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Sartanian (MIS 2) ice wedge pseudomorphs with hydromorphic pedosediments in the north of West Siberia as an indicator for paleoenvironmental reconstruction and stratigraphic correlation

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ABSTRACT

Within the glacier-free scenario of the MIS 2 (Sartanian cryochron) environment in the north of West Siberia, it is important to search for the new regional paleoecological records and stratigraphic markers for this period. We studied large ice-wedge pseudomorphs filled with gleyic pedosediments developed on the high river terraces in the Nadym and Taz rivers basins as a tracer of the surface cryogenic and pedogenic processes during MIS 2. Field morphological observations and measurements, palynological analysis and radiocarbon dating of organic matter from soils and pedosediments were performed. Two sets of paleoecological indicators were discriminated: pseudomorph geometry evidence of the processes and conditions of ice wedge formation during the Last Glacial Maximum whereas the paleopedological and paleobotanic results from the fills recorded the environments of ice wedge melting at the end of MIS 2. Paleotemperatures 7–10 °C lower than at present are inferred during the major part of Sartanian, even at its end continuous permafrost persisted providing development of swampy tundra vegetation and cryohydromorphic palaeosols. We propose to define Taz-Nadym cryopedogenic horizon as a representative regional unit for MIS 2 and to correlate it with synchronous cryogenic and palaeosol units in Central and Eastern Europe.

1. Introduction

The scenario of geological evolution in the north of West Siberia during the Marine Isotope Stage (MIS) 2 (Sartanian cryochron) has suffered major revision over the last decades. Throughout most part of the XX century, it was thought that a large glacier – a continuation of the European ice sheet – covered the north of West Siberian lowlands whereas the area to the south was occupied by an extensive ice-dammed Mansi lake. This version worked out by Saks (1953) and further developed by Grosswald and Hughes (2002) had its followers until recently (Kazmin and Volkov, 2010). The official regional stratigraphic scheme (Unifitsirovannaya…, 2000) describes the Sartanian Horizon corresponding to MIS 2 as "glacial" and represented by "boulder loams" and "varved clays" in the north of West Siberia.

The idea of continuous glacial cover of the lowlands of the West Siberian arctic coast was strongly challenged already in the 1950s (e.g. Popov, 1959); furthermore, about 25 years ago a major revision of MIS 2 ice sheet extension in Eurasia was accomplished by Velichko et al. (1997) and by the group of QUEEN project (Svendsen et al., 2004). This new scenario supposed much more modest size of glaciated area in Europe and left West Siberian plain free of cover glacier during the whole MIS 2. Within this new version, now widely accepted by the geological community, no Sartanian till and associated fluvioglacial and limnoglacial sediments are expected in this area (except local moraines of mountain glaciers at the foothills of the ridges neighboring the plain).

The new scenario puts forward the task to reconstruct the landscape

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setting during the last cryochron under conditions of severe cooling however without ice sheet advance. Various hypotheses have been developed ranging from a cold permafrost environment with alternating humid and arid phases (Hubberten et al., 2004) to “Late Glacial desert” (Velichko et al., 2011). These versions until now rely on quite limited paleoecological evidence: e.g. the “glacial desert” hypothesis is based only on rather limited dataset of morphoscopic analysis of the quartz sand grains surface features in the surface sediments below peat. Thus, the search for reliable paleoecological archives covering MIS 2 becomes an urgent issue of the current geological research in the region.

In the absence of glacial deposits what could be considered as the MIS 2 “geological memory” in the north of West Siberia? Recent works on the Upper Pleistocene stratigraphy attribute to this period the “subaeral sands and aleurites” (Nazarov, 2007) later defined as the Syoyakha climatostratigraphic horizon which incorporates “icy loess, aeolian sands, ice wedges” (Astakhov and Nazarov, 2010). However, this unit has patchy distribution and high variability of all characteristics, so that it’s tracing and correlation even on the short distances meets with major difficulties. Its utilization as a paleoecological archive is quite limited. This situation differs considerably from the southern part of the West Siberian Plain, which forms part of the Eurasian loessic belt. Here extensive loess-palaeosol sequences provide an excellent record of the Quaternary environmental change that could be correlated with loessic profiles of the other regions and also with marine oxygen isotope curve (Zykina and Zykin, 2008). In particular the MIS 2 is represented by the Eltzovka and Bagan loess units, having uniform properties, spread over vast areas and recognized in numerous outcrops.

In the search of representative, informative, and common geological objects which could provide regional geological record for MIS 2 we focused on the phenomena generated by the *in situ* surface processes *i.e.* cryogenesis and soil formation. Within the glacier-free scenario cryogenic processes associated with permafrost are supposed to be widely spread under the cold continental climate of Sartanian cryochron.

Ice wedge polygons are the most representative cryogenic indicators, which reliably demonstrate the development of a low-temperature cryolithozone within the study area (Harry and Gozdzik, 1988). Thawing of ice wedges and filling of the resulting hollow with sediments or redeposited soil materials produces ice wedge pseudomorphs (also referred to as ice wedge casts) - pedosediment formations over thawed ice wedge polygons retaining original wedge shape. On the global scale ice wedge casts are widely used for paleoclimatic and paleocryological reconstructions (Maruszczak, 1987; Harry and Gozdzik, 1988) including quantitative estimations of paleotemperature (Nechaev, 1981; Vandenberghe et al., 1998). Despite certain doubts concerning their interpretation as a precise paleotemperature proxy (Murton and Kolstrup, 2003) they could provide some general conclusion about the paleoenvironmental conditions of their development as was stated already by Romanovskiy (1977). Ice-wedge pseudomorphs are closely associated with palaeosols developed above and between wedges inside the polygons; within the geological record cryogenic and paleopedological phenomena could be both synchronous and heterochronous (Morozova and Nechaev, 1997).

In the extra-glacial regions of Europe relict cryogenic features as well as incipient palaeosols within the loessic sequences are used as important stratigraphic markers and paleoenvironmental indicators within MIS 2 geological record. The East European loess-palaeosol stratigraphic scheme developed by Velichko (1990) defines 2 major cryogenic horizons mostly relying on the large ice wedge preudomorphs and one incipient gleyic palaeosol for the MIS 2 – Late Valday period. Jary (2009) identifies for the same interval one or two strongly developed ice wedge pseudomorph horizons in the Southern Poland and Northern Ukraine, also associated with palaeosols. In the Western Europe multiple horizons of incipient cryohydromorphic palaeosols and cryogenic features are discriminated in the most detailed loess sequences and correlated with the Greenland ice core record (Antoine et al., 2009).

During the last years we collected an extensive dataset about Sartanian paleocryogenic and paleopedological phenomena in a vast area between rivers Nadym and Taz in the north of West Siberia. Recently we published the observations on quartz sand morphology in the fills of the ice wedge pseudomorphs (Sheinkman et al., 2021b). This paper presents the results on the distribution, morphological characteristics, pollen spectra and instrumental dating of these features, their paleoenvironmental interpretation and our first attempts for their inter-regional correlation with the analogous units in Europe.

