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**GEOGRAPHY**

# The Oxygen Isotope Composition of Late Pleistocene and Holocene Ice Wedges of Kotelny Island

**Yu. K. Vasil'chuk[a,*], V. M. Makeev[b], A. A. Maslakov[a], N. A. Budantseva[a], A. C. Vasil'chuk[a], and Ju. N. Chizhova[a]**

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**Abstract**—The aim of the work was to perform paleotemperature reconstructions for the Late Pleistocene and Holocene of Kotelny Island according to oxygen isotope analysis of syngenetic ice wedges. Variations of $\delta^{18}O$ in the Late Pleistocene ice wedges formed on Kotelny Island are significant, exceeding 8‰ (from –30‰ to –22.9‰), while they are insignificant at –1.5‰ (from –23.1‰ to –21.6‰) for those in the Holocene. Reconstructions showed that the mean January temperature in the Late Pleistocene changed over 8 to 13°C. The mean annual temperature of frozen soils was about –19 or –20°C in the Late Pleistocene, and about –13 to –15°C in the Holocene, while the current temperature is about –14°C.

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The aim of our work was to perform paleotemperature reconstructions for the Late Pleistocene and Holocene of Kotelny Island according to oxygen isotope analysis of syngenetic ice wedges.

Kotelny (74°–76° N, 136°–145° E) is the largest island in the archipelago of the Novosibirsk Islands, in the group of the Anjou Islands. The largest river on the island is Balyktakh. The climate is arctic. The mean annual air temperature is –14.3°C; the mean July monthly temperature is +2.9°C, and the mean February monthly temperature is –29.7°C.

The distribution of $\delta^{18}O$ in ice was studied (Figs. 2a, 2b; Table 1) in the syncryogenic Late Pleistocene stratum in the valley of the Balyktakh River (Fig. 1) in the interval of 24.3 to 12.7 ka BP according to $^{14}C$ dating [1, 2].

In the M-3 ice wedge, which is located closer to the base of the stratum, $\delta^{18}O$ values varies from –30.0 to –27.4‰ (mean value of five measurements is –28.5‰), while in the adjacent schlieren, it ranges from –27.4 to –24.6‰ (mean value of three measurements is –25.5‰). At the same time, ice wedges that are located stratigraphically higher (closer to the top) have values of $\delta^{18}O$ varying from –26.2 to –22.9‰ in the first one (mean value of eleven measurements is –23.5‰), and from –27.1 to – 24.9‰ in the other one (mean value of four measurements is –25.9‰).

The autochthonous peat lying under the M-3 ice wedge was dated to 24 230 ± 220 yr BP (LU-1809), while that for the peat above was 8970 ± 100 yr BP (LU-1773). These data substantially supplement the characteristics of the conditions for the formation of ice wedges in the final phase of the Late Pleistocene cryochron. Let us recall that several more mammoth tusks have been dated on Kotelny Island: 15 420 ±

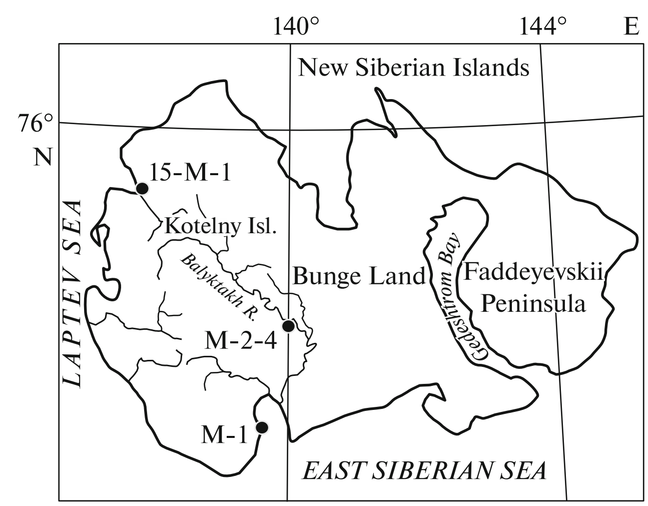


**Fig. 1.** Location of the studied outcrops of ice wedges on Kotelny Island.

[a] Moscow State University, Moscow, 119991 Russia
[b] Russian State Hydrometeorological University, Saint Petersburg, 195196 Russia
*e-mail: vasilch_geo@mail.ru

