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# ICE WEDGES IN THE MAYN RIVER VALLEY AND WINTER AIR PALEOTEMPERATURES IN THE SOUTHERN CHUKCHI PENINSULA AT 38–12 KYR BP

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We studied the structure and composition of Late Pleistocene cyclic ice wedge complexes in the Mayn River Valley and syngenetic ice wedges in adjacent areas of the Southern Chukchi Peninsula. Analysis of stable isotopes ($\delta^{18}O$ and $\delta D$) and major ion chemistry of ice, as well as radiocarbon ages and pollen spectra of the host sediments, allowed detailed quantitative evaluation of changes in Late Pleistocene permafrost and climate conditions of the area, between 38 and 12 Kyr BP. The study has confirmed the previous inference that winters were much colder than now in the latest Pleistocene and rather severe during the Holocene optimum.

*Ice wedge, Holocene, Late Pleistocene, permafrost, stable isotopes, heavy oxygen, deuterium, radiocarbon, pollen and spores, Mayn River, Southern Chukchi Peninsula*

## INTRODUCTION

The Late Pleistocene and Holocene history of ground ice in the southern Chukchi Peninsula was affected by its location at the crossways of two oceans and a complex surface topography with vast plainlands and mountains. The ice types included glaciers in highlands, ground ice in both mountainous and plain areas, and syngenetic ice wedges in yedoma frozen sediments.

This study addresses the structure and composition of Late Pleistocene ice wedges in the Mayn River Valley, near Anadyr Town, and in the adjacent areas of the southern Chukchi Peninsula. The work consisted in determination of stable isotope ($\delta^{18}O$ and $\delta D$) compositions and major ion chemistry of ice, as well as AMS $^{14}C$ dating and pollen analysis of sediments, with implications for Late Pleistocene and Holocene permafrost and climate settings.

There are quite few comprehensively studied reference sections of Late Pleistocene permafrost with ice wedges in the Chukchi Peninsula. Early during permafrost studies in the area, ice wedges, especially syngenetic ice, were thought to be of rare occurrence restricted to Holocene overbank or slope talus deposits. However, ice wedges were reported later from many parts of the peninsula, including the Mayn River Valley (Fig. 1).

*Neustadt and Tyulina* [*1936*] discovered mammoth remnants in the second terrace of the Mayn River, and thick ground ice at the Parfonai locality on the Mayn River. *Tomirdiaro* [*1970*] was among the first to describe the outcrop of Ledovy Obryv (Russian for *Ice Bluff*) on the river as a stratotype ice-loess section of the Chukchi Peninsula. A few years later, Svitoch and his colleagues distinguished six layers (cycles) of ice wedges in the section [*Kaplin, 1980*]. Cyclicity in soil properties and in patterns of ice wedges was also noted by *Dort-Golts* [*1982*] who worked in the area about the same time. However, he found only three cycles, while the group of Svitoch revealed five large sedimentary cycles in the nearby Ust'-Algan section [*Svitoch, 1975; Kaplin, 1980*].

Interesting results were obtained also for Late Pleistocene ice wedges from other areas of the peninsula. Namely, *Vtyurin* [*1964*] reported ice wedges in slope wash affected by solifluction from vicinity of Anadyr Town. Large ice wedges, 1 m or even up to 3 m wide on the top and more than 3 m high, were observed on a bedrock hillslope.

*Gasanov* [*1969*] investigated more than 400 ice wedge outcrops during his trips to the eastern Chukchi Peninsula. He found a small remnant of a river terrace with elevations from 8 to 12 m above sea level south and southeast of the old bottom of Lake Nizhneye (Anadyr plain, northern side of the Anadyr lagoon). The terrace is composed of layered silty sediments that enclose sporadic subrounded pebbles and lenses of outsize sand, sand- to gravel-size pebbles, and peat, as well as syngenetic ice wedges, more than 7 m high. Another ice wedge structure consisting of two nested wedges existed in the lower part of the Grebeshki Ridge, at the boundary with the river terrace. The lower ice wedge is about 3 m wide on the top and over 8 m high; the respective dimensions of the upper wedge are 1.8 and 5 m; the shoulders of the two ice wedges are spaced at 1.7 m [*Gasanov, 1969*]. The vertical extent of ice wedges in the middle reaches of the Kanchalan River may exceed 20 m, as estimated by *Vtyurin* [*1964*].

Kotov performed a large amount of work from 1985 through 2005 to study yedoma deposits in different parts of the southern Chukchi Peninsula: east of the Rogozhny Cape toward the Nerpa Cape in the northern shore of Lake Onemen; in the lower and middle reaches of the Tanyurer River; and in the Uivyrveem River Valley, a tributary of the Anadyr River in its headwaters, etc. [*Kotov, 1988, 1997, 1998a,b*]. He provided careful geocryological description of all sites, AMS $^{14}C$ dating of organic matter, analysis of major ion chemistry, and determination of stable isotopes in ice. Yedoma deposits in the Mayn River Valley were studied in an especially detailed way [*Kotov and Ryabchun, 1986*]; $^{14}C$ dating of the Ledovy Obryv sediments was done in collaboration with Lozhkin [*Lozhkin et al., 2000*].

## LOCATION OF SAMPLED YEDOMA COMPLEXES

***Mayn River Valley.*** Two yedoma complexes are located in the valley of the Mayn River, a large right tributary of the Anadyr River. The Mayn River is 475 km long and flows from Lake Mayn (240 m asl) in the Penzha Ridge of the Koryak Upland into the Anadyr at 9 m asl. The Mayn Valley lies between the upland foothills and the Russky and Slovut mountains. The river feeds from snow and rain water. It is covered with ice from mid-October to the latest May. The largest tributaries of the Mayn are the Vaegi, Algan, and Orlovka rivers. The Ust'-Algan yedoma is situated in the middle reaches of the Mayn River, a few kilometers far from Vaegi Village (64°09′55″ N, 171°02′35″ E); the latter, in its turn, is 60 km far from Markovo Village and 311 km from Anadyr Town. The Ledovy Obryv yedoma occurs farther downstream of the Ust'-Algan yedoma (Fig. 1). The two complexes fall within the subzone boundary of the southern Subarctic shrub tundra and forest tundra (thin boreal larch forests). Warm and quite long summers are favorable for the growth of deciduous forests. The vegetation includes widespread dwarf pine, with some 4–5 m high trees, willow, alder, and dwarf birch (*Betula middendorffii*) thickets and xerophytes on hill slopes. Near Markovo Village, there are abundant alder and willow thickets, as well as poplar, larch, and birch trees [*Andreev, 2004*]. This is an exceptional climate for the Chukchi Peninsula, where vegetables can grow in open ground.

Mean annual air temperatures in Markovo Village were –8.5 °C from 1961 to 1990 and –7.9 °C from 1979 to 2007, with long-term means of –24 °C for January in 1961–1990 and –26.5 °C in 1979–2007 (winter mean –19 °C) and +13.9 °C for July in 1961–1990 and +14.7 °C in 1979–2007 [*Climate Handbook, 1990; Transactions of All-Russian Research Institute, 2017*].

***Vicinity of Anadyr Town.*** Sedge-cotton grass and sedge-shrub tundra with dwarf birch, low alder and *Salix krylovii* shrubs, blueberry, bilberry, crowberry, and ledum are of broad occurrence in the vicinities of Anadyr Town (64°44′ N, 177°31′ E). Mean annual air temperatures were –7.5 °C in 1961–1990 and –6.9 °C in 1979–2007; the long-term means were –19.5 °C for January in 1961–1990 (winter mean –15 °C) and –21.9 °C in 1979–2007, and +10.6 °C for July in 1961–1990 and +11.6 °C in 1979–2007 [*Climate Handbook, 1990; Transactions of All-Russian Research Institute, 2017*].

