RESEARCH PAPER

ISOTOPE SIGNATURE OF THE MASSIVE ICE BODIES ON THE NORTHEAST COAST OF CHUKOTKA PENINSULA

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ABSTRACT. The massive ice (MI) bodies are widespread phenomena on Chukotka coastal plains. Although they have been studying since 1930s, stable isotope method was applied for the ice beds quite recently. In this study cryostratigraphy and stable oxygen and hydrogen isotope composition of MI bodies on the extreme North-Eastern Chukotka (near Lavrentiya settlement and Koolen' lake) have been studied in detail. It was concluded that studied MI bodies have intrasedimental origin and most likely are dated back to the Late Pleistocene age. Mean $\delta^{18}O$ values range from −18.5 ‰ to −15 ‰ whereas mean $\delta^{2}H$ values range from −146‰ to −128 ‰ that is higher than expected for the Late Pleistocene ice bodies in this region, which most likely resulted from isotopic fractionation during freezing of water-saturated sediments in a closed system when forming ice became isotopically enriched compared with initial water. The analysis of co-isotope ratios for MI shows that initial water is mainly of meteoric origin (precipitation, water of lakes and taliks).

KEYWORDS: massive ice (MI), cryostratigraphy, stable isotopes, freezing conditions, North-Eastern Chukotka

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INTRODUCTION

Massive ice bodies represent thick, often bedded, and sometimes deformed layers of massive ground ice and icy sediment and are the most spectacular of ground-ice forms. Massive ice bodies were described in west and east Siberia, Chukotka, Alaska and Yukon, the Tuktoyaktuk Coastlands, the Canadian Arctic Archipelago and Russian Arctic islands, China and the Antarctic. These icy bodies are important not only because of their origin and the light this may throw upon permafrost history but also because of the thaw-settlement properties of terrain underlain by such bodies. There are two explanations advanced for the origin of these massive icy bodies. The first is that it is intra-sedimental and formed largely of segregated ice supplemented by water-injection processes that give rise to intrusive ice. The second is that they are bodies of buried glacier ice, without a clear distinction being made between glacier ice derived from snow and sub-glacier regelation ice (French 2018). For massive ice bodies of intra-sedimental origin the study of stable isotope composition may allow to establish the nature of initial water and the conditions of ice formation (Vasil'chuk 2012; Vasil'chuk & Murton 2016).

Massive ice bodies of different genesis are widely distributed in the Eastern Chukotka seacoast. They have been studying for over than 80 years – since 1930s in Anadyr settlement and Ugolnaya Bay vicinities (Shvetsov 1938, 1947; Soloviev 1947). In the 1950–1960s the MI bodies of Chukotka were studied by Vtyurin (1964, 1975) and Gasanov (1964, 1969) in many parts of the region: the valley of the Anadyr River, the coast of the Krest Bay, Mechigmen Gulf, the Uelen lowland, the coast of Kolyuchinskaya Bay, and in the coastal part of Nizhne-Anadyr lowland.
Isotope composition was defined for MI beds of Koolen' lake coast, Amguema and Anadyr River valleys, Anadyr vicinity, and Onemen Bay coast (Vasil'chuk 1992, 2012; Korolev 1993; Kotov 1997a, b, 1998 a, b, 1999, 2001, 2005; Vasil'chuk & Kotlyakov 2000).

Recent climate warming in the Arctic (IPCC 2013) and in Chukotka region in particular (Bulygina et al. 2020; Maslakov et al. 2020a) facilitated deeper active layer thickening (Abramov et al. 2019) and more intensive thaw slumps formation. Exposed MI beds in vicinities of Lavrentiya and Lorino settlements (Eastern Chukotka Peninsula) allowed conducting detailed cryostratigraphic and stable isotope studies in the summer seasons of 2015–2020.
The purpose of this paper is to identify the conditions for the formation of MI beds and their distribution within northeast of the Chukotka Peninsula based on field studies and stable oxygen isotope data.

MATERIAL AND METHODS

Study region

Chukotka Peninsula is the easternmost part of Siberia; it is washed by the Bering Sea from the south and southeast and by the Chukchi Sea from the north (Fig. 1).

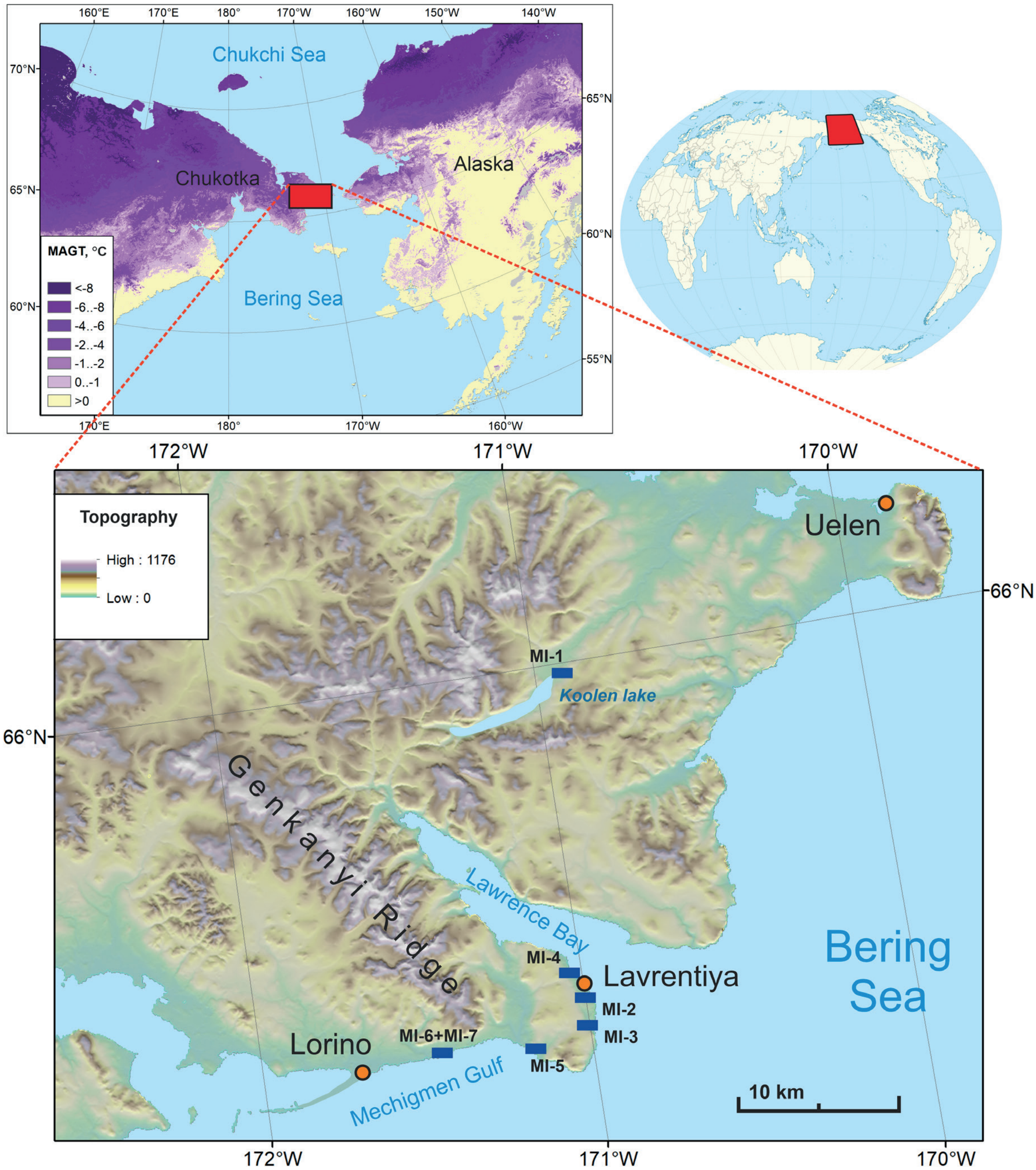

Fig. 1. Map of the study area with MI sites. Massive ice sampled for stable isotope analysis: MI-1 – Koolen' Lake valley; MI-2-7 – near the Lavrentia settlement

Approximately 80% of Chukotka Peninsula is occupied by flattened low-hill terrain of Mesozoic age with a height of up to 1200 meters above sea level (m asl). The height of plains and lowlands ranges from 10 m asl to 80 m asl; they are confined to sea coast and large lagoons. They are composed of marine and fluvial sediments of the Middle and Late Pleistocene and Holocene age.