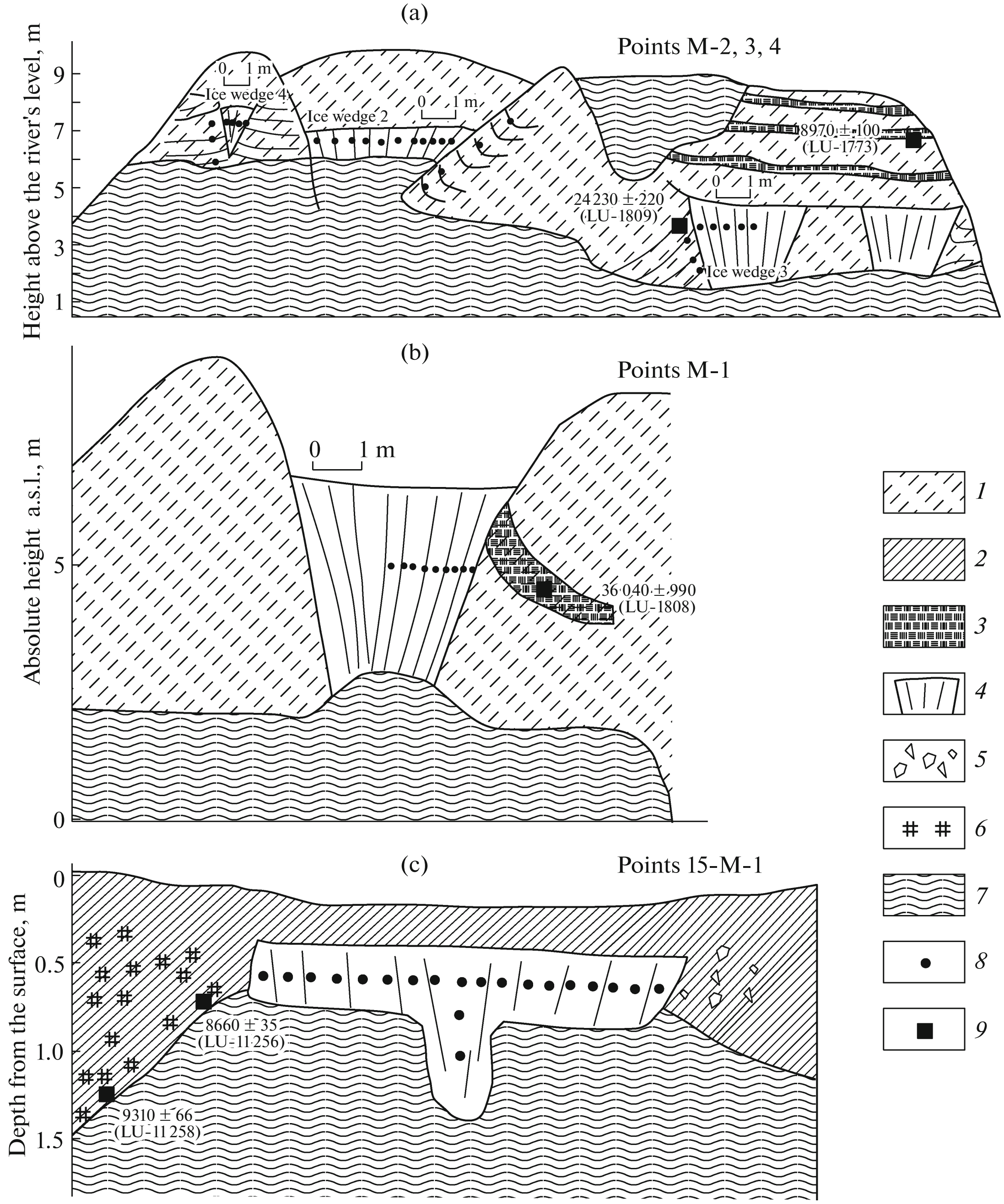


**Fig. 2.** Exposures of ice wedges on Kotelny Island: Late Pleistocene wedges (a) in the valley of the Balyktakh River and (b) on the southern coast of Kotelny Island and Holocene wedges (c) on the northwest coast of Kotelny Island. *1*, sandy loam; *2*, loam; *3*, peat lenses; *4*, ice wedge; *5*, gruss and gravel; *6*, peat stains; *7*, mudflows and screes; *8*, points of sampling the ice wedges for isotopic analysis; *9*, $^{14}$C ages of organic material.

