ECOSYSTEMS: ECOLOGY AND DYNAMICS, 2022, Vol. 6, No. 4, P. 89-104

DYNAMICS OF ECOSYSTEMS AND THEIR COMPONENTS

UDC 551.34 + 551.24

PALEOECOLOGY OF THE NORTH OF WEST SIBERIA IN THE LAST EPOCH OF THE PLEISTOCENE: NEW EVIDENCES AND SCENARIOS

© 2022. V.S. Sheinkman*, **, *, S.N. Sedov*, **, ****, E.V. Bezrukova*******

**Earth Cryosphere Institute of the Tyumen Science Center of the Siberian Branch of the Russian Academy of Sciences*
Russia, 625026, Tyumen, Malygin Str., 86. E-mail: vlad.sheinkman@mail.ru

***Tyumen State University*
Russia, 625003, Tyumen, Volodarskiy Str., 6. E-mail: serg_sedov@yahoo.com

****Tyumen Industrial University*
Russia, 625000, Tyumen, Volodarskiy Str., 36

*****Institute of Geology of the National Autonomous University of Mexico*
Mexico, CdMx C.P.04510, Mexico City, University campus, Del. Coyoacán

******A.P. Vinogradov Institute of Geochemistry of the Siberian Branch of the Russian Academy of Sciences*
Russia, 664033, Irkutsk, Favorski Str., 1a. E-mail: bezrukova@igc.irk.ru

Received December 01, 2022. Revised December 10, 2022. Accepted December 15, 2022.

In this article we present the materials in respect to the Quaternary paleocryological, paleosols and paleobotanic development in the north of the West Siberian Plain. Data demonstrating wide distribution of polygonal-wedge structures in the region are elucidated. The structures represent polygonal ice wedge pseudomorphs and initially ground wedges. The former developed in the terminal phase of the Pleistocene in the end of marine isotope stage[1] 2 (MIS-2), and are the successors of the epigenetic polygonal ice wedges which cut the Karginian (MIS-3) alluvial mass, whereas the second formed in the syncryogenetic alluvial deposits in the course of MIS-3. Redeposited material of cryohydromorphic paleosols has been revealed in the filling of the pseudomorphs; fragments of humus horizon are included – they are used for ^{14}C-dating. Spore-pollen spectrum in that filling shows prevalence of boggy tundra and tundra-steppe vegetation. The set of obtained data casts doubt on hypothesis of prevalence of cold deserts and ice sheets in the study area and shows existence of developed vegetable cover at a background of sufficient and, in places, superfluous moistening. It occurs on account of close position of the permafrost roof. Also the inference in respect to non-glaciated development of the region in the cryochrons, which are similar to MIS-2, is concluded.

Keywords: permafrost, paleocryogenesis, polygonal-wedge structures, paleoecology of West Siberia, spore-pollen spectra, Pleistocene paleosols, polygonal ice wedge pseudomorphs.
DOI: 10.24412/2542-2006-2022-4-89-104
EDN: HRMOLP

Various kinds of cold environment with the developing permafrost and other related phenomena become the main paleoecological markers of the Quateкrnary in the north

[1] Marine isotope stages (oxygen isotope stages) or MIS are alternating warm and cold stages in the history of the planet's climate that reflect temperature changes. They are classified by the content of oxygen isotope and obtained from deep-sea cores. MIS-2 (Fig. 2) corresponds to the cold stage at about ~27-12 thousand years ago; MIS-3 corresponds to the warm stage at about ~60-27 thousand years ago; MIS-1 corresponds to the warm stage in the interval from 12 thousand years ago to the present days. The stages from MIS-1 to MIS-5 ae parts of the last ~100 thousand years climate cycle, while MIS-6 corresponds to the time period ~185-125 thousand years ago (Fig. 2), reflecting the events of the previous ~100 thousand years climate cycle (Editor's note).

of West Siberia. This is determined by the specific formation of the natural environment of this region (Sheinkman et al., 2020). The traces of these phenomena can be reliable indicators for the ecosystems that formed in this region at different points of the Quaternary. Therefore, the analysis of paleocryogenic indicators is especially important for the environmental reconstruction of the last cold time of the Pleistocene, which corresponds to the marine isotope stage 2 (MIS). In recent decades the borders of the ice sheets that formed in that time have been revised and it is generally believed now that the north of the West Siberian Plain had no ice sheets at all. This belief is shown in a number of generalized paleogeographic maps (Velichko et al., 2011; Svendsen et al., 2014). The present authors explain the absence of glacial cover in the region and the dominance of deep freezing in the rocks for the entire Quaternary (Sheinkman et al., 2017, 2020). There is also a question concerning the past of the ecosystems in that cold, continental and ice-free region, since the opinions differ a lot. For example, some authors (Velichko et al., 2011; Zykina et al., 2017) suggested that the said period had the same scenarios with the Antarctic deserts, with extremely cryoarid conditions. Therefore, it is discussed what type of cryogenesis was natural for the area. Our analysis showed the improbability of extreme phenomena related to cold deserts or glacial sheets in the said region. We made these conclusions by giving the dominant properties to the subordinate elements of cryogenic systems, instead of the main elements, and we discuss them further below.

Materials and Methods

When talking about the north of Siberia, we usually mean the area located north of the middle course of the Ob’ River which oriented in the latitudinal direction (Fig. 1). The results of our research explore the events of MIS-3 – MIS-1 (Fig. 2). However, since the depth and volume of the main cryochrons and thermochrons[2] on the paleoclimatic scales of the Quaternary were similar, and since they were approximately the same during MIS-1 – MIS-6 (Lisiecki, Raymo, 2005), then our results can be used as a reference basis for assessing the events of the entire Quaternary, whereas the objects of the research are paleocryogenic structures and pedosediments.

In the studied area we revealed the wide development of polygonal wedge structures (a very informative indicator of the past permafrost zone) and their connection to the cryohydromorphic buried paleosol soils that were naturally present in the region and are discovered there for the first time. During cryochrons these soils were zonal and distributed over the area (Sheinkman et al., 2016, 2021; Sedov et al., 2022), which was impossible in the conditions of cold desert. Moreover, we found out that polygonal ice wedge pseudomorphs were widely developed there and they succeed the polygonal ice wedges, fed by thawing water, which is absent in the hyperarid conditions of cold deserts. In our case, the indicative properties of buried soils and pseudomorphs succeeding the polygonal ice wedges clearly demonstrated that cryoarid conditions with a low-temperature permafrost zone did, in fact, exist during the cryochrons. However, in addition to a long and cold winter with scarce snow, their main features was a warm, albeit short summer, which determined the well-defined seasonally thawing layer and the feeding of polygonal ice wedges achieved through thawing and rainfall, even when their amount was limited.

The buried Pleistocene soils in the studied region have not been studied enough. Besides, whenever the formation of ice sheets was considered as the basis for the development of nature in the past, no search for relicts of buried soils was carried out, because the mere existence of such soils under the ice sheets was negated. Another issue is that the cryohydromorphic buried soils, which should naturally form under cryochron conditions (Goryachkin et al., 2019), are rarely found

[2] Cryochron and thermochron are time intervals in the climate history that correspond to major cold and warm climate stages, which, in their turn, correspond to glaciations and interglacial periods. Usually they are distinguished when interpreting the events of the Quaternary Period (Editor’s note).

in this region in their original form, instead manifesting themselves as reduced relics. Meanwhile, their representative form is preserved as the redeposited pedodeposits in the pseudomorphs filling along the polygonal ice wedges. In many cases, however, the redeposited soils contain fragments of humus horizons with enough organic matter to perform radiocarbon dating. Moreover, we were able to obtain a number of representative spore-pollen spectra from pseudomorphs fillings.