Climate. The climate of the peninsula is arctic and maritime subarctic. Winter lasts up to 10 months a year. The average annual air temperature at the nearest weather station Uelen for 1989–2019 was –6.0 °C (Bulygina et al. 2020). Average air temperature for July is +7.1 °C (interannual variance lies within the range from +5.4 °C to +11.3 °C); for January it is –20.0 °C (interannual variance lies within the range from –13.7 °C to –26.8 °C). The area is experiencing significant climate warming: in the period 1960s–2020s mean annual air temperature increased by 0.6–0.7 °C per decade (Maslakov et al., 2020a). Interannual variance in the precipitation amount lies within the range from 300 mm to 690 mm (Bulygina et al. 2020) with the absence of the long-term trend.

Permafrost. Permafrost is continuous. Non-through taliks (up to 40 m thick) are found only in the lower reaches of large rivers and under the large thermokarst lakes. The mean annual ground temperature for the coastal plains varies from –2°C to –4°C. The permafrost thickness varies from 500–700 m in the highest parts of the ridges to 100–300 m in the valleys and coastal plains of the Chukchi Peninsula (Kolesnikov & Plakht 1989).

Massive ice bodies are widespread in Chukotka; they often confined to the coasts of the gulfs (Krest, Onemen, etc). The Late Pleistocene and Holocene ice wedges are also widespread in the region. They represent an excellent paleoarchive of the Late Quaternary winter climate changes (Vasil'chuk 2006; Opel et al. 2011).

Vegetation. At the altitudes of up to 100 m asl coastal plains of the Eastern Chukotka are covered by a typical Far Eastern hummocky tundra. The hummocks are occupied by dwarf shrubs *Salix pulchra, Betula exilis*, and *Ledum decumhens*. Herbaceous plants are represented by *Eriophorum vaginatum, Carex lugens, C. rariflora, Poa*

Arctica, etc. Humid depressions are mainly occupied by *Eriophorum vaginatum* and *Carex stans* with *Salix pulchra* (Zamolodchikov et al. 2004). The slopes of the hills at the altitudes of up to 250–300 m asl are covered by lichen and low-shrubs tundra. Hilltop surfaces are mostly barrens.

Field studies and analytical methods

Massive ice (MI) bodies exposed in floodplain and terraces at 7 sites (MI-1–7, see Fig. 1) have been studied from 1985 to 2020 (Fig. 2-7). For stable isotope analysis, ice was sampled both vertically and horizontally from the ice beds, depending on the outcrop accessibility.

Isotope oxygen in MI sampled in 1985–1987 was measured using a G-50 device in the isotope geology laboratory at the Institute of Geology, Tallinn, Estonia (Prof. R. Vaykmäe) and in the isotope hydrology laboratory at the Institute of Water Problems of Russian Academy of Science (Dr. A. Esikov). Control measurements were taken in both laboratories.

The massive beds sampled during field studies in 2015–2020 were analyzed in the stable isotope laboratory of the Geography Faculty at Lomonosov Moscow State University (Prof. Yu. Vasil'chuk and Dr. N. Budantseva) using a Finnigan Delta-V Plus mass spectrometer applying equilibration techniques. International water standards (SMOW, GRESP, and SLAP) were used for calibration. Analytical precision was ±0.4‰ for $\delta^{18}O$ and ±1‰ for $\delta^{2}H$. All values are presented in δ-notation in per mille (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW).

RESULTS

Site MI-1. A homogeneous autochthonous MI body is located on the northern coast of the Koolen' lake, 2 km from the mouth of the Koolen'veem River, in a ravine that opens up to the lake at an altitude of 25 m above the lake level.

Cryostratigraphy. Thick ice layer was exposed a 0.4–0.7 m (possibly up to 1.2 m) at a depth of approximately 3 m. The body is overlain by a bedded formation of sand and peat. The sand is coarse-grained, gray-yellow, with inclusions of gravel. The peat contains remnants of grasses, mainly mosses, rarely twigs of shrubs. At an altitude of 0.1 m above the top of the formation we found a boulder with a diameter of 10 cm. Higher up in the sand and peat there are blocks of granodiorites with a diameter of 20–30 cm, which are exposed in the nearby rocky slope at an altitude of 200 m. The ice of the exposed layer is gray, with a weakly expressed vertical banding due to interlayers saturated with yellow and black sand. The ice is saturated with air bubbles ranging in size from 1 mm to 12 mm.

Oxygen isotopes. The values of $\delta^{18}O$ in the MI range from −20.6‰ to −22.4‰ (Fig. 8a) For comparison, the values of $\delta^{18}O$ in the modern seasonal injection ice mound on the floodplain of the lake Koolen' vary from −13.4‰ to −15.3‰; in the Holocene ice wedges on the floodplain of Koolen' lake the values of $\delta^{18}O$ vary from −14.7‰ to −16.2‰ (Vasil'chuk, 2012; Vasil'chuk et al., 2018a,b).

Site MI-2. Homogeneous MI body (Fig. 2) was studied in the summer season of 2017. It is located on the coast of the Lavrentiya Bay (St. Lawrence Bay), 2 km south of the Lavrentiya settlement (65°32 ' 51 "N; 171°58'24" W).

Cryostratigraphy. The MI body is exposed in a thermocirque on the seashore, at an altitude of 5 m asl. The width of the body is 18.6 m; the visible thickness is 3.1 m. It is covered with a layer of unsorted dark yellow loam with inclusions of gravel and boulders with a diameter of 10 cm. The thickness of the overlying sediments varies from 1.5 m to 3.0 m. The ice boundary is smooth and fuzzy. The body is represented by sequence of clear and bubbly ice layers and dark gray ice-rich loam with the inclusions of debris (Fig. 2b, c). The size of the ice bubbles is 0.2–0.9 cm, without orientation. The thickness of the ice layers varies from 0.5 cm to 10 cm; the thickness of the loam layers is 0.2–5.0 cm. The layers are tilted in the opposite direction from the shore at an angle of 45°.

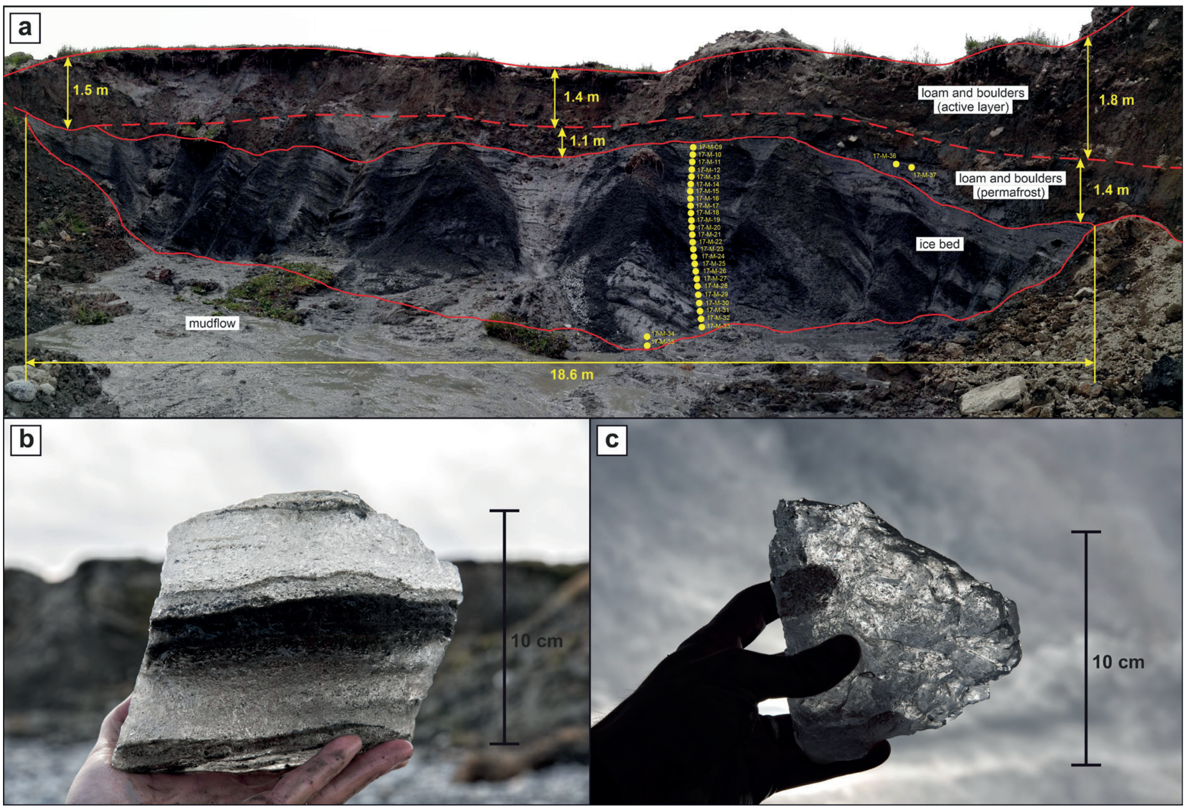

Fig. 2. Massive ice (MI-2): a) general view and sampling scheme; b) and c) detailed views of ice matter. (Photos by A. Maslakov)

Oxygen isotopes. The values of $\delta^{18}O$ in MI range from –18.96‰ to –14.84‰ (Fig. 8b). The distribution of the values $\delta^{18}O$ with the depth traces the change in the trend of isotopic values from positive in the lower part of the bed to negative in the upper one.