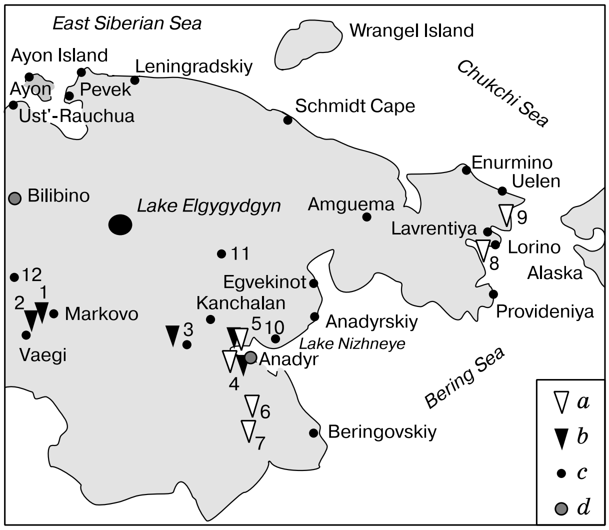


**Fig. 1. Study area of Late Pleistocene and Holocene ice wedges in the southern and eastern Chukchi Peninsula.**

Arabic numerals in the map mark sampling sites: Ledovy Obryv yedoma, Mayn River Valley (1), Ust'-Algan yedoma, Mayn River Valley (2), Tanyurer River Valley (3), vicinity of Anadyr Town (4), Rogozhny Cape (5), Velikaya River Valley (6), Koiverelan River Valley (7), vicinity of Lorino Village (8), Lake Koolen' (9), Lake Nizhneye (10), Kanchalan River Valley (11), Uivyrveem River Valley (12); *a*: Holocene ice wedges; *b*: Late Pleistocene ice wedges; *c*: villages; *d*: towns.

## YEDOMA SECTIONS, STABLE ISOTOPES AND MAJOR ION CHEMISTRY OF ICE

***Yedoma deposits in the Mayn River Valley.*** The Mayn Valley in the southern Chukchi Peninsula belongs to the easternmost Russian permafrost zone where the Late Pleistocene yedoma deposits have been most comprehensively documented at the Ust'-Algan and Ledovy Obryv sites. They are located close to one another and are composed of sediments that vary strongly in lithology and facies: from fluvial coarse sands with pebbles to mudrock deposits of abandoned rivers cut by thick ice wedges of various shapes. The sediments have been dated by the accelerator mass spectrometry radiocarbon ($^{14}C$) method [*Kotov and Ryabchun, 1986*], which places exact time constraints on the yedoma history.

The *Ledovy Obryv* section is located on the left side of the Mayn River 13 km downstream of the Algan inlet. The height of the outcrop was 25 m at the

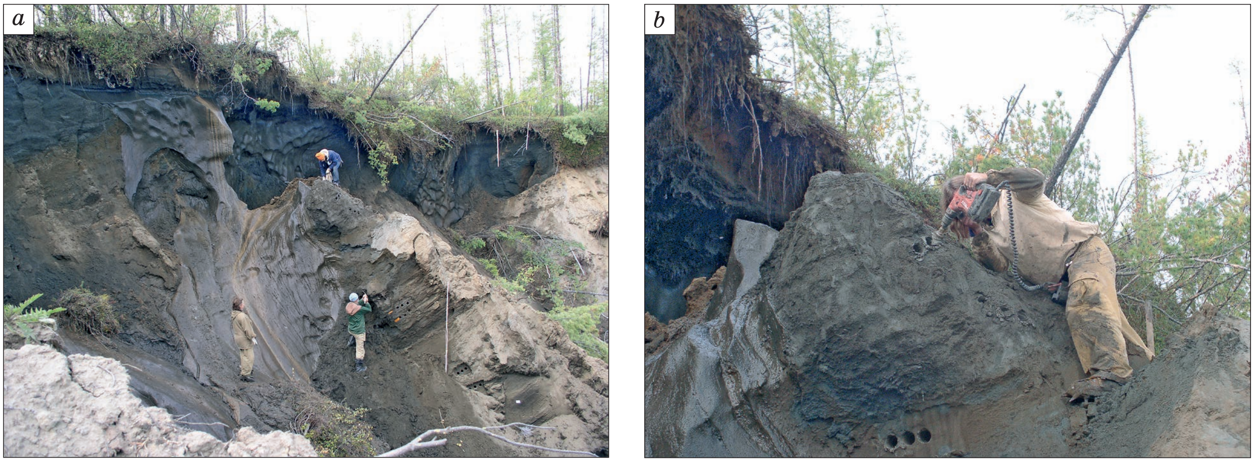


**Fig. 2. Late Pleistocene syngenetic ice wedges in Ledovy Obryv outcrop, Mayn River Valley.**

*a*: general view (photograph by J. Halle); *b*: sampling for biochemical analysis (by E. Willerslev).

time of our work and during later observations by *Willerslev et al.* [*2014*] (Fig. 2), though higher outcrops were reported earlier form the area [*Kaplin, 1980*]. The yedoma thickness changed insignificantly; at the base of the exposure, there are pebbly sediments overlain by lacustrine sands that enclose mollusk shells. The yedoma deposits mainly consist of gray fine silty sand. At the time of observations, the whole section from bottom to top was cut by thick syngenetic ice wedges, which never exceeded 3.5–4 m in width within the outcrop. The yedoma showed a cyclic structure. At sites of alas deposits, a rare phenomenon was observed: syngenetic Holocene ice wedges accreted to (or lying over) intact yedoma fragments with enclosed buried frozen ice wedges.

The cyclic structure of the yedoma section, as described by *Svitoch* [*Kaplin, 1980*], is as follows. There are six cycles consisting of elementary layers in the lithologically diverse lacustrine deposits exposed in the Ledovy Obryv.

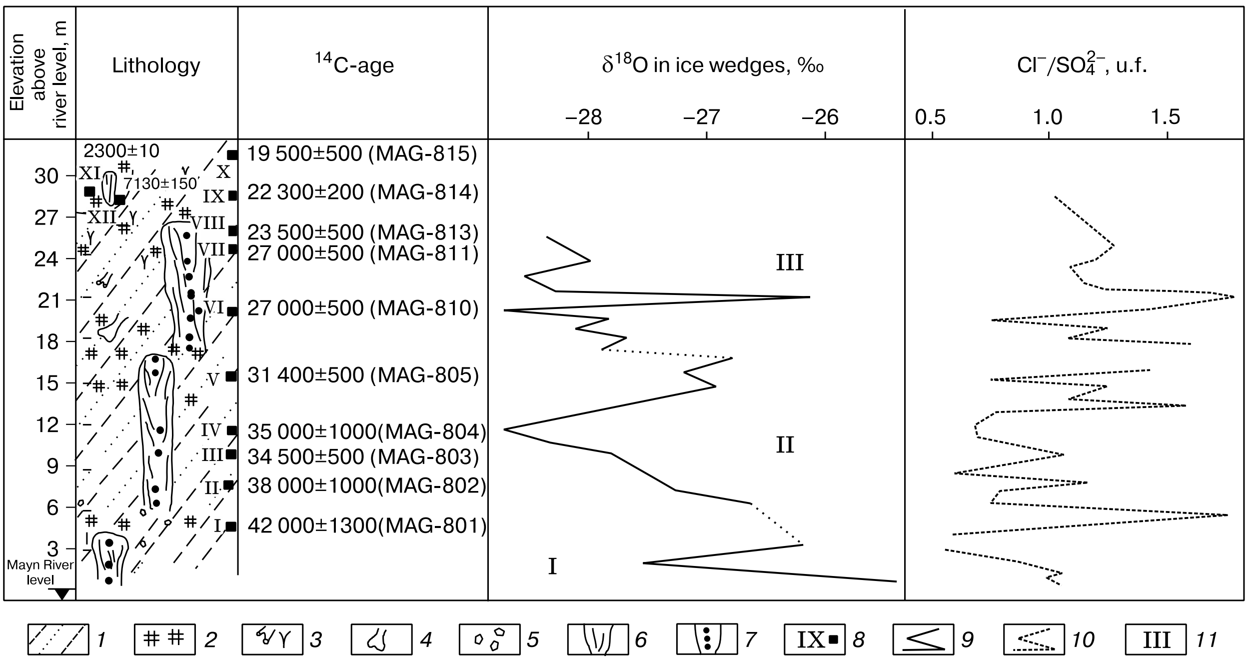


**Fig. 3. $\delta^{18}O$ values and major ion curves of three cycles of ice wedges in the Ledovy Obryv yedoma.**

*1* – sandy silt; *2* – peat; *3* – rootlets and allochthonous plant detritus; *4* – bones; *5* – pebbles and gravel; *6* – ice wedges; *7* – sample sites for oxygen isotope composition of ice; *8* – sample sites for radiocarbon dating of host sediments; *9* – $\delta^{18}O$ curve; *10* – $Cl^-/SO_4^{2-}$ curve; *11* – cycles of ice wedges.

