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GEOGRAPHY

New Oxygen Isotope Diagrams of Late Pleistocene and Holocene Ice Wedges in Mamontova Gora and Syrdakh Lake, Central Yakutia

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Abstract—This paper reports on the oxygen isotope composition of the Late Pleistocene and Holocene syngenetic ice wedges, which were exposed at Mamontova Gora and Syrdakh Lake, the Accelerator Mass Spectrometry dating, and the reconstruction of the winter air temperatures during ice wedge formation. Organic microinclusions from the ice wedges were directly dated, which allowed us to establish seven dates ranging from 13 to 19 ka BP. The age of the ice wedges is shown to be younger than 20 ka, but older than 10 ka BP. In the area of Mamontova Gora, $\delta^{18}O$ is in the range of –24.7 to –30.9‰ for the Late Pleistocene ice wedges, and of –23.2 to –25.9‰ for the Holocene ice wedges. In the area of Syrdakh Lake, $\delta^{18}O$ ranges from –29.2 to –32.5‰. At the Mamontova Gora site, the average winter air temperatures, which were reconstructed from the isotope data, ranged from –28 to –31°C during most of the period when the Late Pleistocene ice wedges were formed; the January temperature was –42°C, –46°C. At the Syrdakh Lake site, the Late Pleistocene winter conditions were more severe: the average winter air temperature ranged from –30 to –32°C, and the average January air temperature was –44, –48°C. In the Holocene, the average winter air temperatures were higher and ranged from –24 to –28°C, while the average January temperatures ranged from –36 to –42°C.

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The main purpose of this work was to study the oxygen isotope composition of Late Pleistocene and Holocene syngenetic ice wedges, which were exposed at Mamontova Gora and Syrdakh Lake, to determine the chronology, and to reconstruct the winter air temperatures during the time of ice wedge formation. The studies were conducted with the use of Accelerator Mass Spectrometry (AMS). Stable oxygen isotope measurements were conducted in the Stable Isotope Laboratory of Moscow State University using Delta V Plus mass spectrometer.

The section of the lake inset of Mamontova Gora on the left bank of the Aldan River (64° N, 134° E, Fig. 1) was quite difficult for us to date.

In the upper part of the 50- to 60-m terrace, ice wedges more than 5 m in height occur in the lacustrine-boggy inset crowning the terrace section. The deposits of 9- to 12-m thickness are presented by dark

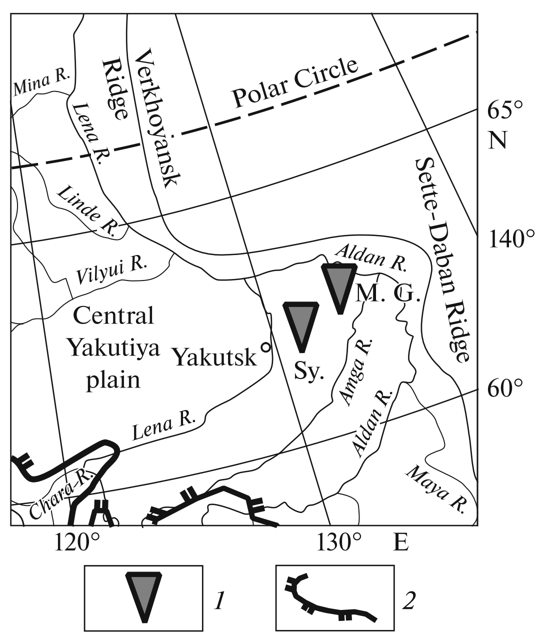

Fig. 1. Location of the sections studied of the Late Pleistocene ice wedge (*1*) of Mamontova Gora (M. G.) and Syrdakh Lake (Sy.) and the southern boundary of the continuous permafrost (*2*).

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Table 1. Radiocarbon dating of organic matter from ice wedge and host sediments of Mamontova Gora [5]

Depth, m	^{14}C dates (years)	Laboratory ID	Calibrated ^{14}C dates (years)
AMS dating on organic microinclusions directly from the ice wedges			
2.6	13950 ± 200	SNU02-141	15544–14373
	16190 ± 250	SNU02-142	18186–16984
	17040 ± 100	SNU01-283	18900–18310
	18400 ± 400	SNU02-140	21306–19325
	18900 ± 200	SNU02-139	21369–20445
5.0	19050 ± 180	SNU01-285	21481–20565
3.2	19800 ± 600	SNU01-284	23421–20592
Dating of the organic matter from the host sediments			
2.2	41230	KI-5183	More than 41230*
2.6	35000 ± 400	GIN-4604	38525–36718
3.0	40600 ± 500	MGU-IOAN-56	43154–41303
5.0	42150 ± 3700	SI-1965	More than 40407*
5.5	26800 ± 600	MGU-IOAN-44	30256–27616
8.0	38400 ± 500	GIN-4603	41262–39887
8.0	44000 ± 1900	MGU-IOAN-121	More than 43043*
8.0	46700 ± 1500	SI-1972	More than 47795*