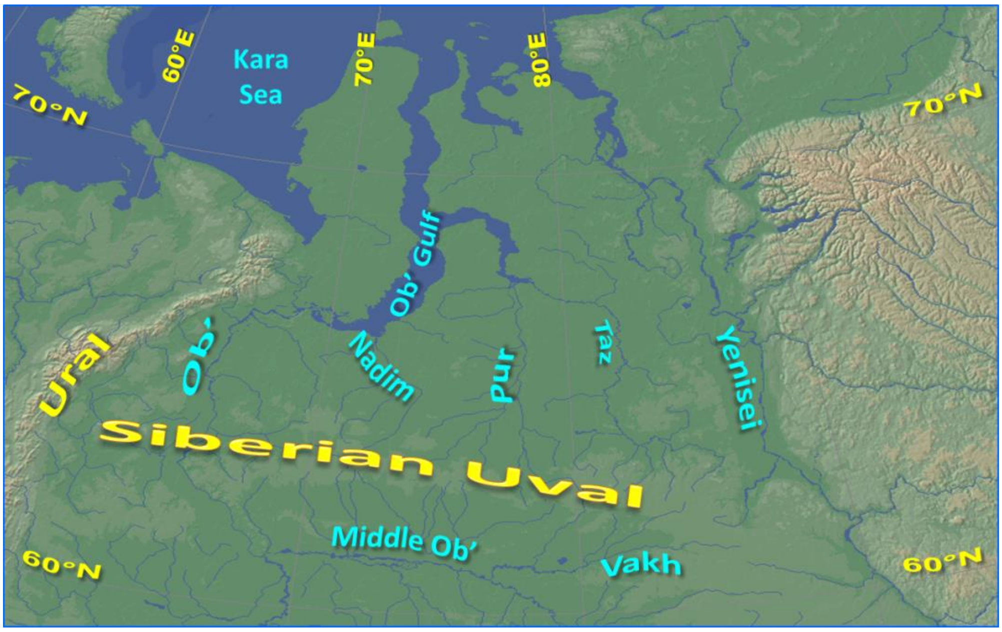

Fig. 1. Schematic map of the north part of West Siberia.

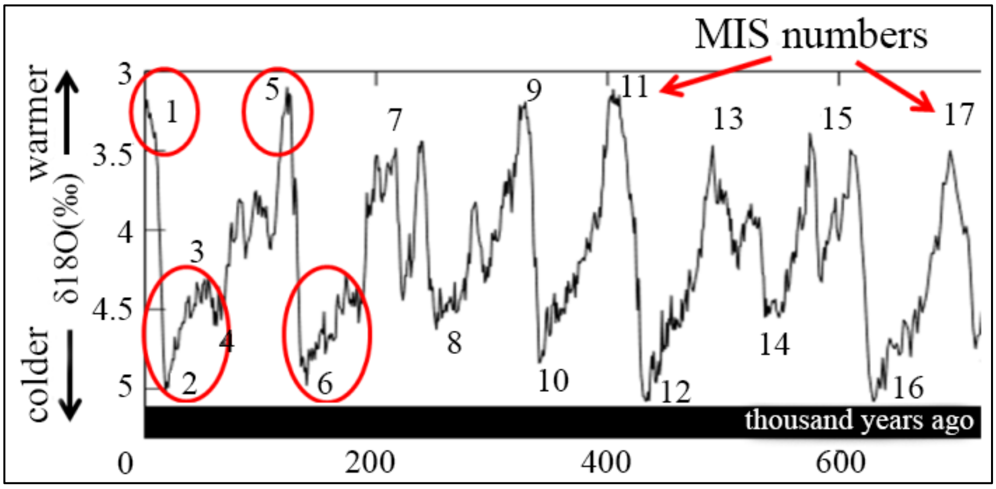

Fig. 2. Paleogeographical records for the second half of the Pleistocene (Lisiecki, Raymo, 2005); cryochrons and thermochrons in the end of the Pleistocene are marked with red circles.

Results and Discussion

Below we discuss the mentioned phenomena, using the representative objects of the lower reaches of the Nadym River. On its left-hand bank, where it meets the Kheygiyakha River, there is a quarry with a wide range of paleocryogenic, pedogenic, and postcryogenic formations (Fig. 3).

There the river cuts into the plain adjacent to the Gulf of Ob, forming 15-20 m terraces of the second above the floodplain terrace category, when the water level is about 10 m. The quarry exposes the sand body of one terrace that has formed in the second half of MIS-3, while being dissected by polygonal ice wedges during MIS-2 (Sheinkman et al., 2022; Sedov et al., 2022).

However, different authors (Zykina et al., 2017; Sheinkman, Melnikov, 2019) interpret the structure of deposits exposed in the quarry wall in different ways, because in some models the input elements that are used as the dominant ones are not dominant at all. And this is unacceptable for their interaction.

This terrace is covered by an active dune (Fig. 3). Earlier A.A. Velichko et al. (2011) suggested that this area was the cold desert with active aeolian processes that formed in the MIS-2 cryochron in the north of West Siberia. This was substantiated by the eolian traces that the authors (Velichko et al., 2011) had found in the sands under the Holocene peat lands However, this is a local phenomenon common for alluviums without the dominance of desert ecosystems in many areas of the low-temperature permafrost zone (Galanin, 2021). After a morphoscopic analysis of quartz grains in the MIS-2 deposits, we revealed (V. Sheinkman et al., 2022) that suggested eolian participation as well, however, not of a prevailing kind. The sedimentation process had cryogenic, wind, and fluvial impacts. The watercourses under the MIS-2 conditions, i.e. during the cold and dry cryochron, were not covered with ice in summer, feeding on the thawing snow and rain waters, while the upper horizon of the frozen mass had a seasonally thawing layer in it.

However, V.S. Zykina et al. (2017) emphasized the development of the cold desert in the region during the MIS-2 by wrongfully (from the standpoint of paleocryological development) giving the dominant role to the sub-elements of their model. The dune, mentioned by V.S. Zykina (Fig. 3), is recognized as a factor for the active material movement specifically under the conditions of a cold desert, while being a young form that sprung up on the site of a burnt forest and partially covered a well-developed Podzol that indicated the occurrence of taiga ecosystems (Sheinkman, Melnikov, 2019). The authors (Zykina et al., 2017) also classify the polygonal wedges as primary sandy wedges, the ones that indicate the extremely cold and dry conditions. However, their designation was based only on the individual external features of the polygonal structures, such as the small height, narrowness and sandy or sometimes streaky filling, whereas the main features that signify the development of polygonal ice wedges in the low-temperature of permafrost zone with active thawing water, were not discussed at all.

The first and foremost feature in our case is the forming the cryohydromorphic buried soils with a basis on the bottom of the former seasonally thawing layer between the polygonal wedge structures conjugated with the framing of the polygonal ice-wedge pseudomorps (Sheinkman et al., 2022; Sedov et al., 2022). At the same time V.S. Zykina et al. (2017) suggested to use the hyperarid and supercold region of the Dry Valleys of Antarctica as an analogue of the regional development model. The Dry Valleys are a unique place in the south of Antarctica, with extremely low annual air temperatures and absence of atmospheric precipitation, the conditions that prevent thawing of permafrost; therefore ~~their~~ its roof is leveled with the day surface (Abramov et al., 2011). Such occurrences would be impossible in the past of the studied area.

The clearing of the quarry revealed that some of the polygonal wedge structures (Fig. 3) were narrow, but all of them radically differed from the primary sand wedges ~~veins~~, which were first described in Antarctica as sand wedges embedded in coarse-grained deposits (Pewe, 1953). The height of the largest structures in our case was 2-2.5 m, with the width at the top reaching 1.5 m; their contours were conjugated with the base of the cryohydromorphic buried soil, therefore showing the previous level of the seasonally thawing layer. The relics of these soils were clearly noticeable 1 m below the day surface as a bluish, several centimeters thick horizon, with a brown border below and rich with humus.