Cycle 1 (lowermost), 2.4 m of visible thickness: relatively fine silt or silty sand, with peat and plant remnants near the top.

Cycle 2: sand and gravel at the base and peat lenses at the top.

Cycle 3: 8.5 to 15 m of laminated sands with interlayers of peated silt.

Cycle 4: 4.5 m of thinly interbedded gray-bluish sandy silt and peated silt which were apparently deposited at quite shallow depths in a repeatedly drying stagnant lake.

Cycle 5: 13.5 m of laminated ferruginous sand and gray silty sand, with a layer of coarse sand at the base. The sediments contain plant remnants and layers of peat and peated silt and thus apparently were deposited in a repeatedly drying flood lake.

Cycle 6: 6.3 m thick, lies over a slightly eroded surface of cycle 5 [*Kaplin, 1980*].

Kotov [*Kotov and Ryabchun, 1986*] likewise noted that the yedoma section has channel and overbank alluvium at the base, overlain by 2–5 m of lacustrine deposits, with ice casts and a 20–50 cm thick marker peat layer.

Radiocarbon dating [*Kotov, 1988; Lozhkin et al., 2000*] applied to samples of rootlets and peat remnants washed and dried in the field brackets the Ledovy Obryv yedoma history between 42 and 19 Kyr BP (Fig. 3).

Later high-resolution AMS $^{14}C$ dating of the Ledovy Obryv deposits [*Willerslev et al., 2014*] fully confirmed the estimates of *Kotov* [*1988*] and *Lozhkin et al.* [*2000*] and constrained the age of the yedoma sampled in the 1980s and in the 2010s to within the 40 to 20 Kyr BP interval.

Oxygen isotope compositions of large syngenetic ice wedges vary from –28.6 to –26.2 ‰ $\delta^{18}O$ (Table 1, Fig. 3), while they are –20.4 to –20.0 ‰ $\delta^{18}O$ in present and Late Holocene small ice wedges. Ice becomes isotopically lighter up the section, with three levels in the $\delta^{18}O$ curve. $\delta^{18}O$ values in pore ice from the ice wedge hosts are from –23.9 to –19.6 ‰, which is slightly more negative than in pore ice from Holocene alas deposits ($\delta^{18}O$ values to –16.2 ‰).

The $\delta^{18}O$ values for the Late Pleistocene ice wedges converted to paleotemperatures using the equation of *Yu. Vasil'chuk* [*1991*] indicate that mean

Table 1. **$\delta^{18}O$ variations in ice wedge (IW) and pore (PI) ice from Ledovy Obryv and Ust'-Algan outcrops in Mayn River Valley**

| Sample ID | Sampling site elevation above Mayn River, m | $\delta^{18}O$, ‰ | Ice type | Sample ID | Elevation above sea level, m | $\delta^{18}O$, ‰ | Ice type |
|---|---|---|---|---|---|---|---|
| *Syngenetic Late Pleistocene ice wedges in Ledovy Obryv yedoma* | | | | | | | |
| 350-YuV/1 | +15.0 | –26.8 | IW | 350-YuV/34 | +24.8 | –28.4 | IW |
| 350-YuV/3 | +15.7 | –27.3 | IW | 350-YuV/43 | +6.0 | –26.8 | IW |
| 350-YuV/6 | +17.0 | –26.7 | IW | 350-YuV/46 | +7.4 | –27.2 | IW |
| 350-YuV/12 | +18.8 | –27.7 | IW | 350-YuV/52 | +8.5 | –27.3 | IW |
| 350-YuV/13 | +17.8 | –27.8 | IW | 350-YuV/55 | +9.8 | –27.9 | IW |
| 350-YuV/16 | +19.5 | –28.2 | IW | 350-YuV/59 | +11.0 | –28.4 | IW |
| 350-YuV/21 | +20.3 | –27.9 | IW | 350-YuV/61 | +12.0 | –28.6 | IW |
| 350-YuV/24 | +20.9 | –28.8 | IW | 350-YuV/67 | +2.0 | –27.4 | IW |
| 350-YuV/27 | +22.1 | –28.4 | IW | 350-YuV/72 | +4.0 | –26.2 | IW |
| 350-YuV/31 | +23.0 | –28.5 | IW | 350-YuV/78 | +21.4 | –26.2 | IW |
| 350-YuV/32 | +23.5 | –28.0 | IW | 350-YuV/90 | +1.5 | –25.6 | IW |
| *Syngenetic Late Pleistocene ice wedges in lacustrine sands that facially replace Ledovy Obryv yedoma* | | | | | | | |
| 350-YuV/92 | +8.5 | –28.0 | IW | 350-YuV/99 | +5.0 | –23.8 | IW |
| 350-YuV/94 | +9.8 | –26.7 | IW | | | | |
| *Syngenetic Late Pleistocene pore ice in yedoma* | | | | | | | |
| 350-YuV/17 | +19.8 | –22.5 | PI | 350-YuV/49 | +7.6 | –23.9 | PI |
| 350-YuV/18 | +20.2 | –22.6 | PI | 350-YuV/50 | +6.5 | –23.9 | PI |
| 350-YuV/19 | +19.9 | –19.6 | PI | | | | |
| *Syngenetic Holocene wedge and pore ice in alas deposits* | | | | | | | |
| 350-YuV/39 | +23.5 | –20.4 | IW | 350-YuV/98 | +26.0 | –16.2 | PI |
| 350-YuV/41 | +24.8 | –20.0 | IW | | | | |
| *Syngenetic Late Pleistocene ice wedges in Ust'-Algan yedoma* | | | | | | | |
| 351-YuV/1 | +4.0 | –23.4 | IW | 351-YuV/6 | +8.0 | –27.8 | IW |
| 351-YuV/3 | +4.8 | –24.1 | IW | 351-YuV/7 | +9.5 | –27.1 | IW |
| 351-YuV/4 | +5.7 | –24.9 | IW | | | | |

winter temperatures were −26 to −28 °C and the January means were from −39 to −42 °C in the first half of the deposition interval (42–30 Kyr BP), while the respective present temperatures are −19 and −27 °C. The second half of the interval, between 30 and 19 Kyr BP, was the coldest, with winter and January means −28 to −30 °C and −42 to −45 °C, respectively.

Notable differentiation of $\delta^{18}O$ values in the yedoma pore ice may suggest cyclic freezing of >5 m sedimentary layers, which led to cryogenic fractionation during the formation of segregation ice.

