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BURIED SNOW IN THE LENA-AMGA PLAIN

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Some new forms of buried stratified ice have been discovered in the Late Pleistocene section of the Lena-Amga Plain (Central Yakutia, Russia) in the course of core drilling at several watershed sites elevated to 220–250 m asl. The buried ice, which belongs to the traditionally distinguished ice complex, makes three separate layers of firn (snow recrystallized to difference degrees), at the depths 12.0 to 17.0, 23.3 to 24.5, and 33.6 to 39.0 m below the ground surface lying under wedge ice found in the uppermost section between 2.5 and 5.0 m. The firn layers are separated by syngenetically frozen sandy silt and silt.

INTRODUCTION

Buried ice is widespread in plainland Central Yakutia, especially in the Lena–Amga–Aldan interfluve (Lena-Amga Plain) where it belongs to the ice complex [*Soloviev, 1959; Katasonov, 1975, 1979; Ivanov, 1984*]. The ice complex of the area consists of up to 70–80 m thick fine-grained sediments that bear frozen water in the form of ice wedges and structure-forming ice. The total permafrost thickness reaches hundreds of meters, the upper layer of at least 100 m being syngenetically frozen ground.

More evidence of the composition, age, and geomorphic setting of the ice complex has been obtained recently through core drilling in the Lena-Amga Plain, at altitudes 220–250 m asl (Fig. 1), run by the Institute of Permafrost (Yakutsk) [*Spektor and Spektor, 2002*].

Boreholes drilled at several sites of the plain near watersheds stripped previously unknown forms of buried stratified ice which turned out to be snow recrystallized to difference degrees (firn). The discovery of firn ice in drill sections, a very important outcome of the drilling project, provides clues to the Late Pleistocene climate in the area and has additional implications for the origin of the ice complex.

FIELD DATA

The most complete section with different forms of buried ice was found in the borehole drilled in 2004 at 62°08′ N, 131°18′ E, 82 km east of Yakutsk city. The experiment of 2004 consisted in core drilling with successive bit diameters of 147, 127, 108, 89, and 76 mm, and core recovery using an air-flushing system. Thus obtained undisturbed core material selected for further studies was then transported, in the frozen state, to an underground laboratory of the Institute of Permafrost (Yakutsk).

The core section included three ice layers of different thicknesses: wedge ice in the uppermost part at 2.5–5.0 m below the ground surface and two firn layers at 12.0–17.0 m and 33.6–39.0 m separated by syngenetically frozen sandy silt and silt [*Spektor et al., 2008*].

Another hole drilled in 2011 three meters off the former one provided more details of the section as it tapped layered ice at two depth intervals of 13.5–14.2 m and 23.31–24.50 m below the ground surface. Additionally, the upper and lower snow cover was sampled above the hole (5–10 and 30–40 cm below the snow surface, respectively, the total snow thickness at the time of 19.03.2011 being 43 cm).