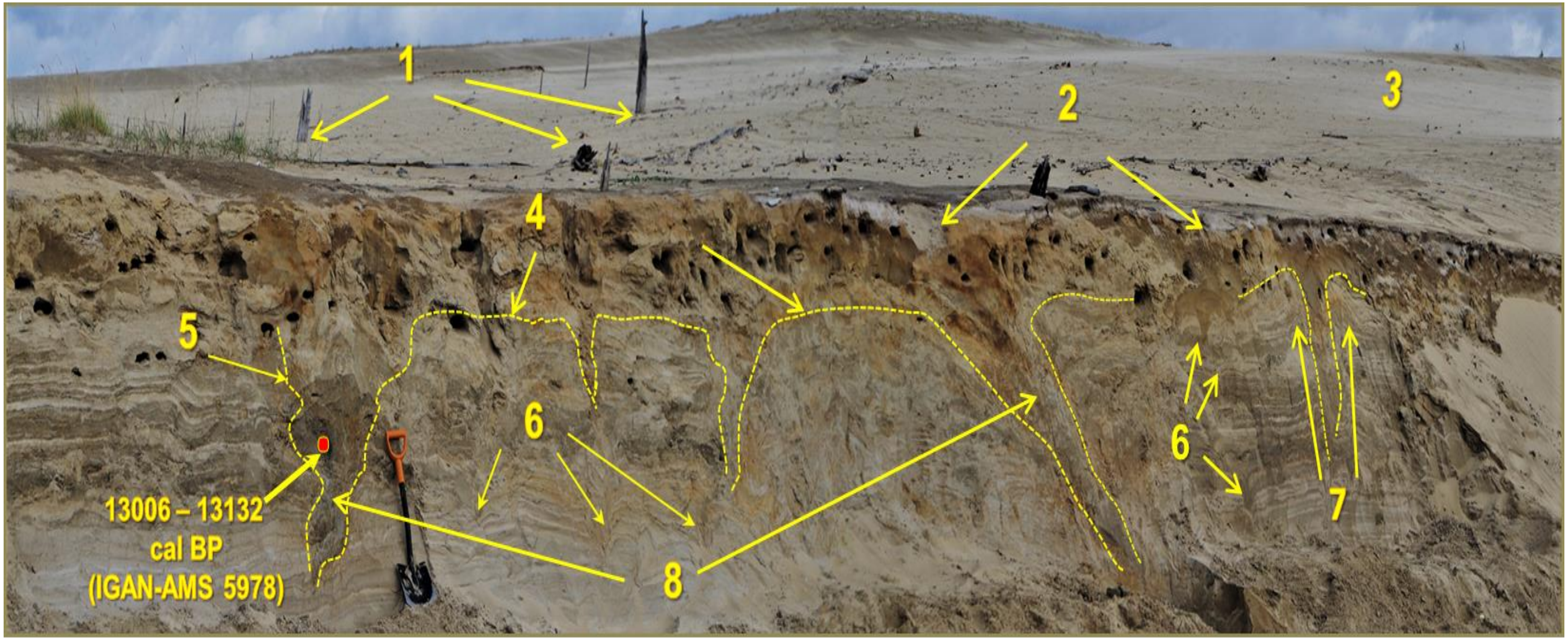

Fig. 3. Stripping quarry wall on the left-hand bank of the Nadym River near the mouth of the Kheigyiakha River (photo from V.S. Sheinkman's archive). *Legend:* 1 – remains of a burnt forest, 2 – current Podzol and its pockets along the pseudomorphs axis on the polygonal ice wedges, 3 – sand dune, 4 – base of the relic cryohydromorphic soil, 5 – outlines of polygonal ice wedge pseudomorphs, 6 – buried initially ground wedges, 7 – traces of layers being squeezed, 8 – polygonal ice wedge pseudomorphs, with pedosediments in their filling.

The development of these soils is reflected on the matrix of permafrost rocks, where the freezing deposits would stabilize, switching from the process of floodplain accumulation to the state of a stable terrace (Sedov et al., 2022).

The signs of a former, well-pronounced seasonally thawing layer are emphasized by cryohydromorphic soil, indicating the impact of thawed waters that soak the upper alluvium layers and penetrate the cracks, thereby confirming that the polygonal wedge structures are, indeed, the polygonal ice wedge pseudomorphs. According to N.N. Romanovsky (1977), they preserve the outlines of former polygonal ice wedges in the deposits with low ice saturation, which is true for our case as well.

Figure 3 shows that the pseudomorphs are of a distinguished triangle shape, narrow in their middle and bottom, wider at the top, squeezed upwards and outwards where they touch the surrounding sediment rock, with the slightly smoothed ridges above the heads of the veins. This is a typical image of the polygonal ice wedge development under the stabilization of the day surface they cut through (Popov et al., 1985). It also implies their epigenetic nature, while the streaky structure of pseudomorphs can be explained by the specific ways of their development.

Cryohydromorphic soils that are partially reduced by the illuvial horizon of the surface Podzol above (Fig. 3) can be clearly seen in the filling of the pseudomorphs in the form of frozen buried pedosediments that slid down from the space between the wedges, together with the sedimentary rocks, along the walls of thawing polygonal ice wedges. This explains the well-pronounced subvertical streaks in the structure of the pseudomorphs which, in our opinion, was caused in the past by the structures, similar to polygonal sand-ice wedges, currently common in the north Yakutia and described as sandy-icy wedges by A. Yu. Derevyagin et al. (2010). The outlines of the precursors of the pseudomorphs along these structures are preserved even better and have a more pronounced streaky structure.

We analyzed the humus filling of the pseudomorphs and carried out ^{14}C-dating. The results showed that the pseudomorphs began to fill during the terminal phase of the Pleistocene, i.e. 15-16 thousand years ago, during an early manifestation of climate warming at the end of the MIS-2 cryochron, but with the permafrost still present (Sedov et al., 2022). The polygonal ice wedges require the permafrost conditions with ground temperatures from –5°C to –6°C for their development of in the sands (Romanovsky, 1977). When the temperatures become higher, but remained negative in the permafrost, the ice substance of polygonal wedges and sand-ice wedges began to thaw, allowing the fragments of cryohydromorphic soil and sedimentary rock to slide down the walls of the wedge and freeze along them, layer by layer.

Figure 3 shows other wedge structures, located at different depths much closer to each other and reaching up to 1 m. The bottom layers of the surrounding rock curl downwards, gentle at the top and then smoothly merging with the horizontal deposits above. These features mean there are initially ground wedges forming in the active layer (Romanovsky, 1977). They indicate that the ground wedge deposits of the MIS-3 were frozen, while the temperature was higher than the level required for the development of polygonal ice wedges, and therefore the deposits accumulated under conditions of an unstabilized terrace surface, turning into syncryogenic formations. By the moment the cryohydromorphic soil started to form (during MIS-2), the surface of this sedimentary body had already stabilized (otherwise the soil would not have formed) and acquired some epigenetic formations of polygonal ice wedges that cut through and thawed at the end of MIS-2 to be replaced by pedodeposits, or the derivatives of cryohydromorphic soil. By the Middle Holocene a significant part of the frozen mass thawed, as evidenced by well-pronounced Podzols in its top part. According to V.O. Targulyan (1971), they are distinguished by their development under conditions of good aeration and free drainage, which means that they were formed only after the sedimentary rocks had almost thawed and the former permafrost aquiclude had disappeared, fixed by the base of cryohydromorphic buried soils before that. A series of radiocarbon dating (^{14}C) carried out for the humus substance of these Podzols proves as well that it happened in the Middle Holocene (Sedov et al., 2022; Sheinkman et al., 2022); some of the radiocarbon dating (^{14}C) results are shown in Figures 4 and 5.

A clearer situation was observed in the lower reaches of the Nadym River, 5 km north of the Pangody Village, where the Tyyakha River flows into the Pravaya Khetta River (the right-hand tributary of the Nadym River), creating a 10-meter terrace (Fig. 4). The terrace is composed of Karginian (MIS-3) alluvium, which was confirmed by a series of radiocarbon dating (^{14}C), one of which is shown in Figure 4-B. The terrace is dissected by a network of MIS-2 pseudomorphs formed along the polygonal ice wedges (Fig. 4-A, which is better seen on the cleared quarry wall a few hundred meters from the terrace edge (Fig. 5). Those pseudomorphs were quite large, of various shapes, up to 4 m high and 3 m wide. Their filling was grayish as well, with a brown border between them and the cryohydromorphic soil above. Aside from polygonal ice wedges, pseudomorphs we found the initially ground wedges buried at different levels, which confirms for some time the MIS-3 deposits were freezing under the high-temperature permafrost conditions or, at least, at the temperature higher than the threshold required for formation of polygonal ice wedges.

Similar observations were made on the opposite, eastern flank of the plain that adjoins the Siberian Uval from the north; namely, in the basin of the upper Taz River, in the wright-hand bank of the Pyulky River. These pseudomorphs are large (Fig. 6), stretched along the former Sartanian (MIS-2) epigenetic polygonal ice wedges and created in the upper part of the thickness of alluvial deposits, the age of which is 30-45 thousand years old according to radiocarbon dating (^{14}C). Similar to the previous cases, the dating determined the Karginian age (MIS-3) for this mass as well. The Sartanian age (MIS-2) of the polygonal ice wedges that cut through them was determined on the basis of the radiocarbon dating (^{14}C) carried out for the filling material of pseudomorphs that inherit these ices; according to it, the range is 10-13 thousand years ago (Fig. 6).We collected unique paleobotanical materials from this profile (Sedov et al., 2022), and even though only 4 samples contained spore-pollen spectra, in which the calculated number of pollen grains and spores exceeded 100 pieces (from 106 to 502), the reasonable interpretation was made nevertheless.