We also studied three cycles of ice wedges, 3–4 m high each, in lacustrine sediments that facially replace the Ledovy Obryv yedoma deposits (Fig. 4). Ice wedges in each cycle occur in fine sand under a layer of peat and silt. Ice wedges from different cycles have $\delta^{18}O$ values from −23.8 ‰, −28.0 ‰, and −26.7 ‰ at 5 m, 8.5 m, and 9–10 m above the river level, respectively (Fig. 4). The lower wedge apparently feeds from river or lake water with $\delta^{18}O$ heavier than in snow. Possible involvement of river or lake water is further supported by the presence of fine gravel in the lower ice wedge that contacts lake sand. This ice, at 1.5 m above the river level, has −25.6 ‰ $\delta^{18}O$, or slightly less negative than in other ice wedge fragments from the main yedoma (Fig. 4).

Yellow lacustrine sands form several horizontal dikes cutting through the older yedoma wedges, i.e., the sands were deposited later: the lower dike formed between 39 and 34 Kyr BP. The youngest dates correspond to the end of lacustrine sand deposition at 15–14 Kyr BP. The latter date is worth special note, as it bases upon the ages obtained by A. Kotov for small branches sampled in sand at 30–35 m above the river table, at ~5–7 m below the top (14 000 ± 200 yr, sample MAG-1026), and a mammoth tusk from the same level (15 100 ± 70 yr, sample GIN-5370). Note that the dating is reliable because it was applied to different samples, and the tusk looked fresh, being a kind of material that commonly gives robust $^{14}C$ ages.

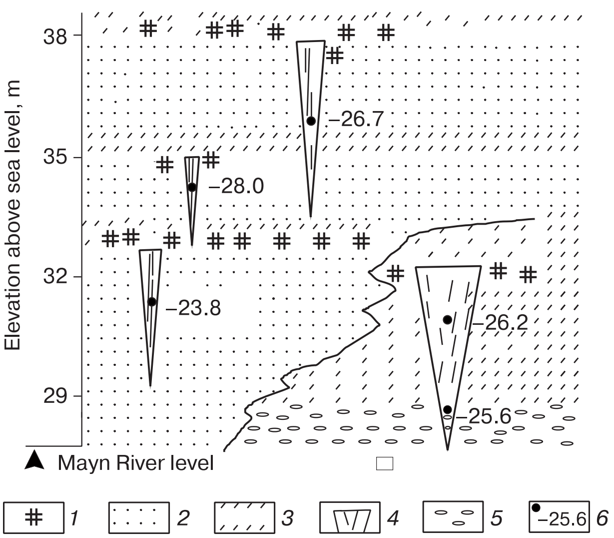


**Fig. 4. Hypsometric levels of ice wedge cycles in the lower part of lacustrine sands in Ledovy Obryv that facially replace yedoma deposits (near the contact with a classical yedoma remnant, shown in the right bottom corner) and oxygen isotope composition of ice wedges:**

*1* – peat; *2* – sand; *3* – silt; *4* – ice in syngenetic wedges; *5* – gravel and pebbles; *6* – $\delta^{18}O$ values in ice wedges, ‰.

Pollen analysis of the Ledovy Obryv samples (by T. Boyarskaya [*Kaplin, 1980*]) indicates that the lower and middle parts of the section were deposited mainly in meadow landscapes: Artemisia and Chenopodiaceae are the main components of the pollen spectra. The grasses are highly diverse, with predominant Caryophyllaceae pollen and Selaginella spores. The upper section contains abundant pollen of tree and shrub species, with minor amounts of *Picea* pollen besides local elements of *Pinus pumilla*, *Betula nana*, *Larix*, and *Pinus sibirica*. The spore-pollen diagram of Boyarskaya shows inverse correlation with the $\delta^{18}O$ curve for the Ledovy Obryv section. This is most likely evidence of opposite winter and summer trends: periods of warmer winter temperatures and cooler summers and, vice versa, warmer summers and colder winters.

Major ion concentations (six components) analyzed in ice samples from the Ledovy Obryv on the Mayn River (Table 2) correspond to mainly fresh and ultrafresh composition (classification of *Yu. Vasil'chuk* [*1992*]). Five ice samples show relatively weak proteolytic activity, from 4 to 60 enzyme units (U) per 1 L, which suggests mostly meteoric origin of water that formed ice wedges [*Vasil'chuk and Vasil'chuk, 1998; Korneeva et al., 2002*].

Lacustrine sediments in the upper Ledovy Obryv section enclose a Holocene sand wedge with a dark brown peat ice cast (Fig. 5) intruded by a Holocene wedge of sugar-white ice. The Holocene wedge has an oxygen isotope composition (−20.0 to −20.4 ‰ $\delta^{18}O$) close to the present one (Fig. 5). It formed about 7 Kyr BP, i.e., during the Holocene optimum, judging by dating of birch from an almost coeval ice cast (7130 ± 150 yr BP). The $\delta^{18}O$ values converted to temperatures indicate mean temperatures of −20 to −21 °C for winter and about −30 °C for January.

The Ledovy Obryv yedoma includes two distinct ash layers, more than 10 cm thick, one above another, found by Vasil'chuk and co-authors (and reported also earlier by Kotov and Glushakova [*Lozhkin et al., 2000*]). Ash may be of fire origin, judging by its association with the organic-rich layer (Table 1), or it may be volcanic ash brought from some remote areas. The upper and lower ash layers, at the depths 21.6 and 25 m, formed about 34.5 and 39 Kyr BP, respectively, as constrained by $^{14}C$ ages of soil below and

Table 2. **Major ions and dissolved salts in syngenetic ice wedges in the 25–30 m thick Late Pleistocene Ledovy Obryv yedoma and the 60-m thick Ust'-Algan Obryv yedoma**