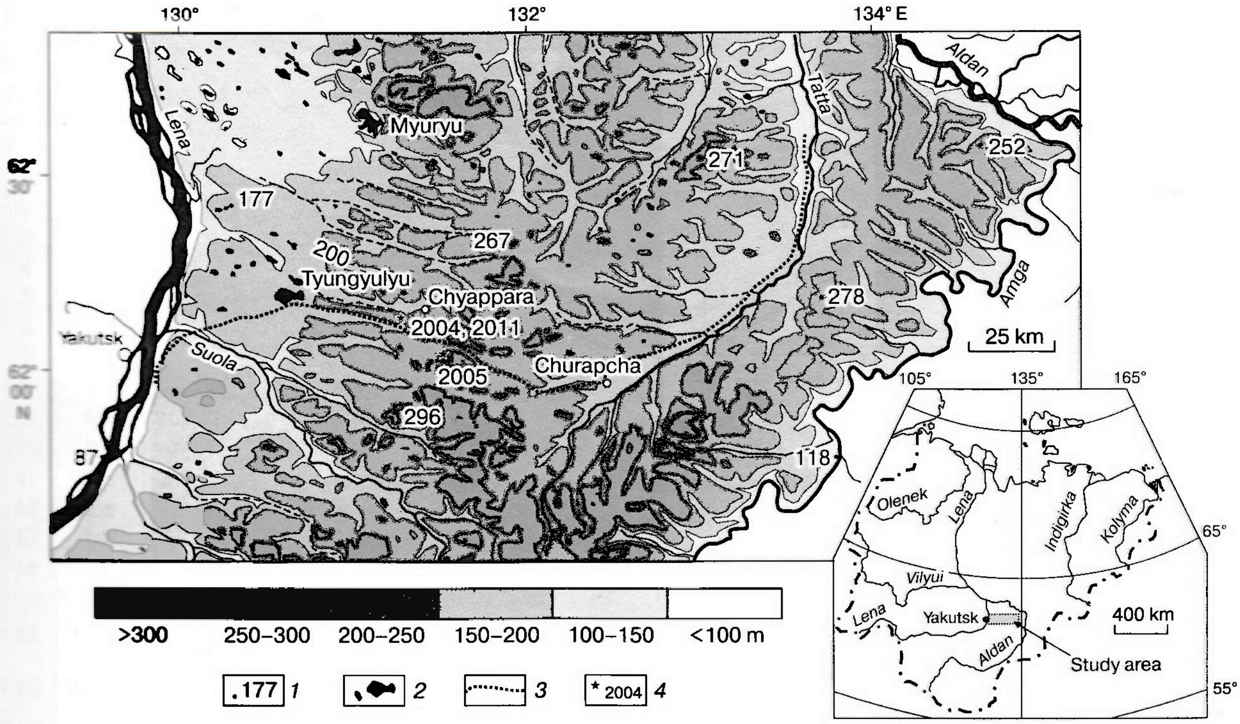

Fig. 1. Location map of boreholes in the Lena-Amga Plain (Central Yakutia).
1 – elevations, meters above sea level; 2 – lakes; 3 – roadway; 4 – boreholes.

One more borehole, which was drilled in 2005 at 94 km east of Yakutsk (62°04′ N, 131°33′ E), stripped firn buried at 2.8–8.2 m below the surface. This firn layer correlates with the 33.6–39.0 m interval of the 2004 borehole in its stratigraphic position, structure, and texture.

The ice layers in the drill section of 2004 were as follows.

Uppermost layer (2.5–5.0 m): wedge ice. The stripped ice wedge is at least 30 cm wide and about 2.5 m thick. Ice is transluscent and yellowish, has a vertical banded texture (1–2 cm wide bands), and encloses various mineral and organic lenses and elongate gas bubbles.

Upper firn layer (12.0–17.0 m): thinly stratified ice with very fine, fine, or less often coarse particles (Fig. 2, *a*). In our view, this ice type may result from recrystallization of buried snow. Buried snow within this depth interval is poorly compressed and weakly recrystallized, and shows intricate stratification. The whole firn layer consists of several smaller banded layers of (i) 3–5 cm thick pure banded firn, (ii) 1–2 cm thick banded firn with soil, and (iii) 1–4 cm thick brecciated and coarse-crystalline firn (Fig. 2, *b*).

The compacted snow layer includes tentatively distinguished annual cycles consisting of pure white snow (formed in wet and warm seasons) and grayish snow with mineral particles (dry and cold season). Each cycle is 2–3 mm thick, with about 20 such cycles in a banded layer, i.e., there were at least 20 year-long spells of harsh climate.

The 1–3 cm thick layers of coarse-crystalline firn consist of up to 5 mm round or rectangular ice crystals with molten edges. There are pieces of columnar upright ice crystals, which is typical of firn glaciers.

Lower firn layer (33.6–39.0 m): stratified ice, slightly denser and more strongly recrystallized than that in the upper layer. In the lower portion of the interval, ice layers alternate with frozen silt which, in turn, grades into lens-type or reticulate ice-rich soil.

The section of the 2011 borehole drilled near that of 2004 included two layers of stratified ice we sampled: one between 13.5 and 14.2 m and the other between 23.31 and 24.50 m below the surface. It was coarse-crystalline ice with its structure similar to that of the lower firn layer at 33.6–39.0 m (see above).