Sample 1 (Fig. 6) was taken from the surface, recently formed Late Holocene deposits. The composition of its spore-pollen spectrum shows the prevailing forest vegetation, which was formed by spruce-cedar forests with a predominance of Siberian spruce (*Picea obovata*[3]), Siberian pine (*Pinus sibirica*), as well as participation of Scots pine (*Pinus sylvestris*) and tall birch (*Betula alba*), and sometimes with Siberian fir (*Abies sibirica*). The shrub communities were formed by shrubby birch (*Betula nana*) and alder (*Alnus alnobetula*). The forb-shrub layer in the spore-pollen spectrum is represented by the rare encounters of heather (*Ericaceae*) and the small amount of anemogamous forbs, such as sagebrush (*Artemisia* spp.), as well as goosefoot (*Chenopodiaceae*). These data matches the vegetation structure of the modern middle taiga ecosystem of this territory.

Sample 2 was collected from the filling of the largest pseudomorphs formed along the polygonal ice wedges (Fig. 6). It characterizes the thin forest stand, presumably, of the forest-tundra landscape, with patches of spruce, birch, alder and willow. The dominant species are the ones common for the waterlogged wetland landscapes, i.e. horsetail-sphagnum moss-sedge forb-shrubby tundra, including the pollen samples of *Alnus alnobetula, Salix* spp., *Poaceae, Cyperaceae, Polemonium* sp., *Polygonaceae* ind. and *Polygonum bistorta*. Additionally, club moss (*Huperzia arctica* (Tolm.) Sipl. (=*H. petrovii* Sipl.)) and *Meesia* mosses are very abundant there, characterizing the development of tundra vegetation and lowland sedge bogs. It is possible that Poacea could also be present in forb tundras and steppe areas. The diversity of forbs which currently form the steppe vegetation in the area and which are present in the pollen samples, indicate the significant development of steppe associations: *Artemisia* spp., *Chenopodiaceae, Asteraceae, Caryophyllaceae, Onagraceae, Fabaceae* and *Polygonum bistorta*.

[3] The Latin species, genera and families are provided according to The World Flora Online (WFO, 2022).

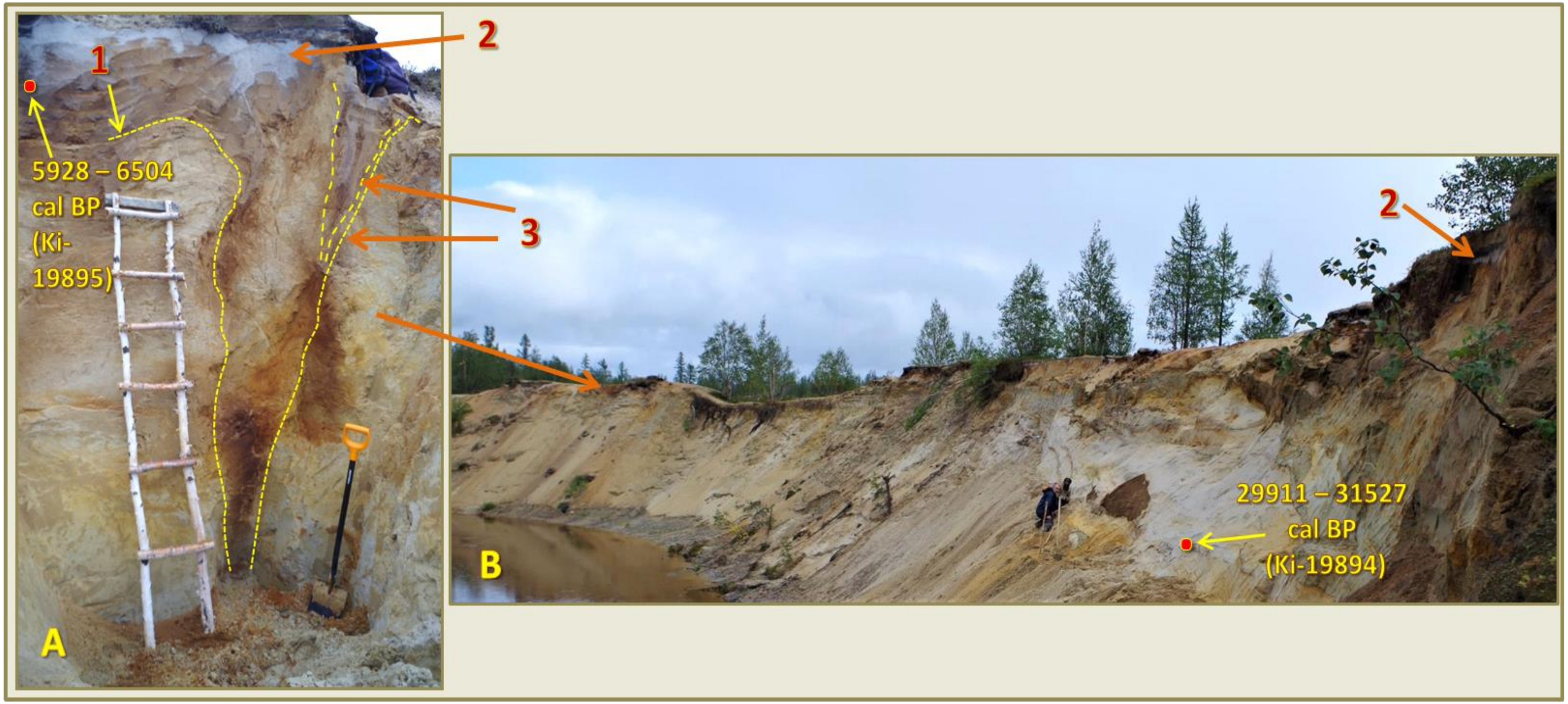

Fig. 4. Stripping wall of the terrace at the wright-hand bank of the Tyiakha River (photo from V.S. Sheinkman's archive). *Legend:* 1 – base of the relic cryohydromorphic soil, 2 – current Podzol, 3 – outlines of polygonal ice wedges pseudomorphs of different generations.