2. Regional setting

2.1. Geology and environmental conditions

The study sites are spread over a vast area in the north of West Siberian Plain, from the southern part of Ob’ estuary in the west to the upper reaches of the Taz River valley in the east. Within this low flat area large lowland areas associated with the valleys of major rivers alternate with uplands which correspond to major interfluves. Our sites are located within the Nadym lowland (Razduv and Khetta), Nenets upland (Pangody) and Upper Taz upland (Pyul’ky) (Trofimov, 1977).

This area corresponds to the northern part of the West Siberian plate. Its sedimentary mantle (3.5–4 km thick) developed over crystalline basin since Jurassic till Paleogene. During the Neogene this part of the platform converted into predominantly denudation area due to moderate uplift (Trofimov, 1977). Intensive sedimentation returned in the Quaternary: a complex sequence of alluvial, lacustrine, marine (left by Arctic Ocean transgressions) and glacial deposits formed a continuous upper unit of the platform mantle.

The issue of occurrence of glacial deposits is still strongly debated. As mentioned above, the absence of MIS 2 ice sheet (and thus – corresponding sediments and geoforms) in the north of West Siberia is shared by the majority of geologists. However according to the reconstruction of Pleistocene glacial advances by the QUEEN members, the glaciations in the beginning of the Late Pleistocene (90–60 ka BP) could affect the northernmost coastal area (Svendsen et al., 2004). The southern limit of these glaciations which gave rise to “Zyryanka cryomer horizon” (Astakhov and Nazarov, 2010) was reconstructed some 100–200 km to the north of our sites. These authors state that the maximal Middle Pleistocene glaciations were even larger and reached the Middle Ob’ and Vakh river valleys (Svendsen et al., 2004), leaving behind the “Middle Pleistocene glacial complex” (Astakhov and Nazarov, 2010) that should be spread throughout the study area. Within this reconstruction the Siberian Uval upland is interpreted as an end moraine of the Middle Pleistocene glaciations. The alternative scenario supposes complete absence of ice sheets during the whole Pleistocene in the north of West Siberia (Kuzin, 2005; Sheinkman, 2016). Within this version formation of the Siberian Uval is explained by the Neogene–Quaternary tectonic uplift and river erosion/deposition along major sub-latitudinal faults (Sheinkman et al., 2017).

Climate of the study area is rather cold continental with certain tendency towards stronger seasonal contrast from west to east. Winters are colder whereas summers are warmer in Pyul’ky that in the sites within Nadym basin: mean temperatures of January are $\sim$–25°C and $\sim$–24°C and of June - +16°C and +15°C respectively. The sites are located within the zones of northern and middle taiga where coniferous forests (*Pinus* sp., *Picea* sp., *Larix* sp.) in better drained terrace positions alternate with extensive olygotrophic swamps with sphagnum moss (Atlas Yamalo-Nenetskogo avtonomnogo okruga, 2004).

2.2. Soils and palaeosols

Under the forest stands Podzols and Stagnosols are formed, whereas the swampy areas are occupied by Histosols (Vasilevskaya et al., 1986). The thickness of peat layers varies in the range of 1–3 m (rarely up to 5 m), its accumulation started during the Pleistocene/Holocene transition, as shown by multiple radiocarbon datings (Kremenetski et al., 2003).

Late Pleistocene palaeosols were discovered recently in the region of Siberian Uval – a sub-latitudinal upland at the right-hand bank of the Ob' River (Sheinkman et al., 2016, 2021a; Sedov et al., 2016). The main paleopedological horizons correspond to the thermochrons – periods of warmer climate: Kazantsevo interglacial/MIS 5e and Karginsky interstadial/MIS 3. However, during Sartanian cryochron/MIS 2 palaeosol development was also possible especially during the milder second half (Late Glacial). Buried peat seams (incipient Histic horizons) in the Beliy Island (Yurtaev et al., 2018) and relict humus morphons in the loamy Stagnosol profile near Nadym (Pogosyan et al., 2021) produced the radiocarbon dates in the range 12–15 ka cal BP – that point to their formation during the Terminal Pleistocene.

2.3. Permafrost and cryogenic phenomena

The study area belongs to the zone of discontinuous permafrost distribution (Trofimov, 1977; Vasil'chuk, 2006); patches of permafrost correspond to the peat deposits within the wetlands. The well drained terrace positions with Podzols (in which the study sites are located) are free from ground ice in the upper part of the geological section although relict permafrost bodies could be found at the depth of 100–300 m (Ananjeva et al., 2003). Further to the north at the Arctic coast, Yamal and Gydan Peninsula permafrost becomes continuous.

At the present time, ice wedges (both recent and preserved since the Pleistocene) within the north of West Siberia have been found only to the north of the Arctic Circle, with most prominent polygons occurring to the north of 68°N (Dubikov, 2002; Vasil'chuk, 2006) (Fig. 1). These bodies of ground ice have received major attention as paleoclimatic archives especially in relation to their isotopic composition as paleotemperature proxy (Vasil'chuk, 1992).

To the south of the Arctic circle and down to the middle Ob' River valley ice wedge pseudomorphs are common. These features have previously been described in the north of West Siberia only generally in very few studies, in particular on the coast of the Gulf of Ob'River (Dubikov, 1962; Baulin et al., 1967; Danilov, 1972). The only detailed study on Sartanian ice wedge casts in the vicinity of Nadym city (Zykina et al., 2017) gives their incorrect interpretation, in our opinion – as discussed below. Primary ground ice vein pseudomorphs prevail at the latitude of the forest-steppe zone, to the south of the middle reaches of the Ob' River, in the Tobol River basin (Larin et al., 2020). Formation of these veins within the active layer occurred at significantly higher temperatures as compared to those required for the formation of ice wedge polygons (Romanovskiy, 1977).