The uppermost section contained wedge ice 2.5 m below the surface lying under massive light brown silt and a thin soil layer at the top. Between the ice (firn) layers, the drill hole tapped syngenetically frozen silt and sandy silt with reticulate or massive cryostructures in the depth intervals 5.0–12.0 and 17.0–33.6 m. Massive silt is cut in many places by branching thin (a few mm to 3 cm) nearly upright cracks filled with ice.

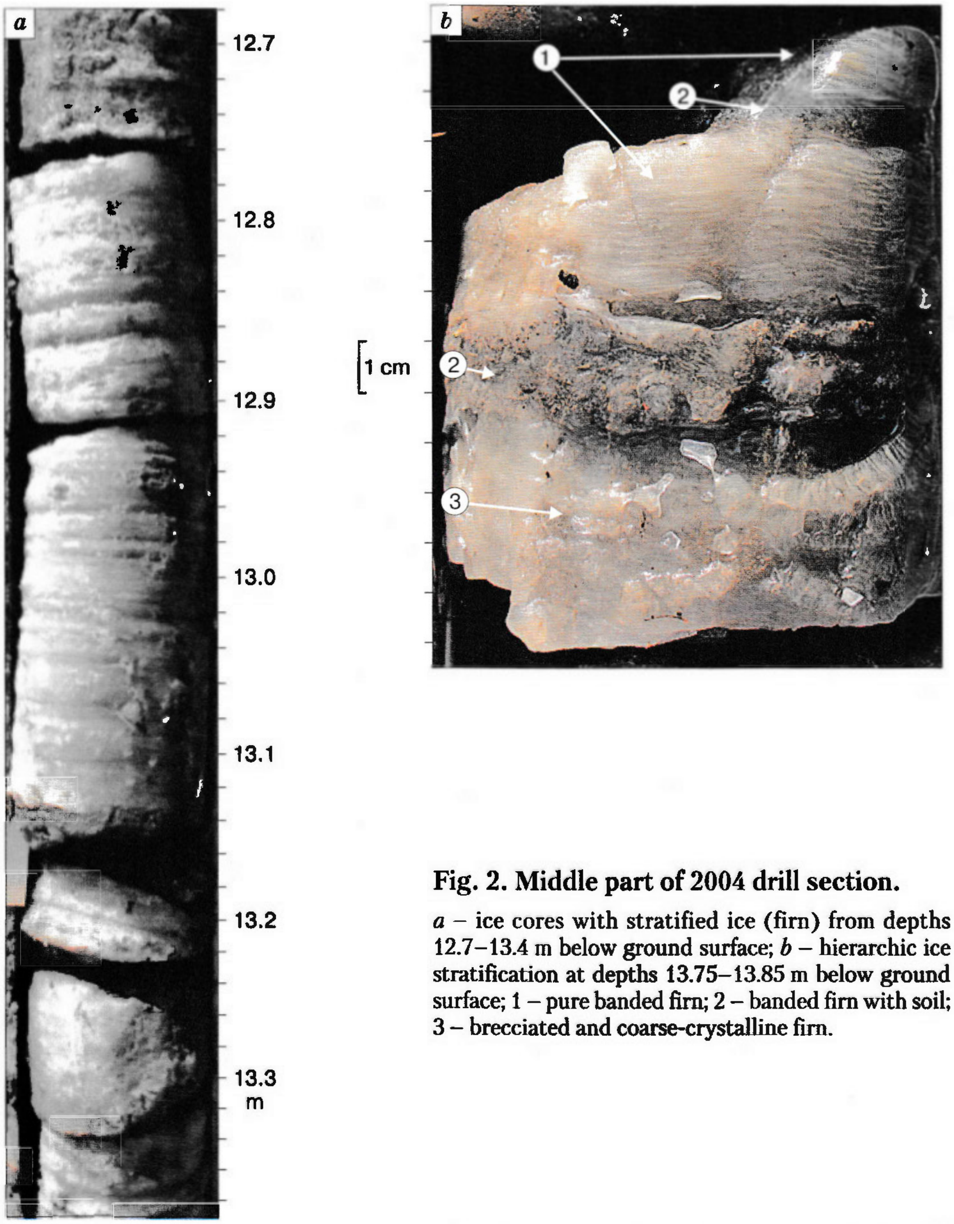

Fig. 2. Middle part of 2004 drill section.

a – ice cores with stratified ice (firn) from depths 12.7–13.4 m below ground surface; *b* – hierarchic ice stratification at depths 13.75–13.85 m below ground surface; 1 – pure banded firn; 2 – banded firn with soil; 3 – brecciated and coarse-crystalline firn.