110 yr BP (LU-1671), 19990 ± 110 yr BP (LU-1790), and 29020 ± 190 yr BP (LU-1791) [1], as well as 13700 ± 100 yr BP (GIN-8230) and 34 400 ± 400 yr BP (GIN-8254) [3].

At the M-1 point, the date of 36 040 ± 990 yr BP. (LU-1808) was obtained from the enclosing peat (most likely synchronous to the beginning of ice wedge formation), while in the ice wedges the values of $\delta^{18}O$ varied from –30.6 to –29.9‰ (mean of eight measurements was –30.3‰).

This confirms the conclusion about the active accumulation of syncryogenic yedoma deposits with thick ice wedges on the island from 36 to 10–12 ka BP.

Previously, on the southern shore of Kotelny Island, at an altitude of 2.5–3.5 m above sea level, ice wedges were found by A.Yu. Derivyagin et al. in the layer of icy gravel sands [4]. The width of the wedge

**Table 1.** Variations of $\delta^{18}O$ values (‰ to SMOW) in the Late Pleistocene ice wedges (IW) and segregated (segr.) ice (schlieren) located in the valley of the Balyktakh River and on the Sopochnaya Karga Peninsula, Sannikov Strait, Kotelny Island

| Sample ID | Ice type | Altitude, in meters above river level (distance from the right edge of the wedge) | $\delta^{18}O$, ‰ | Sample ID | Ice type | Altitude, in meters above river level (distance from the right edge of the wedge) | $\delta^{18}O$, ‰ |
|---|---|---|---|---|---|---|---|
| Balyktakh River valley | | | | | | | |
| M-2/1 | IW | 6.5 (0.3) | –22.9 | M-4/1 | segr. | 6.0 | –25.6 |
| M-2/2 | IW | 6.5 (0.7) | –23.3 | M-4/2 | segr. | 6.5 | –24.2 |
| M-2/3 | IW | 6.5 (1.1) | –23.9 | M-4/3 | segr. | 6.8 | –26.4 |
| M-2/4 | IW | 6.5 (1.5) | –26.3 | M-3/1 | IW | 3.8 (0.2) | –29.7 |
| M-2/5 | IW | 6.5 (1.8) | –24.8 | M-3/2 | IW | 3.8 (0.6) | –30.0 |
| M-2/6 | IW | 6.5 (2.1) | –24.8 | M-3/4 | IW | 3.8 (1.0) | –28.2 |
| M-2/7 | IW | 6.5 (2.5) | –25.1 | M-3/5 | IW | 3.8 (1.5) | –27.4 |
| M-2/8 | IW | 6.5 (2.8) | –24.5 | M-3/6 | IW | 3.8 (1.9) | –27.4 |
| M-2/9 | IW | 6.5 (3.1) | –24.9 | M-3/7(1) | segr. | 2.0 | –27.4 |
| M-2/10 | IW | 6.5 (4.0) | –26.2 | M-3/8(2) | segr. | 2.5 | –24.6 |
| M-2/11 | IW | 6.5 (4.5) | –24.0 | M-3/9(3) | segr. | 3.3 | –24.6 |
| M-2/12 | segr. | 5.0 | –26.7 | M-4/1 | IW | 6.8 (0.2) | –26.1 |
| M-2/13 | segr. | 5.5 | –27.7 | M-4/2 | IW | 6.8 (0.5) | –25.7 |
| M-2/14 | segr. | 6.4 | –28.6 | M-4/3 | IW | 6.8 (0.8) | –24.9 |
| M-2/15 | segr. | 7.3 | –29.9 | M-4/4 | IW | 6.8 (1.2) | –27.1 |
| Sopochnaya Karga Peninsula, coast of Sannikov Strait | | | | | | | |
| – | – | Absolute height above sea level | – | – | – | Absolute height above sea level | – |
| M-1/1 | IW | +5 (0.1) | –30.1 | M-1/5 | IW | +5 (1.3) | –30.6 |
| M-1/2 | IW | +5 (0.4) | –30.5 | M-1/8 | IW | +5 (1.9) | –30.5 |
| M-1/3 | IW | +5 (0.7) | –30.3 | M-1/8 | IW | +5 (2.0) | –30.2 |
| M-1/4 | IW | +5 (1.0) | –29.9 | M-1/9 | IW | +5 (2.3) | –30.4 |

sampled in detail was about 1 m, the exposed thickness was 1.5 m. The age of the wedges was established according to two $^{14}C$ dates from plant remains and moss in the ice complex deposits: 45960 + 2460/–1880 yr BP (KIA-25741) and 52790 + 4110/–2710 yr BP (KIA-25743). The isotopic variations in the ice wedges of the southern coast on Kotelny Island are not very large: the values of $\delta^{18}O$ range from –31 to –26.2‰ (mean value from six samples is –29.5‰), δD values are from –240 to –208.4‰ (mean value is –229.9‰), the values of $d_{exc}$ range from 1.5 to 8‰ (mean value is 5.9‰) [4].

