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SYNGENETIC ICE WEDGES AND AGE OF SLOPE YEDOMA DEPOSITS IN THE FOOTHILLS OF THE KULAR RIDGE

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The structure and composition of Late Pleistocene ice wedges in the ice complex outcropping onto the gently sloping Kular ridge in the western Yana-Indigirka Lowland are considered. Ice wedges are dated 47–42 and 37–32 kyr BP. Over this time, relatively high temperatures of the growing season were recorded twice. Their rise appeared to be sufficient for the growth of trees, while a relatively warm summer season activated slope processes and accumulation of slope yedoma deposits.

Ice wedges, Late Pleistocene, permafrost, yedoma, radiocarbon dating, Kular ridge, Northern Yakutia

INTRODUCTION

This study sets out to investigate peculiar structural features of yedoma sequences containing ice wedges which are widespread in the Kular ridge area, along with radiocarbon dating of their sediments. In the Russian literature, the term "yedoma" has several meanings: in the geomorphic sense ("yedoma surface") in the stratigraphic sense (yedoma suite); and in the geocryological sense, as a special type of frozen syngenetic ice-rich sediments penetrated by ice wedges [*Sher, 1997*]. The general concept of "yedoma" adopted in the foreign literature, refers specifically to ice-rich deposits with syngenetic ice wedges [*Schirrmeister et al., 2013*]. The term "yedoma" used herewith reflects the definition given by Yu. Vasil'chuk, as follows: "yedoma" is syngenetic extremely ice-rich (ice content: >50–90 %) frozen earth material commonly enriched in organic material (organic matter content: >1–2 %) and represented by clayey silts, silty sands, and fine sands of Late Pleistocene age hosting large syngenetic ice wedges (15–20 m and more in height, 1.0–3.5 m in width), often with multi-layered structure. In the intermountain basins and on slopes, yedoma sequences may be saturated with silty medium gravel and rubble material, while yedoma sequences in valleys and river deltas may contain gravel and pebbles [*Vasil'chuk, 1992*]. The age of yedoma sequences varies from 11.7 to 50 calibrated (cal) thousand years and older. One of the specific characteristics of these deposits is the pungent odor ("smell of horse stables") given off by the decomposing organic matter.

ENVIRONMENTAL CONDITIONS IN THE STUDY AREA

Geographical location

The studied cross-section of the yedoma ice-wedge polygon system is located in the foothills of the Kular ridge near the abandoned rural settlement of Kular (70°38′02″ N, 134°19′57″ E), on the south-facing slope of the Burguat River valley, which is part of the Omoloy River basin (Fig. 1). In terms of tectonic setting, the Kular gold-bearing region comprising the study area is subsumed into the continental zone of the rift system [*Konstantinov et al., 2013*]. Hence, rifting is implicated in to the slope processes intensity in this region.

Climate, terrain and surface waters

According to climate zoning pattern discussed in [*Alisov, 1956*], the study region is located in the onshore area of the Arctic belt. The key temperature/precipitation data reported from the nearest Kazach'e weather station include: the mean January air temperature (t_J) over the past 20–30 years (from –36 to –39 °C), the mean July temperature (from + 4 to +11 °C), and the mean annual air temperature (MAAT) (around –14 °C); the annual precipitation amounting to 200–250 mm/year and unevenly distributed between the winter (ca. 50 mm) and summer (from 50 to 200 mm) seasons in [http://ru. Climate-Data.org]. Note that the data obtained by the authors from the study of elementary ice wedges which formed during the last 100 years on the floodplain served as the basis for the paleotemperature in-

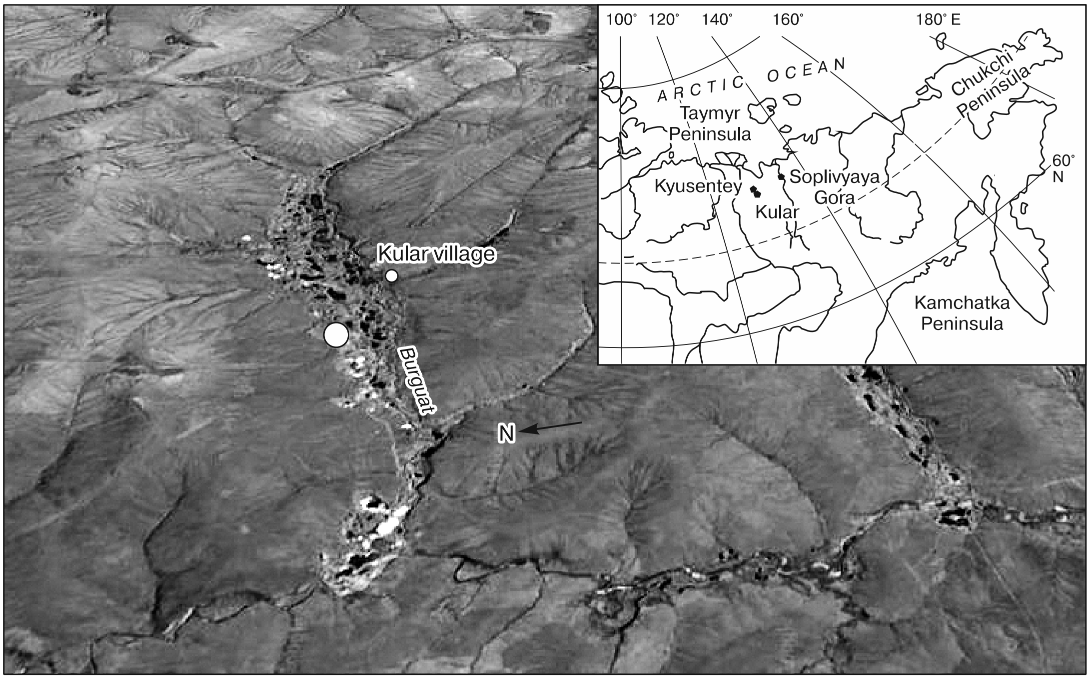

Fig. 1. Map showing location of the yedoma sequence cross-section near Kular village.

terpretation of the stable isotope composition of ice wedges [*Vasil'chuk, 1991*]; it is therefore critical to additionally provide the available data from the Kazach'e weather station for earlier period spanning from 1930 to 1966, where t_J varied from –39 to –37.4 °C [*Reference Books, 1966*].