LABORATORY MEASUREMENTS

Isotope composition of ice and snow. The oxygen and hydrogen isotope compositions of buried firn ice from the borehole of 2004 was studied at the Laboratory of Isotope and Nuclear-Physics Methods (Science & Technology Center, All-Russian Research Institute of Hydrogeology and Engineering Geology, VSEGINGEO, Moscow, reports by V.A. Polyakov and A.F. Bobkov). The samples of ice from the 2011 borehole and fresh snow cover of the same year were analyzed at the Laboratory of Isotope Geochemistry and Geochronology (Institute of Geology of Mineral Deposits, Petrography, Mineralogy, and Geochemistry, IGEM, Moscow, reports by E.O. Dubinina). The results are synthesized in Table 1 and in Fig. 3.

The oxygen isotope composition ($\delta^{18}O$) of firn ice sampled from the intervals 13.5–14.1 and 23.4–24.41 m varies in a narrow range relative to the SMOW standard, according to data of the IGEM Laboratory. In the upper interval, $\delta^{18}O$ is from –32.25 to –29.20 ‰, and deuterium (δD) ranges from –213.5 to –236.9 ‰. The respective ranges in the lower interval are between –31.70 ‰ and –30.32 ‰ $\delta^{18}O$ and –234.7 to –219.9 ‰ δD. Firn from the 12.0–17.0 and 33.6–39.0 m intervals was analyzed at the VSEGINGEO Laboratory, one sample from each interval. The results (Table 1) were similar to the $\delta^{18}O$ and δD data for the 13.5–14.1 and 23.4–24.41 m intervals.

Table 1. $\delta^{18}O$ **and** δD **contents in buried firn of the Lena-Amga Plain and surface snow cover**

No.	Deposit	Sampling interval, m below ground surface	$\delta^{18}O$, ‰	δD, ‰
		Borehole 2011		
1	Ice	13.50–13.58	–29.73	–213.5
2	Ice	13.62–13.70	–29.20	–214.3
3	Ice	13.72–13.80	–29.77	–223.8
4	Ice	13.82–13.90	–30.44	–232.0
5	Ice	13.92–14.00	–31.20	–236.9
6	Ice	14.05–14.10	–32.25	–232.1
7	Ice	23.41–23.44	–30.54	–219.9
8	Ice	23.51–23.56	–30.32	–223.8
9	Ice	23.62–23.68	–30.73	–226.7
10	Ice	23.71–23.78	–30.95	–230.0
11	Ice	23.88–23.94	–31.55	–234.7
12	Ice	24.00–24.07	–31.70	–232.5
13	Ice	24.25–24.30	–31.63	–229.1
14	Ice	24.37–24.43	–31.23	–225.3
		Surface snow cover above borehole 2011		
15	Snow	Upper layer, 5–10 cm below ground surface	–38.63	–288.8
16	Snow	Lower layer, 30–40 cm below ground surface	–31.60	–229.3
		Borehole 2004		
17	Ice	12.0–16.0	–30.60	–275.0
18	Ice	33.50–33.65	–26.60	–226.0

The isotope composition of the analyzed ice samples is almost identical to that of meteoric water in Central Yakutia [*Popp, 2006*]. The values of $\delta^{18}O$ and δD in snow are related as $y = 7.66x - 2.90$, with the lower and upper bounds of –42 to –19 ‰ $\delta^{18}O$ and –330 to –180 ‰ δD. The local meteoric water line for Central Yakutia differs from the global line [*Ferronsky and Polyakov, 2009; Craig, 1961*] in lower $\delta^{18}O$, while δD is the same.