Two outcrops of syngenetic ice wedges were studied and sampled in 2012 by N. Belova et al. within the RGS expedition on the southern coast of Kotelny Island [5]. In the K-1 outcrop, a homogeneous stratum with ice wedges of a visible thickness of 5 m was exposed from a height of 14.5 m above sea level. In the interval from 11.2 to 14.7 m above sea level, 33 samples were taken. The values of $\delta^{18}O$ range from –29 to –24‰ in the lower 2.5 m of the tested part of the ice to –25 to –20‰ in its upper part [5]. In the K-2 outcrop, ice wedges with a visible thickness of 8 m were exposed from an altitude of 18.5 m above sea level. At the K-2 point, 32 samples were taken. The mean value of $\delta^{18}O$ is –30.7‰ (from –32.2 to –28.4‰). The mean $\delta^{18}O$ values range from –31‰ in the lower part of the wedges to –29.5‰ in the upper part [5].

In the northwestern part of Kotelny Island, a Holocene ice wedge was investigated by A. Maslakov and B. Petrov in summer 2015. The permafrost containing the wedge consists of gray loam, less often light brown, sometimes with a large content of gruss and gravel, with black and dark brown lenses and stains of peat. The top of the wedge lies at a depth of 0.37 m from the surface. The ice from wedges is sampled in more detail in 0.2 m horizontally at a depth of 0.57 m (Fig. 2c; Table 2).

The performed isotope-oxygen measurements allow us to prove with a high degree of accuracy the mean winter ($t_{m.w}$) and the mean January ($t_{m.J}$) temperatures of the formation time of ice wedges on Kotelny Island, using the known equations of correla-

**Table 2.** Variations of $\delta^{18}O$ values (‰ to SMOW) in the Holocene ice wedges (from a depth of 0.57 m) located in the northwestern part of Kotelny Island

| Sample ID | Ice type | Distance from the right edge of the wedge, m | $\delta^{18}O$, ‰ | Sample ID | Ice type | Distance from the right edge of the wedge, m | $\delta^{18}O$, ‰ |
|---|---|---|---|---|---|---|---|
| 15-M-02 | IW | 0.3 | –22.64 | 15-M-12 | IW | 2.3 | –23.14 |
| 15-M-03 | IW | 0.5 | –21.64 | 15-M-13 | IW | 2.5 | –21.81 |
| 15-M-04 | IW | 0.7 | –22.12 | 15-M-14 | IW | 2.7 | –22.64 |
| 15-M-05 | IW | 0.9 | –22.80 | 15-M-15 | IW | 2.9 | –22.64 |
| 15-M-06 | IW | 1.1 | –22.76 | 15-M-16 | IW | 3.1 | –22.71 |
| 15-M-07 | IW | 1.3 | –22.98 | 15-M-17 | IW | 3.3 | –22.18 |
| 15-M-08 | IW | 1.5 | –22.25 | 15-м-18 | IW | 3.5 | –22.35 |
| 15-M-09 | IW | 1.7 | –21.95 | 15-M-19 gl. 0.77 m | IW | 1.7 | –22.30 |
| 15-M-11 | IW | 2.1 | –22.69 | | | | |
| 15-M-10 | IW | 1.9 | –22.85 | 15-M-20, gl. 1.07 m | IW | 1.7 | –23.07 |

**Table 3.** Correspondence of $\delta^{18}O$ and winter temperatures in the Late Pleistocene and Holocene syngenetic ice wedges and their comparison with modern ice wedges on the islands of the Eastern Arctic of Russia (according to Yu.K. Vasilchuk [7] with additions)