| Sample ID | Sampling site elevation above Mayn River, m | TDS*, mg/L | Major ions, mg/L | | | | | | pH | $Cl^-/SO_4^{2-}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $HCO_3^-$ | $Cl^-$ | $SO_4^{2-}$ | $Ca^{2+}$ | $Mg^{2+}$ | $Na^++K^+$ | | |
| *Holocene ice wedges in upper section of northern yedoma remnant* | | | | | | | | | | |
| 350-YuV/40 | +24.0 | 36 | 18 | 6 | 7 | 3 | 2 | 6 | 6.27 | 0.85 |
| 350-YuV/39 | +23.5 | 40 | 12 | 8 | 10 | 4 | 5 | 1 | 6.46 | 0.8 |
| *Late Pleistocene ice wedges in section of northern yedoma remnant* | | | | | | | | | | |
| 350-YuV/37 | +26.0 | 52 | 31 | 9 | 8 | 6 | 5 | 6 | 6.73 | 1.12 |
| 350-YuV/30 | +22.5 | 46 | 18 | 11 | 8 | 6 | 4 | 4 | 6.77 | 1.38 |
| 350-YuV/24 | +20.9 | 32 | 21 | 6 | 5 | 4 | 3 | 3 | 6.20 | 1.2 |
| 350-YuV/16 | +19.5 | 42 | 18 | 8 | 6 | 4 | 5 | 1 | 6.44 | 1.33 |
| 350-YuV/15 | +19.1 | 44 | 24 | 8 | 4 | 6 | 4 | 3 | 6.57 | 2.0 |
| 350-YuV/13 | +17.8 | 40 | 24 | 8 | 5 | 6 | 4 | 3 | 7.06 | 1.6 |
| 350-YuV/11 | +17.0 | 42 | 18 | 7 | 8 | 6 | 2 | 4 | 6.77 | 0.85 |
| 350-YuV/5 | +16.5 | 38 | 21 | 7 | 5 | 3 | 3 | 6 | 6.26 | 1.4 |
| 350-YuV/8 | +15.6 | 36 | 15 | 8 | 7 | 4 | 1 | 7 | 5.85 | 1.14 |
| 350-YuV/7 | +15.5 | 36 | 24 | 7 | 4 | 4 | 2 | 7 | 6.25 | 1.75 |
| 350-YuV/2 | +15.4 | 32 | 18 | 7 | 5 | 4 | 2 | 4 | 6.07 | 1.4 |
| 350-YuV/1 | +15.0 | 34 | 15 | 6 | 7 | 4 | 1 | 6 | 6.00 | 0.85 |
| 350-YuV/63 | +12.9 | 38 | 18 | 7 | 9 | 4 | 2 | 6 | 6.20 | 0.77 |
| 350-YuV/61 | +12.0 | 36 | 21 | 6 | 5 | 5 | 3 | 3 | 6.28 | 1.2 |
| 350-YuV/58 | +10.4 | 42 | 21 | 6 | 9 | 3 | 2 | 9 | 6.47 | 0.66 |
| 350-YuV/55 | +9.8 | 40 | 12 | 9 | 7 | 8 | 1 | 3 | 6.30 | 1.3 |
| 350-YuV/54 | +9.2 | 36 | 18 | 6 | 7 | 3 | 2 | 7 | 6.37 | 0.85 |
| 350-YuV/52 | +8.5 | 38 | 21 | 6 | 7 | 5 | 2 | 5 | 6.10 | 0.85 |
| 350-YuV/51 | +8.2 | 36 | 18 | 6 | 7 | 5 | 2 | 5 | 6.60 | 0.85 |
| 350-YuV/48 | +7.5 | 50 | 18 | 14 | 7 | 8 | 2 | 5 | 6.53 | 2.0 |
| 350-YuV/45 | +6.8 | 38 | 18 | 7 | 7 | 6 | 2 | 3 | 6.46 | 1.0 |
| 350-YuV/64 | +6.5 | 34 | 15 | 6 | 9 | 4 | 3 | 4 | 5.95 | 0.67 |
| *Late Pleistocene ice wedges in lower part of southern yedoma remnant* | | | | | | | | | | |
| 350-YuV/74 | +5.5 | 32 | 15 | 5 | 10 | 4 | 2 | 5 | 6.40 | 0.5 |
| 350-YuV/72 | +4.0 | 36 | 21 | 6 | 7 | 5 | 3 | 4 | 6.31 | 0.85 |
| 350-YuV/67 | +2.0 | 42 | 24 | 7 | 7 | 6 | 2 | 6 | 6.65 | 1.0 |
| 350-YuV/90 | +1.5 | 110 | 92 | 11 | 12 | 12 | 7 | 20 | 6.69 | 0.9 |
| 350-YuV/65 | +1.2 | 40 | 18 | 7 | 7 | 8 | 1 | 3 | 6.12 | 1.0 |
| 350-YuV/76 | +22.0 | 44 | 24 | 8 | 7 | 5 | 3 | 7 | 6.20 | 1.14 |
| 350-YuV/78 | +21.4 | 56 | 31 | 11 | 9 | 12 | 2 | 4 | 7.15 | 1.22 |
| 350-YuV/79 | +21.0 | 60 | 37 | 11 | 10 | 8 | 6 | 5 | 7.02 | 1.1 |
| 350-YuV/86 | +20.7 | 46 | 24 | 8 | 8 | 6 | 4 | 5 | 6.69 | 1.0 |
| 350-YuV/82 | +20.0 | 68 | 49 | 7 | 8 | 12 | 4 | 6 | 6.58 | 0.88 |
| *Late Pleistocene ice wedges in lacustrine deposits* | | | | | | | | | | |
| 350-YuV/92 | +8.5 | 52 | 31 | 14 | 7 | 8 | 7 | 1 | 7.08 | 2.0 |
| 350-YuV/99 | +5.0 | 50 | 31 | 8 | 9 | 6 | 5 | 5 | 6.68 | 0.88 |
| *Late Pleistocene ice wedges in lower part of Ust'-Algan yedoma* | | | | | | | | | | |
| 351-YuV/7 | +9.5 | 58 | 37 | 7 | 11 | 8 | 5 | 5 | 6.40 | 0.64 |
| 351-YuV/6 | +8.0 | 60 | 46 | 4 | 9 | 11 | 4 | 4 | 6.45 | 0.44 |
| 351-YuV/3 | +4.8 | 36 | 21 | 7 | 6 | 4 | 2 | 7 | 6.20 | 1.16 |
| 351-YuV/1 | +4.0 | 46 | 31 | 5 | 8 | 6 | 3 | 6 | 6.10 | 0.63 |

* TDS = Total dissolved solids.

peat above. A similar age was obtained in the Yuzhny quarry on the Tanon River near Magadan (41 500 ± 900 yr BP, sample GIN-6081). The age interval of the Mayn and Magadan volcanic ashes matches perfectly the span of volcanic activity in the Kamchatka and Kurile areas [*Melekestsev et al., 1991*]. The Mayn volcanic ash has a composition corresponding to dacitic rhyolite with 68.45 and

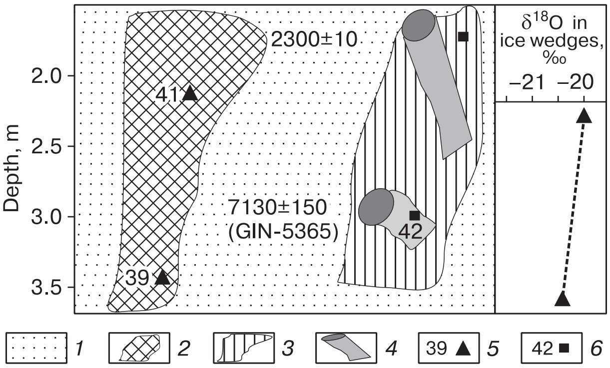


**Fig. 5. Holocene ice wedge and ice cast filled with peat and wood in the upper lacustrine sediments of the Ledovy Obryv outcrop (a field sketch):**

*1* – sand; *2* – ice wedges; *3* – peat; *4* – plant remnants; *5* – sample sites for oxygen isotope composition and sample number (Table 2); *6* – sample sites for radiocarbon dating and $^{14}$C-ages.

69.32 wt.% $SiO_2$; 3.66 and 4.11 wt.% $Na_2O$; and 2.13 and 3.48 wt.% $K_2O$, in the upper and lower ash layers, respectively. Like the Mayn ash samples, the Tanon ones have a rhyolitic major-element composition: 74.00 wt.% $SiO_2$, 4.10 wt.% $Na_2O$, and 2.07 wt.% $K_2O$.

The Mayn upper ash is compositionally similar to pyroclastics from Krasheninnikova, Uzon III, Big Semyachik, Small Semyachik, and Lake Karym volcanoes and the lower one to those ejected by Khangar and Gorely volcanoes [*Melekestsev et al., 1991*]. The marker ash layers may be evidence of intense Pacific air transport to the Mayn Valley.

The *Ust'-Algan* yedoma section is located on the left side of the Mayn River, 6 km downstream of the Algan mouth, i.e., 7 km upstream of the Ledovy Obryv yedoma. The Ust'-Algan site is about 60 m high, and the sediments are lithologically similar to the Ledovy Obryv lacustrine deposits. They are mainly yellowish-gray and gray laminated fine sand. We observed closely spaced 0.5 to 2 cm thick layers of allochthone peat at the depths 20–23 m, 49–53 m, and 55.3–55.7 m (37–40 m, 7–11 m, and 4.7–4.3 m above the river table, respectively). Two lower peat layers contain abundant shrub branches and occasionally tree trunks. The section comprises seven cycles of narrow ice wedges (Fig. 6), rarely wider than 1 m, 7–8 m high, and spaced at 3 to 4 m.