Accumulation landforms are represented mainly by surfaces of slope accumulation encircling watersheds and superimposed on river terraces. The Burguat River and Kuchuguy-Kuegyulyur River valleys, whose width reaches 1.5 km in man-made extensions, are characterized by a box-shaped asymmetric cross-section exposing steep slopes, which becomes V-shaped in the upper reaches. A detailed study of the region's terrain by Gravis [*1969*] allowed to distinguish three major elements in the asymmetric valleys: 1) the bottom, which includes the riverbed, floodplain and (locally) one above-floodplain terrace; 2) terrace-ridge, which is a flat area, most often located at the foot of south- or west-facing slope; 3) the valley slopes composed of bedrock, overlain by thin layers of loose deposits. In the upper reaches of small rivers, where neither the floodplain nor permanent riverbed are developed, the slopes' asymmetry is not pronounced. Lower down the river, they gradually pass into shallow, but fairly wide gullies with matted walls and bottom. A narrow riverbed is characterized by developing small meandering bends which favor the formation of disparate small segments of the floodplain. These gradually coalesce to form a single terrace reaching 100 m and more in width. Its surface is generally swampy and is occasionally interspersed with oxbow landforms like small ox bow lakes. This type of terrain has been studied fairly thoroughly in the vicinity of Kular village. The terrace-ridges are often cross-cut by tributaries of the main river. Extensive, flat alluvial fans which commonly develop on the floodplain (opposite to the mouths of the tributaries) completely block the riverbed, thereby diverting the main river towards the opposite slope.

The beginning of the Late Pleistocene saw a decrease in the local erosion basis (Yana and Omoloy Rivers), against the backdrop of general uplift of the Kular arch, which largely governed the ongoing relief-forming processes [*Soloviev et al., 2003*]. This indicates that slope processes had played a significant role in sediment distribution and accumulation.

Geocryological conditions

According to the data obtained at the Russian Research Institute for Hydrogeology and Engineering Geology, permafrost thickness in the Kular village area varies from 90 m (Burguat River valley) to ~300 m (summit surfaces). The mean annual temperature of permafrost averages between –6 and –8 °C, with the frost cracking, cryogenic weathering, as well as curum formation and thermokarst being widespread phenomena. Deposits containing ice wedges, are encountered both on slopes (more frequently, in the cross-sections of terrace-ridges) and in river valleys. Slope deposits are represented by brownish-grey silty sands and clayey silts with inclusions of rubble material, slate, which are often iron-rich, and abound in organic remains. The sediment thickness in the middle and lower parts of hillslopes can reach 10–15 m or more.

HISTORY OF RESEARCH

The cryostructure of deposits in the Kular ridge has been studied fairly thoroughly from cross-sections of mine shafts, boreholes, pits and open-cut mines over recent decades [*Kuznetsova, 1967; Gravis, 1969; Ventskevich et al., 1969; Konishchev, 1981; Vasil'chuk, 1990; Kanevskiy, 2004*]. The area provides intriguing features, unequaled elsewhere in permafrost areas. The structure of ice wedges and pseudomorphs in the pebble-blocky-rubble horizon is studied in detail, which in itself is an infrequent phenomenon. Thus, Kuznetsova [*1967*] described the structure of sediments containing thick ice wedges exposed in the inclined ca. 50 m long mine shaft in the Burguat River valley. Results of the study of ice wedges occurring in the layer of pebble admixed with rubble material in the Kular mines revealed [*Ventskevich et al., 1969*] that ice wedges often dissect the gold-bearing deposits to the bedrock (Fig. 2, *a*, *b*). While they may not reach the bedrock base (Fig. 2, *b*), most of them have an unusual configuration.

Gravis [*1969*], who studied the cryolithological structure of the Kular foothills in mines next to numerous pits dug during winter for four years, revealed evidences of ice wedge formation in slopes, and signs suggesting solifluction origin for the sediments. He found that, depending on the rate of the soil mass movement, elementary wedges can be arranged either in the form of a fan (high displacement rate) (Fig. 3, *a*) or become asymmetric, without being separated (low displacement rate) (Fig. 3, *b*).

In the Kyusentey River valley, 40 km northeast from Kular village, Gravis described five layers (tiers) of ice wedges (Fig. 4). At this, their number varied even within a single slope, which strongly reflects the slope-specific variability of sediment accumulation conditions. At the slopes base, Gravis identified the riverbed and floodplain alluvium facies. Analysis of the cross-sections allowed him to infer that the sediments accumulated the most thickly in the ancient Kyusentey River valley in parallel to accumulation of