Site MI-3. The homogeneous the MI body studied in 2019 and 2020. It is located on the coast of the Lavrentiya Bay (St. Lawrence Bay), 7 km south of the Lavrentiya settlement (Fig. 3).

Cryostratigraphy. The vertical thickness of the body MI-3 is approximately 2.5 meters; the upper boundary is smooth, clear and discordant. The overlying sediment is 0.7–2.0 thick. It is dark grey loam, with gravel inclusions and bunches of black peat. The layer has a vertical and horizontal lenticular cryogenic structure (ice fills the cracks between the slab ground particles). The MI bed is composed of pure, dislocated layered ice. Layers with a thickness of from 0.2–0.3 cm to 20 cm are sustained with horizontal extent (see Fig. 3d). The layering is emphasized due to the interlayers of the grey loam, including 0.2–3.0 cm thick rubble. Sometimes, layering is disordered with the inclusion of slightly rolled boulders 30 cm in diameter. The boundary with overlying sediments is clear and discordant. The foot of the ice body lies beneath the mudflow.

Stable isotopes. The values of $\delta^{18}O$ in MI-3 range from –24.5‰ to –17‰ (Fig. 8b); the values of $\delta^{2}H$ range from –148.4‰ to –116.3‰. The values of $\delta^{18}O$ are distributed fairly uniformly along the depth and are close to –18‰, –17‰, while at a depth of approximately 1 m from the top (and slightly away from the main section), one sharply negative peak of the values of $\delta^{18}O$ –24.5‰ and $\delta^{2}H$ –148.4‰ was recorded.

Site MI-4. A homogeneous ice body discovered in a thermocirque 2.5 km north of the Lavrentiya settlement (Fig. 4) was studied in 2019 and 2020.

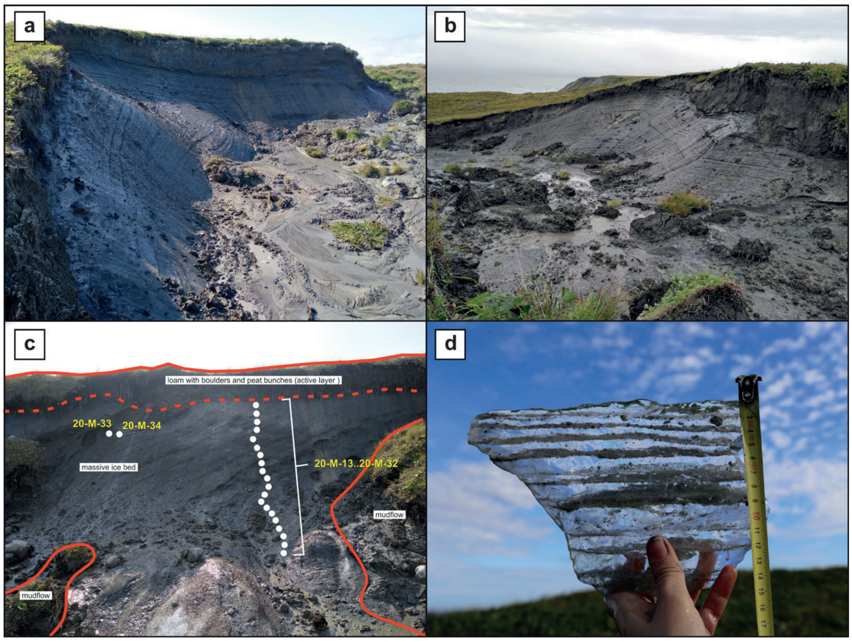

Fig. 3. Massive ice body MI-3: general view (a, b), sampling scheme in 2020 (c), and detailed view of the ice (d). (Photos by A. Maslakov)

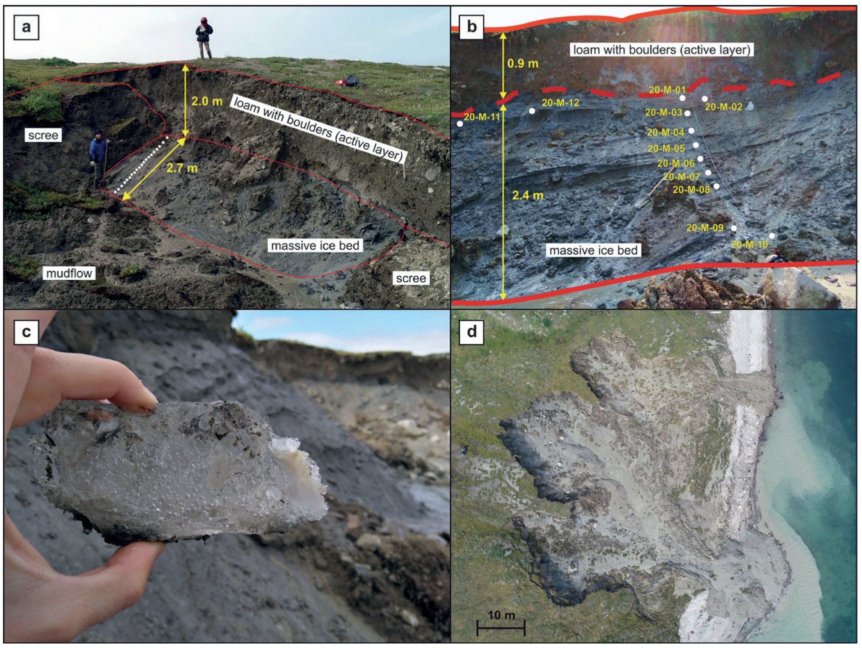

Fig. 4. Massive ice body MI-4: sampling schemes: a – 2019, b – 2020; c – detailed view of ice matter; d – aerial photo of the thermocirque from UAV. (Photos by A. Maslakov)

Cryostratigraphy. MI body is exposed in a large thermocirque (approximately 70 m wide, 45 m deep), eroding lower levels of the plain. Covering sediments are dark beige loam with the inclusion of boulders up to 1 m in diameter and bunches of black peat. Near MI top, the color of the loam changes to gray and blue-gray. The thickness of the overlying sediments is 1–2 m. The upper boundary of the body is smooth and discordant. Apparently, the overlying sediments were formed from Pleistocene loam with coarse-grained material, which was reworked after subsequent thaw slumps and armored the ice body. This is evidenced by the occurrence of black peat bunches and inclined lenses, which were buried by slump. MI body is an interlayer of clear, transparent ice (with a rare inclusion of bubbles) with gray loam, including boulders and gravel. The thickness of the ice layers varies from 2–3 cm to 20–30 cm; the thickness of the soil layers varies from 0.5 cm to 10 cm. These layers are inclined by 5–8° to the horizon line. The ice body is slightly dislocated with rare inclusions of boulders up to 20 cm in diameter, which though do not break the layering sequence.

Stable isotopes. The values of $\delta^{18}O$ in the MI-4 samples of 2019 vary from −19.02‰ to −18.16‰. The values of $\delta^{18}O$ are distributed fairly uniformly over the depth and are close to −18.5‰ (Fig. 8d). The range of values of $\delta^{18}O$ for the same body in the samples of 2020 is wider (from −21.3‰ to −16.6‰) whereas the values of $\delta^{2}H$ lie in the range from −163.9‰ to −123.9‰. More negative isotopic values are observed in the middle part of the ice layer (Fig. 8e).