Most of material early during the deposition was apparently allochthonous, brought by rivers, which produced thick lenses and layers. This origin of sediments is also consistent with inversion of radiocarbon ages obtained for well preserved branches and wood: a younger date of 32 700 ± 1800 yr BP (sample GIN-5367) at 5 m above the river table but 42 400 ± 2100 yr BP (GIN-5366) at 7 m. Earlier *Kotov and Ryabchun* [*1986*] reported an age of 43 Kyr BP for the section

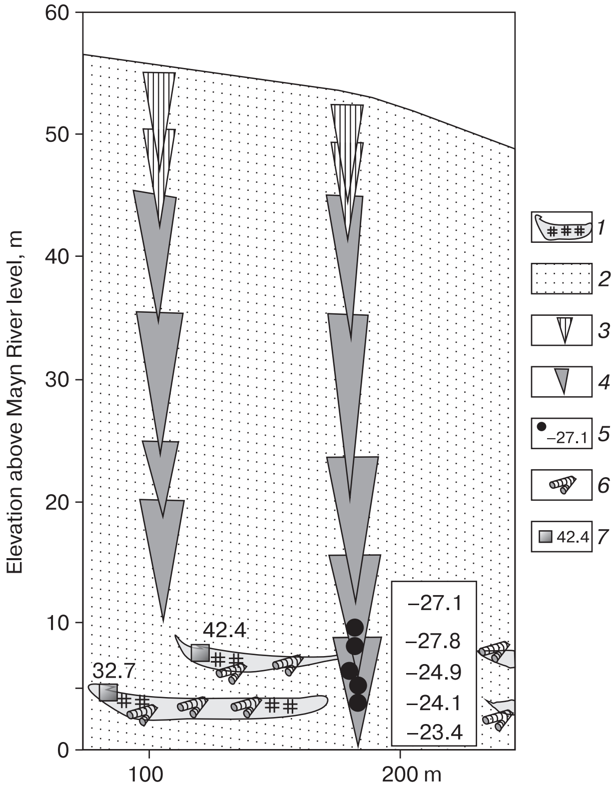


**Fig. 6. Reference permafrost section with ice wedge cycles of the Late Pleistocene ice complex in the Mayn River Valley, Ust'-Algan Bluff outcrop, and δ$^{18}$O values for wedge and pore ice:**

*1* – peat; *2* – sand; *3* – ice wedges; *4* – plant remnants; *5* – δ$^{18}$O in ice wedges, ‰; *6* – sample sites for oxygen isotope composition; *7* – sample sites for radiocarbon dating and $^{14}$C-ages.

base and >57 Kyr BP for a hypsometrically higher level. The age inversion is due to inputs of older organic material from sediments exposed to erosion upstream. The younger age may correspond to the base of the section; then, the deposition must have been very fast judging by the large thickness of sediments.

This inference is consistent with oxygen-isotope data for ice wedges which also forms several cycles, like that in the Ledovy Obryv lacustrine sediments. The δ$^{18}$O values are from –24.9 to –23.4 ‰ in the lowest cycle, at 4–6 m above the river level, and from –27.8 to –27.1 ‰ in the second lower layer at 8–10 m above the river (Fig. 6). The difference may indicate that ice in the higher cycle fed mainly from melt snow water while that in the lowest cycle received water from rivers or lakes (abandoned rivers), though the more positive δ$^{18}$O values may be due to warmer winters at 32–30 Kyr BP.

The quite negative oxygen-isotope composition of ice in the reference Mayn River yedoma allows us to assign the whole 38 to 12 Kyr BP interval to the Late Pleistocene cryochron.

***Yedoma deposits near Anadyr Town stripped in a quarry on a hillslope*** (64°44′10″ N, 177°31′10″ E), about 30 m asl, contain wedge and massive ice in Late Pleistocene slope wash sands. Ice wedges, more than 7 m high, cut through massive ice (most likely of segregation origin), up to 2 m thick. The ice is columnar while massive ice shows no layering. $\delta^{18}O$ variations in ice wedges are about 5 ‰, with a range from −23.4 to −18.6 ‰ (Table 3). The $\delta^{18}O$ values in massive ice are about −19.6 or −19.7 ‰ while pore ice from the host sand varies from −22.7 to −18.6 ‰. Ice in Holocene epigenetic ice wedges in the upper section part has $\delta^{18}O$ values from −17.3 to −16.4 ‰. Ice wedges in the Holocene first terrace 3–5 km farther to the north, on the Onemen Gulf coast, show similar heavier values of −16.7 and −15.8 ‰ $\delta^{18}O$. Large (more than 3 m high) wedges of syngenetic Holocene ice in the first terrace show a range of −17.3 to −16.4 ‰ while pore ice has $\delta^{18}O$ values from −16.7 to −14.9 ‰ in sand, −15.0 ‰ in silt, and −13.5 ‰ in peat on the surface (Table 3).

In this case, the $\delta^{18}O$ values difference between Late Pleistocene and present ice wedges is quite notable: the former are 4–7 ‰ lighter. These data provide evidence of more severe permafrost conditions in the Chukchi Peninsula in the latest Pleistocene, mainly because of colder winters.

Ice shows high proteolytic activity: 330 U/L in Late Pleistocene wedges from slope wash and 224 U/L in Holocene layda deposits (six and eight samples, respectively). This suggests the presence of marine aerosol moisture in air during the formation of the Late Pleistocene and Holocene ice wedges [*Vasil'chuk and Vasil'chuk, 1998; Korneeva et al., 2002*].

We also studied $\delta^{18}O$ and $\delta D$ ($^{2}H$) distribution in snowpacks near Anadyr Town (Table 4) which showed notable variations in $d_{exc}$ on the background of relatively stable $\delta^{18}O$ patterns. This may indicate the effect of Pacific air moisture during deposition and, on the other hand, may be partly due to mixing of snow layers in the snowpack with rain and melt water percolating from above. Some difference between snow sampled at 60 m asl and that from 20 m asl may result from the altitude effect, but the main reason is that the sampled snow came from different air masses. Furthermore, the snow from the higher altitude experienced a much lower effect of isotopically heavier summer rainfall and fog (samples were collected in earliest July, in the beginning of snow melting season).

Table 3. **$\delta^{18}O$ in ice wedge (IW) and pore (PI) ice from vicinity of Anadyr Town**

| Sample ID | Depth, m | $\delta^{18}O$, ‰ | Ice type | Sample ID | Depth, m | $\delta^{18}O$, ‰ | Ice type |
|---|---|---|---|---|---|---|---|
| *Syngenetic Holocene ice wedges in terrace I of Onemen Gulf, vicinity of Anadyr Town* | | | | | | | |
| 347-YuV/1 | 2.7 | −17.0 | IW | 347-YuV/9 | 0.7 | −16.9 | IW |
| 347-YuV/5 | 1.3 | −17.3 | IW | 347-YuV/10 | 0.6 | −16.6 | IW |
| 347-YuV/6 | 1.2 | −16.6 | IW | 347-YuV/11 | 0.6 | −16.4 | IW |
| 347-YuV/7 | 0.9 | −17.2 | IW | 339-YuV/2 | 1.2 | −17.0 | IW |
| *Present growing ice wedges in terrace I of Onemen Gulf, vicinity of Anadyr Town* | | | | | | | |
| 339-YuV/5 | 0.5 | −16.7 | IW | 339-YuV/6 | 0.4 | −15.8 | IW |
| *Pore ice from Holocene sediments that host ice wedges in terrace I of Onemen Gulf, vicinity of Anadyr Town* | | | | | | | |
| Silt | | | | | | | |
| 339-YuV/4 | 1.0 | −15.0 | PI | – | – | – | – |
| Peat | | | | | | | |
| 339-YuV/3 | 1.2 | −13.5 | PI | 339-YuV/25 | 1.0 | −13.2 | PI |
| Sand | | | | | | | |
| 339-YuV/27 | 2.0 | −14.9 | PI | 339-YuV/30 | 2.9 | −16.7 | PI |
| 339-YuV/29 | 2.6 | −16.1 | PI | 339-YuV/39 | 4.0 | −16.4 | PI |
| *Syngenetic Late Pleistocene ice wedges in a quarry on hillslope, coast of Onemen Gulf, near Anadyr Town* | | | | | | | |
| 338-YuV/4 | 3.0 | −22.8 | IW | 338-YuV/10 | 3.2 | −19.5 | IW |
| 338-YuV/5 | 3.4 | −19.8 | IW | 338-YuV/11 | 4.7 | −20.7 | IW |
| 338-YuV/6 | 3.8 | −22.4 | IW | 338-YuV/12 | 5.0 | −20.7 | IW |
| 338-YuV/7 | 4.0 | −18.6 | IW | 338-YuV/13 | 5.3 | −21.7 | IW |
| 338-YuV/8 | 4.3 | −19.9 | IW | 338-YuV/20 | 4.0 | −23.4 | IW |
| 338-YuV/9 | 4.5 | −19.5 | IW | | | | |
| *Syngenetic Late Pleistocene massive ice (MI) in a quarry on hillslope, coast of Onemen Gulf, near Anadyr Town* | | | | | | | |
| 338-YuV/17 | 7.0 | −19.7 | MI | 338-YuV/18 | 8.0 | −19.6 | MI |
| *Pore ice (PI) from Late Pleistocene sediments that host ice wedges and massive ice in a quarry on hillslope, coat of Onemen Gulf, vicinity of Anadyr Town* | | | | | | | |
| 338-YuV/14 | 5.5 | −22.7 | PI | 338-YuV/19 | 6.7 | −18.6 | PI |