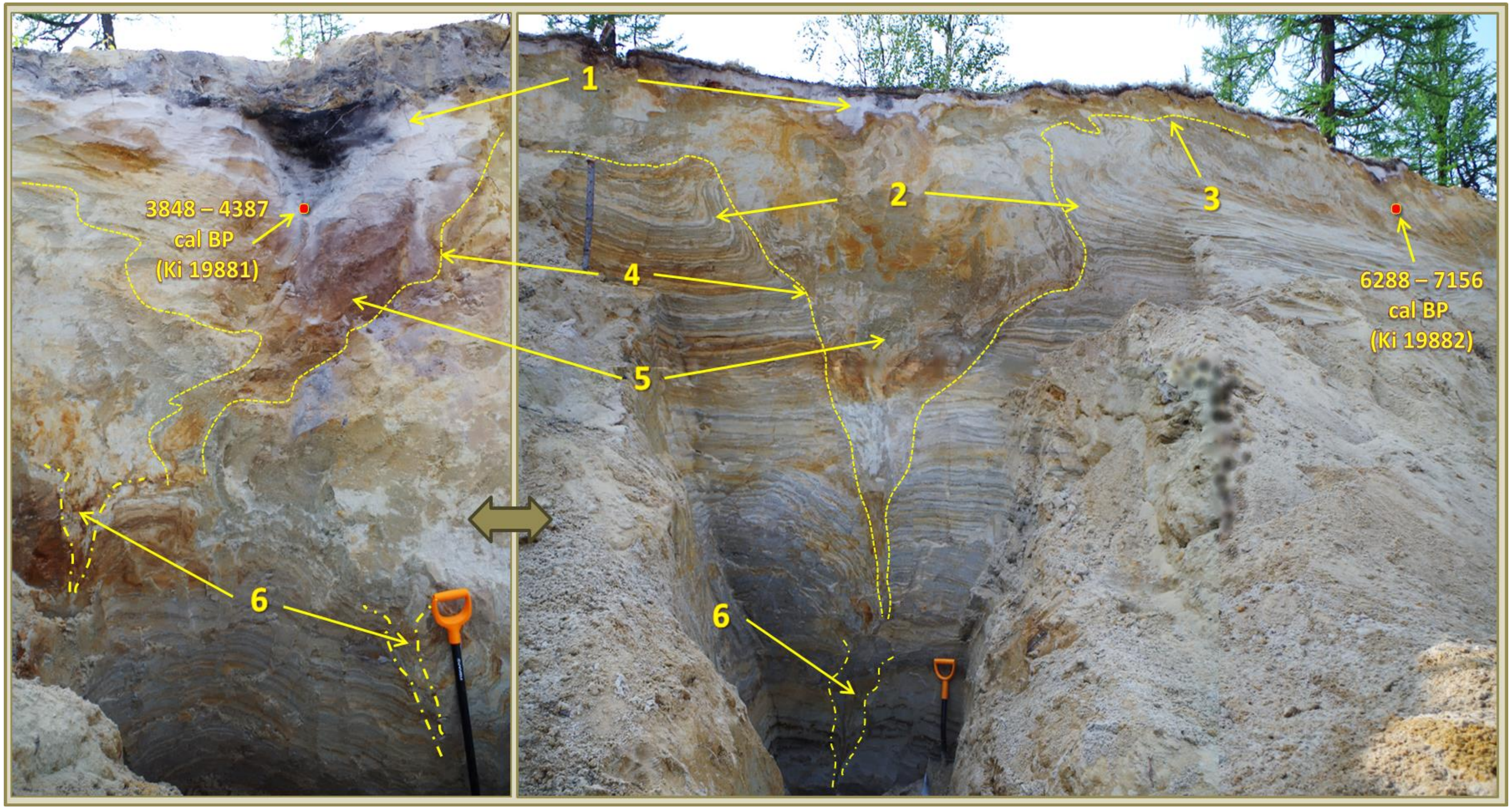

Fig. 5. Stripped quarry wall near the Tyiakha River (photo from V.S. Sheinkman's archive). *Legend:* 1 – surface Podzol and its pockets over the polygonal ice wedge pseudomorphs, 2 – traces of layers being squeezed, 3 – base of the relic cryohydromorphic soil between the polygonal ice wedge pseudomorphs, 4 – borders of the polygonal ice wedge pseudomorphs, 5 – body of the polygonal ice wedge pseudomorphs, 6 – buried initially ground wedges.

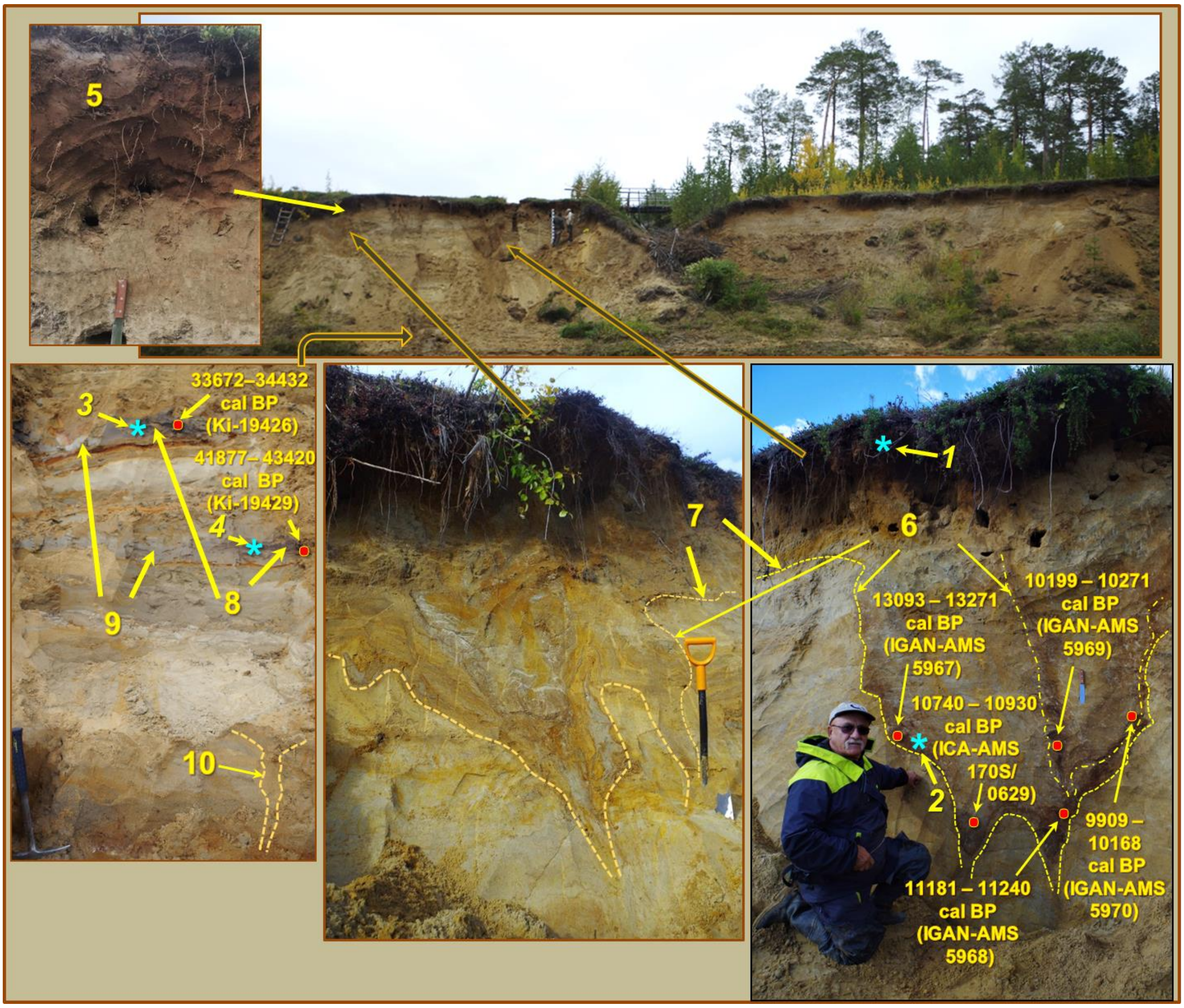

Fig. 6. Pyulky object (photo from V.S. Sheinkman's archive). *Legend:* 1-4 – sample sites for spore-pollen analysis, 5 –modern soil, 6 – outlines of polygonal ice wedge pseudomorphs of different generations, 7 – base of the relic cryohydromorphic soil between polygonal ice wedge pseudomorphs, 8 – inclusions of organic detritus, 9 – Karginian buried soils of different generations, 10 – buried initially ground wedges.

Therefore, when this sample was prepared the vegetation was mosaic due to a mix of forest-tundra, tundra, steppe (possibly, of slope kind) types.

In the lower part of the alluvial terrace sequence at the Pyulki object we detected two layers enriched in organic detritus. We suppose they are incipient syn-sedimentary alluvial paleosols. We found those two paleosols in the alluvial deposits of this outcrop, located 60 cm and 150 cm above the water surface of the river (Fig. 6). According to radiocarbon dating (^{14}C) of the humus substance taken from these buried soils, they belong to the Karginian period (MIS-3). With the syncryogenic accumulation of alluvium in the background, these buried soils experienced noticeable that their formation, while the alluvium surface stabilized within the floodplain for some time from one flood to another. This process ensured the accumulation of spores and pollen in the soils composition, which now reflects the nature of the landscapes. We obtained the samples for spore-pollen analysis from the buried soils as well.

The amount of forb pollen in the general composition of the spore-pollen spectrum that was acquired from the Sample 4 (Fig. 4), at the bottom of the profile or 60 cm above the water edge, is slightly higher than the amount of tree species. The composition of tree pollen implies that the local forest vegetation was formed mainly by spruce and birch. A noticeable content of *Pinus sylvestris* indicates that it was present in the warm, relatively dry areas, the grass cover of which consisted of modern steppes, such as *Artemisia* spp., *Poacea*, *Chenopodiaceae* and *Caryophyllaceae*. Meanwhile, wet sphagnum-sedge groups were very limited.

Sample 3 was collected higher on the profile, from another buried soil, 150 cm above the water edge (Fig. 6). Its spore-pollen spectrum is dominated with forbs, while the amount of trees is less significant. Similar to the previous sample, acquired 1 m lower, the composition of tree pollen suggests that patches of local forest vegetation were formed by *Picea obovata* and *Betula alba*. The amount of *Pinus sylvestris* pollen here is half as much in this sample, which means either its reduced participation in the local vegetation or the fact that its border started to move southward, indicating the beginning of permafrost. The increased amount of modern tundra shrubs pollen (*Betula nana*, *Alnus alnobetula*, *Salix* spp.) signifies an expansion of their range near the profile. Additionally, the role of humid, water-logged sphagnum-sedge groups increased. The high share of pollen from plants of steppe and/or disturbed habitats suggests the presence of relatively dry areas that used to warm up during summer and had species from modern steppes in their herbaceous cover, such as *Artemisia* spp., *Asteraceae*, *Chenopodiaceae*, *Caryophyllaceae* and *Onagraceae*.

Generally speaking, the spore-pollen spectra in the deposits of MIS-3 and late MIS-2 are relatively similar and reflect the nature of landscapes with permafrost rocks that existed at temperatures above those required for polygonal ice wedges formation. A slightly increased temperature drop took place in this territory during the first half of MIS-3, which was recorded by the spore-pollen spectrum from the Sample 4. It is an indirect evidence of a gradual transition from cold MIS-4 to warm MIS-3 (Fig. 2).