Site MI-5. Heterogenic MI body was studied in 2016. It was located (65°30'28,4" N, 171°11'50,2" W) 2 km south-east from Chulkheveem (Akkani) river mouth and 1 km west from Akkani sea hunters base, on the Mechigmen Gulf coast (Fig. 5).

Cryostratigraphy. A thick and relatively extended layer of ice 45 m wide and up to 2.7 m thick was exposed in a thermocirque 25 meters from shoreline, 50 m wide with walls up to 4.5 m high. The thermocirque foot is located at an altitude of 3 m asl. The ice in the entire massif is clean and bubbly. It has a slightly dislocated layered structure. Ice layers of 10–15 cm alternated with 0.1–3.0 cm layers of grey loams. The boundary between the ice and the overlying sediments is smooth, clear, and discordant. The overlying deposits are 1.7–3.0 meters thick and represented by dark-yellow and blue-gray loam with boulder inclusions. The structure of the dark yellow loam is slab parting with traces of layering and smears of ocher loam. The blue-gray loam is confined to the base of the overlying sediment layer with a maximum thickness (2.1 m) in the central part of the outcrop; it is structureless, occasionally contains interlayers and bunches of black peat. The cryogenic structure near the contact is oblique lenticular with a lens up to 3 mm thick and up to 5 cm long. The more detailed cryostratigraphy is presented in (Vasil'chuk et al., 2018c). Apparently, the presented ice body is the remnant of the larger one exposed in the grassed thermocirque (see Fig. 5c) and buried by thawed slump deposits.

Stable isotopes. Variations of $\delta^{18}O$ and $\delta^{2}H$ values in ice samples were insignificant – $\delta^{18}O$ varied from −16.6‰ to −17.88‰; $\delta^{2}H$ varied from −123.7‰ to −135.8‰ (Fig. 8f).

Site MI-6. A homogeneous ice body was studied in 2015. It was exposed in a coastal thermocirque in an outlier of a Pleistocene 30–50 m high terrace, 8 km west of the mouth of the Chulkheveem (Akkani) river mouth (65°31'10.8" N; 171°25'04.9" W). The thermocirque base was at an altitude of approximately 5 m asl. (Fig. 6).

Cryostratigraphy. The width of the thermocirque was approximately 20 m; the width of the exposed ice body was approximately 6 m. The upper contact was clear and discordant; the foot of the body lied under the mudflow. The visible thickness of the ice was up to 4.7 m (see Fig. 6a). The overlying deposits 17 m thick are entirely represented by heavy, ice-poor loam of slab parting structure with rare inclusions of small boulders and pebbles and rare detritus of marine mollusks shells. The ice of the body is clean, with rare inclusions of bubbles and well-visible layering, which does not conform to the upper contact. The thickness of pure ice layers varies from 5 cm to 15 cm; they are interspersed with thin films (up to 5 mm) of bubbly ice, muddy ice, or grey loam (Maslakov et al. 2018).

Stable isotopes: Variations of $\delta^{18}O$ values in the body are insignificant – from −16.1‰ to −14.8 ‰ for $\delta^{18}O$ (Fig. 8g).

Site MI-7. Massive ice body on the coast of the Mechigmen Gulf is located 8.3 km west of the Chulkheveem (Akkani) river mouth, in front of the picket «23 km» of road from Lavrentiya to Lorino, 300 m west from site MI-6 (65°31'07.5" N, 171°25'29.9" W) and was studied in 2018 (Fig. 7).

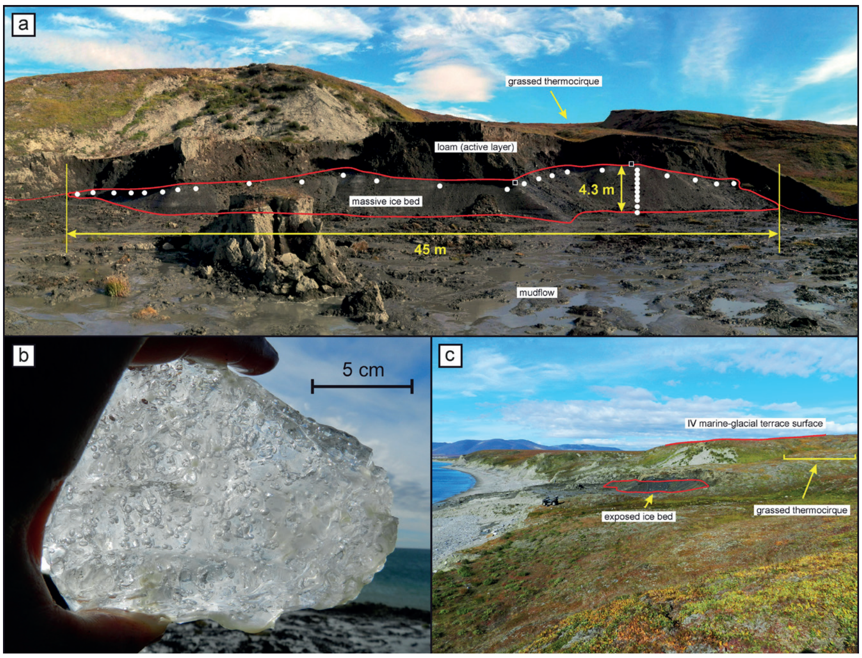

Fig. 5. Massive ice body MI-5: a) sampling scheme; b) detailed view of ice matter; c) general view from the side. (Photos by A. Maslakov)

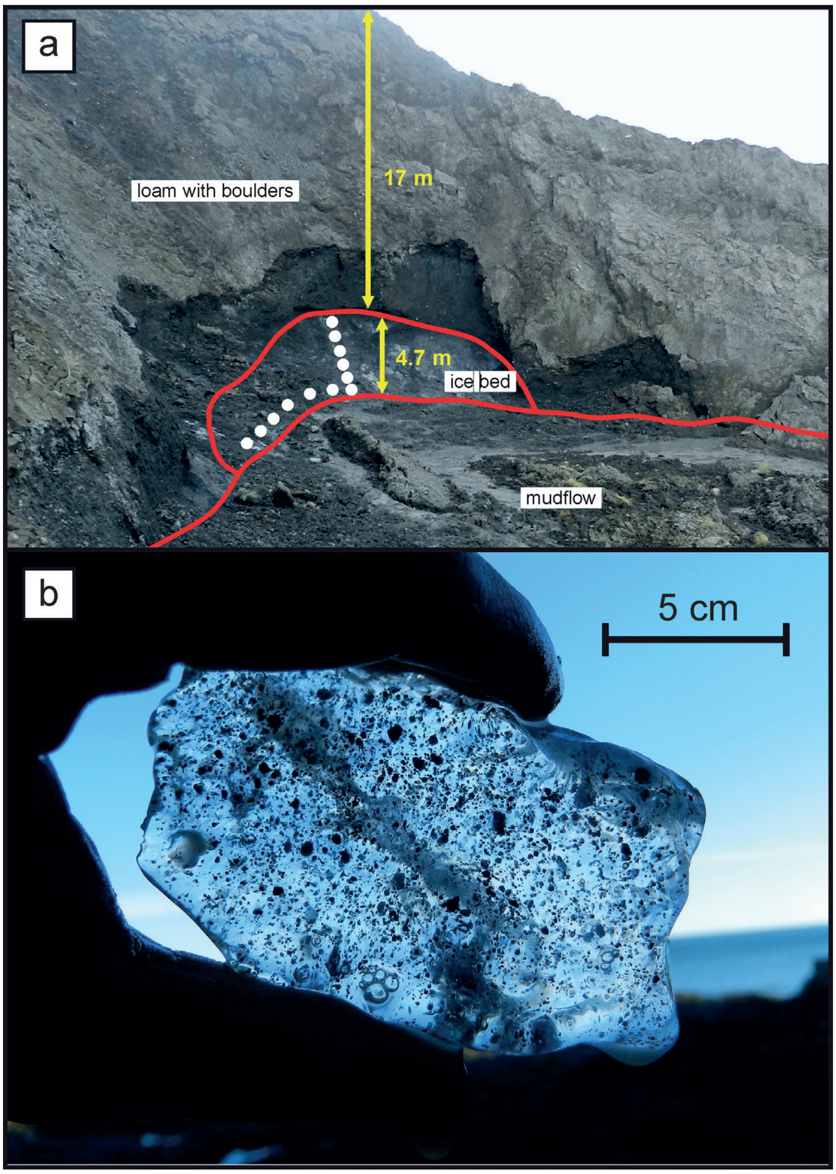

Fig. 6. Massive ice MI-6: a) sampling scheme; b) detailed view of ice matter. (Photo by A. Maslakov)