*Beyond the calibration range.

gray lacustrine lean clays. Primarily, the lean clay accumulation was dated to the period from 35 to 46 ka BP on the basis of wood material from the lacustrine lean clays [1, 2]. The age of wood material from lean clays is shown be 35 ka BP at a depth of 2.6 m and 38.4 ka BP at a depth of 8.0 m. Based on the assumption that the wood material was redeposited, and considering the Holocene age (4.8 ka BP) of the autochthonous peat lying at the depth of 2 m on the contact of gray and brown lean clay, Yu.K. Vasil'chuk assumed that the age of the ice wedges is much younger, and even the Holocene for some of them [3]. The direct AMS dating of organic microinclusions from the ice wedges brought some clarity [4]. Seven dates ranging from 13 to 19 ka BP show that the ages are younger 20 ka, but older than 10 ka BP (Table 1).

It is interesting that one of the first ages was shown to be 26800 ± 600 years (MGU–IOAN-44) for the wood material from lean clays at a depth of 5.5 m. However, this date was considered excessively young due to the poor preservation of wood material ([1], p. 163). In view of the AMS ice dating of the ice wedges, this date appears to be closer to the real time of the lean clay accumulation [5]; however, it is rather older, because, most likely, almost all wood material in lean clays was reworked by creeks from more ancient Late Pleistocene sediments. The increase in the radiocarbon age of organic microinclusions downwards through the section clearly demonstrates the presence of horizontal stratification of ice wedge, which, in spite of its accumulation in repeatedly arising frost cracks, is formed almost simultaneously with the accumulation of deposits.

It is not possible to state with certainty that the ice wedge complex of Mamontova Gora is definitively dated. In our opinion, further dating of ice wedges

Table 2. Minimal, average, and maximum values of $\delta^{18}O$ in ice wedge of the sections from Mamontova Gora and Syrdakh Lake

Point	Location	$\delta^{18}O$, ‰ in ice wedges		
		minimum	average	maximum
Mamontova Gora				
2	Late Pleistocene ice wedge	–30.89	–29.69	–27. 89
3	Late Pleistocene ice wedge	–29.58	–28.06	–24.69
5	Late Pleistocene ice wedge	–28.82	–27.85	–27.00
6	Late Pleistocene ice wedge	–29.7	–27.63	–24.43
7	Holocene ice wedge, high flood plain of the Aldan River	–25.91	–24.23	–23.22
Syrdakh Lake				
8	Late Pleistocene ice wedge	–32.49	–31.13	–29.20