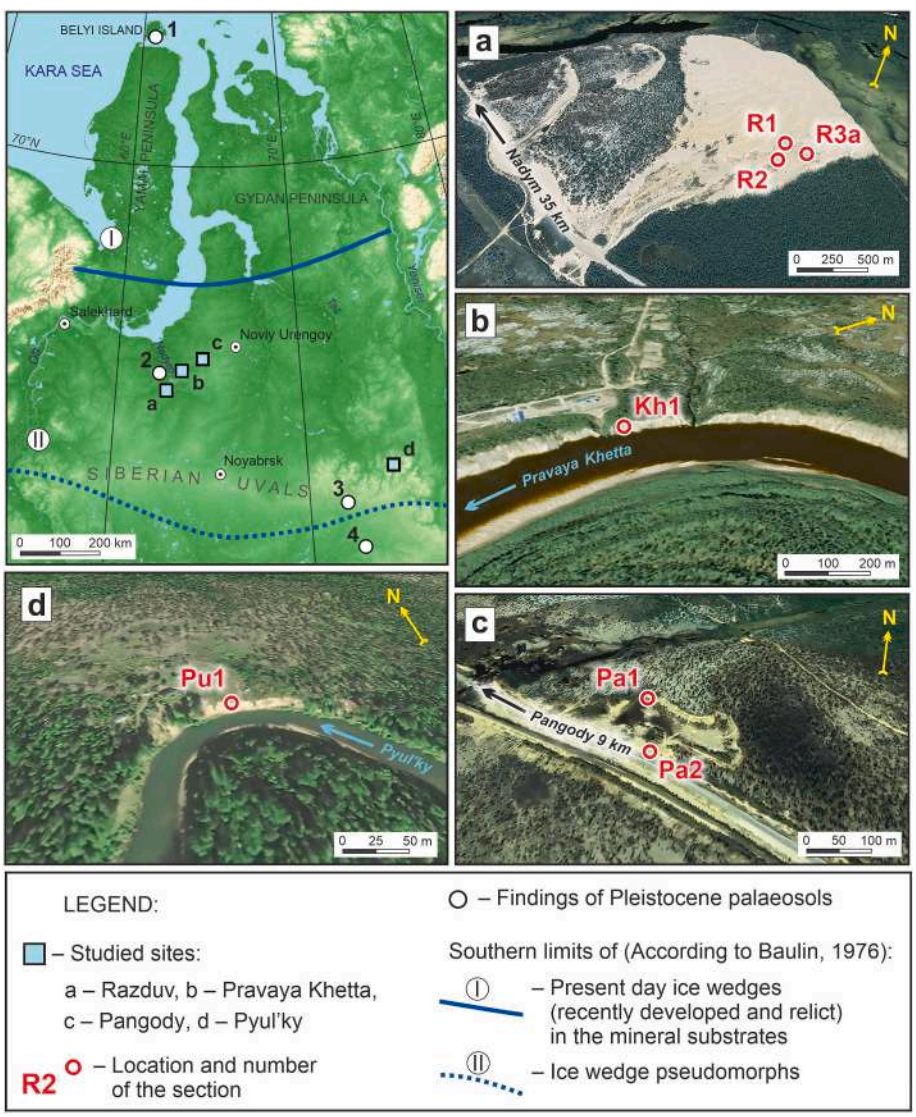

Fig. 1. Geographical location of the study area and investigated sections. Earlier findings of the Pleistocene palaeosols: 1 - Yurtaev et al. (2018); 2 - Pogosyan et al. (2021); 3 - Sheinkman et al. (2016); 4 - Sheinkman et al. (2021a).

3. Materials and methods

3.1. Field research and sampling

In the course of paleopedological and paleocryological prospection carried out in 2013–2019, we selected four sites for more detailed study of the Sartanian ice wedge casts and associated palaeosols and pedosediments: three in the basin of the Nadym River and one in the upper reaches of the Taz River basin (Fig. 1), all at the alluvial terraces. Among them two sites: Pravaya Khetta and Pyul'ky are extensive and profound natural exposures of high river terraces produced by the recent lateral fluvial erosion. Two or more ice wedge pseudomorphs could be observed so that the distance between them could be measured in these exposures. They also allowed us to study the relation of wedge structures with the host sediments observing the latter down to the depth of 15 and 8 m respectively. Two other sites: Razduv and Pangody are artificial exposures in the shallow quarries where sand was extracted for the road construction. These exposures are much less profound, so we had to excavate pits to observe the complete vertical profile of pseudomorphs. However, these quarries provided extensive exposed surfaces where the net of ice wedge polygons could be observed on the horizontal cuts, that gave a possibility to measure size of polygons. Detailed morphological

Table 1
Radiocarbon dating of organic materials from ice wedge pseudomorphs, host alluvial deposits, and the Holocene soil horizons.

N	Laboratory index	Section, Profile, Sample	Dated material	^{14}C age, BP (1σ)	Calibrated age intervals, cal BP				
					68.3 (1 sigma)		95.4 (2 sigma)		Median Probability
1	$IGAN_{AMS}$ 5967	Pyulky Pu1 Ice wedge pseudomorph, Humus-rich mottle.	TOC[a]	11335 ± 35	13171–13242 13279–13288	0.914 0.086	13128–13131 13161–13306	0.003 0.997	13220
2	$IGAN_{AMS}$ 5968	Pyulky Pu1 Ice wedge pseudomorph, Humus-rich mottle.	TOC	9780 ± 30	11197–11230	1.000	11180–11244	1.000	11213
3	$IGAN_{AMS}$ 5969	Pyulky Pu1 Ice wedge pseudomorph, Humus-rich mottle.	TOC	9090 ± 30	10220–10250	1.000	10193–10290	1.000	10237
4	$IGAN_{AMS}$ 5970	Pyulky Pu1 Ice wedge pseudomorph, Humus-rich mottle.	TOC	8890 ± 30	9912–9967 9983–10048 10056–10070 10113–10151	0.311 0.383 0.086 0.220	9900–10174	1.000	10029
5	Ki-19426	Pyulky Pu1 Thin layer of organic detritus, 150 cm above river level.	Humic Acid	29940 ± 210	34256–34574	1.000	34022–34769	1.000	34415
6	Ki-19429	Pyulky Pu1 Thin layer of organic detritus, 60 cm above river level.	Humic Acid	38640 ± 550	42289–42723	1.000	42067–42986	1.000	42510
7	$IGAN_{AMS}$ 5971	Khetta Kh1, 210 cm. Ice wedge pseudomorph, Humus-rich mottle.	TOC	9950 ± 30	11270–11355 11368–11396	0.752 0.248	11251–11405 11430–11499 11556–11605	0.836 0.100 0.064	11346
8	$IGAN_{AMS}$ 5972	Khetta Kh1, 130 cM. Holocene Podzol, bottom of Bs horizon.	TOC	4610 ± 25	5308–5323 5416–5439	0.418 0.582	5295–5328 5382–5449	0.392 0.608	5412
9	$IGAN_{AMS}$ 5973	Khetta Kh1, 70 cm. Holocene Podzol, upper part of Bs horizon.	TOC	1730 ± 20	1586–1624 1667–1694	0.587 0.413	1546–1635 1656–1699	0.653 0.347	1616
10	$IGAN_{AMS}$ 5974	Khetta Kh1, 280 cm. Ice wedge pseudomorph, Concentration of organic detritus.	Cellulose	10290 ± 30	11938–12059 12083–12097 12412–12417	0.927 0.058 0.015	11833–11853 11878–11919 11923–12106 12115–12174 12236–12252 12306–12325 12356–12372 12392–12439	0.011 0.038 0.781 0.061 0.012 0.015 0.009 0.073	12015
11	$IGAN_{AMS}$ 5975	Khetta Kh1, 180 cm. Ice wedge pseudomorph, Humus-rich mottle.	TOC	10840 ± 30	12737–12770	1.000	12735–12823	1.000	12759
12	$IGAN_{AMS}$ 5976	Khetta Kh1, 160 cm. Ice wedge pseudomorph, Humus-rich mottle.	TOC	13830 ± 40	16699–16908	1.000	16609–16976	1.000	16800
13	$IGAN_{AMS}$ 5977	Khetta Kh1, 130 cm. Ice wedge pseudomorph, Humus-rich mottle.	TOC	8170 ± 30	9023–9131	1.000	9014–9142 9174–9210 9212–9265	0.773 0.102 0.125	9100
14	Ki-19420	Khetta Kh1. Ice wedge pseudomorph, Humus-rich mottle.	Humic Acid	14170 ± 240	16916–17563 17623–17713	0.921 0.079	16530–17972	1.000	17246
15	Ki-19421	Khetta Kh1 Ice wedge pseudomorph, Humus-rich mottle.	Humic Acid	5040 ± 150	5603–5639 5646–5917	0.101 0.899	5475–6120 6141–6182	0.978 0.022	5790
16	$IGAN_{AMS}$ 5978	Razduv R3a, Ice wedge pseudomorph, Humus-rich mottle.	TOC	11200 ± 35	13095–13121 13139–13157	0.628 0.372	13088–13166	1.000	13122
17	$IGAN_{AMS}$ 6648	Razduv prof. R1, 0.2 m. Ice wedge pseudomorph, Humus-rich mottle.	TOC	10000 ± 30	11344–11375 11392–11408 11426–11502 11531–11607	0.155 0.078 0.402 0.365	11283–11295 11306–11641 11670–11689	0.012 0.958 0.031	11474
18	$IGAN_{AMS}$ 6649	Razduv prof. R2, 0.5 m Ice wedge pseudomorph, Humus-rich mottle.	TOC	10610 ± 35	12620–12691	1.000	12498–12533 12611–12715	0.133 0.867	12652
19	$IGAN_{AMS}$ 6653	Pangody prof. Pa2, 0.2 m. Ice wedge pseudomorph, Humus-rich mottle.	TOC	11720 ± 35	13507–13556 13574–13598	0.674 0.326	13485–13611 13632–13654 13711–13737	0.928 0.029 0.043	13552
20	$IGAN_{AMS}$ 6654	Pangody prof. Pa1, 2 m. Ice wedge pseudomorph, fine charred material.	TOC	11275 ± 30	13116–13178	1.000	13100–13190 13198–13237	0.840 0.160	13158

