition of modern ice wedges at Bykovsky and Lyakhovsky sites probably reflect the different conditions of snow

accumulation (the duration of the period without snow, the thickness of the snow cover as well as its origin and distribution). This fact provides the basis for paleoclimatic reconstruction in this region.

CONCLUSIONS

The atmospheric precipitation shows the seasonal variation in tritium concentrations in the Laptev Sea region. High tritium concentration in snow of more than 100 TU (1997/98) can be associated with the input of modern probably technogenic tritium to atmospheric precipitation. High tritium concentrations found in snow, in the active layer and in the upper part of permafrost can be considered as a new regional tritium mark, which can date the end of the last decade in the region.

Results on tritium analyses point to intensive processes of ground ice formation in the upper part of permafrost at present time. Active ice wedges (which contain ice younger than 50 years) have occurred widely in the region and are located mainly in alases, peat bogs, logs and fluvial terraces. The growth of active ice wedges is not annual. At the surface of the Ice Complex, modern ice wedges are mainly inactive.

Modern ice wedges are predominantly fed by snowmelt water. The mean isotopic composition ($\delta^{18}\text{O}$, δD) of active ice wedges at Bykovsky Peninsula is in good agreement with the mean isotopic composition of modern snow.

The analysis of the isotopic composition of modern ice wedges shows that on Bol'shoy Lyakhovsky Island the isotopic composition of modern ice wedges and snow is considerably different. The isotopic composition of ice and snow gets probably modified during the winter (or spring) period. The low d-excess value in ice of modern ice wedges reflects this modification. The processes of evaporation and sublimation both in snow cover and in ice can be responsible for this modification. For the identification of the cause of these distinctions further research is necessary.