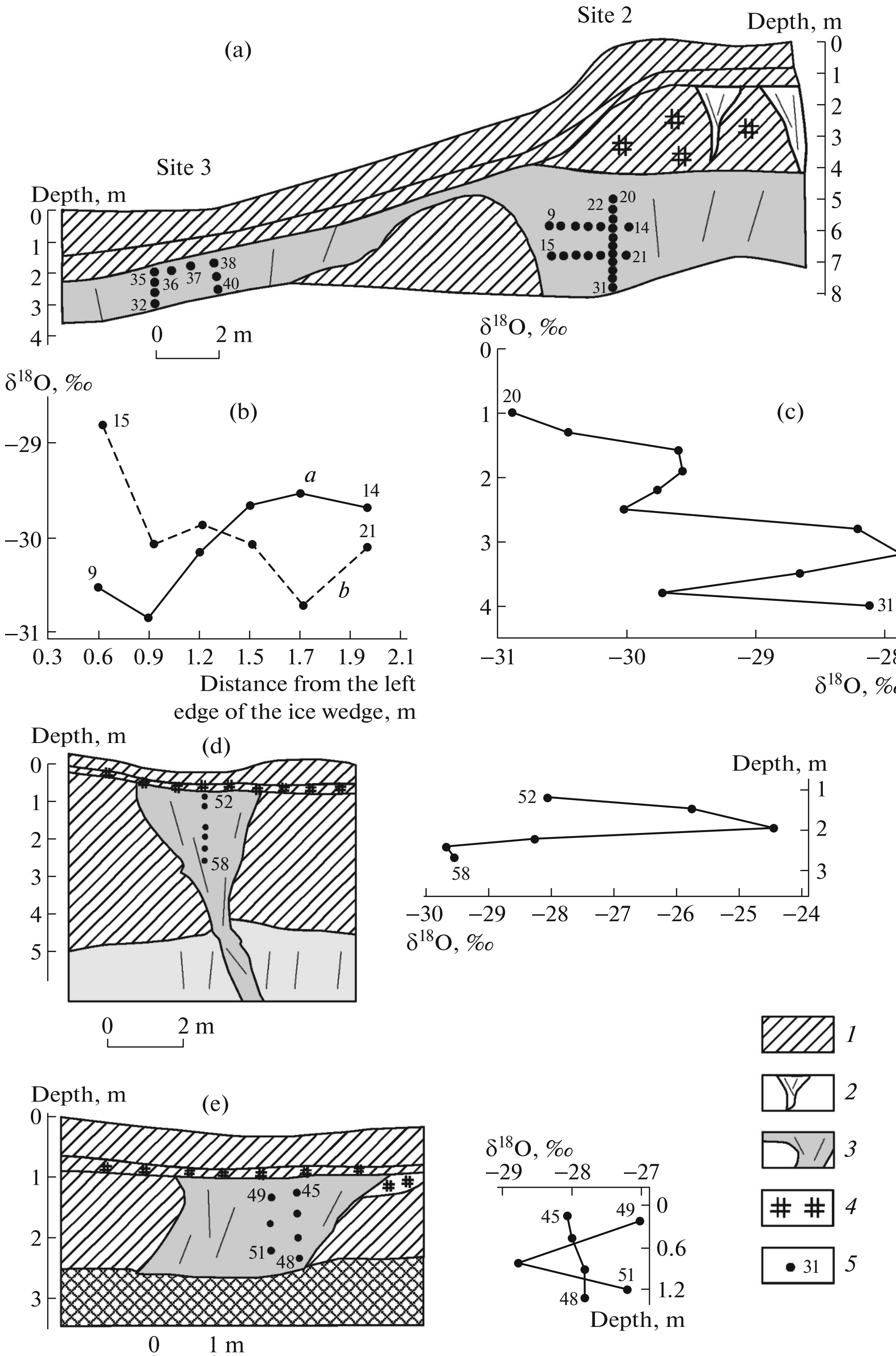

Fig. 2. The Late Pleistocene ice wedges of the 50-m terrace of the Mamontova Gora section (a–c, sites 2 and 3; d, site 6; e, site 5); *1*, lean clay; *2*, ice wedge of milky white color; *3*, ice wedge; *4*, peat and plant remains; *5*, the sampling points of ice wedge for the isotope analysis. $\delta^{18}O$ distribution in the ice wedge (point 2): b, along the horizontal profile at the depths of 2 m (1) and 3 m (2); c, along the vertical profile.

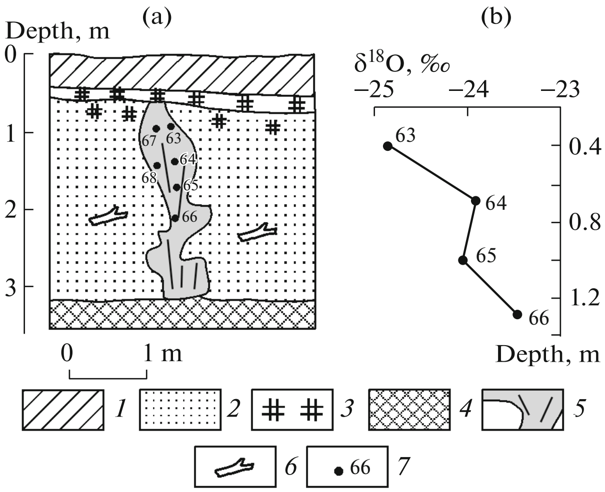

Fig. 3. The Holocene ice wedge (a) and $\delta^{18}O$ distribution (b) in the exposure of the high flood plain on the right bank of the Aldan River: *1*, lean clay; *2*, sand; *3*, peat and plant remains; *4*, mud-flow; *5*, ice wedge; *6*, wood remains; *7*, the sampling points of wedge ice for the isotope analysis.

from this section has to resolve these and other questions of this interesting cryogenic phenomenon.