[a] TOC – total organic carbon.

description included characterization of size and shape of the ground wedges, properties of the fill as well as sedimentological characteristics of the host sediments (texture, sorting, lamination and its deformation at the contact with the wedge, etc.).

Dark morphons enriched in soil organic matter within the pseudomorph fills were selected to take samples for radiocarbon dating. In the Pravaya Khetta profile we also took samples from the buried peat layer and from the lower and upper parts of the Spodic (iron-humus-illuvial) horizon of the recent Podzol above the ice wedge casts. In the Pyul'ky section we were lucky to find the detritus-rich lenses at the base of the alluvial terrace some 6m below the pseudomorph – they were also sampled for radiocarbon dating.

The scheme of sampling for palynological analysis was the following: in the pseudomorph fill the sample was taken close to the sample for ^{14}C dating, in the host sediment we selected the layers enriched with organic detritus where concentration and preservation of pollen and spores is higher, additional sample was taken from the top horizon of the surface soil to study recent pollen spectrum.

3.2. Laboratory analyses

Radiocarbon dating of most samples was done using accelerated mass spectrometry (AMS) for measuring radiogenic isotope C14. The pre-treatment procedure consisted of the following steps: the samples were submerged in 0.5 M HCl heated to 80 °C for 20 min, then centrifuged, decanted, rinsed in deionized water and dried at 105 °C. The dates were obtained from total organic carbon using AMS technique at the Center for Applied Isotope Studies, University of Georgia, the USA. All pre-treatments and preparation for AMS: graphitization and pressing on a target, were carried out at the Laboratory of Radiocarbon Dating and Electron Microscopy of the Institute of Geography RAS (Moscow, Russia). This set of dates received $IGAN_{AMS}$ indexes; more details about the dating technique used for these samples could be found in the paper by Zazovskaya et al. (2017). Some samples of larger size and higher concentration of organic matter were dated by the liquid scintillation counting (LSC) in the ^{14}C Laboratory of the Institute of Environmental Geochemistry of the National Academy of Sciences of Ukraine, Kiev; these dates have indexes Ki. All dates were calibrated using the Calib 8.2 program (http://calib.org/calibcalib.html) using the Northern Hemisphere Radiocarbon Age Calibration Curve IntCal20 (Reimer et al., 2020). The complete information about all datings is presented in the Table 1, whereas in the Figs. 2–5 location of the samples and corresponding calibrated age median probability values are marked on the photos of studied profiles.

For palynological analysis samples were processed following standard procedure (Fægri and Iversen, 1989), including HCl, KOH, HF. Pollen and spores were identified at magnifications of 400 × , 600 × and 1000 × , with the aid of published pollen keys and atlases (Kupriyanova and Alyoshina, 1972; Demske et al., 2013; Savelieva et al., 2013) and a modern pollen reference collection stored at the Institute of Geochemistry, Irkutsk (Russia). At least 200 terrestrial pollen and spore grains were counted in each sample. Relative percentages for all terrestrial pollen taxa at each sample were calculated from a terrestrial pollen sum taken as 100%. Percentages for cryptogam taxa (spores) were calculated based on the total sum of counted pollen and spores. We use the ratio of arboreal pollen (AP) to non-arboreal pollen (NAP) to interpret the proximity of the forested areas to the sampling location (Cheung et al., 2014). The Pyulky section pollen diagram was constructed using the TILIA software (Grimm, 2004).