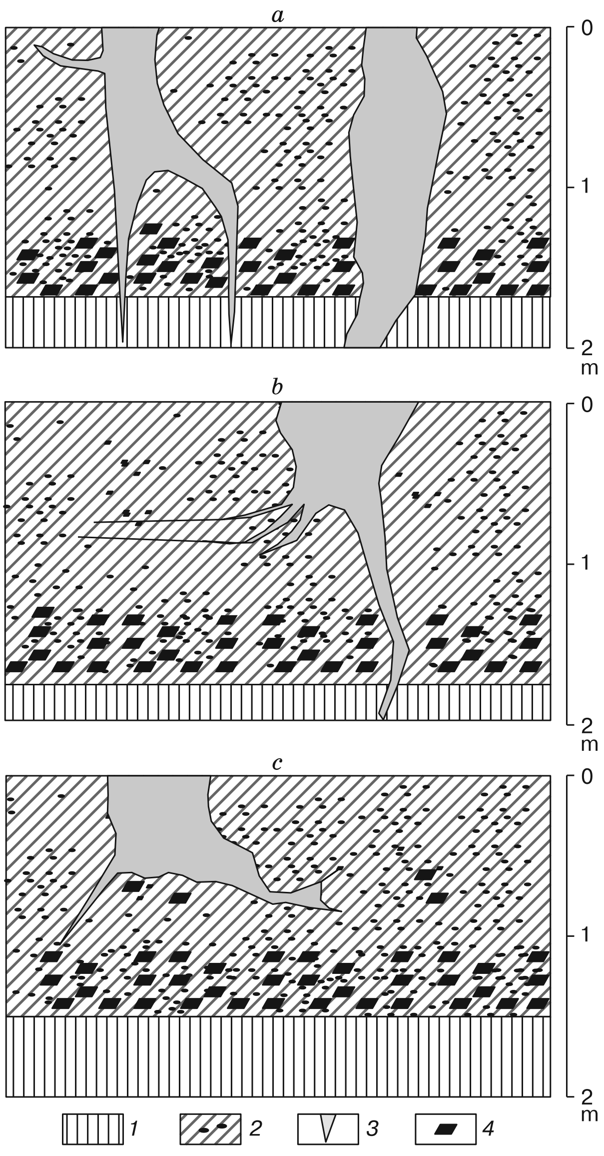

Fig. 2. Field sketches of the shape of "tails" (tips) of ice wedges observed in a mine shaft in the Kular yedoma sequence, intersected by the cross-section across the strike (after: [*Ventskevich et al., 1969*], simplified).

1 – bedrock eluvium; *2* – pebbles with silty sands and clayey silt infill; *3* – ice wedge; *4* – rubble material.

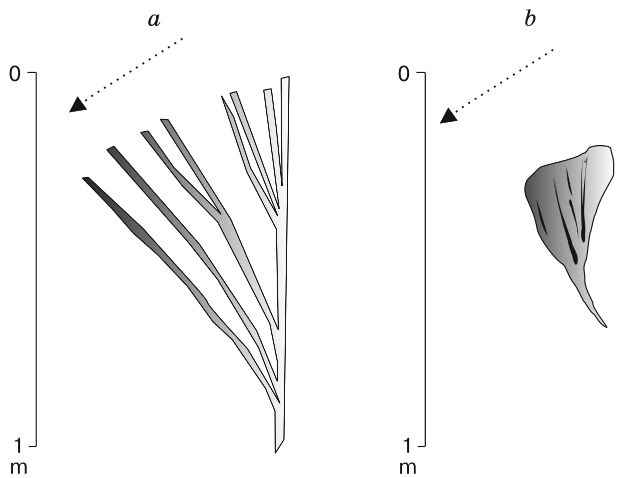

Fig. 3. Ice wedges formed in the slope deposits (after: [*Gravis, 1969*], amended):

a – fan-shaped, *b* –asymmetric. The arrow indicates the direction of the material displacement.

riverbed and floodplain deposits, and of the lowermost part of silty sands and clayey silts. After the incision had taken place, further sedimentation was dominantly controlled by the steep hillslopes.

The cryolithological structure of deluvial-solifluction slope deposits of the Burguat River valley was studied by Kanevskiy [*2004*]. A total of about 40 boreholes were drilled into the slope (Fig. 5, *A*). At least two generations of ice wedges were identified in this sequence. The thickness of slope deposits varies from 3 to 20 m. A major part of the slope sediment sequence is composed by grey silty sands with micro- and inner-thinly-lenticular cryostructure, with their layers locally growing extremely ice-rich (thickness: 0.1–3 m) with ataxitic(suspended)/reticulate cryostructure, encountered at different depths (Fig. 5, *B*, *C*). Their total moisture content is 150–200 %. According to Kanevskiy, these deposits are generally extremely ice-rich, have relatively low thickness, and lack a distinct rhythmicity in their