Either way, the spore-pollen spectra and the nature of the polygonal vein structures show that in the Karginian period (MIS-3) the landscapes had not yet acquired those features favorable for the development of polygonal ice wedges and the temperatures had not yet passed the value threshold required for polygonal formations. At that period only easily traced layers of initially ground veins (Fig. 3-6), the precursors of polygonal ice wedges, were forming in the alluvial mass during the progressive climate cooling. The temperature of rocks formations increased and exceeded the threshold for polygonal ice wedges formation in the terminal phase of the Pleistocene, i.e. at the end of MIS-2, when the polygonal ice, common for the cold Sartanian period (MIS-2), were thawing and getting replaced by pseudomorphs underneath.

In this regard, it is interesting to learn about the data from the recently published work by E.A. Slagoda et al. (2022), who described a core of small diameter (5 cm) taken from a 9-meter-deep well in the alluvial deposits in the lower reaches of the interfluve of the Pur and Taz Rivers, near the bank of the Taz Estuary. Judging by the data of this research (Slagoda et al., 2022), the samples of plant detritus were taken at a depth of 5.2 m and 7.7 m. The following radiocarbon dating (^{14}C), same as our research, determined the Karginian age (MIS-3) of the deposits, or rather their belonging to the first half of the Karginian period (Fig. 7). Moreover, the value of this radiocarbon dating (^{14}C) turned out to be very close to the age that we determined for the Sample 4 (Fig. 6) and the nearby profiles.

Both samples of plant detritus (Fig. 7) had *Drepanocladus* spp. mosses which are common in coniferous and mixed forests, shrub thickets, on rocks and boulders with the layer of humus and fine soil, on rotten trunks, stumps, deadwood, trees and protruding roots; and are sometimes found on moist humus soil. These are widespread species of arctic deserts, tundras and forests that require moist habitats. The mosses of the genus *Calliergon* spp. that were found at a depth of 7.7 m grow in sphagnum bogs or separately, and are also common for the waterlogged habitats.

Brachythecium spp. mosses, presented there as well, are common in the Arctic, often found in willow thickets and are widespread even today, for example, in Yakutia, where they grow on soil and rocky outcrops in alder thickets and thin larch forests, once again preferring wet habitats. In other words, these mosses choose cold and wet bogs, river floodplains and wet soils, characterizing cool and humid climatic conditions, which is consistent with the aforementioned characteristics of spore-pollen spectra from Karginian deposits (MIS-3).

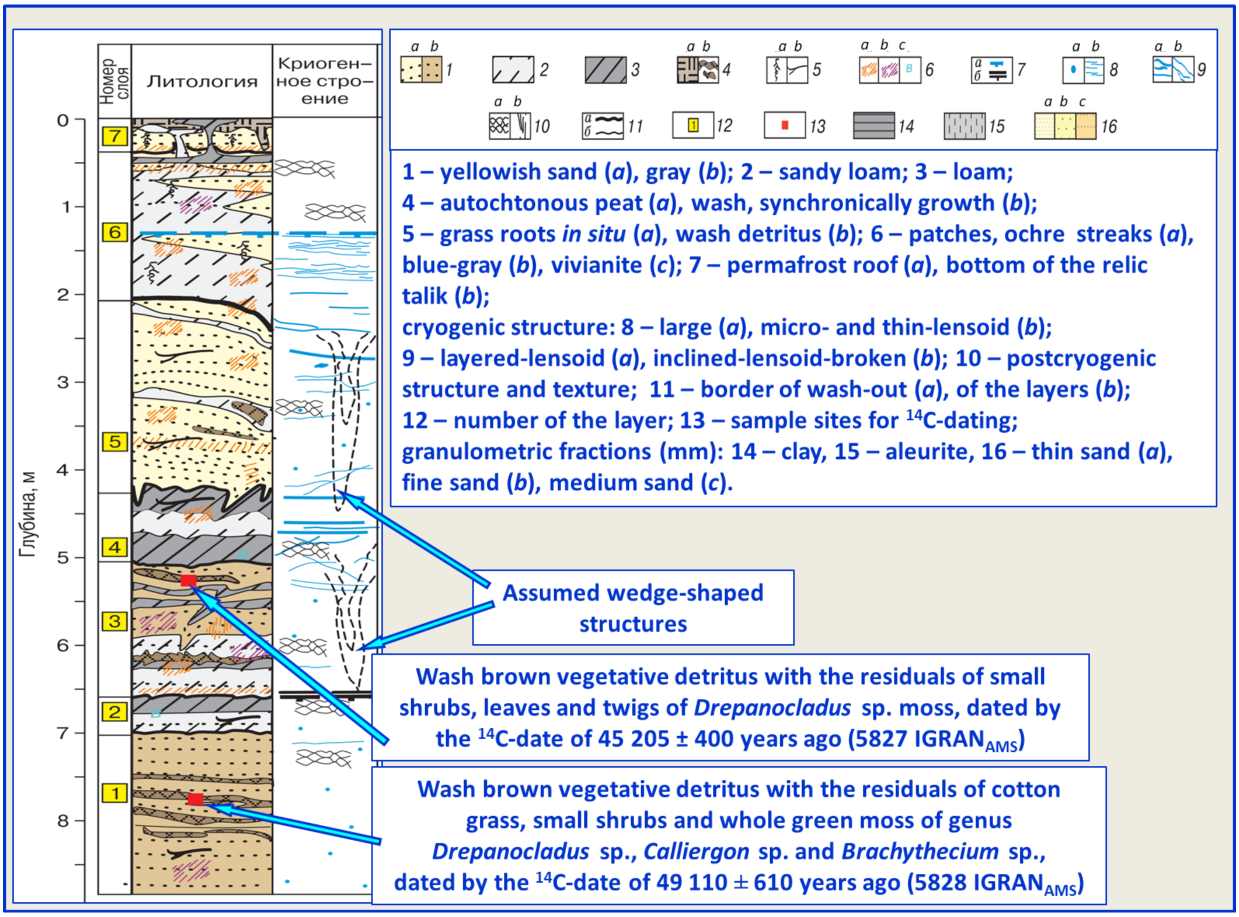

Fig. 7. Core depiction of 9-meter-deep borehole at the interfluve of the lower reaches of the Pur and Taz Rivers (After Slagoda et al., 2022, with additions made by the authors of this article).

On the other hand, E.A. Slagoda et al. (2022), using individual indirect data obtained from the core of small diameter (5 cm), made an assumption about the possible fixation of two layers of wedge structures (Fig. 7), determined as pseudomorphs along the former polygonal ice wedges. However, polygonal ice wedges are specific for the low-temperature permafrost zone. According to N.N. Romanovsky (1977), such wedgesy form in sands, as noted above, when the temperatures of the permafrost rocks are from –5°C to –6°C, and are typical in the studied region only for the Sartanian cryochron (MIS-2) instead of the Karginian thermochron (MIS-3). As evidenced by paleobotanical data and paleoclimatic records, MIS-3 was enough cold, but not so cold for the low-temperature permafrost zone to form and ensure the formation of polygonal ice wedges in the sands. The development of a cryolithozone with these indicators is not consistent with the cryolithogenic conditions of the Karginian time (MIS-3). Besides, individual indirect data obtained from small-diameter cores are not enough to reconstruct the polygonal ice wedges. We believe that for this the representative, fully represented structures are required, reflected in the deposit structure of the profiles, i.e. similar to the method described above in this article.

As for the reconstruction of the wedge structures mentioned by E.A. Slagoda et al. (2022), it would be more plausible to assume that they formed as the initially ground wedges. Those ground wedges are the same wedge structures of the same genesis as polygonal ice wedges, forming along the polygons of frost-shattered cracks, they are also accompanied by the development of ice wedges, which, however, are small and seasonal only, although sometimes lasting until the next season. Over the course of a progressively climate cooling, these forms play the role of the precursors of the polygonal ice wedges, reflecting the instances of less cold conditions. As shown above, they are widely common in the study area in the Karginian deposits (MIS-3) throughout the entire frozen mass, located at different depths and often forming complex many-tier systems. The location and dimension of the initially ground wedges that we studied match the assumed wedge structures in Figure 7.