| Name of the reference section, source | Paleoreconstructions | | | | | Current values | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\delta^{18}O_{iw}$, ‰ | $\Sigma t^{\circ}_{w}$ | $t^{\circ}_{mw}$ | $t^{\circ}_{J}$ | $t^{\circ}_{paleo.gr}$ | $\delta^{18}O_{iw}$, ‰ | $\Sigma t^{\circ}_{w}$ | $t^{\circ}_{mw}$ | $t^{\circ}_{J}$ | $t^{\circ}_{current.gr}$ |
| 35–25 ka BP | | | | | | | | | | |
| Kotelny Island | –29 | –7250 | –29 | –43 | –19 | –18 | –5408 | –19 | –29 | –14 |
| Zhokhov Island [9] | –28.5 | –7150 | –28 | –43 | –19 | –20 | –5363 | –18 | –29 | –13 |
| Bolshoi Lyakhovskii Island [10] | –31.5 | –7870 | –32 | –48 | –20 | –20 | –5400 | –20 | –31 | –14 |
| Ayon Island | –31.2 | –7750 | –31 | –46 | –19 | –21 | –5047 | –20 | –29 | –12 |
| 22–12 ka BP | | | | | | | | | | |
| Kotelny Island | –25 | –6250 | –25 | –37 | –16 | –18 | –5408 | –19 | –29 | –14 |
| Ayon Island | –29.6 | –7400 | –30 | –44 | –18 | –21 | –5047 | –20 | –29 | –12 |
| 9–2 ka BP | | | | | | | | | | |
| Kotelny Island | –22.5 | –5600 | –22 | –34 | –13 | –18 | –5408 | –19 | –29 | –14 |
| Bolshoi Lyakhovskii Island [10] | –24.5 | –6100 | –24 | –36 | –15 | –20 | –5400 | –20 | –31 | –14 |
| Malyi Lyakhovskii Island | –21 | –5500 | –21 | –32 | –13 | –18 | –5408 | –20 | –31 | –14 |
| Zhokhov Island | –21 | –5300 | –21 | –32 | –11 | –20 | –5363 | –18 | –29 | –13 |
| Ayon Island | –22 | –5500 | –22 | –33 | –12 | –21 | –5047 | –20 | –29 | –12 |

The values of $\delta^{18}O_{iw}$ are for a fragment of the ice wedge formed in a given period of time, ‰; $\Sigma t^{\circ}_{w}$, total annual freezing index; $t^{\circ}_{mw}$, mean winter air temperature °C; $t^{\circ}_{J}$, mean January air temperature, °C; $t^{\circ}_{paleo.gr}$, the reconstructed mean annual ground temperature, without snow and vegetation cover, °C; $t^{\circ}_{paleo.gr}$, paleotemperature of the ground (for a given period of time),°C; $t^{\circ}_{current.gr}$, the current mean annual ground temperature, without snow and vegetation cover, °C.

tion between winter air temperatures and the isotopic composition of wedges [6–8]:

$$t^{\circ}_{m.w.} = \delta^{18}O_{ice\ wedges} \pm 2°C$$

and $$t^{\circ}_{m.J.} = 1.5\delta^{18}O_{ice\ wedges} \pm 3°C.$$

These equations, derived for modern veins of the entire northern Russian permafrost, approximate well the data on modern veins of the Arctic islands (Table 3).

Variations of $\delta^{18}O$ values in the Late Pleistocene ice wedges formed on Kotelny Island are significant, exceeding 8‰ (from –30‰ to –22.9‰), while for those in the Holocene, they are insignificant at 1.5‰ (from –23.1‰ to –21.6‰).

Comparing the variations of $\delta^{18}O$ values in the Late Pleistocene [7, 9–13] and Holocene [3, 7, 9, 10] syngenetic ice wedges on other islands of the Eastern Arctic of Russia (Table 3), one can see that in the Holocene the paleotemperature and paleogeocryological parameters are almost identical. In the Late Pleistocene, in the wedges of Kotelny Island, as well as on Ayon Island, much lighter values of $\delta^{18}O$ were recorded for the period of 35–25 ka BP, in comparison with the wedges that formed 22–12 ka BP. This indicates a possibly less severe winter climate on Kotelny Island from 22 to 12 ka BP, which has already been seen in a number of yedoma sections of Siberia [7, 8]. Perhaps, in part, this is a reflection of higher isotope values at the very end of the Pleistocene, during the Dryas-Allerod.

This work shows that the variations of $\delta^{18}O$ values in the Late Pleistocene ice wedges are significant, exceeding 8‰, while they are less than 1.5‰ for those in the Holocene. The mean January temperatures in the Late Pleistocene varied by more than 8–13°C. The mean annual temperature of frozen soils in the Late Pleistocene was about –19 to –20°C, and in the Holocene, about –13 to –15°C, while the current temperature is about –14°C.

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