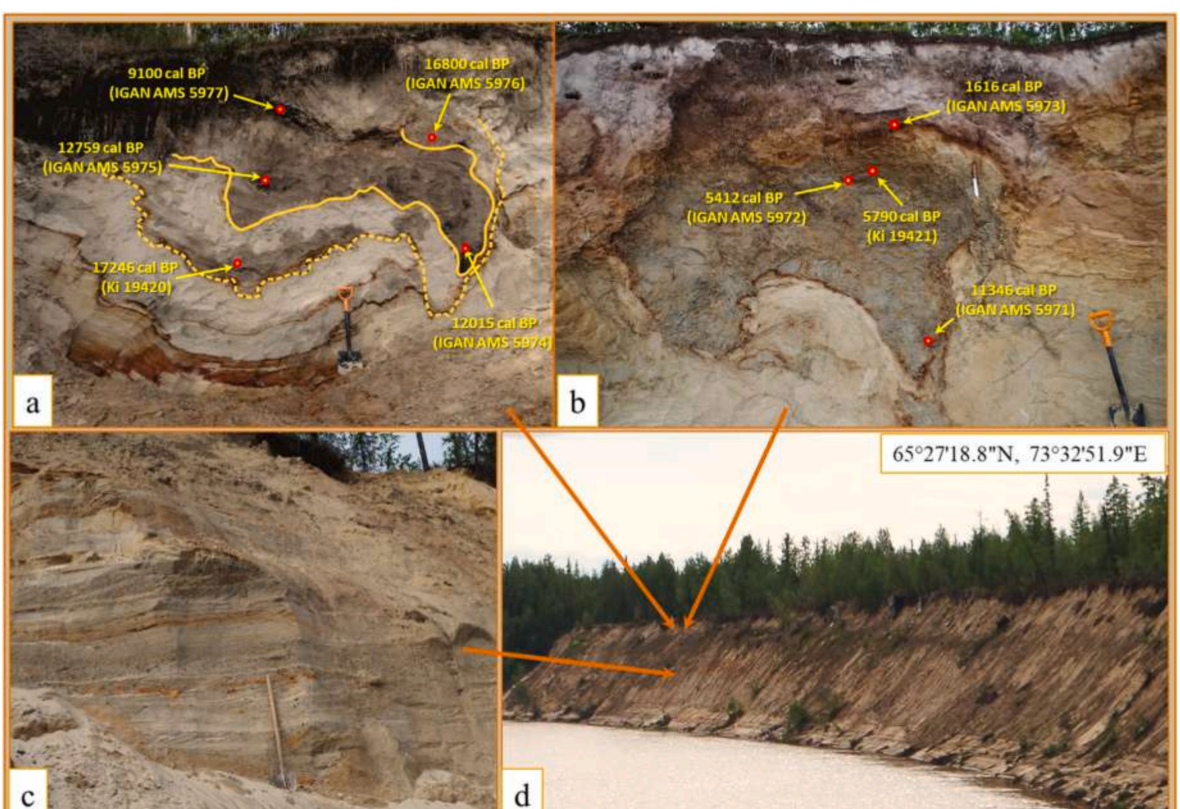

Fig. 2. Site Pravaya Khetta: a) and b) ice-wedge pseudomorphs, c) host alluvial deposits below pseudomorphs, d) general view of the exposure in the river bank.

Fig. 3. Site Razduv: a) General view of the quarry wall with two ice wedge pseudomorphs, overlain by the Holocene Podzol and recent dune sand – section R3a; b) and d) pits with transversal sections of the ice wedge pseudomorphs – sections R1 and R2 respectively; c) horizontal cleaning at the quarry bottom, polygonal wedge net is visible.

Fig. 4. Site Pangody: a) the quarry floor, polygonal wedge net is visible; b) profile in the quarry wall with the ice wedge pseudomorph overlain by the Holocene Podzol (pit Pa1); c) pit at the quarry bottom with the transversal section of the ice wedge pseudomorph (pit Pa2).

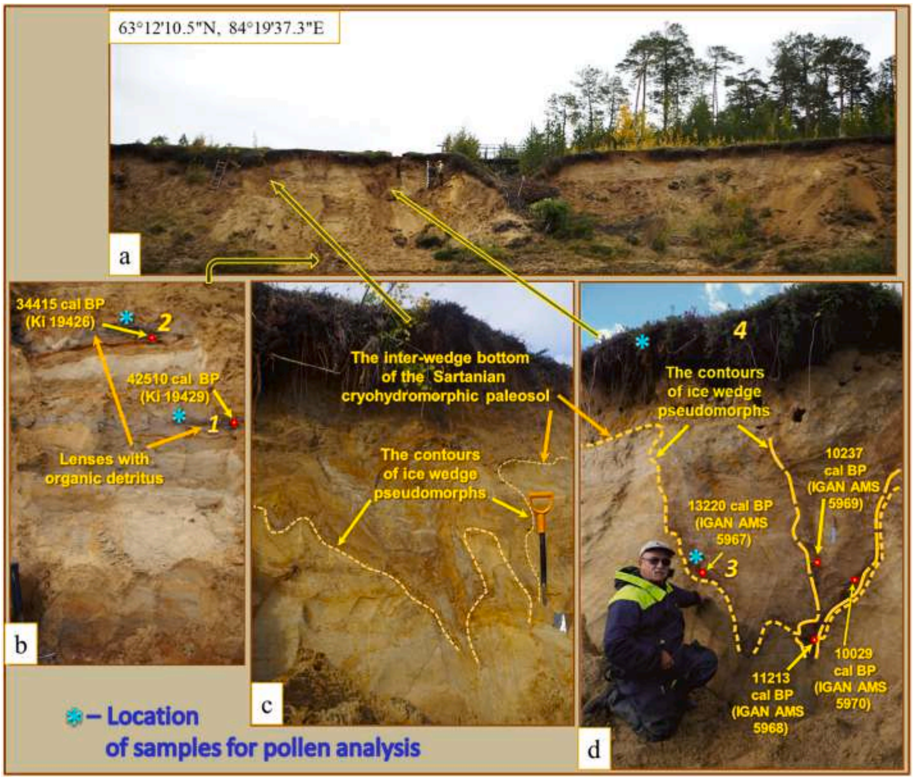

Fig. 5. Site Pyul'ky: a) general view of the exposure Pu1 in the river bank; b) lower part of the section Pu1: host alluvial sequence with two dated detritus lenses; c) and d) – profiles of the ice wedge pseudomorphs. 1–4 – location of samples for palynological analysis.

4. Results

4.1. *Morphological characteristics and radiocarbon dating of the ice wedge pseudomorphs*

4.1.1. *The Pravaya Khetta site*

The Pravaya Khetta site (65°27′18.8"N, 73°32′51.9"E) was located at the north-eastern edge of the Pravokhettinsky village, in the valley of the Pravaya Khetta River that is a tributary of the Nadym River in its middle reaches. A steep right bank of the Pravaya Khetta River has a terrace, the surface of which has an altitude of about 50 m a.s.l. and a relative elevation of about 20 m above the mean water level (Figs. 1b and 2d). The alluvial sediments of the terrace are represented by light-coloured sorted stratified sands with occasional ferruginous layers (Fig. 2c). In the upper part of the terrace side, we discovered a series of ice wedge pseudomorphs, in a large cleaned outcrop (section Kh1) we described two of them. Some wedge pseudomorphs in the Pravaya Khetta profile have a height of over 3m and a width of up to 5m at the top. However, in this exposure the visible width of the wedges could be exaggerated because the section is not at right angle to the extension of the pseudomorph. Other profiles, especially that of Razduv and Pangody where we could study strictly perpendicular cross-sections in our excavation provide more reliable horizontal dimensions of the wedge structures. Each pseudomorph consists of 2–3 of consequently inserted wedge-like and U-shaped structures, contoured by rusty-brown ferruginous rims. The pseudomorphs are filled with strongly gleyed whitish-bluish sandy material with rusty mottles. In the left part of the profile within a large U-shaped pseudomorph this material is better sorted, more bleached and has an indistinct stratification, that makes us think that the pedosediment developed after the ice wedge melting was partly reworked by fluvial processes (Fig. 2a). Grey humified morphons with inclusions of black strongly decomposed plant detritus were found in all pseudomorphs from this profile and sampled for ^{14}C-dating. We also took a ^{14}C sample from a fragmentary buried peat horizon lying above the polygonal wedge structure in the left part of the profile.

The polygonal wedge structures at the Pravaya Khetta site are overlain by a well-developed recent Podzol profile, which consists of a surface litter, a thick bleached eluvial – E horizon and a coffee-brown humus-Fe-illuvial (Spodic, Bs) horizon, better expressed in the right part of the section (Fig. 2b). This recent soil was characterized by the absence of gleyic and grey humus materials (which were present within the wedge psedomorphs). Two samples – from the lower and the upper parts of the illuvial horizon were taken for radiocarbon dating to establish the age of podzolization.