Conclusions

From the paleoecological point of view it is obvious that the polygonal ice wedges and cryohydromorphic soils were a typical phenomenon during the Quaternary cryochrons in the north of West Siberia, which confirms the non-glaciated development of this region under conditions that were close to those during MIS-3 and MIS-2. They indicate ecosystems of tundra or tundra-steppe, which, in its turn, can be supported by the data obtained from the spore-pollen analysis. Considering the shortage of soil moisture in the seasonally thawing layer and the extremely weak vegetation cover, the existence of a glacial sheet or a supercold and hyperarid desert in the Quaternary in this area seems impossible.

The authors of this article think that the described scenario may also be suitable for earlier cryochrons of the Middle and Early Pleistocene. Therefore, in the future it will be necessary to look for older paleoecological records that cover said cryochrons, since we believe that cryogenic and pedogenic fossils found in them will be of key importance.

Funding. This research was funded for the State Assignments No. 121041600042-7 of the Earth Cryosphere Institute of the Tyumen Science Center of the Siberian Branch of the Russian Academy of Sciences “Researching the Ways of Formation, Structure and Variability, and Forecasting of the Cryosphere Condition, Including Permafrost and Cryogenic Landscapes”; No. 121042000078-9 of the Tyumen Science Center of the Siberian Branch of the Russian Academy of Sciences “Development of Methodological Foundations for Interdisciplinary Studies of the Role of the Cryosphere in the Evolution of Substantial and Energetic Interactions on the Earth’s Surface, in the Life Support Mechanisms of the Biosphere and the Ecological Aspects of Human Life. Assessing and Forecasting the Changes in Cryogenic Landscapes and Ecosystems in the North Part of West Siberia under the Influence of Natural and Anthropogenic Factors”; No. 0284-2021-0003 of the A.P. Vinogradov Institute of Geochemistry of the Siberian Branch of the Russian Academy of Sciences “Spatio-Temporal Ecosystems and Climate Variability in Eastern Siberia during the Late Pleistocene-Holocene”.

REFERENCES

1. Abramov AA, Sletten RS, Rivkina EM, Gilichinskiy D. Geocryological conditions of Antarctica [Geokriologicheskiye usloviya Antarktidy] *Cryosphere of the Earth [Kriosfera zemli]*. 2011;XV (3):3-19.
2. Galanin AA. Late Quaternary sand covers of Central Yakutia (Eastern Siberia): structure, facies composition and paleoecological significance

REFERENCES

1. *Абрамов А.А., Слеттен Р.С., Ривкина Е.М., Гиличинский Д.А.* 2011/ Геокриологические условия Антарктиды // Криосфера Земли. Т. XV. № 3. С. 3-19.
2. *Галанин А.А.* 2021. Позднечетвертичные песчаные покровы Центральной Якутии (Восточная Сибирь): строение, фациальный состав и палеоэкологическое значение //

[Pozdnechetvertichnyye peschanyye pokrovy Tsentral’noy Yakutii (Vostochnaya Sibir’): stroyeniye, fatsial’nyy sostav i paleoekologicheskoye znacheniye] *Cryosphere of the Earth [Kriosfera zemli]*. 2021;XXV (1):3-34.
3. Goryachkin SV, Mergelov NS, Targulyan VO. Extreme Pedology: Elements of Theory and Methodological Approaches. *Soil Science*. 2019;52 (1):1-13.
4. Derevyagin AYu, Kunitsky VV, Mayer H. Sand-ice veins in the extreme north of Yakutia [Peschano-ledyanyye zhily na kraynem severe Yakutii] *Cryosphere of the Earth [Kriosfera zemli]*. 2007;XI (1):62-71.
5. Zykina VS, Zykin VS, Volvakh AO, Ovchinnikov IYu, Sizov OS, Soromotin AV. Structure, cryogenic formations and formation conditions of the Upper Quaternary deposits of the Nadym Ob region [Stroyeniye, kriogennyye obrazovaniya i usloviya formirovaniya verkhnechetvertichnykh otlozheniy Nadymskogo Priob’ya] *Cryosphere of the Earth [Kriosfera zemli]*. 2017;XXI (6):14-25.
6. Popov AI, Rosenbaum GE, Tumel NV. Cryolithology [*Kriolitologiya*]. Moscow: MGU, 1985:240.
7. Romanovsky NN. Formation of polygonal-vein structures [*Formirovaniye poligonal’no-zhil’nykh struktur*]. Novosibirsk: Nauka, 1977:215.
8. Slagoda EA, Novoselov AA, Koroleva ES, Kuznetsova AO, Butakov VI, Tikhonravova YaV, Zazovskaya EP. Traces of cryogenic processes in the Late Pleistocene deposits of the Pur-Taz interfluve of West Siberia [Sledy kriogennykh protsessov v pozdneneopleystotsenovykh otlozheniyakh Pur-Tazovskogo mezhdurech’ya Zapadnoy Sibiri] *Cryosphere of the Earth [Kriosfera zemli]*. 2022;XXVI (1):21-35.
9. Targulyan VO. Soil formation and weathering in cold humid areas [*Pochvoobrazovaniye i vyvetrivaniye v kholodnykh gumidnykh oblastyakh*]. Moscow: Nauka, 1971:270.
10. Sheinkman VS, Melnikov VP, Sedov SN, Parnachev VP. New evidence of extraglacial development in the north of the West Siberian Lowland [Novyye svidetel’stva vnelednikovogo razvitiya severa Zapadno-Sibirskoy nizmennosti] *DAN*. 2017;477 (4):480-484.
11. Sheinkman VS, Melnikov VP. Evolution of ideas about cold and possible ways of their development in the Earth sciences [Evolyutsiya predstavleniy o kholode i vozmozhnyye puti ikh razvitiya v naukakh o Zemle] *Cryosphere of the Earth* Криосфера Земли. Т. XXV. № 1. С. 3-34.
3. *Горячкин С.В., Мергелов Н.С., Таргульян В.О.* 2019. Генезис и география почв экстремальных условий: элементы теории и методические подходы // Почвоведение. № 1. С. 5-19.
4. *Деревягин А.Ю., Куницкий В.В., Майер Х.* 2007. Песчано-ледяные жилы на крайнем севере Якутии // Криосфера Земли. Т. XI. № 1. С. 62-71.
5. *Зыкина В.С., Зыкин В.С., Вольвах А.О., Овчинников И.Ю., Сизов О.С., Соромотин А.В.* 2017. Строение, криогенные образования и условия формирования верхнечетвертичных отложений Надымского Приобья // Криосфера Земли. Т. XXI. № 6. С. 14-25.
6. *Попов А.И., Розенбаум Г.Э., Тумель Н.В.* 1985. Криолитология. М.: МГУ. 240 с.
7. *Романовский Н.Н.* 1977. Формирование полигонально-жильных структур. Новосибирск: Наука. 215 с.
8. *Слагода Е.А., Новосёлов А.А., Королева Е.С., Кузнецова А.О., Бутаков В.И., Тихонравова Я.В., Зазовская Э.П.* 2022. Следы криогенных процессов в поздненеоплейстоценовых отложениях Пур-Тазовского междуречья Западной Сибири // Криосфера Земли. Т. XXVI. № 1. С. 21-35
9. *Таргульян В.О.* 1971. Почвообразование и выветривание в холодных гумидных областях. М.: Наука. 270 с.
10. *Шейнкман В.С., Мельников В.П., Седов С.Н., Парначев В.П.* 2017. Новые свидетельства внеледникового развития севера Западно-Сибирской низменности // ДАН. Т. 477. № 4. С. 480-484.
11. *Шейнкман В.С., Мельников В.П.* 2019. Эволюция представлений о холоде и возможные пути их развития в науках о Земле // Криосфера Земли. Т. XXIII. № 5. С. 3-16.
12. *Шейнкман В.С., Мельников В.П., Парначев В.П.* 2020. Анализ криогенных и тектонических процессов на севере Западной Сибири в плейстоцене с позиций криогетеротопии // Доклады РАН. Науки о Земле. Т. 494. № 1. С. 82-86.
13. *Lisiecki L.E., Raymo M.E.* 2005. A Pliocene-Pleistocene Stack of 57 Globally Distributed Benthic δ18O Records // Paleoceanography. Vol. 20. P. PA 1003.

[Kriosfera zemli]. 2019;XXIII (5):3-16.