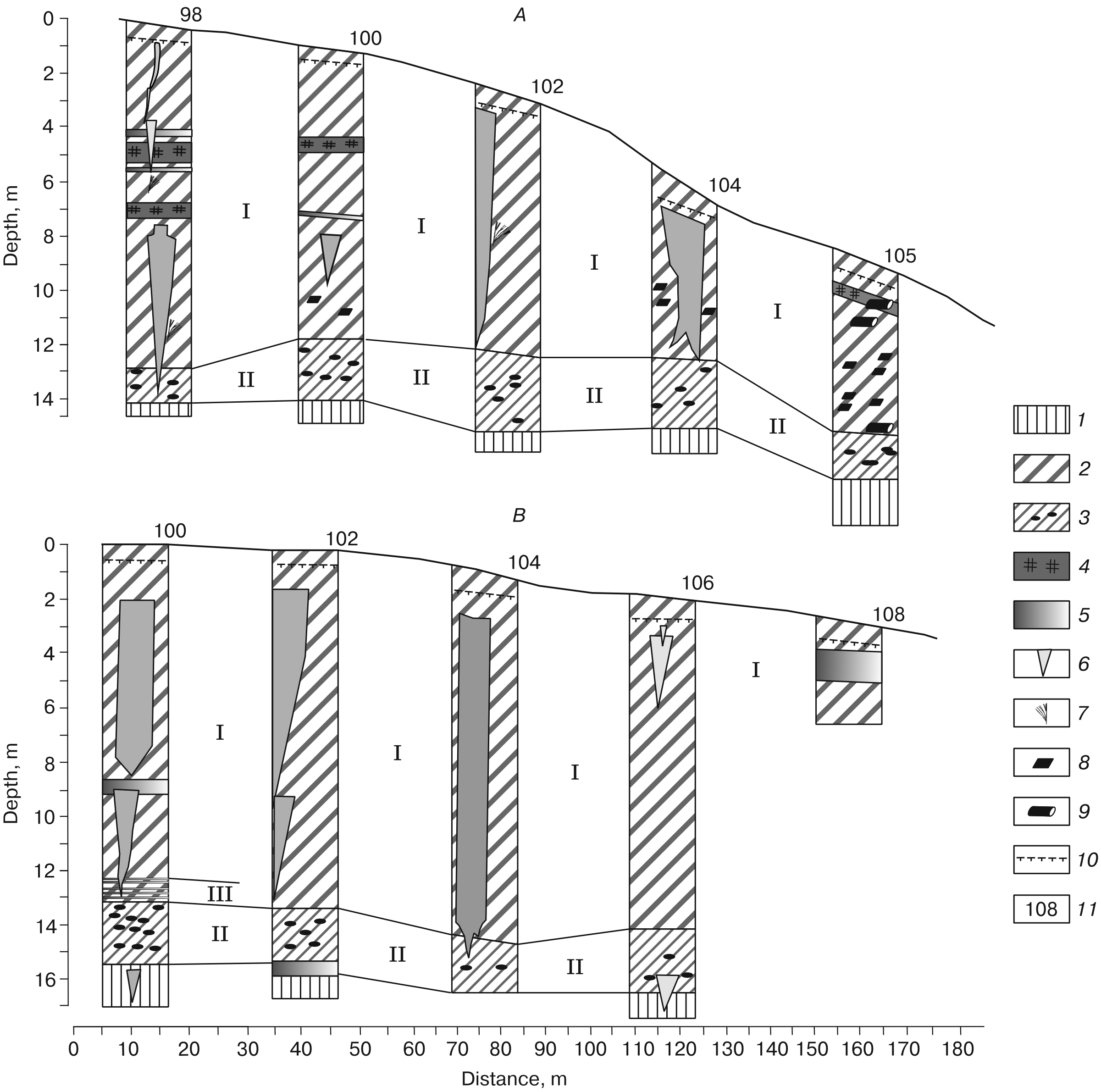

Fig. 4. Cryostructure of slope deposits in the Kyusentey River valley (40 km NE from Kular village) (after: [*Gravis, 1969*], simplified).

A – cross-sections of pits along line 138; *B* – cross-sections of pits along line 157. I – deluvial solifluction sediments; II – riverbed alluvium; III – floodplain alluvium; *1* – bedrock eluvium; *2* – silty clay, frozen, with fine-lens-like, cross-bedded and horizontally-layered cryostructure; *3* – pebble-bed with silty sands and clayey silts, frozen, with dominantly crust-like cryostructure; *4* – peat, frozen with discontinuous layered reticulate cryostructure; *5* – ice-lens; *6* – ice wedge; *7* – fan-shaped ice wedges; *8* – rubble material; *9* – buried branches of large shrubs; *10* – lower limit of the active layer; *11* – numbering of pits.

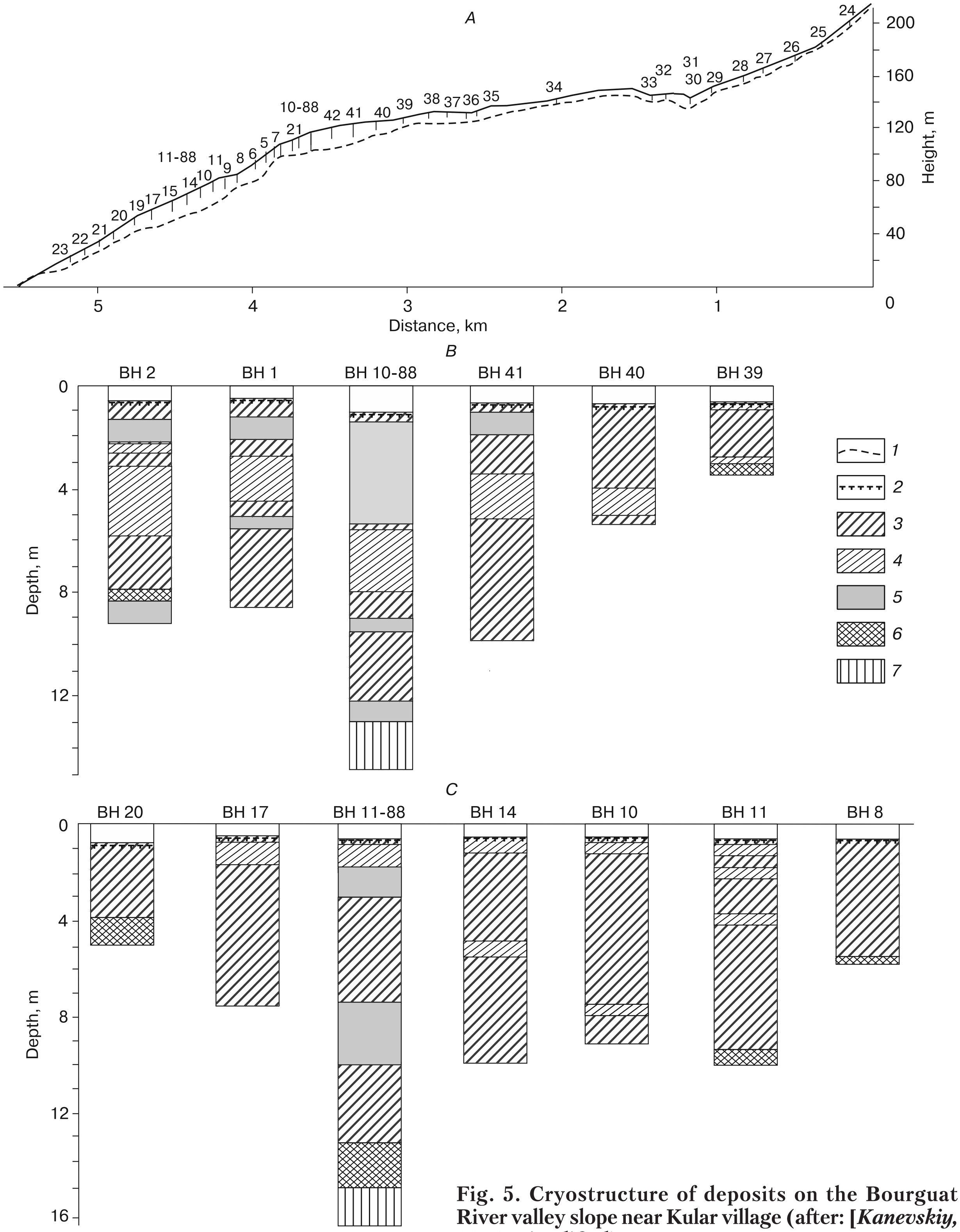

Fig. 5. Cryostructure of deposits on the Bourguat River valley slope near Kular village (after: [*Kanevskiy, 2004*], simplified).