The revision of all datings from this section that have been obtained allows us to consider the age of the ice wedges as Late Pleistocene and to date the time of their formation from 13 to 19 ka BP [4].

The studies on this section carried out by German and Russian scientists showed that $\delta^{18}O$ varies in the range of –28.5 to –31.5‰ in the ice wedges [6]. The wider range of $\delta^{18}O$, from –25.9 to –29.2‰, was obtained in the upper part of the ice wedge, and that from –16.5 to –22.7‰, in the high-mineralized ice wedge "tail" [3].

In 2016, we repeatedly studied the glacial complex of Mamontova Gora. On the left bank of the Aldan River, in the outcrop of the 55-m terrace, the following sediments are exposed: the upper 5-m part of the section is composed of dark gray and black lean clays, with a thick-schilieren cryogenic structure, with organic inclusions, and with narrow ice wedge 3 m in height; a Late Pleistocene sequence 10 m thick lies below, it is composed of gray and dark gray lean clays with a massive cryogenic structure, with inclusions of plant remains containing ice wedge up to 3–4 m wide and up to 8 m in height. Lean clays are underlain by sands and pebbles containing pseudomorphs. Fragments of four Late Pleistocene ice wedges (Fig. 2) and one Holocene ice wedge (Fig. 3) were sampled in the thermocirques. The samples were collected in the vertical and horizontal direction for oxygen isotope analysis. In the Late Pleistocene ice wedge (site 2), $\delta^{18}O$ variations in the horizontal direction are no greater than 2‰ (Table 2, Fig. 2); $\delta^{18}O$ ranges from –29.5 to –30.9‰ at a depth of 2 m and from –28.8 to –30.8‰ at a depth of 3 m. Along the vertical profile, $\delta^{18}O$ variation is 3‰, from –27.9 to –30.9‰, where $\delta^{18}O$ increases downwards through the section. The higher values of $\delta^{18}O$, from –24.7 to –29.6‰ (Table 2) were obtained in the upper part of the Late Pleistocene ice wedge (point 3, Fig. 2). This ice wedge probably contains ice inclusions of the Holocene ice wedge or was formed with participation of lacustrine-boggy waters.

The ice wedges were studied on the right bank and flood plain of the Aldan River in Holocene sands containing wood remains. In one of these ice wedges, $\delta^{18}O$ values varies in the range of –23.2 to –25.9‰ (Table 2, Fig. 3), which is somewhat higher than in the recent veinlets on the flood plain of the Aldan River.

In 2016, we studied the Late Pleistocene ice wedges in the area of Syrdakh Lake. Within the alas in the thermocirque wall, a fragment of the ice wedge was revealed in dark gray ice-bearing lean clays. The ice wedge "head" is overlain by a layer of lean clay with organic inclusions. Ice was sampled in the horizontal and vertical directions. In the horizontal direction, $\delta^{18}O$ varies in the range of –29.2 to –32.5‰ at the depth of 0.5 m and from –30.5 to –31.5‰ at the depth of 1.2 m. In the vertical direction, $\delta^{18}O$ varies in the narrow range of –30 to –31.8‰ (Table 2, Fig. 4).

In the vicinity of Syrdakh Lake and Ulakhan Syrdakh Lake, which is located next to it, S. Popp et al. [6] studied the isotope composition of ice wedges. The width of the ice wedges is 2–3 m. Their vertical thickness varies from 0.8 to 2.3 m, but supposedly can reach 10 m. In AMS dating of organic matter, which was sampled in the Syrdakh Lake exposure, the ^{14}C age is shown to be 21 710 ± 680 years (KIA-26367). Organic matter from ice wedges of the Ulakhan Syrdakh Lake is dated as 13 110 ± 680 years and 3755 ± 30 years. The average $\delta^{18}O$ value of ice wedges is –31.3‰ in Ulakhan Syrdakh Lake and –30.8‰ in Syrdakh Lake. These values, as well as their narrow range, are very close to the values for Mamontova Gora. Nevertheless, it should be noted that the Late Pleistocene ice wedges studied in Syrdakh Lake are generally characterized by lower values of $\delta^{18}O$ and a narrower range of the variations in comparison with the Late Pleistocene ice wedges from the Mamontova Gora section.