Table 4. **$\delta^{18}O$, $\delta^{2}H$, deuterium excess ($d_{exc}$), and protease activity (PA) in snowpacks at different elevations of Mikhail hill, vicinity of Anadyr Town, Chukchi Peninsula**

| Sample ID | Depth, m | $\delta^2H$, ‰ | $\delta^{18}O$, ‰ | $d_{exc}$ | PA, U/L |
|---|---|---|---|---|---|
| *Snow, Mikhail hill, 20 m asl* | | | | | |
| V-K-S-98/1 | 0.05–0.15 | –133.7 | –16.91 | 1.56 | 826 |
| V-K-S-98/2 | 0.25–0.35 | –130.4 | –16.49 | 1.50 | – |
| V-K-S-98/3 | 0.55–0.65 | –131.3 | –17.27 | 6.90 | – |
| V-K-S-98/4 | 0.85–0.95 | –130.2 | –17.25 | 7.85 | – |
| V-K-S-98/5 | 1.15–1.25 | –131.7 | –17.32 | 6.88 | 28 |
| V-K-S-98/6 | 1.45–1.55 | –129.3 | –16.08 | –0.66 | – |
| V-K-S-98/7 | 1.65–1.75 | –136.4 | –17.67 | 4.92 | – |
| V-K-S-98/8 | 1.85–1.95 | –142.2 | –18.17 | 3.12 | 124 |
| *Snow, Mikhail hill, 60 m asl* | | | | | |
| V-K-S-98/9 | 0.05–0.15 | –195.6 | –24.56 | 0.88 | 18 |
| V-K-S-98/12 | 0.85–0.95 | –167.3 | –21.23 | 2.58 | 892 |
| V-K-S-98/14 | 1.4–1.5 | –148.5 | –19.11 | 4.41 | 54 |

N o t e. Isotope determinations by M.A. Geyh, Hannover Isotope Laboratory, Geological Survey of Lower Saxony.

***Rogoznhy Cape, 25 km from Anadyr Town*** (64°47′ N, 176°58′ E). Syngenetic ice wedges were reported from an outcrop in terrace II of the Anadyr River, on the northern side of the Onemen Gulf [*Vtyurin, 1964*]. They occur in sand and originate from different depth levels. The top of some wedges reaches the active layer base, i.e., they either keep growing or have stopped growing quite recently. The syngenetic growth of some wedges stopped at the depth 10 m below the surface. The wedges are from 3 to 20 cm on top, and their width varies markedly with depth: e.g., one wedge extending to a depth of 12 m is 20 cm on the top, only 3 cm wide at the 3 m depth, but 15 cm at depths of 6–8 m. The wedge broadens at the account of more numerous elementary components and narrows down as some layers pinch out. Therefore, this is a typical syngenetic ice wedge [*Vtyurin, 1964*].

Ice wedges in the Anadyr Town vicinity are widespread also in slope wash deposits affected by solifluction [*Vtyurin, 1964*], with wedges most often 0.5–0.7 m wide on top and 2–3 m high. Larger wedges (up to 2 m wide) were observed on the bedrock hillslope buried under unsorted frozen clay silt with debris. Coarse material in clay silt in the lower slope part is of a lesser amount and more rounded. Ice wedges in this section part are more frequent and often exceed 1 m in width on the top, reaching occasionally 3 m. One quarry stripped four >1 m wide ice wedges within a 20 m long interval. Unlike the wedges from the upper slope, ice is distinctly columnar and encloses gravel, pebble, and debris particles [*Vtyurin, 1964*].

Geocryological studies on the northern coast of the Onemen Gulf were performed by *Kotov* [*1991*] yearly from 1989 through 2005 and revealed a three-stage system of Late Pleistocene ice wedges, 25 km far from Anadyr Town. An outcrop located 2 km north of the Rogozhny Cape includes three permafrost layers of different ages with three independent cycles of ice wedges. The age of the deposits was con-

Table 5. **$\delta^2H$ in ice wedge (IW), sand wedge (SIW), massive (MI) and pore (PI) ice at Rogozhny Cape, northern coast of Onemen Gulf, 25 km from Anadyr Town**

| Sample ID | Depth, m | $\delta^2H$, ‰ | Ice type | Sample ID | Depth, m | $\delta^2H$, ‰ | Ice type |
|---|---|---|---|---|---|---|---|
| *Syngenetic Holocene sand-ice wedge (SIW)* | | | | | | | |
| YuV/R-1 | 2.05 | –162.1; –161.9 | SIW | YuV/R-3 | 2.8 | –164.4; –168.7 | SIW |
| YuV/R-2 | 2.5 | –172.2; –171.4 | SIW | | | | |
| *Syngenetic Holocene ice wedges (IW)* | | | | | | | |
| YuV/R-4 | 0.8 | –166.3; –165.7 | IW | YuV/R-5 | 1.0 | –171.1; –170.4 | IW |
| *Massive ice (MI)* | | | | | | | |
| YuV/R-6 | 2.5 | –143.5; –138.7 | MI | YuV/R-8 | 9.0 | –123.4 | MI |
| YuV/R-7 | 7.5 | –149.0; –148.0 | MI | YuV/R-9 | 12.2 | –138.3 | MI |
| *Pore ice (PI)* | | | | | | | |
| YuV/R-4 | 9.5 | –90.2 | PI | – | – | – | – |

N o t e. Isotope determinations by M.A. Geyh, Hannover Isotope Laboratory, Geological Survey of Lower Saxony; sampling by A. Kotov.

strained by more than ten $^{14}C$ dates showing that two lower layers formed in the Late Pleistocene and the upper one in the Holocene.

The oxygen isotope composition of molten ice wedges from sands overlying glacial-marine deposits with massive ice (13 samples from the upper section) is –22.79 to –20.80 ‰ $\delta^{18}O$; the hydrogen isotope composition is in the range –174.4 to –161.1 ‰ $\delta^{2}H$ (the wedges may contain Holocene ice) [*Kotov, 1997*].

There are also abundant growing Holocene ice wedges in the area. Their molten ice has Cl–Na chemistry, and a salinity of 0.018–0.053 g/L. Ice in the Holocene wedges has slightly heavier isotopic values of –19.26 to –17.22 ‰ $\delta^{18}O$ and –143.7 to –128.2 ‰ $\delta^{2}H$. Similar compositions, with –20.68 to –17.90 ‰ $\delta^{18}O$ and –153.8 to –131.2 ‰ $\delta^{2}H$, are observed in molten snow samples from a snowpack on the northern gulf coast. The molten snow shows the same Cl–Na chemistry and a salinity of 0.022–0.045 g/L [*Kotov, 2001*]. We also obtained heavier stable isotope compositions of ice from Holocene wedges at the Rogozhny Cape (Table 5).