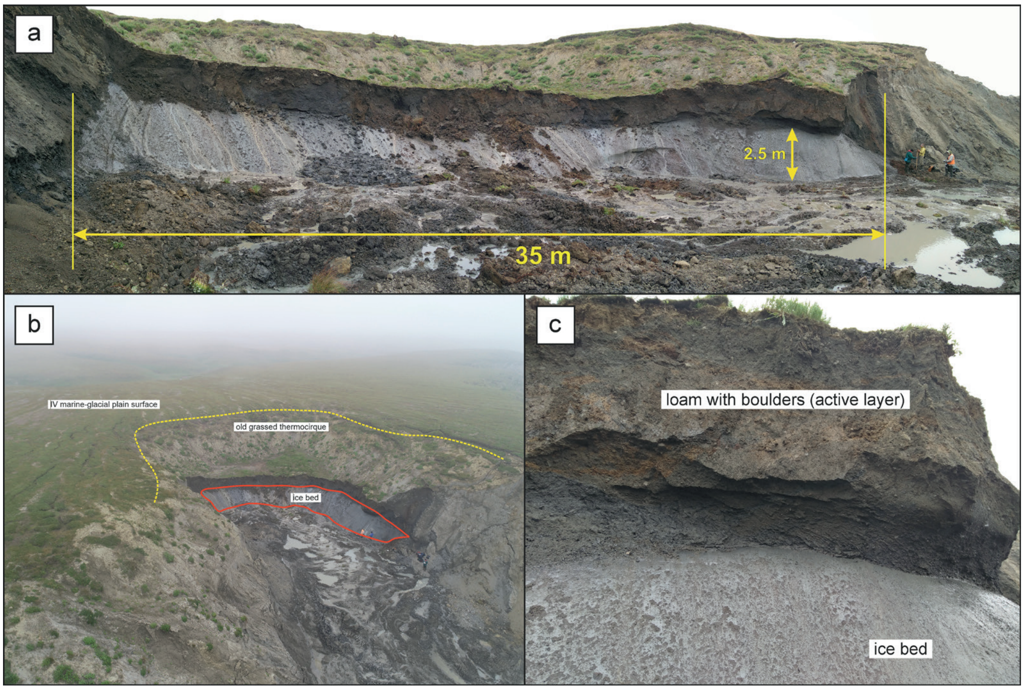

Fig. 7. Massive ice MI-7: a) and b) general view; c) the upper boundary with overlying sediments. (Photo by A. Maslakov, 2018)

Cryostratigraphy. The body was discovered in a thermocirque approximately 30 meters wide eroding IV marine terrace with surface altitudes of 40–60 m asl. The apparent thickness of the ice layer varies from 1.5 m to 3.5 m. The body top is smooth, discorded with overlying sediment's structure; the bottom of the body goes under the mudflow. The thickness of the overlying sediments in the central part of the cirque is approximately 1 m, increasing to 5–7 m at the edges. These are unsorted loams of dark beige color with inclusions of boulders and peat bunches. The ice is clear, bubbly; the bubbles do not have a strict orientation and reach 3–5 mm in diameter. Stratification in the ice can be traced only in the upper part of the deposit. Ground layers are found on the edges of the ice body; they are lying according to the top of the formation. The main part of MI is pure bubble ice, almost devoid of ground inclusions. In polarized light, ice is coarse-grained, with crystals ranging in size from 1–2 cm to 5 cm in width. Layered ice is characterized by smaller crystals (several mm wide). This thermocirque is embedded in an older one, and the exposed ice body had been forming the lower or middle part of a more massive ice body, partially degraded as a result of the formation of the previous thermocirque. The isotope analysis has not yet been performed in this body, and here it is listed as one of the best outcrops of MI in the north-east of Chukotka, studied by A. Maslakov, N. Belova, F. Romanenko, and A. Baranskaya (Maslakov et al. 2018).

DISCUSSION

Isotope composition of MI bodies of Chukotka

Although MI beds in Chukotka have been studied for more than 80 years, their isotopic study began less than 30 years ago. There are some publications devoted to isotope composition of MI near Anadyr and the coast of Onemen Bay (Vasil'chuk 1992; Kotov 2001, 2005), in the Amguema River valley (Korolev 1993; Kotov 1997a, b) and in the Tanyurer River valley (Kotov, 1998a), located in Western and Central Chukotka region.

Massive ice near the city of Anadyr. Massive ice body exposed in a quarry on a slope near the city of Anadyr was 2 m thick and was dissected by syngenetic ice wedges more than 5 m high. δ^{18}O values in MI varied from –19.6‰ to –19.7‰, while in wedge ice they varied in more wide range – from –23.4‰ to –18.6‰; in segregated ice from enclosing sand they varied from –22.7‰ to –18.6‰. Higher isotope values (from –17.3‰ to –16.4‰) were obtained for Holocene epigenetic ice wedges from the upper part of slope deposits (Vasil'chuk 1992).

Massive ice in the Amguema River valley. In the middle course of the Amguema River (130 km north of the Arctic Circle), Korolev (1993) and Kotov (1997a) studied the structure and isotope composition of MI in the exposure of the ridge. Isotope composition of MI at the depth 4–12 m is uniform; δ^{18}O values vary from –26.6‰ to –25.2‰. Isotope oxygen composition of modern snow in this area is much heavier, average δ^{18}O value is –21‰; δ^{18}O value in Holocene ice wedges and modern ice veinlets vary from –20‰ to –18‰.

In total 30 samples were analysed from these MI bodies. The range of δ^{18}O values in vertical and horizontal directions is insignificant, not more than 4‰: from –29‰ to –25‰ (mean value is –26.1‰). Isotope composition of the Late Pleistocene ice wedge is generally lighter than that of the MI: δ^{18}O values in the ice wedge range from –29.2‰ to –27.3‰ (Korolev 1993). A radiocarbon date of 20600±600 years BP (MAG-1309) obtained from a peat layer in slope sediments from a depth of 12 m indicates that the slope complex and the end-moraine ridge were formed in the Late Pleistocene (Kotov, 1997a).

Homogeneous autochthonous MI on the Onemen Bay coast. On the northern coast of the Onemen Bay, 25 km from the city of Anadyr, MI bodies were studied by Kotov (1997a,b, 2001) in two thermocircues exposed to the east of Cape Rogozhny. In the outcrop located at Cape Glubokiy, three cryogenic horizons of different ages with polygonal ice wedge structures were identified. Based on radiocarbon dates, it was determined that two lower cryogenic horizons were formed in the last stage of the Late Pleistocene (after 40 ka BP), and upper one is of Holocene age. In similar and apparently synchronous strata on the northern coast of Onemen Bay, 4 km southeast of the Cape Rogozhny outcrop, we studied ice wedges, in which δ^{18}O values vary from –27.3‰ to –23.8‰.

In one thermocircus, two layers of MI were separated by a layer of loam with coarse-grained material with a thickness of up to 8 m. The isotope-oxygen composition was studied for the four MI layers. One of them was analyzed in the Estonian Academy of Sciences: δ^{18}O values in the upper part of the ice ranged from –16.7‰ to –20.7‰. Other three layers were analyzed in the Alfred Wegener Institute for Polar and Marine Research in Potsdam: δ^{18}O values ranged from –20.64‰ to –20.03‰. Higher values (–19.78‰ to –18.99‰) were obtained in the ice layers enriched with soil.

Heterogeneous allochthonic MI in the Tanyurer River valley. In the middle and lower reaches of the Tanyurer River (in the valley of the Kuiviveyem River) A.N. Kotov traced a series of long and rather high arc-shaped ridges. The age of the outer ridge is determined on the basis of ^{14}C dates between 16.86 ka and 21.5 ka BP from plant residues from peaty sand (Kotov, 1998a). δ^{18}O values in MI range from –23.56‰ to –21.73‰; the mean value is –22.96‰. δ^{2}H values vary from –181.3‰ to –165.2‰. In the Late Pleistocene ice wedge δ^{18}O values vary from –24.9‰ to –21.3‰; δ^{2}H values vary from –191.5‰ to –165.9‰ (Kotov, 1998a).