Stable oxygen isotope composition in the Late Pleistocene and Holocene ice wedges allow us to estimate the winter temperatures with the use of the functional relationship proposed by Yu.K. Vasil'chuk [7]. The average winter air temperature was in the range of –28 to –31°C during most of the period, when the Late Pleistocene ice wedges of Mamontova Gora were formed; the average January temperatures were –42 and –46°C. In the area of Syrdakh Lake, the winter conditions were slightly more severe: the average winter temperature mainly varied in the range of –30 to –32°C; the average January temperatures were –44 and –48°C. In the Holocene, the average winter tem-

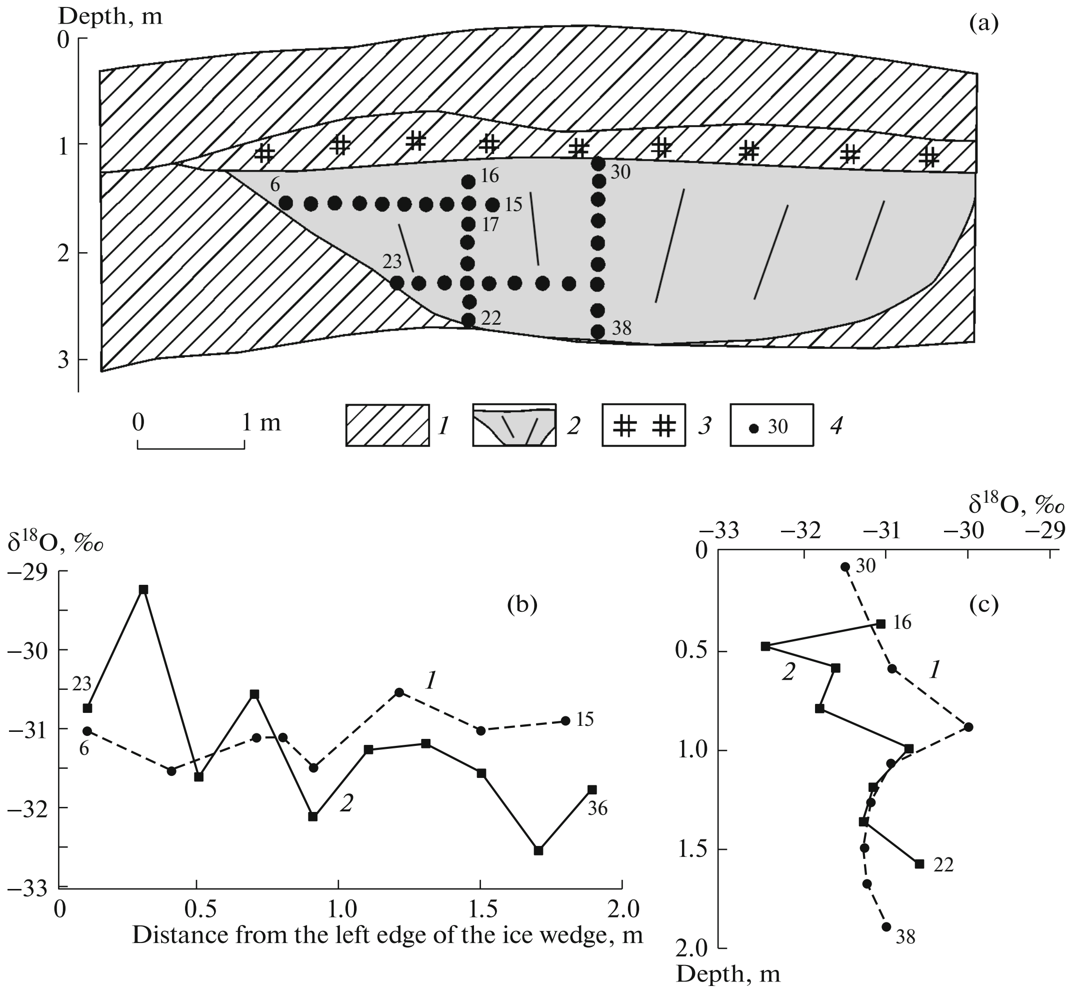

Fig. 4. The Late Pleistocene ice wedge in the Syrdakh Lake exposure (a): *1*, lean clay; *2*, ice wedge; *3*, peat and plant remains; *4*, the sampling points of ice wedge for the isotope analysis. $\delta^{18}O$ distribution: b, in the horizontal profile at the depth of 0.5 m (*1*) and 1.2 m (*2*); c, in the vertical direction along the line of samples 30–38 (*1*) and along the line of samples 16–22 (*2*).

peratures were higher, from –24 to –28°C, and the average January temperatures ranged from –36 to –42°C.

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