A – boreholes location plan; *B* – borehole sections in the mid-slope part; *C* – cross-sections of boreholes in the lower part of the slope. *1* – slope base deposits; *2* – lower limit of the active layer; *3* – silty sand, grey, frozen with micro- and thin ice lenses, lenticular cryostructure; *4* – silty sand, grey, frozen with ataxitic and reticulate cryostructure; *5* – ice wedge; *6* – medium to fine gravel; *7* – bedrock eluvium.

structure. This author described subhorizontally occurring syngenetic ice wedges oriented perpendicular to the slope dip [*Kanevskiy, 2003*]. Kanevskiy [*2004*] showed that differentiation by composition between Ice Complex deposits and slope deluvial solifluction deposits is almost indiscernible in the Kular area. Ice Complex deposits basically make up terrace-ridges and watershed slopes, while terrace-ridges tend to develop in their pediment areas (deluvial solifluction deposits). Ice wedges inherent in this area are accentuated by their multilayer occurrence and diversity of shapes, while yedoma sequences display a complex structure.

RESEARCH RESULTS OBTAINED FOR ICE WEDGES AND THE SURROUNDING KULAR YEDOMA SEDIMENTS

The structure and composition of yedoma sequence

In the outcrop fragment studied in detail by the authors on the gentle sloping, south-facing Burguat River valley slope (0.5 km west of the mouth of the Emis Creek), the ice wedge-bearing sequence occurs in the form of a terrace-ridge stretching for more than 1 km along the slope, with surface slope angle of 4–5°.

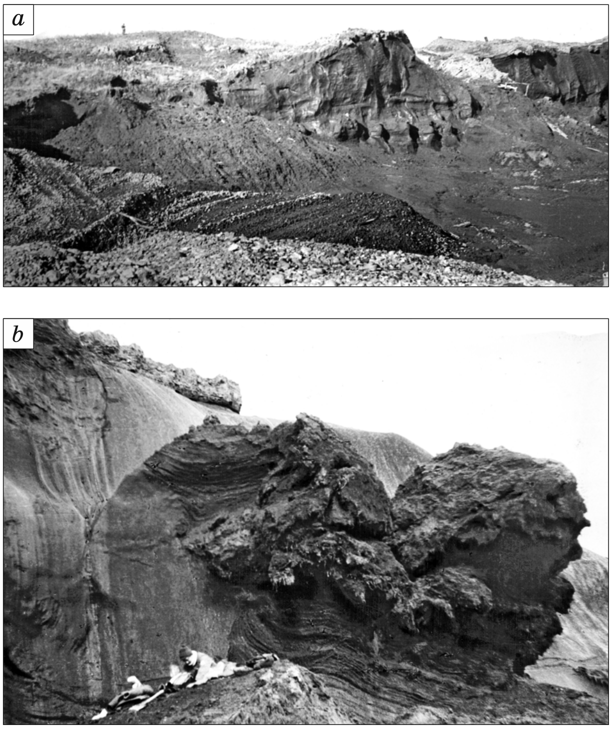

Fig. 6. Ice wedges in the yedoma exposure near Kular village.

a – general view of the open-cut mine (ice wedges are shown in the background against a vertical wall); *b* – vertically-banded syngenetic ice wedge (*on the left*) and a thick peat layer. Photograph by Yu.K. Vasil'chuk.

Absolute elevation marks of yedoma vary from 95 m (near the stream) to 110–120 m (in the upper part of the slope), and from 105 to 140 m (in the topmost layer).

The yedoma sequence in the described outcrop fragment averages ca. 22 m in thickness, which may reach 28 m. The structure of one of the most representative terrace-ridge portion was studied by the authors in abandoned open-cut mine within a mid-slope segment (Fig. 6, *a*, 7). The bedrock exposed at the base of the terrace-ridge, is overlain by up to 1 m thick gravelly eluvium bed. The layer of fine black sand (thickness: from 0.5 to 2–3 m) atop it is cross-stratified, with inclusions of gravel and subrounded pebbles. By all appearances, the sand is of alluvial origin and is attributed to the riverbed sediment facies. At the interface between sands and overlying grey silty sands, the authors observed a layer of bluish-grey segregated ice (up to 1.5 m thick) with inclusions of minute pebbles. The yedoma sequence is composed of grey silty sand and clayey silt with thick lenses of peat and discrete interlayers of organic material. Layers of peat are usually contorted and disrupted, which is typical of solifluction deposits. The fuzzy, intermittent ice inclusions and asymmetric ice wedges identified in the section, according to Gravis [*1969*], are also indicative of solifluction origin of the sequence.

Both thick syngenetic ice wedges and multi-tier ice wedge identified in the section, are abound across the entire sequence (Fig. 6). The heads of multi-tier ice wedges occur at different depths (0.7–1.0, 4–5, 8.5–10, 15–17 m), and at least three or four tiers of ice wedges are observed. Ice wedges reach 3.5 m in width and exhibit brownish-grey ice, with admixture of peat and silty sands. The distance between ice wedges is 13–15 m. The “tails” (tips) of wedges occur at different depths, and either cross-cut the eluvium, or occur at a height of 3–5 m from the yedoma sequence base. Ice wedges are contorted (deviation of the wedges' axes from vertical position is usually 1.0–1.2 m). Ice wedges oriented along and across the slope tend to differentiate.