The snow isotope composition reported in [*Popp, 2006*] was obtained in samples collected in November through April of 1997/98 near Yakutsk. The snow we sampled near the borehole of 2011 gave –38.63 ‰ $\delta^{18}O$ in the upper layer (5–10 cm below the surface) and –31.6 ‰ $\delta^{18}O$ in the layer 30–40 cm below the surface, which is almost the same as in the buried firn.

Spore-and-pollen composition. Spore-pollen assemblages in the core samples differ qualitatively and quantitatively from the present ones. The present spore-pollen spectra of the topsoil (0–0.1 m) are dominated by tree and shrub pollen (68.4–75.0 %), with 28.7 and 17.0 % grasses and subshrub species, respectively, the spores being 2.9 and 8.0 %.

Subaerial loam lying under present loam and wedge ice, as well as the upper wedge-ice layer (0.75–4.0 m) contains mostly grasses and subshrub pollen (62.7–67.0 %), with highest percentages of *Cyperaceae* (27.2–16.8 %) and *Poaceae* (12.4–36.1 %). The spores (27.8–20.8 %) belong mainly to *Polypodiaceae* (20.1–7.2 %). Tree and shrub pollen, of relatively low percentages (9.5–12.2 %), consist of *Betula middendorfii, Betula exilis* (7.7–9.0 %) and *Alnaster* (0.3–1.5 %).

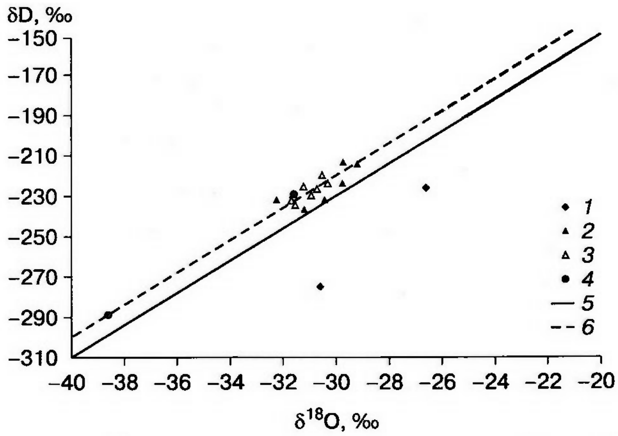

Fig. 3. $\delta^{18}O$ **vs.** δD **relationship in buried firn of Lena-Amga Plain and in present surface snow cover.**

1 – samples from 2004 borehole; *2* – samples from 2011 borehole, interval 13.5–14.2 m below ground surface; *3* – samples from 2011 borehole, interval 23.31–24.5 m; *4* – snow cover above borehole of 2011; *5* – global meteoric water line; *6* – local meteoric water line.

These spore-pollen spectra of the upper section correspond to a tundra environment.

Spore-pollen assemblages in lacustrine loam lying between wedge ice and buried snow (interval 10.11–12.15 m) and in bluish-gray silt with plant detritus (interval 7.50–10.11 m) are poor, with 100–296 grains found in no more than four specimens. The spectra are dominated by grasses (35.0–90.3 %), especially xerophytes: *Chenopodiacae* (0.5–47.5 %), *Poaceae* (7.6–40.0 %), *Artemisia* (7.0–27.8 %), *Cichoriaceae* (1.0–26.7 %), and *Caryophyllaceae* (0.5–5.8 %). The tree-shrub pollen (7.7–37.2 %, most often 22.0 %) is almost uniformly distributed over the section and consists of *Betula nana* (1.7–20.0 %, the percentages growing upwards), *Alnaster* (0.5–4.0 %), *Salix* (0.5–4.0 %), and *Pinus pumila* (0.5–9.9 %, the percentages likewise growing upwards). The tree pollen includes higher percentages of *Larix* (1.8–10.0 %) and lower percentages of *Betula* sect. *Albae* (0.5–7.0 %), *Pinus sylvestris* (0–1.8 %), and sporadic *Picea*.