The range of ^{14}C-dates in the ice wedge casts from Pravaya Khetta was rather wide (Fig. 2 a, b, Table 1). There were three dates from pseudomorphs within the interval of 13–11 ka cal BP corresponding to the terminal Pleistocene – transition to the Holocene. However, from those pseudomorphs we also obtained two dates of more than 16.5 ka cal BP, which correspond to the beginning of warming in the second half of MIS 2 – Sartanian cryochron (see below). The buried peat found above those pseudomorphs was dated at about 9 ka cal BP. The illuvial horizon of the recent Podzol was dated from 5 to 6 ka cal BP in its lower part up to about 1.5 ka cal BP in its upper part – thus corresponding to the Middle/Late Holocene.

4.1.2. *The Razduv site*

The Razduv site (65°21′02.0"N, 72°58′05.3"E) was located within the lowland (about 20m a.s.l.) on the right side of the Ob' Gulf at a distance of 27 km south-east of the town of Nadym, in one of the sand quarries developed at the edge of the first alluvial terrace above the floodplain on the left bank of Nadym River (Fig. 1a). The land adjacent to the quarry is occupied by currently active sand dunes lacking any vegetation cover (Fig. 3a). The flat bottom of the quarry has a visible network of polygonal wedge structures (Fig. 3c), which was exposed as a result of the removal of the upper layers of sand, being quarried for building purposes. The heads of the wedge pseudomorphs exposed on the scalped surface are slightly convex, because their material is more resistant to denudation as compared to the surrounding sediments; we attribute this resistivity to the higher compaction of pedosediments because of pore space collapse under hydroconsolidation and also to partial impregnation with iron oxides due to redoximorphic processes. These pseudomorphs form a polygonal network, with individual polygons having a width of 10–15m.

At the Razduv site, in the profile R3a which was studied in 2017 in the cleaned quarry wall, the sand dune material was underlain by the Holocene soil – Podzol (Fig. 3a). Below Podzol there was a series of well-developed pseudomorphs after ice wedge polygons, which cut through stratified sandy sediments. In addition, in 2018 two pits (profiles R1 and R2, Fig. 3b, d) were made in the quarry bottom in order to study the exposed wedge heads in cross-section, perpendicular to the pseudomorph extension. Ice wedge pseudomorphs in the studied profile and pits were about 2–2.5m deep and 1–1.5m wide (in the upper part); they consisted of a strongly gleyed non-stratified material, heterogenous in colour, with rusty mottles on a bluish background. Each pseudomorph was outlined by a bright brown ferruginous rim. The gleyic pedosediment fill also contained small dark inclusions of humified material, the age of which was determined at around 13 ka cal BP in all samples from the Razduv profile and pits (Fig. 3a, b, d; Table 1).

4.1.3. The Pangody site

The Pangody site (65°52′54.2"N 74°39′05.4"E) was located in the vicinity of the Pangody settlement, near the highway between Nadym town and Novy Urengoy city (at a distance of 9 km from Nadym), on an alluvial terrace at the right bank of the Pravaya Khetta River (Fig. 1c). 3 km to the north its right tributary Tiyakha joins Pravaya Khetta and the terrace occupies the interfluve between these two rivers. The altitude of the terrace surface is about 70m a.s.l., it is about 10m higher than the river level. Due to the quarrying of sand materials for the highway construction, there is a scalped horizontal surface, where a network of polygonal wedge structures is exposed (Fig. 4a). It is similar to the exposure observed at the quarry bottom of the Razduv site. Likewise, the heads of the exposed wedge pseudomorphs have convex shapes, because their dense material is more resistant to the current erosion as compared to the surrounding sediments. At the Pangody site, two pits (cross-sections) of ice wedge pseudomorphs were excavated by us in the following positions: 1) Pa2 on the scalped surface at the quarry bottom and 2) Pa1 by the quarry side under natural forest vegetation.

Pit Pa2 exposed an incomplete vertical profile of an ice wedge pseudomorph, which was formed within stratified fine-sandy alluvial sediments, with the strata being bent down at the contact with the wedge pseudomorph (Fig. 4c). The wedge had a total height of about 3m (taking into account its scalped upper part) and a width of about 1m at the top. Like in the above-described cases, the pseudomorph had a brown rim around its contour, whereas its main fill had mostly bluish colour, which is typical for gleyic waterlogged soils. In the bluish background of the fill, there were single black mottles that were sampled for ^{14}C-dating. It should be noted that brown rims of the Pangody pseudomorphs is formed in the materials of surrounding alluvial sediments.

Pit Pa1 exposed a complete pseudomorph (with characteristics similar to those of the Pit Pa2 pseudomorph) overlain by a profile of recent Podzol (Fig. 4b). The Podzol's eluvial and illuvial horizons increased in thickness and formed pockets above the pseudomorph. In this pseudomorph, a dark humified morphon was found in the lowest part of the gleyed fill.

The humified morphons of the pseudomorphs from pits 1 and 2 were characterized by comparable ^{14}C-dates in the narrow range 13–14 ka cal BP. (Fig. 4b and c; Table 1).

4.1.4. The Pyul'ky site

The Pyul'ky site (63°12′10.5"N, 84°19′37.3"E) was located at a distance of 48 km south-east of the Ratta village, in the eastern part of the Sibirskie Uvaly upland, in the Pyul'ky River valley that belongs to the upper part of the Taz River basin (see Fig. 1d). The profile Pu1 was exposed in a steep cliff of an alluvial terrace. The terrace surface has an absolute altitude between 70 and 80m a.s.l. and a relative elevation of 8–10 m above the mean water level of the Pyul'ky River. The terrace sediments are mostly represented by a well sorted laminated sandy material typical for alluvial plains.

When the terrace outcrop was cleaned a series of well-developed wedge-like pseudomorphs over ice wedge polygons was observed in the upper part of the exposed profile, directly under the recent soil. The wedges are 2–2.5 m in height, with their top parts being 1.5–2m wide, spaced at 15–20m intervals that correspond to the dimensions of former polygons (Fig. 5a). The significantly wider topmost parts of the wedges are indicative of the epigenetic type of their development (i.e posterior to deposition of the host sediment), when the ice wedges grew in width without increasing in height. The former active layer, which was observed above the wedge tops, was only 0.6–0.7m in thick.

An example of typical ice wedge pseudomorphs uncovered at the Pyul'ky site is shown in Fig. 5d, complemented with the ^{14}C-dates of the stages of formation and thawing of ice wedge polygons. Pedosediments that fill the polygonal wedge structures are predominantly sandy, without visible inclusions of plant residues. They typically have an intensive gley colour pattern: bright reddish-yellow and rusty-brown mottles and stripes/lenses on a bluish-whitish background. The bluish colour is mostly in the central part and the rusty brown colour forms a bright rim along the contours of ice wedge pseudomorphs. As can be seen in the picture, there is a smaller wedge inserted into a bigger wedge (at its right side) with the contours of both wedges being marked by the rusty-brown rims. Particularly darkest spots within the rims in the middle and lower parts of the wedge pseudomorphs were supposed to contain humus and, therefore, they were sampled for the ^{14}C-AMS analysis with the exact sampling points being marked in the figure. It should be noted that the material of ice wedge pseudomorphs significantly differs from that of the recent soil, which at the Pyul'ky site is represented by a well-developed Podzol in which the forest litter horizon is underlain by a thick Spodic Bs horizon of a homogenous reddish-brown colour without gley features. There are occasional lenses of a whitish material of the E horizon at the boundary between the litter and the Bs horizon.