The analysis of the obtained isotope data showed that δ^{18}O values in MI bodies in most areas of continental Chukotka vary from –29‰ to –23‰, and in the coastal areas, for example, near the city of Anadyr, they are closer to –20‰, –18‰.

Preliminary interpretation of the isotope composition of the studied massive ice bodies of the North-East Chukotka

New stable isotope data do not allow clearly establishing the age and conditions of the ice formation yet, but some conclusions can be made:

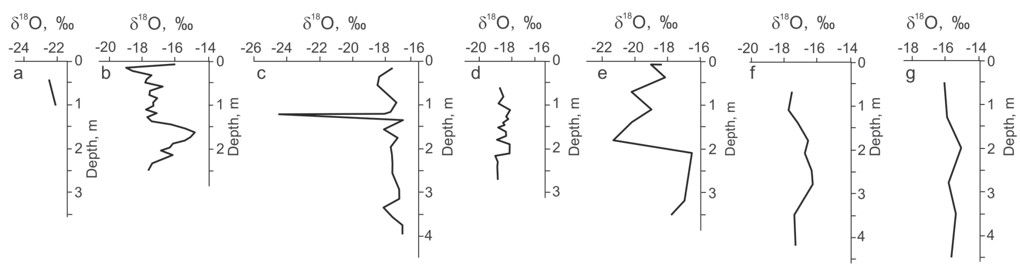

Fig. 8. Distribution of δ^{18}O values in the MI bodies of the north-eastern Chukotka by depth (the depth of the bodies roof is taken as 0 m): a – MI-1; b – MI-2; c – MI-3; d – MI-4 (2019); e – MI-4 (2020); f – MI-5; g – MI-6

1. First of all, most of the six studied MI bodies have a relatively «enriched» isotope composition, the mean $\delta^{18}O$ values vary from –15.4‰ to –18.7‰, mean δ^2H values vary from –128.1‰ to –145.8‰. And only MI near the Koolen' lake has mean $\delta^{18}O$ value of –21.5‰ (Table 1).

2. Two patterns of vertical isotope profiles are clearly observed for MI bodies. The first pattern is a uniform distribution of the $\delta^{18}O$ values in the range from –17‰ to –18‰; the second pattern presents significant variations of the $\delta^{18}O$ values in the range from –16‰ to –22‰. In the first case, the monotonous vertical distribution indicates a single rapid freezing of water by the congelation type. In the second case, sharp changes of isotope values reflect gradual freezing by segregation type, most likely upward and downward from the horizon, where the ice has the most positive value. In this case, more and more isotopically negative ice is formed during gradual freezing.

3. $\delta^{18}O$ values for the MI close to –17‰ and –18‰ are almost equal to the winter Holocene precipitation in this region (Vasil'chuk et al. 2018), which would seem to indicate a possible Holocene age of the ice. However, it is known that during water freezing, forming ice always became «heavier» by 2–3‰ compared to the original water due to fractionation, even at one stage of freezing. In this regard, we can suppose that $\delta^{18}O$ values of the source water are close to –20––21‰. Moreover, evaporation from water reservoirs that served as a source for MI formation, should not be excluded. Thus, it can be assumed that the initial water was characterized by $\delta^{18}O$ values in the range from –23‰ to –25‰. These values are undoubtedly more realistic for the Late Pleistocene surface waters of the Eastern Chukotka. Modern surface waters are usually isotopically enriched by 6-10‰ for the $\delta^{18}O$ values (Table 2). According to our data, the waters of rivers, streams, and lakes sampled in summer are characterized by $\delta^{18}O$ values from –9.6‰ to –14.7‰, in snowpatches $\delta^{18}O$ values vary from –10.4‰ to –18.9‰; in the ground water $\delta^{18}O$ value is –14.6‰. Our data are consistent with the data obtained by Polyak et al. (2008), who studied isotope composition of hydrotherms and surface waters of the Eastern Chukotka: according to them $\delta^{18}O$ values in surface waters vary from –11.1‰ to –16.4‰.

Slopes of the δ^2H-$\delta^{18}O$ lines lower than eight commonly indicate the evaporation of initial water. On the co-isotope diagram (Fig. 9), the slope of the δ^2H-$\delta^{18}O$ ratio line for MI-5 is close to 6 that may indicate evaporation of water before freezing and massive ice formation. For two MI bodies (MI-2 and MI-4, 2020) the slopes of the δ^2H-$\delta^{18}O$ ratio lines are close to the global meteoric water line (GMWL) and are equal to 7.71 and 8.36, respectively (Fig. 9). This most likely indicates that in this case we studied lower part of a once thick MI body, where ice was formed under the equilibrium conditions of a closed system according to the Rayleigh type. This is also indicated by contrast distribution of the $\delta^{18}O$ values in these ice bodies (see Fig. 2, b, e).

For the MI-3 clustering of the isotope values does not allows to construct a regression line, moreover, for one sample the much lower value was obtained (see Fig. 8c, 9). Such negative shift (compared to the other values) most likely indicates a noticeable fractionation during ice formation when isotopically enriched ice was formed at the first stages of water freezing, and isotopically depleted ice – on the last stage of water freezing.

Table 1. Stable isotope ($\delta^{18}O$, δ^2H and d_{exc}) minimum, mean, and maximum values; standard deviations, slopes, and intercepts for MI bodies, eastern Chukotka

Site ID	Field site ID	N	$\delta^{18}O$ (‰)			δ^2H (‰)			d_{exc} (‰)			Slope	Intercept	R^2
			Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.			
MI-1	343-YuV	2	–22.4	–21.5	–20.6	–	–	–	–	–				
MI-2	17-M	26	–18.96	–16.97	–14.84	–148.4	–131.4	–116.3	–2.48	4.52	11.02	7.71	–0.6	0.9
MI-3	20-M	20	–24.5	–18.0	–17	–191.3	–142.6	–121.1	–8.6	–0.5	11.7	6.86	–19.5	0.7
MI-4 (2019)	19-M	19	–19.02	–18.57	–18.16	–	–	–	–	–	–	–	–	–
MI-4 (2020)	20-M	11	–21.3	–18.7	–16.6	–163.9	–145.8	–123.9	–6.5	4.1	14.2	8.36	11	0.8
MI-5	16-M	33	–17.88	–17.13	–16.27	–135.8	–128.1	–121.6	4.2	9.0	15.8	6.42	–18.1	0.5
MI-6	15-L	12	–16.1	–15.4	–14.8	–	–	–	–	–	–	–	–	–

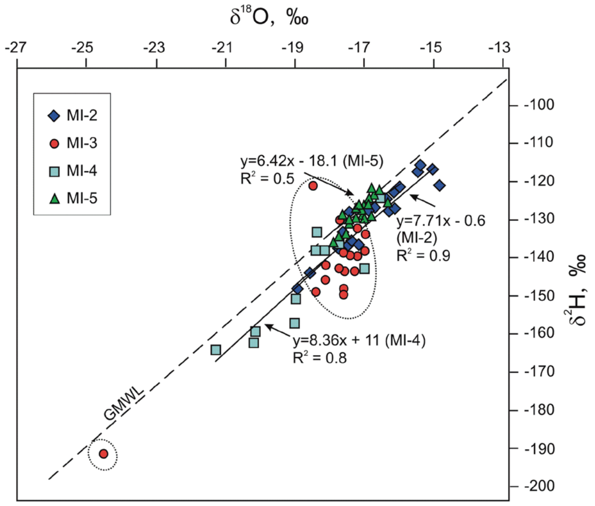

Fig. 9. Co-isotope δ^2H-$\delta^{18}O$ lines for the MI bodies of the extreme northeast of Chukotka. GMWL (global meteoric water line) is given for comparison

Table 2. The δ¹⁸O values in the surface water (spring – SW, river – RW, creek – CW, lake water – LW, bay – BW), snowpatches (S) of the northeast coast of Chukotka. From Vasil'chuk (1992, vol. 2) and additional data