Spores are from 3.2 to 39.0 %, most of them being *Bryales* (1.2–24.4 %) and *Polypodiaceae* (0.5–29.0 %) species. The samples contain *Pediastrum* green alga and other microfossils. Note that the interval is rich in redeposited material from Mesozoic and Cenozoic sediments.

The taxonomic composition and relative percentages of the spore-pollen spectra at these depths correspond to tundra and steppe landscapes dominated by xerophytes and sparsely growing larch-birch or larch-pine forests (forest-tundra). Large percentages of green moss spores and *Cyperaceae* pollen, as well as some pollen of beach and water plants, indicate hypnum bog and sedge fen environments.

The spore-pollen spectra in samples of buried firn and underlying silt between 12.15 and 17.35 m differ from those in the interval above in having rather high percentages of tree-shrub pollen (13.7–44.0 %), which are however lower than grasses and subshrubs (47.1–70.3 %).

Trees and shrubs are small-leave angiosperms (12.4–36.0 %), mostly *Betula nana* (5.5–24.0 %). *Betula* sect. *Albae* is from 3.0 to 12.0 %, *Alnaster* and *Salix* are from a few grains to 5.0 % and 3.0 %, respectively.

The spectra of conifers (2.1–15.1 %) comprise greater percentages of *Larix* (1.0–10.0 %), lower percentages of *Pinus sylvestris* (0.3–5.3 %), and sporadic grains of *Picea sibirica* and *Pinus pumila*.

The components in grass and subshrub pollen from this depth interval again change in relative amounts: the percentages of *Artemisia* (9.6–16.0 %), *Poaceae* (6.0–24.0 %), and *Chenopodiacae* (4.0–14.8 %), and especially *Ericales* (5.0–13.0 %) are higher than in the overlying section while *Cichoriaceae* are lower (1.8–13.0 %).

The composition of spores (5.5–13.7 %) in this interval misses *Selaginella sibirica* and includes lower percentages of *Bryales* (1.1–5.6 %) and *Hepaticae* (few grains to 3.5 %) mosses but higher percentages of *Sphagnum* (0.3–3.0 %).

The low abundances of spore and pollen (100–223 grains in two or three specimens) and low percentages of tree pollen in the spectra prompt that deposition was in open landscapes with sparse forests but extensive steppes and saline-land heaths which were dominated by wormwood-goosefoot and grass communities, with heath and shrub patches. The sparse forests consisted of *Larix* or locally *Pinus sylvestris*, *Betula platyphylla*, and, possibly some *Picea*.

Slightly higher percentages of shrub birch, quite abundant *Ericales*, and greater spread of mesophytic grasses and *Sphagnum*, as well as lower percentages of xerophytes (*Chenopodiacae* and *Selaginella sibirica*) may be, to a certain extent, evidence of a slightly warmer and wetter climate compared to that of the previous interval, though a severe environment likely persisted.

Periglacial alluvium (20–31 m) and lower part of buried firn (31–43 m) bear the lowest amounts of spore and pollen (13 to 128 grains in one to five specimens). Seven out of sixteen specimens were almost barren (containing a few grains). The spore-pollen assemblages consist mainly of grasses (47.0–83.0 %), especially *Chenopodiacae* (to 56.0 %) whose percentages hold nearly the same in all samples. *Poaceae* and *Artemisia* are likewise quite high: up to 20.4 % and 10.0 %, respectively. All spectra contain notable amounts of *Caryophyllaceae* (0.3–11.2 %), *Cichoriaceae* (1.1–6.9 %), and *Asteraceae* (0.3–3.0 %). Grasses (*Ericales, Rosaceae, Onagraceae, Polygonaceae*) are rare or sporadic.

Tree and shrub pollen is 4.0–23.9 %, or occasionally as high as 34.0 %, being mainly *Larix* (0.3–19.0 %). Less abundant is *Pinus sylvestris* (0–4.0 %), *Betula platyphylla* (0–5.0 %) and *Betula nana* (*B. Middendorffii, B. exilis*), *Alnaster*, and *Pinus pumila*.

The compositions of spores, diverse microfossils, and redeposited pollen and spores from older sediments are similar to their counterparts from the overlying layers.