Ice wedges located along the slope are symmetric and occur subvertically, reaching 3.0–3.5 m in width, while those located perpendicular to the slope dip are generally asymmetric, much narrower, with a width of 1.5–2.0 m in the upper part and their bedding varies from inclined to subhorizontal. The enclosing sediments at the contact with ice wedges are deformed, with the deformations traced as upwards curved schlieren of segregated ice. Segregated ice is characterized by medium-bedded medium- and fine lens- or belt-like cryostructures. In places where silty sands are overlapped by peat lenses, the thickness of ice schlieren in silty sands declines from 2–3 to 0.05 cm, while the peat material is characterized by densely layered micro-schlieren cryostructure. The cross-section is generally represented by three-fold

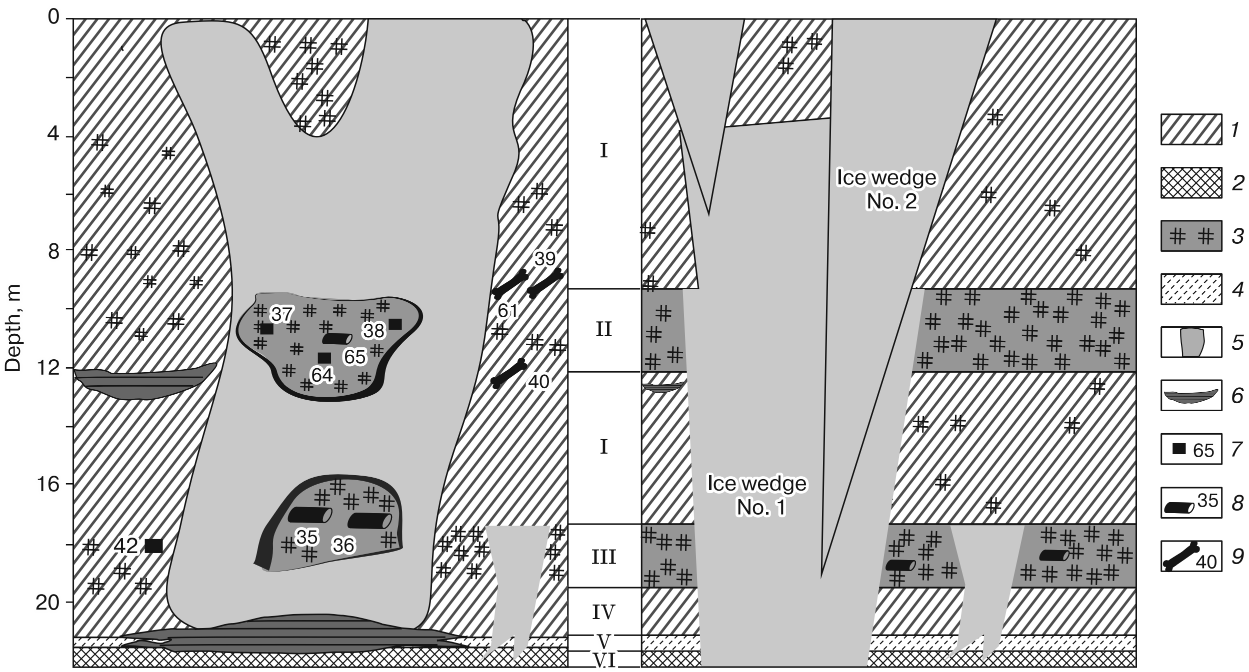

Fig. 7. Sampling points schematic and the structure of yedoma cross-section near Kular village.

I – solifluction-deluvial sediments; II – lacustrine-boggy sediments; III – alluvial-deluvial sediments; IV – deluvial sediments; V – alluvium; VI – eluvium. *1* – grey silty sand, frozen, peatified, with medium-to fine ice lenses lenticular cryostructure; *2* – medium to fine gravel with rubble; *3* – peat, frozen, with irregular reticulate and regular reticulate cryostructures; *4* – sand, black, fine, frozen; *5* – ice wedge; *6* – massive segregated ice. Sampling points (see Table 1) for: *7* – peat for ^{14}C-dating; *8* – wood for ^{14}C-dating; *9* – bones for ^{14}C-dating.

layering of silty sand units and peat lenses. The total moisture content of deposits averages 70–100 %.

The cryogenic structure of silty sands varies across different depth intervals, as follows: 17–12 m: lenticular layered (lenses up to 3 cm thick), complicated by 0.1 cm vertical ice lenses; 10.0–4.5 m: lenticular (ice lenses thickness: 2 cm); 4.5–0 m: grey silty sand, ice-poor, sparsely bedded, lenticular cryostructure with medium and fine ice lenses.

One of the ice wedges at the yedoma base has intruded into the bedrock eluvium composed by rubble, and, because of being thereby contorted, the direction of its growth changes. As such, the unusual shape of ice wedge, in our opinion, was caused by the eluvium debris acting as obstacles for frost cracks propagation. Given that this largely affected the orientation of frost cracks, ice wedges in the gravelly eluvium have a peculiar curved shape. Noteworthy is that syngenetic ice wedges of usual shape were reported from the intermountain basins of the upper Kolyma River [*Vasil'chuk, Vasil'chuk, 1998*]. In this case, they were completely buried in gravelly sediments slightly admixed with silty sand infill.

A lens of pure autochthonous peat occurring in the 10–12 m depth interval (this peat bog is probably the best descriptive of all Siberian yedoma sequences that the authors have come across) is accentuated by incompletely decomposed twigs of shrubs, roots, stems of grass and mosses in the primary occurrence, which bears evidence of autochthonous origin of peat. The peat lens is characterized irregular reticulate cryostructure, which indicates parasyngenesis (according to Katasonov), when all-out freezing (from side, from bottom up and from top down) takes place immediately after sedimentation. Fossil bones (fauna remains of horse, mammoth, and bison) were found in the peripheral part of the peat lens. It stands to reason that because of its huge thickness, the layer of peat could have accumulated in the conditions of lake-bog landscapes.

In the lower part of the section (the 19–17 m depth interval), fragments of birch and larch trunks were encountered in silty sands exposed to significant peatification. There are no signs of autochthonous origin, while heterogeneous plant remains are characterized by rather chaotic distribution.