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References

- Burn, C.R. (1990): Implications for paleoenvironmental reconstruction of recent ice wedge development at Mayo, Yukon Territory.- *Permafrost and Periglacial Processes* 1: 3-14.
- Chizhov, A.B., Chizhova, N.I., Morkovkina, I.K. & Romanov, V.V. (1983): Tritium in permafrost and in ground ice.- *Proceedings, IV International Conference on Permafrost*, National Academy Press, Washington D.C.: 147-150.
- Chizhov, A.B., Dereviagin, A.Yu., Simonov, E.F. Hubberten, H.-W. & Siegert, Ch. (1997): Isotopic composition of ground ice at Labaz Lake region (Taymyr).- *Earth Cryosphere*. 1 (3): 79-84 (in Russian).
- Chizhov, A.B. & Dereviagin, A.Yu. (1998): Tritium in Siberia's permafrost.- In A.G. LEWKOVICH & M. ALLARD (eds.), *Proceedings, Seventh International Conference on Permafrost*, Yellowknife, June 23-27, 1998. *Nordica* 57, University Laval, Quebec City: 151-156.
- Clark, I.D. & Fritz, P. (1997): *Environmental isotopes in hydrology*.- Lewis Publishers. N.Y.: 85-86.
- Craig, H. (1961): Isotopic variation in meteoric waters.- *Science* 133: 1702-1703.
- Dansgaard, W. (1964): Stable isotopes precipitation.- *Tellus* 16: 436-468.
- Dereviagin, A.Yu., Chizhov, A.B., Brezgunov, V.S., Hubberten, H.-W. & Siegert, Ch. (1999): Isotopic composition of ice wedges of Cape Sabler (Taymyr Lake).- *Earth Cryosphere*. v. III, 3: 41-50 (in Russian).
- Dereviagin, A.Yu., Chizhov, A.B., Brezgunov, V.S., Simonov, E.F. & Hubberten, H.-W. (2000): Snowy-firn ground ice in Taymyr.- *Earth Cryosphere*. v. IV, 4: 3-18 (in Russian).
- Dostovalov, B.N. (1957): Change in volume of unconsolidated ground during the freezing and formation of frost cracks.- *Data on laboratory studies of frozen ground* 3, Academy of Science of the USSR: 41-51 (in Russian).
- Feronsky, V.I., Polyakov, V.A. & Romanov, V.V. (1984): *Cosmogenic isotopes in the hydrosphere*.- Nauka Press, Moscow: 268 pp. (in Russian).
- Gasanov, Sh.Sh. (1977): Sublimation redistribution of material in ice wedges.- *Problems of Cryolithology*. 6: 224-229 (in Russian).
- Geizvestnov, I.V. & Solov'ev, V.A. (1989): Oceanic and shelf regions.- In E.D. ERSHOV (Ed.), *Geocryology of USSR, Eastern Siberia*. Nedra, Moscow: 176-184 (in Russian).
- Grigor'ev, N.F. (1966): *Permafrost in the coastal zone of Yakutia*.- Nauka Press, Moscow: 181 pp. (in Russian).
- Grechishchev, S.E. (1970): Basis of methods for predicting thermal stresses and deformations in frozen soils.- *Vsegoingeo Press, Moscow* 53 pp. (in Russian).
- Konyakhin, M.N. (1988): Oxygen isotope composition of polygonal ice wedges as an indicator of conditions of its formation.- *Moscow State University. Ph.D. Dissertation*: 182 pp. (in Russian).
- Lachenbruch, A.H. (1962): Mechanics of thermal contraction cracks and ice wedge polygons in permafrost.- *Geol. Soc. Amer. Spec. Pap.* 70: 1-69.
- Mackay, J. R. (1975): The closing of ice wedge cracks in permafrost, Garry Island, Northwest Territories.- *Canadian J. Earth Sci.* 12: 1668-1674.
- Mackay, J. R. (1983): Oxygen isotope variations in permafrost, Tuktoyaktuk Peninsula area, Northwest Territories.- *Current Research, Part B, Geol. Surv. Canada Paper* 83-1B: 67-74.
- Mackay, J. R. (1992): The frequency of ice-wedge cracking (1967-1987) at Garry Island, western Arctic coast, Canada.- *Canadian J. Earth Sci.* 29: 236-248.
- Meyer, H., Schönicke, L., Wand, U., Hubberten, H.-W. & Friedrichsen H. (2000): Isotope studies of hydrogen and oxygen in ground ice – Experiences with the equilibration technique.- *Isotopes in Environmental and Health Studies* 36: 133-149.
- Meyer, H., Dereviagin, A.Yu., Siegert, Ch & Hubberten, H.-W. (2002): Paleoclimatic studies on Bykovsky Peninsula, North Siberia - hydrogen and oxygen isotopes in ground ice.- *Polarforschung* 70: 37-51.
- Meyer, H., Dereviagin, A.Yu., Siegert, Ch, Schirmermeister, L. & Hubberten, H.-W. (submitted): Hydrogen and oxygen isotopes in ground ice – A valuable tool for paleoclimatic studies on Big Lyakhovsky Island, North Siberia.- *Permafrost and Periglacial Processes*
- Michel, F.A. (1982): Isotope investigations of permafrost waters in northern Canada.- *Ph.D. Thesis, Dept. of Earth Sciences, Univ. of Waterloo, Waterloo, Ontario, Canada*: 227 pp.
- Moser, H. & Stüchler, W. (1975): Deuterium and oxygen-18 contents as index of the properties of snow blankets.- *Snow Mechanics. Proceedings, Grindelwald Symposium, April 1974, IAHS Publication* 114: 122-135.
- Pévé, T. L. (1966): Ice wedges in Alaska – classification, distribution and climatic significance.- *Proceedings First International Conference on Permafrost*: 76-81.
- Romanovsky, N.N. (1977): Polygonal ice-wedge structures formation.- *Nauka Press, Novosibirsk*: 216 pp. (in Russian).
- Schirmermeister, L., Siegert, C., Meyer, H., Dereviagin, A., Kienast, F., Andreev, A., Kumitsky, V., Tumskey, V. & Grootes, P. W. (2000): Paleoenvironmental and paleoclimate records from permafrost deposits in the Arctic region of Northern Siberia.- *Geolines* 11: 147-150.
- Shevchenko, V.P., Lisitzyn, A.P., Vinogradova, A.A., Smirnov, V.V., Serova, V.V. & Stein, R. (2000): Aerosols of the Arctic – the results of ten-year investigations.- *Optic of the atmosphere and ocean* 13 (6-7): 551-576 (in Russian).
- Vaikmae, R. (1989): Oxygen isotopes in permafrost and in ground ice - a new tool for paleoclimatic investigations.- 5th Working Meeting „Isotopes in Nature“, *Proceedings, Leipzig*: 543-553.
- Vasil'chuk, Yu. K. (1989): Oxygen isotope composition of ground ice.- *Data on glaciology investigations* 66: 196-210 (in Russian).
- Yershov, E.D. (1998): *General Geocryology*.- Cambridge University Press: 64-68.