Sample ID	Location	Type of water	$\delta^{18}O$, ‰
342-YuV/1	Creek near Lavrentia settlement (sampled in July)	CW	–11.7
342-YuV/2	Snowpatch 1 near Lavrentia settlement	S	–18.9
342-YuV/5	Snowpatch 2 near Lavrentia settlement	S	–10.4
342-YuV/3	Water of Lavrentia Bay	BW	–1.4
342-YuV/4	Small lake near Lavrentia settlement (sampled in July)	LW	–9.6
342-YuV/8	Snowpatch 3.7 km southern Lavrentia settlement (sampled in July)	S	–14.4
342-YuV/9	Water of Chul'cheveem River	RW	–12.2
343-YuV/37	Creek near Koolen' lake (sampled in August)	CW	–14.7
17-M-01-17-M-02	Near glacier lake in the car (sampled by A.Maslakov in 2017)	LW	From –10.67 to –11.97
17-M-03-17-M-08	Snowpatch 4 in glacier car, near Lavrentia settlement (sampled by A.Maslakov in 2017)	S	From –12.39 to –12.69
17-M-70	Spring water at 21 km picket of «Lavrentia –Lorino» road (sampled by A.Maslakov in 2017)	SW	–14.6

Analysis of the isotope composition of MI bodies of Chukotka shows a negative trend from the coast inland: mean $\delta^{18}O$ values of MI bodies near the Lavrentiya settlement vary from –15.4‰ to –18.7‰; MI on the coast of the Onemen Gulf and near the city of Anadyr vary from –19.6‰ to –20.6‰; in the more continental areas, i.e. at the Koolen' Lake, mean $\delta^{18}O$ value for MI is –21.5‰; for farther inland, in the Tanyurer River and Amguema River valleys, $\delta^{18}O$ values of MI bodies vary from –21.7‰ to –23.6‰ and from –25‰ to –29‰, respectively. This is most likely due to the continental isotope effect of precipitation (which was the primary source of water for ice formation), when precipitation becomes more isotopically depleted from coastal to continental areas.

4. If to assume that studied MI bodies are the fragments of burial glacial ice, then, first of all, it should be noted that modern glaciation in the highest mountains of the Eastern Chukotka is mainly of the glacial cirque type, less often of the cirque-valley type. This involves approximately 25–30 small glaciers. For the largest of them, the margin moraine forms were noted near the edge of the glacier. In total, there were 47 glaciers in Chukotka with an area of 13.53 km^2 (Sedov 1997) divided into five groups. The largest group is represented by 21 glaciers with a total area of 8.65 km^2. They were discovered near the Iskaten ridge, most of them are of cirque, cirque-valley, and cirque-hanging types. In the mountain range near the Provideniya Bay (1194 m), there is enough moisture from the Pacific Ocean, the total area of glaciers is approximately 2.5 km^2 (Sedov 1997).

In the Late Pleistocene these glaciers could advance only by 100–300 meters. By morphology and environmental conditions, they are very close to the glaciers of the Polar Ural mountains (Vasil'chuk et al. 2016). According to Mangerud et al. (2008), in the Late Pleistocene these glaciers never occupied a much larger area compared to the present time.

5. In the Arctic Siberia, we studied territories such as the Arctic islands with glacial domes – Severnaya Zemlya, Novosibirsk Islands, Wrangel Island, the mountainous areas of Verkhoyansk mountains, Sayan, and Stanovoy Ridge, etc. and could not find any Late Pleistocene glacier or its part under the Holocene glacier. There is no reason to assume the active disappearance of the Pleistocene glaciers during the Holocene, as along the extensive north Siberian coast and on the arctic islands Late Pleistocene ice wedges not only degraded but are also located directly beneath the modern active layer (Vasil'chuk Yu., Vasil'chuk A. 2018).

At the same time, the Late Pleistocene glaciers are quite widespread in the North American Arctic and on the islands of the Canadian Arctic Archipelago – these are, first of all, the glacial domes of Greenland, Ellesmere, Devon, Agassiz, etc. Therefore, the preservation of the buried Late Pleistocene glacial ice is possible in the permafrost sediments of the North America, whereas their existence in the Eurasian Arctic, including Chukotka, is impossible (Vasil'chuk 2020).

6. Isotopic curves for polar caps of the Russian Arctic can demonstrate a very contrasting distribution of $\delta^{18}O$ values (even in the bottom ice the range is more than 5–6‰, in spite of the compacted ice and almost untraceable seasonal differences) as a quite uniform distribution of $\delta^{18}O$ values with the range of no more than 2–4‰. Vasil'chuk (2020) observed that the isotopic composition of the majority of the MI bodies of the Northern Eurasia is very close to the Holocene values.

7. It should be noted that the existence of the Late Pleistocene yedoma strata with thick ice wedges in Chukotka, in the valleys of the Main, Tanyurer, and Ekityki rivers (Kotov, 1997a,b, 2001; Vasil'chuk, Vasil'chuk, 2021) near mountains with glacial cirque glaciers clearly indicate the impossibility of glaciation expanding in these valleys, since syngenetic ice wedges do not form under glaciers.

8. Ice bodies MI 2- MI 7 were found either within Pleistocene plain (MI 2-4) or under sediments of Pleistocene terrace (MI 5-7) that allows assuming that MI bodies are confined to Pleistocene deposits and may be formed during epigenetic freezing. Among the studied MI bodies, three of seven objects (MI 3, 5, and 7) were found in the old grassed thermocirques, which were possibly activated by the recent climate warming. Apparently exposed ice bodies are the parts of larger ones, which were partly melted from the top during previous period of increased summer temperatures. The foot of the bodies was not exposed in all outcrops. In this way, core drilling may be a potential direction of further studies of the distribution and morphology of the MI bodies in the Chukotka region.

9. Summing all the presented reasons it may be concluded that the studied MI bodies are of intrasedimental genesis; they were formed by congelation and congelation-segregation processes. However, this is still only a motivated assumption. A more definite conclusion about the age and origin of MI can be made after its dating and pollen analysis.

CONCLUSIONS

a. Recent climate warming in the Arctic and in the Chukotka region in particular facilitated deeper active layer thickening and more intensive thaw slumps formation. Exposed MI beds in vicinities of Lavrentiya and Lorino settlements allowed conducting detailed cryostratigraphic and stable isotope studies in the summer seasons of 2015–2020.

b. For the first time cryostratigraphy and stable isotope composition of six MI bodies of the extreme north-east of Chukotka (Koolen' Lake – Lavrentiya settlement) were studied.

c. $\delta^{18}O$ and $\delta^{2}H$ values in the MI samples were rather high: the mean $\delta^{18}O$ values vary mainly from −18.5‰ to −15‰; $\delta^{2}H$ values vary from −146‰ to −128‰.

d. The studied MI bodies are of intrasedimental genesis and highly likely are dated back to the Late Pleistocene age.

e. Analysis of the isotope composition of MI bodies of Chukotka shows a negative trend of $\delta^{18}O$ values from the coast inland, from −15.4‰ to −18.7‰ (near the Lavrentiya settlement) and from −25‰ to −29‰ (in Amguema River valley) that is mainly explained by continental isotope effect for precipitation, which was the primary source of water for ice formation.

f. More definite conclusion about the age and origin of the MI can be made after their direct dating and pollen analysis direct from ice. ■

REFERENCES

Abramov A., Davydov S., Ivashchenko A., Karelin D., Kholodov A., Kraev G., Lupachev A., Maslakov A., Ostroumov V., Rivkina E., Shmelev D., Sorokovikov V., Tregubov O., Veremeeva A., Zamolodchikov D. & Zimov S. (2019). Two decades of active layer thickness monitoring in northeastern Asia, Polar Geography, 3(44), 186-202, DOI: 10.1080/1088937X.2019.1648581.

Bulygina O.N., Razuvayev V.N., Trofimenko, L.T., Shvets, N.V. (2020). Automated Information System for Processing Regime Information (AISPRI). Available at: http://aisori.meteo.ru/ClimateR [Accessed on 28 February 2020].

French H.M. (2018). The Periglacial Environment, 4th Edition. Wiley, 544.

Gasanov Sh.Sh. Ground ice of the Chukotka Peninsula. In Permafrost of Chukotka. Magadan. Publ: SVKNII SO AN SSSR, 1964, 14-41. (in Russian).

Gasanov Sh.Sh. (1969). Structure and formation history of permafrost of the Eastern Chukotka. Moscow: Nauka, 168. (in Russian).

Kolesnikov S.F., Plakht I.R. Chukotka Area. (1989). In: Popov A. I, ed. Regional'naya Kriolitologiya (Regional Cryolithology). University Press: Moscow; 201-217. (in Russian).

Korolev S.Yu. (1993). Late Pleistocene glacier ice finding in the valley of the Amguema River (Northern Chukotka). Doklady of the Russian Academy of Sciences, 329(2), 195-198. (in Russian).