Affected by slope processes, the axes of ice wedges were displaced during aggradation of the yedoma sequence, hence, the ice wedges were found to be displaced relative to each other by 1.2–1.5 m (Fig. 7), i.e. similarly to those described by Gravis [*1969*] in the Kyusentey River valley (Fig. 4).

Table 1. **Radiocarbon dating of organic material from yedoma sediments in the Kular cross-section**

Sample ID	Depth, m	Type of the dated material	^{14}C-age, years BP	Lab. ID	Calibrated age, cal yr BP
340-YuV/39	9.0	Bone	37 700 ± 600	GIN-4981	43 457–40 570
340-YuV/61	9.0	Horse bone	38 700 ± 1000	GIN-4965	45 896–40 660
340-YuV/38	11.0	hII, peat	Over 36 900	GIN-4980	–
340-YuV/38	11.0	Peat	Over 23 800	GIN-4980	–
340-YuV/64	11.2	hII, peat	33 300 ± 1100	GIN-4987	41 799–34 597
340-YuV/65	11.2	Twigs	42 400 ± 1000	GIN-4982	49 630–43 435
340-YuV/37	11.5	Peat	35 700 ± 1500	GIN-4979	45 935–35 911
340-YuV/40	12.0	Bone, skull	40 500 ± 1200	GIN-4964	48 864–41 890
340-YuV/35	17.6	Wood	41 100 ± 800	GIN-4977	47 244–42 769
340-YuV/36	17.8	Wood	Over 43 700	GIN-4978	–
340-YuV/42	18.0	Peat	Over 40 000	GIN-4983	–

Note. hII is hot alkaline extract.

Radiocarbon dating

Radiocarbon dating was performed at the Radiocarbon Laboratory of the Geological Institute of the Russian Academy of Sciences, with participation of L. Sulerzhitsky. Statistical parameters were derived from the data processing with the use of STATISTICA 10 software package. A series of dates were obtained for pure peat (with only few mineral inclusions), for wood from twigs, as well as for bone remains (Table 1; Fig. 7). All radiocarbon (^{14}C) dates were calibrated using the OxCal calibration and analyst software, v. 4.3 [*Bronk Ramsey, 2009*], based on the IntCal13 calibration data set [*Reimer et al., 2013*].

Because of the limitations of the radiocarbon method, dating of wood and peat in the lower peat lens, at a depth of 17.8–18.0 m is all but impossible, however, at a depth of 17.6 m, the estimated age of larch trunk varied between 47,244 and 42,769 cal yr BP (Fig. 8). Thus, reliable ^{14}C ages were obtained only for the lowermost part of the yedoma cross-section (the lowest 10 meters), which abounds with diverse organic material. Considering the slope depositional pattern, the dates obtained for wood, bone material and pure peat are generally consistent, i.e. the sediments accumulated synchronously in slope depositional environments may be localized in different parts of the slope.

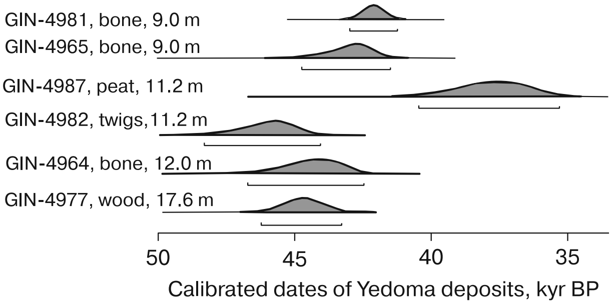

Fig. 8. Time intervals of yedoma deposits accumulation near Kular village according to ^{14}C-dating of bones, peat and wood.

Calibrated according to: [*Bronk Ramsey, 2009; Reimer et al., 2013*].

History of the yedoma sequence accumulation

Results of the ^{14}C dating (Fig. 7, 8) demonstrated that the initiation of yedoma formation in the analyzed cross-section correspond to ca. 47(50),000 cal yr BP.

Wood recovered from a depth of 17.6 m was dated to ca. 47,000 cal yr BP, while peat from a depth of 11.2 m – to about 37,000 cal yr BP, i.e., yedoma deposits aggraded at a rate of about 0.7 m per 1 thousand years (this estimate is largely tentative, inasmuch as sedimentation regime changed significantly throughout the time of the sequence accumulation). Such a rate of vertical growth of ice wedges and enclosing sediments was interpreted by the authors to be constant for the Kular yedoma. It can be assumed that the uppermost 11 meters of the enclosing sediments accumulated during a time period spanning at least 10,000–17,000 yr BP. Proceeding from the fact that large syngenetic wedges incepted as accumulation of peat and then silty sands and clayey silts, the period of their formation can be attributed to the interval straddling ca. 37,000–25,000 cal yr BP. Hence, accumulation of yedoma deposits had ceased not earlier than 25(22),000 cal yr BP, and probably later, inasmuch as the topmost unit has not been dated.

Most likely, intensive accumulation of peat which began about 47,000 cal yr BP, caused active synchronous growth of wedge ice which often intruded into the underlying eluvium. Intensive inundation probably occurred either within the polygonal ice wedge systems or in topographic lows. The erosion basis lowering ca. 42,000–40,000 cal yr BP entailed accumulation of solifluction silty sands that overlaps the low-level peat bog in the cross-section. Ice wedges appear to have ceased to grow at that time, despite the harsh geocryological conditions that marked the period of formation of silty sands. About 37,000 cal yr BP, the erosion basis elevated again, which prompted accumulation of a thick peat layer and re-activation of the growth of ice wedges. The parameters characterizing the upper layer of peat bog include: its thickness in excess of 2 m; clear peat showing no mineral inclusions; *in situ* distribution of plant remains; peat material of probably autochthonous origin. To the authors' knowledge, there are no such thick autochthonous peat mantles of Late Pleistocene age in the northernmost permafrost regions. The accumulation of peat remarkably involves a combination of favorable factors, such as sufficiently high temperatures during the growing season and optimal moisture content. The phenomenon of frost cracking, whose episodes may have been quite common, resulted in extensive and deep fissuring, thereby promoting penetration of the middle-tier wedges to a depth 6–8 m and more. The tips of many newly formed mid-tier wedges reached the surface of the buried lower-tier wedges, to coalesce into a unified ice wedge. Given different penetration depth of the tips of newly formed wedges, some of them did not reach the earlier buried wedges. This process became recurrent concomitantly with silty sands accumulation 33,000–27,000 cal yr BP, which translated to intensive growth of ice wedges in width beginning ca. 27,000 cal yr BP. The largest wedges that formed during this period also intruded and merged with the previously formed ice-wedge complex, whereas the smaller ones or those standing somewhat apart formed independently.