12. Sheinkman VS, Melnikov VP, Parnachev VP. Analysis of cryogenic and tectonic processes in the north of West Siberia in the Pleistocene from the standpoint of cryoheterotopy [*Analiz kriogennykh i tektonicheskikh protsessov na severe Zapadnoy Sibiri v pleystotsene s pozitsiy kriogeterotopii*] *Reports of the Russian Academy of Sciences [Doklady RAN] Earth Sciences [Nauki o zemle]*. 2020;494 (1):82-86.
13. Lisiecki LE, Raymo ME. A Pliocene-Pleistocene Stack of 57 Globally Distributed Benthic δ18O Records. *Paleoceanography*. 2005;20:PA 1003.
14. Péwé TL. Sand-wedge Polygons (Tesselations) in the McMurdo Sound Region, Antarctica – Progress Report. *American Journal of Science*. 1959;257 (8):545-552.
15. Sedov S, Sheinkman V, Bezrukova E, Zazovskaya E, Yurtaev A. Sartanian (MIS-2) Ice Wedge Pseudomorphs with Hydromorphic Pedodeposits in the North of West Siberia as an Indicator for Paleoenvironmental Reconstruction and Stratigraphic Correlation. *Quaternary International*. 2022;632:192-205.
16. Sheinkman V, Sedov S, Shumilovskikh S, Korkina E, Korkin S, Zinovyev E, Golyeva A. First Results from the Late Pleistocene Paleosols in Northern Western Siberia: Implications for Pedogenesis and Landscape Evolution at the End of MIS-3. *Quaternary International*. 2016;418:132-146.
17. Sheinkman V, Sedov S, Shumilovskikh L, Bezrukova E, Dobrynin D, Timireva S, Rusakov A, Maksimov F. A Multiproxy Record of Sedimentation, Pedogenesis, and Environmental History in the North of West Siberia during the Late Pleistocene Based on the Belaya Gora Section. *Quaternary Research*. 2021;99:204-222.
18. Sheinkman V, Sharapov D, Sedov S. Northwest Siberia as a MIS-2 Desert? Inferences from Quartz Morphoscopy and Polygonal Ice Wedges. *Quaternary International*. 2022;620:46-47.
19. Svendsen JI, Krüger LC, Mangerud J, Young NE. Glacial and Vegetation History of the Polar Ural Mountains in Northern Russia During the Last Ice Age, Marine Isotope Stages 5-2. *Quaternary Science Review*. 2014;92:409-428.
20. Velichko AA, Timireva SN, Kremenetski KV, MacDonald GM, Smith LC. West Siberian Plain as a Late Glacial Desert. *Quaternary International*. 2011;237:45-53.
21. WFO. The World Flora Online. 2022, Available at www.worldfloraonline.org (Date of Access 10/10/2022).

14. *Péwé T.L.* 1959. Sand-wedge Polygons (Tesselations) in the McMurdo Sound Region, Antarctica – Progress Report // American Journal of Science. Vol. 257. No. 8. P. 545-552.
15. *Sedov S., Sheinkman V., Bezrukova E., Zazovskaya E., Yurtaev A.* 2022. Sartanian (MIS-2) Ice Wedge Pseudomorphs with Hydromorphic Pedodeposits in the North of West Siberia as an Indicator for Paleoenvironmental Reconstruction and Stratigraphic Correlation // Quaternary International. Vol. 632. P. 192-205.
16. *Sheinkman V., Sedov S., Shumilovskikh S., Korkina E., Korkin S., Zinovyev E., Golyeva A.* 2016. First Results from the Late Pleistocene Paleosols in Northern Western Siberia: Implications for Pedogenesis and Landscape Evolution at the End of MIS-3 // Quaternary International. Vol. 418. P. 132-146.
17. *Sheinkman V., Sedov S., Shumilovskikh L., Bezrukova E., Dobrynin D., Timireva S., Rusakov A., Maksimov F.* 2021. A Multiproxy Record of Sedimentation, Pedogenesis, and Environmental History in the North of West Siberia during the late Pleistocene Based on the Belaya Gora Section // Quaternary Research. Vol. 99. P. 204-222.
18. *Sheinkman V., Sharapov D., Sedov S.* 2022. Northwest Siberia as a MIS-2 Desert? Inferences from Quartz Morphoscopy and Polygonal Ice Wedges // Quaternary International. Vol. 620. P. 46-47.
19. *Svendsen J.I., Krüger L.C., Mangerud J., Young N.E.* 2014. Glacial and Vegetation History of the Polar Ural Mountains in Northern Russia during the Last Ice Age, Marine Isotope Stages 5-2 // Quaternary Science Review. Vol. 92. P. 409-428.
20. *Velichko A.A., Timireva S.N., Kremenetski K.V., MacDonald G.M., Smith L.C.* 2011. West Siberian Plain as a Late Glacial Desert // Quaternary International. No. 237. P. 45-53.
21. WFO. The World Flora Online. 2022 [Электронный ресурс www.worldfloraonline.org (дата обращения 10.10.2022)].

УДК 551.34 + 551.24

ПАЛЕОЭКОЛОГИЯ СЕВЕРА ЗАПАДНОЙ СИБИРИ В ПОСЛЕДНЮЮ ХОЛОДНУЮ ЭПОХУ ПЛЕЙСТОЦЕНА: НОВЫЕ СВИДЕТЕЛЬСТВА И СЦЕНАРИИ

© 2022 г. В.С. Шейнкман*, **, *, С.Н. Седов*, **, ****, Е.В. Безрукова*****

***Институт криосферы Земли Тюменского научного центра Сибирского отделения РАН*
Россия, 625026, г. Тюмень, ул. Малыгина, д. 86. E-mail: vlad.sheinkman@mail.ru

****Тюменский государственный университет*
Россия, 625003, г. Тюмень, ул. Володарского, д. 6. E-mail: serg_sedov@yahoo.com

*****Тюменский индустриальный университет*
Россия, 625000, г. Тюмень, ул. Володарского, д. 36.

*****Институт геологии Национального автономного университета Мексики*
Мексика, C.P.04510, г. Мехико, Университетский городок, Дель. Койоакан

*******Институт геохимии им. А.П. Виноградова Сибирского отделения РАН*
Россия, 664033, г. Иркутск, ул. Фаворского, д. 1а. E-mail: bezrukova@igc.irk.ru

Поступила в редакцию 01.12.2022. После доработки 10.12.2022. Принята к публикации 15.12.2022.

Представлены материалы о палеокриологических, палеопочвенных и палеоботанических индикаторах развития экосистем на территории севера Западносибирской низменности в квартере. Приведены данные о широком распространении в данном регионе полигонально-жильных структур, представленных псевдоморфозами по полигонально-жильному льду и изначально-грунтовыми жилами. Первые образовались в терминальную фазу плейстоцена в конце морской изотопной стадии-2 (МИС), будучи наследниками эпигенетических полигонально-жильных льдов, которые в сартанское время (МИС-2) рассекли толщу каргинского (МИС-3), аллювия, тогда как вторые формировались на протяжении времени МИС-3 в синкриогенных отложениях аллювия. В заполнениях псевдоморфоз обнаружен переотложенный материал криогидроморфных палеопочв, включая фрагменты гумусовых горизонтов, использованных для радиоуглеродного (^{14}C) датирования. Спорово-пыльцевые спектры из этих заполнений указывают на преобладание растительности заболоченных тундр и тундро-степей. Совокупность полученных данных ставит под сомнение гипотезу о преобладании на исследованной территории холодных пустынь и ледниковых щитов и указывает на существование развитого растительного покрова при достаточном и местами избыточном увлажнении почв из-за близкого залегания кровли многолетней мерзлоты. Также обосновывается вывод о внеледниковом развитии региона в более древние криохроны, подобные тому, что имел место во время МИС-2.

Ключевые слова: криолитозона, палеокриогенез, полигонально-жильные структуры, палеоэкология севера Западной Сибири, спорово-пыльцевые спектры, плейстоценовые палеопочвы, псевдоморфозы по полигонально-жильному льду.

Финансирование. Работа выполнена при финансовой поддержке по госзаданиям № 121041600042-7 Института криосферы Земли СО РАН «Изучение формирования, структуры, изменчивости и прогнозирование состояния криосферы, в том числе многолетнемерзлых толщ и криогенных ландшафтов», № 121042000078-9 Тюменского научного центра СО РАН «Разработка методологических основ для междисциплинарных исследований роли криосферы в эволюции вещественно-энергетических взаимодействий на поверхности Земли, механизмах жизнеобеспечения в биосфере и экологических аспектах жизнедеятельности человека. Оценка и прогноз изменения криогенных ландшафтов и экосистем севера Западной Сибири под влиянием природных и антропогенных факторов», и № 0284-2021-0003 Института геохимии им. А.П. Виноградова СО РАН «Пространственно-временная изменчивость экосистем и климата Восточной Сибири в позднем плейстоцене-голоцене».

DOI: 10.24412/2542-2006-2022-4-89-104
EDN: HRMOLP