The spore-pollen spectra represent vegetation of periglacial steppe tundra with sporadic forests and swampy lowlands in a very cold climate.

DISCUSSION

Judging by the isotope compositions, the discovered layers of buried stratified ice are congenetic and similar to the present snow. The latter fact, along with fine grain sizes, banding, presence of columnar ice crystals, and horizontal stratification, allows us to identify the buried ice as firn.

The presence of firn is evidence of alternating positive and negative temperatures and dramatic changes in moisture contents of near-surface air.

The discovery of snow patches in the southern plainland part of the Lena River catchment indicates that the summer air temperatures were only slightly above zero during some spells of the Late Pleistocene. By analogy with present Arctic areas, one may infer that the mean annual air temperature in Central Yakutia did not rise above –20 °C during those cold spells, which is about 10 °C lower than the today temperature.

Mean annual air temperatures are known to correlate with mean annual $\delta^{18}O$ in precipitation [*Dansgaard, 1964*]. The $\delta^{18}O$ content in water of a basin approximately correspond to that at the snow-rain boundary in the respective area or to the highest content in snow [*Popp, 2006*]. In our case, with the obtained –29.2 ‰ $\delta^{18}O$, the mean annual air temperature may have been as low as –20 °C, the winter and summer means being, respectively, –45... –50 °C and slightly above +5 °C. The relatively cold summer temperatures are corroborated by the vegetation composition corresponding to steppe-tundra, or occasionally, forest-tundra environments in the time when the ice-bearing sediments were deposited. Snow patches may have been preserved in small depressions on hillslopes which were shaded though being elevated, and thus were favorable for snow accumulation.

CONCLUSIONS

Thus, the investigated three layers of stratified ice were formed on the ground surface and are most likely buried snow patches (firn). The buried ice has its isotope composition similar to that of snow in the study area. The sediments that host the buried ice lenses bear spore-pollen assemblages corresponding to cold climates of Late Pleistocene glacials.

The presence of buried firn, ice, and ice soil in the upper sedimentary section of the Lena-Amga Plain means that the upper syngenetic permafrost of the area underwent a more complex evolution than it was thought before. Until recently, syngenetic frozen ground in Central Yakutia was attributed to a cold and dry climate with sharp seasonal temperature variations which produced wedge ice and maintained a large extent of a thick ice complex. However, the reduced thickness of the ice complex and the existence of several layers of buried snow recrystallized to different degrees indicates that syngenetic permafrost was formed in a relatively wet climate at quite low summer air temperatures, as it commonly occurs in areas subject to glaciation. On the other hand, the very fact of firn preservation and burial is evidence of rather rapid sedimentation which may occur only under tectonic (or rather glacial-tectonic) subsidence.

According to climate and permafrost reconstructions, the greatest portion of syngenetic permafrost in Central Yakutia originated under the influence of a large ice sheet, most likely the Verkhoyansk one.

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LANDSCAPE GEOCHEMICAL TRACERS OF CONTAMINATION IN DELTAS OF RIVERS DISCHARGING INTO THE ARCTIC BASIN

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Terrestrial ecosystems located in the Yenisei and Pechora delta and estuary zones have been studied for radionuclide and heavy metal contamination from remote global and regional sources. Radionuclides and heavy metals in soil, water, and plants were determined at different distances from the sea on landscape-geochemical transects across riverbanks and delta islands. In the Yenisei delta and estuary zone, local ^{137}Cs accumulation was found being associated with operation of the Krasnoyarsk Chemical Combine. The highest ^{137}Cs were measured at test sites located on islands within the Yenisei delta front, which thus appears to be a natural barrier for river-borne contaminant fluxes into the Arctic basin. Heavy metals (Cu and Ni) in mosses and willow (leaves) species collected on terraces and watersheds in the lower Yenisey showed a slowly increasing trend toward the Norilsk Combine. The measured ^{137}Cs contamination of the Pechora test sites was within the global background. Relatively high Cu and Zn were revealed in Pechora water sampled 3 km downstream of Naryan-Mar city. These patterns may be used for purposive contamination tracing.