The research results describing the structure of the studied yedoma cross-section near Kular village, as well as its comparison with region-specific yedoma structures, suggest a remarkable activity of deluvial solifluction processes involved in the formation of yedoma sequences next to alluvial and lacustrine-boggy sediments. Ice wedges aggraded on par with deposits accumulation. Initially, deposition of sediments hosting ice wedges occurred across the riverbed and floodplain facies, while involvement of slope processes was characteristic of the entire region at later stages. Structural analysis of the cross-sections revealed numerous similarities between the Kyusyuntey River valley slope [*Gravis, 1969*] and the Kular River slope sediments. Thus, a black fine-sand interlayer corresponds to the Burguat River alluvium, while formation of the overlying layer of peaty silty sands with tree trunks probably involved floodplain alluvium and deluvial solifluction sediments. This strongly suggests that the lens formed as a result of slope deposits slumping and their superimposition over alluvial sediments. The presence of woody vegetation in the interval spanning 47,244–42,769 cal yr BP reflects depositional environments affected by fairly high temperatures of the growing season (sufficient for the growth of trees), which activated the slope processes, although in places where woody vegetation was present, conversely, the slope processes may have been slowed down. Thus, accumulation of the yedoma slope tended to be more intense during warm summer seasons. During this period, besides the Kular ridge area, woody vegetation became also seen in the north, on Kotelny island [*Galanin et al., 2015; van Geel et al., 2017; Vasil'chuk et al., 2019*] and Bolshoy Lyakhovsky Island [*Wetterich et al., 2014*]. Twigs of shrubs were dated to 49,630–43,435 cal yr BP, lying approximately within the same interval [*van Geel et al., 2017*]. Note that such mild climate ("climatic optimum") conditions of early MIS 3 were defined by Wetterich and colleagues [*2014*] within the 48,000–38,000 cal yr BP interval for Bolshoy Lyakhovsky, and within 40,000–32,000 cal yr for the Lena River delta.

In addition to slope sediments, aggradation of wedge ice deposits in the Kular region was accompanied by syngenetic accumulation of yedoma deposits in river valleys. In the cross-section of Soplivyaya Gora (195 km to the Yana River mouth), Basilyan and coauthors [*2015*] identified a total of 10 sedimentation cycles. The yedoma complex shapes the 40-meter surface area of the Soplivaya Gora cross-section and, in itself, represents a sequence of deposits exhibiting different facies types and containing syngenetic ice wedges that may reach 3–5 m or more in width. The sequence of sedimentation is highlighted by determinate up-section change in the lithological composition. The sedimentation cycles established by Basilyan and coauthors [*2015*] culminate in horizons with abundant organic matter, and are derived from the change in cryogenic structures associated with: i) corresponding levels of the cessation of ice wedge growth; ii) truncation of belt-like ice schlieren as a result of the ancient active layer base lowering or erosion which accompanies the formation of the overlying sediments. Alluvium of the second river terrace (16–18 m a.s.l.) composing a high, 40-meter surface, has cut into the sediments comprising the cultural layer of the Yana Palaeolithic site which dates to 28.5–27.0 ka BP [*Pitulko et al., 2004*]. Deposits of the second terrace in the lower reaches of the Yana River [*Pavlova et al., 2015*] are represented by syncryogenic sediments represented by the alluvium from the riverbed and floodplain facies with the polygonal ice wedge system divided into upper and lower ice-wedge generations and totaling 14–16 m in thickness. Initiation of both the intrusion [*Basilyan et al., 2015*] and accumulation of the yedoma deposits is attributed to ca. 40 ka BP. Ice wedges occur on level with the cultural layer of the Yana site at elevation of 7.5–8.0 m above the river's water line.

The most favorable conditions in the vegetation period according to palynological data were reported from ca. 42 and 40–32 ka BP [*Wetterich et al., 2008*] on Kurungnakh island in the Lena River delta, which corresponds to age of larch wood in the Kular yedoma cross-section 41 100 ± 800 years (47,244–42,769 cal yr BP). Noteworthy is that favorable conditions of the growing season were likely responsible for the intensified solifluction and deluvial processes, which caused both an increase in thickness of slope deposits related to this period, and peat bogs expansion in the region.

The descriptions discussed here, confirm an intensive formation of the yedoma complex throughout the Late Pleistocene cryochron in the foothills as well, rather than on the plains alone. A marriage of ice wedge complexes and organic material in the sequences is indicative of both a possible increase in winter severity, and some improvement in vegetation conditions during individual periods of the Late Pleistocene cryochron.

CONCLUSIONS

• The presence of Late Pleistocene multi-tier ice wedges in yedoma sequences whose accumulation involved inputs of slope material, is remarkable on hillslopes of the Kular ridge area (most often, in the cross-sections of terrace-ridges).

• At least two records of relatively high temperatures of the growing season during the Late Pleistocene have proven to be sufficient for existence of tree species.

• High rate of the solifluction material accumulation probably due to increased oversummer temperatures provided for considerable thicknesses of hillslope yedoma.

• Syngenetic ice wedges formed mainly during the two periods of the Late Pleistocene: 47–42 and 37–32 ka BP.

• An unusual shape of ice wedges in the lowermost part of the cross-section is associated with a change in the orientation of frost cracks diverted due to amassed debris inclusions.

• The hillslope ice wedges in the Kular ridge area are characterized by the ice wedges' axes displacement relative to the vertical position.

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