Kotov A.N. (1997a). Features of cryolithogenesis in the ablation zone of Late Pleistocene glaciers. In: Results of fundamental studies of the Earth's cryosphere in the Arctic and Subarctic. Novosibirsk: Nauka, 249-259. (in Russian).

Kotov A.N. (1997b). Massive ice on the northern coast of Onemen Bay (Chukotka). In: Late Pleistocene and Holocene of Beringia. Magadan. Publ: SVKNII SO AN SSSR, 92-98. (in Russian).

Kotov A.N. (1998a). Cryolithogenic ridges in the Tanurer River valley (Chukotka). Earth's Cryosphere, II(4), 62-71. (in Russian).

Kotov A.N. (1998b). Ground ice formation and problems of the regions of new development of Chukotka. In: Chukotka: nature and man. Magadan. Publ: SVKNII SO AN SSSR, 38-51. (in Russian)

Kotov A.N. (1999). Late Pleistocene cryolithogenic deposits and glacier ice in the valley of the Ekityki River (northern Chukotka). In complex studies of Chukotka (problems of geology and biogeography). Magadan. Publ: SVKNII SO AN SSSR, 93-102. (in Russian).

Kotov A.N. (2001). Peculiarities of occurrence, composition, and structure of layer-type ice deposits on the northern coast of Onemen Bay (Chukotka). Materials of the second conference of geocryologists of Russia, volume 1, part 2. Lithogenetic geocryology. Engineering geocryology. Moscow State University M.V. Lomonosov 6–8 June 2001 Moscow: Moscow University Press, 218-225. (in Russian).

Kotov A.N. (2005). Comparative analysis of the composition and structure of stratal ice deposits of Chukotka. In Materials of the third conference of geocryologists of Russia. Moscow State University M.V. Lomonosov June 1-3, 2005 Volume 1. Part 2. Lithogenetic geocryology and soil cryogenesis. M .: Moscow University Press, 168-175. (in Russian).

Mangerud J., Gosse J., Matiouchkov A., Dolvik T. (2008). Glaciers in the Polar Urals, Russia, were not much larger during the Last Global Glacial Maximum than today. Quaternary Science Reviews, 27(9), 1047-1057, DOI: 10.1016/j.quascirev.2008.01.015.

Maslakov A.A., Belova N.G., Baranskaya A.V., Romanenko F.A. (2018). Layered ice on the eastern coast of the Chukchi Peninsula during climate warming: some results of expeditions in 2014–2018. Arctic and Antarctic, 4, 30-43. (in Russian)).

Maslakov A.A., Nyland K.E., Komova N.N., Yurov F.D., Yoshikawa K., Kraev G.N. (2020). Community Ice Cellars In The Eastern Chukotka: Climatic And Anthropogenic Influences On Structural Stability. Geography, Environment, Sustainability, 13(3), 49-56, DOI: 10.24057/2071-9388-2020-71.

Opel T., Dereviagin A.Yu., Meyer H., Schirrmeister L., Wetterich S. (2011). Palaeoclimatic Information from Stable Water Isotopes of Holocene Ice Wedges on the Dmitrii Laptev Strait, Northeast Siberia, Russia. Permafrost and periglacial processes, 22, 84-100, DOI: 10.1002/ppp.667.

Polyak B.G., Dubinina E.O., Lavrushin V.Yu., Cheshko A.L. (2008). Isotopic Composition of Thermal Waters in Chukotka. Lithology and Mineral Resources, 43(5), 429-453, DOI: 10.1134/S0024490208050027.

Soloviev P.A. (1947). Ice in permafrost soils in the Anadyr city area. Mineral resources of Arctic, Iss. 2, Moscow-Leningrad, 213-232. (in Russian).

Shvetsov P.F. (1938). Permafrost and geotechnical conditions of the Anadyr region. Edited by Sumgin M.I. and Efimov A.I. (eds.). Moscow-Leningrad: Publ. Glavsevmorput, 78. (in Russian).

Shvetsov P.F. (1947). Groundwater and fossil ice in the area of the city of Anadyrand the Ugolnaya bays. Nedra of Arctic. Iss. 2. Moscow-Leningrad, 204-211. (in Russian).

Sedov R.V. Chukotka glaciers. Materials of glaciological research, iss. 82. 1997, 213-217.

Vasil'chuk Yu.K. (2012). Isotope Ratios in the Environment. Part 2: Stable isotope geochemistry of massive ice. Moscow: Moscow University Press, 472. (in Russian).

Vasil'chuk Yu. K. (2006). Massive ice bodies. In Vasil'chuk Y., Krylov G., Podborny Y. Eds. Cryosphere of oil-gas fields of Yamal Peninsula. Vol. 1. Cryosphere of the Kharasavey gas-condensate field.: Nedra, 160-193. (in Russian).

Vasil'chuk Yu. K. (1992).Oxygen isotope composition of ground ice (application to paleogeocryological reconstructions). Volume 1, 420 pp., Volume 2, 264 pp. Theoretical Problems Department, Russian Academy of Sciences and Lomonosov Moscow University Publications, Moscow (in Russian with English contents section).

Vasil'chuk Yu. K. (2020). Some clear evidences of the intrasedimental origin of massive ice in northern Eurasia. Arctic and Antarctic, 1, 23-34, DOI: 10.7256/2453-8922.2020.1.32283 (in Russian).

Vasil'chuk Yu.K., Budantseva N.A., Vasil'chuk A.C., Podborny Ye.Ye., Chizhova Ju.N. (2016). Multistage Holocene massive ground ice in Northern West Siberia. Earth's Cryosphere, XX(1), 34-45. http://www.izdatgeo.ru.

Vasil'chuk Yu.K., Budantseva N.A., Farquharson L., Maslakov A.A., Vasil'chuk A.C., Chizhova Yu.N. (2018a). Isotopic evidence for Holocene January air temperature variability on the East Chukotka Peninsula. Permafrost and Periglacial Processes, 29(4), 283-297, DOI: 10.1002/ppp.1991.

Vasil'chuk Yu.K., Budantseva N.A., Vasil'chuk A.C., Maslakov A.A., Chizhova Ju.N. (2018b). Oxygen isotope composition of Holocene ice wedges of the Eastern Chukotka. Doklady Earth Sciences, 480(2), 759-763, DOI: 10.1134/S1028334X18060107.

Vasil'chuk Yu.K., Chizhova Ju.N., Maslakov A.A., Budantseva N.A., Vasil'chuk A.C. (2018c). Oxygen and hydrogen isotope variations in a recently formed massive ice at the mouth of the Akkani River, Eastern Chukotka. Led i Sneg. Ice and Snow, 58(1), 78-93, DOI: 10.15356/2076-6734-2018-1-78-93 (in Russian).

Vasil'chuk Yu.K., Vasil'chuk A.C. (2017). Ice wedges in the Mayn River valley and winter air paleotemperature in the Southern Chukchi Peninsula at 38-12 Kyr BP) // Earth's Cryosphere, XXI(5), 27-41, DOI: 10.21782/KZ1560-7496-2017-5(27-41)

Vasil'chuk Yu.K., Kotlyakov V.M. (2000). Principles of Isotope Geocryology and Glaciology. A comprehensive textbook. Moscow University Press, 616. (in Russian).

Vasil'chuk Yu.K., Murton J.B. (2016). Stable isotope geochemistry of massive ice // Geography, Environment, Sustainability, 3, 4-24, DOI: 10.15356/2071-9388_03v09_2016_01

Vasilchuk Yu.K., Vasilchuk A.C. (2018). The oxygen isotope composition of ice wedges of Ayon Island and paleotemperature reconstructions of the Late Pleistocene and Holocene of the North of Chukotka. Moscow University Geology Bulletin, 73(1), 87-99, DOI: 10.3103/S0145875218010131.

Vtyurin B.I. (1964). Cryogenic structure of Quaternary deposits (the case of the Anadyr lowland). Moscow: Nauka, 152. (in Russian)

Vtyurin B.I. (1975). Ground ice of the USSR. Moscow: Nauka, 214. (in Russian).

Zamolodchikov D.G., Kotov A.N., Karelin D.V., Razzhivin V.Y. (2004). Active-Layer Monitoring in Northeast Russia: Spatial, Seasonal, and Interannual Variability. Polar Geography, 28(4), 286-307.