Yedoma deposits with large ice wedges (15 m high, 2–3 m wide on top) having their heads 1.5–2.5 m below the surface (20 m above the river table) and tails penetrating 5–6 m into clay silt below lie over thick ice layers exposed in a large glacial cirque on the right side of the Tanyurer River (southern Chukchi Peninsula) [*Kotov, 1998a*]. Three radiocarbon dates were obtained for plant remnants from

Table 6. **$\delta^{18}O$ in present growing syngenetic ice wedges (PSI) in southern Chukchi Peninsula, complemented after *Vasil'chuk* [*1992*]**

| Locations of present ice wedges | $\delta^{18}O_{PIW}$, ‰ | $\Sigma t_{wint}$, °C·day | $t_{wint.mean}$, °C | $t_J$, °C | $t_{pram}$, °C |
|---|---|---|---|---|---|
| Anadyr Town | –16.0 | –3570 | –15 | –21 | –7 |
| Koiverelan River | –20.0 | –4328 | –18 | –26 | –9 |
| Velikaya River | –18.0 | –3949 | –17 | –25 | –8 |
| Markovo Village | –20.0 | –4397 | –19 | –27 | –9 |

Note. $\delta^{18}O_{PIW}$ = $\delta^{18}O$ in present growing syngenetic ice wedges, ‰; $\Sigma t_{wint}$ = total annual freezing index (°C·day); $t_{wint.\ mean}$ = mean winter temperature; $t_J$ = mean January temperature; $t_{pram}$ = present annual mean ground temperatures (stripped snow and vegetation).

Table 7. **$\delta^{18}O$ in ice wedges ($\delta^{18}O_{iw}$) of yedoma deposits in Chukchi Peninsula and Late Pleistocene paleotemperatures, 38–12 Kyr BP**

| Reference section | $\delta^{18}O_{iw}$, ‰ | Reconstructed paleotemperatures, °C | | | | Present temperatures, °C | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $\Sigma t_{wint}$ | $t_{wint.\ mean}$ | $t_J$ | $t_{palamgr}$ | $\delta^{18}O_{piw}$, ‰ | $\Sigma t_{wint.\ mean}$ | $t_{wint.\ mean}$ | $t_J$ | $t_{pram}$ |
| *38–35 Kyr BP* | | | | | | | | | | |
| Ledovy Obryv | –27.0 | –6700 | –27 | –41 | –15 | –20 | –4397 | –19 | –27 | –9 |
| *30–28 Kyr BP* | | | | | | | | | | |
| Ayon Island | –31.2 | –7800 | –31 | –46 | –19 | –20 | –5047 | –20 | –29 | –12 |
| Ledovy Obryv | –27.5 | –6900 | –28 | –42 | –16 | –20 | –4397 | –19 | –27 | –9 |
| *24–22 Kyr BP* | | | | | | | | | | |
| Ayon Island | –31.6 | –7900 | –32 | –47 | –18 | –20 | –5047 | –20 | –29 | –12 |
| Ledovy Obryv | –28.5 | –7100 | –29 | –43 | –17 | –20 | –4397 | –19 | –27 | –9 |
| *20–18 Kyr BP* | | | | | | | | | | |
| Ayon Island | –29.3 | –7300 | –30 | –44 | –18 | –20 | –5047 | –20 | –29 | –12 |
| Ledovy Obryv | –28.2 | –7000 | –28 | –43 | –17 | –20 | –4397 | –19 | –27 | –9 |
| Anadyr Town | –20.7 | –5200 | –21 | –32 | –12 | –16 | –3570 | –15 | –21 | –7 |
| *16–12 Kyr BP* | | | | | | | | | | |
| Ayon Island | –29.6 | –7400 | –30 | –44 | –18 | –20 | –5047 | –20 | –29 | –12 |
| Ledovy Obryv | –27.0 | –6800 | –29 | –41 | –16 | –20 | –4397 | –19 | –27 | –9 |
| Tanyurer River [*Kotov, 1998a*] | –23.0 | –5800 | –23 | –35 | –14 | –18 | –3949 | –17 | –25 | –8 |
| Anadyr Town | –20.5 | –5100 | –21 | –31 | –12 | –16 | –3570 | –15 | –21 | –7 |

Note. $\delta^{18}O_{iw}$ = $\delta^{18}O$ in ice wedge fragment deposited at the respective time, ‰; $\Sigma t_{wint.\ mean}$ = total annual freezing index (°C·day); $t_{wint.\ mean}$ = mean winter temperature; $t_J$ = mean January temperature; $t_{palamgr}$ = annual mean ground paleotemperatures (stripped snow and vegetation); $t_{pram}$ = present annual mean ground temperatures (stripped snow and vegetation).

Mean annual ground temperatures are calculated using reconstructions of total annual thawing index from pollen spectra of the respective sections, by the technique of *A. Vasil'chuk* [*2007*].

sand with inclusions of poorly degraded peat, 6 m above the water level [*Kotov, 1998a*]: 16 860 ± 260 (GX-21531-AMS), 21 500 ± 2750 (GX-21525) and 17 000 ± 360 yr BP (MAG-1502). The ice complex is overlain by 1.0–1.5 m of silt with 5–10 cm thick peat lenses. A peat lens from the 1.5 m depth was dated at 6880 ± 130 yr BP (MAG-1505). The ranges of stable isotopes in the latest Pleistocene samples are –24.90 to –21.29 ‰ $\delta^{18}$O and –191.5 to –165.9 ‰ $\delta^{2}$H [*Kotov, 1998a*].

## RECONSTRUCTIONS OF WINTER PALEOTEMPERATURES FROM ISOTOPE DATA

Winter mean ($t_{\text{wint.mean}}$) and January ($t_J$) air temperature means for the Southern Chukchi Peninsula were inferred by comparing the oxygen isotope composition of present growing ice wedges ($\delta^{18}O_{piw}$) and winter temperatures for the period of their growth, i.e., for the past 60–100 yr (Table 6) [*Vasil'chuk, 1991, 1992*]. The resulting equations are:

$$t_J = 1.5\,\delta^{18}O_{piw}(\pm 3\ ^\circ C),\ t_{\text{wint.mean}} = \delta^{18}O_{piw}(\pm 2\ ^\circ C).$$

The equations were used to calculate winter air temperatures for the Late Pleistocene, 38–12 Kyr BP (Table 7). The obtained winter means are the coldest for the time spans 24–22 and 20–18 Kyr BP; the January temperatures fell to –43 and –44 °C in the Mayn River Valley and to –32 °C on the Anadyr coast, while the respective present values are –27 °C and –21 °C (Table 6).

## CONCLUSIONS

- Late Pleistocene cyclic complexes of ice wedges and syngenetic ice wedges have been comprehensively studied in the Ledovy Obryv and the Ust'-Algan Bluff yedoma outcrops in the Mayn River Valley.
- Oxygen isotope compositions of ice with low $\delta^{18}$O values in the yedoma reference sections of the southern Chukchi Peninsula allowed us to assign the whole time span from 38 to 12 Kyr BP to a single Late Pleistocene cryochron.
- The reported stable isotope data for ice wedges in the Mayn Valley yedoma deposits near Anadyr Town and in other areas of the Chukchi Peninsula indicate that winters in the latest Late Pleistocene cryochron were more severe than they are now.
- The lowest mean winter air temperature (8–11 °C lower than the present values) within the time span between 24 and 18 Kyr BP was obtained for both central and coastal areas of the peninsula.
- Very cold winters, with the air temperatures 2–3 °C colder than now, predominated in the central and coastal parts of the peninsula during the Holocene optimum.

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