Sediments around and below the ice wedge pseudomorphs are shown in Fig. 5b. Those sediments consist of a sorted medium-fine sandy stratified alluvium with occasional small lenses of a pebbly material. At the base of the terrace, we found layers of a sandy loam material containing plant detritus lenses, which were sampled for ^{14}C-dating.

The ^{14}C-AMS dates of humified morphons within the brown rims of ice wedge pseudomorphs significantly varied but were generally close to the boundary between the Pleistocene and the Holocene. For example, the dates around 10–11 ka cal BP were obtained for samples from the right side of the pseudomorph where the smaller wedge structure is inserted, whereas more ancient dates of >13 ka cal BP were obtained for the sample from the left side of that pseudomorph. The ^{14}C-dates for plant detritus from the base of the terrace were within the interval between 33 and 43 ka cal BP, which corresponds to the second half of MIS 3, i.e., the Karginsky thermochron (Fig. 5b).

4.2. Palynological results from the Pyul'ky section

The pollen spectrum of sample 1 consisted predominantly (92%) of tree species including Scots pine (*Pinus sylvestris*), Siberian pine (*Pinus sibirica*), larch (*Larix* sp.) and birch (*Betula alba*-type). There was a small percentage (4.2%) of shrub pollen originated mainly from shrubby alder (*Alnaster*). The ratio of AP/NAP (arboreal to nonarboreal pollen) was nearly 12.

The pollen spectrum of sample 2 contained 45% of pollen of on-land herbs represented mainly by sedges (Cyperaceae), grasses (Poaceae), buttercups (Ranunculaceae) and polemonium (*Polemonium* sp.) and 46% of spores of Pteridophytes, predominantly, lycopodium (*Diphasium* *apressum*). The AP/NAP ratio was 0.05.

The pollen spectrum of sample 3 (Fig. 6) had an arboreal pollen content of up to 42.5%, which is nearly 10 times as high as that in sample 2. The tree species were represented mainly by *Pinus sylvestris*, with lower proportions of *Betula alba*-type*, Pinus sibirica* and Siberian spruce (*Picea obovata*). Sample 3 contained more than 48% of non-arboreal pollen, predominantly, species of Cyperaceae, Poaceae, sagebrush (*Artemisia* sp.), goose-foot (Chenopodiaceae/Amaranthaceae) and clove (Caryophyllaceae). The AP/NAP ratio was 0.7.

The pollen spectrum of sample 4 was dominated by on-land herbs (42.5%), with lower percentages of arboreal species (35%) and spores of Pteridophytes (18%). The tree species included predominantly *Picea obovata* and *Betula alba*-type. In contrast to the composition of the above spectra, sample 4 contained higher proportions of shrubby birch (*Betula nana*-type), *Artemisia* sp., Amaranthaceae, Asteraceae and Caryophyllaceae, but a lower proportion of Cyperaceae. Spores were dominated by *Sphagnum* species. The AP/NAP ratio was 0.5.

5. Discussion

5.1. General considerations: complex nature of the ice wedge pseudomorph record and its main components

The stratigraphic position of the studied ice wedge pseudomorph horizons in the upper part of MIS 3–2 alluvial sequences, geomorphological context – near the surface of high river terraces directly below the Holocene soils as well as all obtained radiocarbon dates point to formation of these features during the last Sartanian/MIS 2 cryochron. Repeated occurrence of the similar fossil polygonal structures throughout the vast area in the north of West Siberia points to their significance as a regional record of surface processes throughout MIS 2. Romanovskiy (1977) in his classic monography dedicated to the polygonal ice wedge structures stresses that the ice wedge pseudomorphs integrate two sets of properties: those related to the ice wedge formation and growth and those developed at the stage of ice melting and filling the empty space with the sediments. This division of properties leads to the idea that the pseudomorph horizons provide a complex record of changing environmental conditions, from which different proxies could be extracted to document this change. Following the Romanovskiy's idea we discriminate the following sets of diagnostic features in the studied ice wedge casts which could be used for paleoenvironmental reconstructions as described below.

First, we identify the features corresponding to the ice wedge growth which took place during the coldest period of cryochron (equivalent of the Last Glacial Maximum). The paleoecological record is mostly comprised of the geometric characteristics of the fossil ice wedge structures: size and shape of the polygons, depth and width of the individual wedges, configuration of the wedge contour, deformations in the host sediment, etc. These parameters account for the paleocryological block of the ice wedge pseudomorph record. In general terms the paleoenvironmental interpretation of the ice wedge casts was considered by a number of authors predominantly on the basis of the observations in the Pleistocene periglacial zone of Europe and North America (Péwé, 1966; Maruszczak, 1987; Harry and Gozdzik, 1988) The approach to quantitative paleoclimatic interpretation of these objects was developed by Nechaev (1981) who stated that the ice wedge casts are indicative of the winter paleotemperatures, and Vandenberghe et al. (1998).

In the second place we specify the features related to the ice melting and filling of the resulting cavity which occurred during the warming at the end of cryochron/transition to the thermochron (equivalent of the Late Glacial). In this case paleoecological proxies should be obtained by the investigation of the pseudomorph fill so first the nature of their material should be established. Romanovskiy (1977) defined two "phases" of deposition in the hollow formed after ice wedge melting: first collapse of the layer overlying the ice wedge and sliding of material from the sides; after that in case of continuing deposition the groove in place of the wedge is filled with new sediments. However, it is clear from the geological and geomorphological context that no considerable new deposition occurred after the melting of ice wedges in the studied case. Pseudomorphs are located on the high terraces where the alluvial sedimentation had already seized, directly below the profiles of the Holocene soils with no considerable sedimentary layer in between. In the uppermost parts the wedge structures are strongly widened that is indicative of epigenetic (post-depositional) development when the surface is stabilized, and additional sedimentation was minimal if any (as discussed below in more detail). This means that pseudomorph fills were produced mostly by the processes of the first "phase", namely collapse of the "roof" and sliding from the sides. We argue that this collapsing and sliding material could be derived only from the soil developed in the active layer above and aside the ice wedges.

Morozova and Nechaev (1997) who discussed the interaction between cryogenesis and pedogenesis in the periglacial environment, stated that soil development and the genesis of cryogenic features may be contemporaneous ("syneventual"), or pedogenesis may pre-date or post-date cryogenic activity. In our case pedogenesis responsible for the properties of the pseudomorph fill took place at the last phase of ice wedge formation and during their melting. Similar scheme of the ice

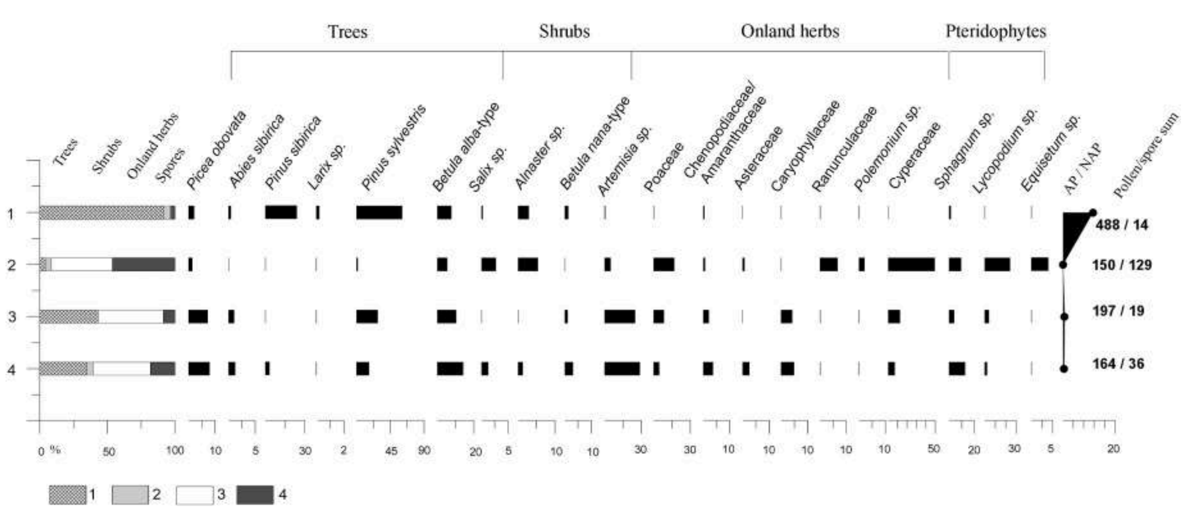

Fig. 6. Pollen diagram of the Pyul'ky section.
1 — Trees, 2 — Shrubs, 3 — Onland herbs, 4 — Spores.

wedge degradation during MIS 2 warmer periods (Greenland interstadials) and their filling with the material of the surrounding "tundragley" soils developed in the active layer (however complicated by the aeolian dust deposition) was developed for the loess areas of Northern France and Belgium by Antoine et al. (2009). Thus, the pseudomorph fill could be considered as a pedosediment from which we could extract information of the pedogenetic processes and related paleobotanical record, both indicative of the ecosystem which existed during the ice melting and pseudomorph filling.

Below we discuss these two sets of indicative features and paleoecological inferences from them.

5.2. Cryological proxy from ice wedge casts: inferences for reconstructing Sartanian (MIS 2) environment in the north of West Siberia

Paleoenvironmental interpretation of the encountered wedge-shaped ground structures should be based on an adequate reconstruction of their formation processes. By now contradictory opinions about the origin of these objects have been generated. Zykina et al. (2017) who studied similar objects in the same region of Nadym, among them the Razduv site, stated that they are former primary sand wedges (PSW). However, such structures should have been developed without influence of snowmelt water, when the deep open fissures produced by strong frost contraction are filled directly with the available sediment material, predominantly dry sand (Romanovskiy, 1977). PSW could thus develop in the coldest and very dry desertic environments, their present day areal has been first described by Péwé (1959) in the Dry Valleys in Antarctica – similar conditions reconstructed Zykina et al. (2017) in the Nadym region during the MIS 2 cryochron.

The PSW hypothesis in respect to the polygonal wedge structures of West Siberia however is strongly challenged by several facts. First, their size and shape does not fit into the typical parameters of PSW: they are wide especially in the upper part and their contours are stepwise, all this typical of the ice wedge pseudomorphs; on the contrary PSW are narrow (Black, 1976), their width is much smaller than the depth and contours are smooth. Second, the properties of the pseudomorph fill also do not agree with the PSW hypothesis: it is made up of the strongly gleyed pedosediments with organic inclusions presenting collapse structure typical for ice wedge pseudomorphs. In contrast PSW should be filled with sand or other unaltered sediment without gleyzation – that could not develop under the very cold arid environment in the absence of thaw water. Geographical distribution of the studied wedge structures also does not support the PSW hypothesis: if the preudomorphs were sand wedges they should occur also further to the north under even more severe climate. However, to the north of Arctic Circle only recent and relict polygonal ice wedges, significant part of them contains Pleistocene ice (Dubikov, 2002; Vasil'chuk, 2006) and some of them has been dated back to 60 ka BP (Streletskaya et al., 2015); no PSW are encountered there. Finally, the independent paleoenvironmental records does not agree with the PSW hypothesis: the conditions of the Sartanian (MIS 2) cryochron were cold and arid, however they still supported some tundra-steppe vegetation (Hubberten et al., 2004) and were rather not as harsh as in Antarctic Dry Valleys. We conclude that all accumulated evidence points to ice wedge polygons as the precursors of the studied pseudomorphs.

Despite the reasonable doubts concerning the possibility of precise quantitative paleoclimatic interpretation of the ice wedge casts (Murton and Kolstrup, 2003) still some inferences about MIS 2 climate are possible. We assume however that for correct reconstruction the grain size characteristics of the host sediments should be taken into account. Romanovskiy (1977) established the relation between the temperature of the permafrost deposit needed for ice wedge development and their textural class. He showed that coarser materials need rather low permafrost temperatures for ice wedge development: if in loamy deposits they appear already at a temperature of permafrost layer of −2.5 °C, in the sands −4.5 °C to −5 °C are required. In the studied case ice wedge pseudomorphs were formed within the sandy alluvial deposits; this means that they are indicative of lower permafrost paleotemperatures. Further quantitative reconstruction of the mean air temperature from the temperature of permafrost layer is quite difficult task, the latter is usually considered to be 6–9° higher than the former however depends also on a number of other factors like seasonal amplitude of temperatures and geological and geomorphological setting (Yershov, 1998), thus we base our inferences just on direct comparison with the modern environments with analogous characteristics of permafrost and ice wedge pattern. The present day climatic conditions which provide the required permafrost temperatures correspond to the north of Eastern Siberia (Dereviagin et al., 2010) – its Arctic coast has been characterized by mean annual air temperatures of about −14 °C and January air temperature of −31 °C. We suppose similar paleoclimatic conditions to dominate in the studied region of North-West Siberia during the major part of MIS 2 – Sartanian cryochron when the ice wedge polygons were widely developed there. This reconstruction suggests the drop of temperature in MIS 2 as compared to present day conditions of about 7–10 °C that is similar to the reconstruction by Vasil'chuk et al. (2000) from the isotopic composition of wedge ice in the eastern Yamal Peninsula some 500 km to the north of the studied region and reconstruction by Streletskaya et al. (2015) on the Kara Sea Coast. We think that the possible decrease by 20 °C inferred by Zykina et al. (2017) basing on the PSW hypothesis is grossly over-estimated.

Concerning the moisture conditions, despite the decrease of precipitation during MIS 2 in West Siberia (Hubberten et al., 2004) there was enough water for development of large ice wedges. As already mentioned above, the size of pseudomorph – 2–3 m deep and 1–2 m wide – and their clear triangle shape with strong widening upwards points to epigenetic development of original ice wedges (i.e formation of ice wedge body took place after sediment accumulation had finished). Geomorphological evidence – location of polygonal structures on the high river terraces and rather old (MIS 3) age of host sediments also support the epigenetic origin. This means that floods as a possible source of water for ice wedge growth are excluded and the process was fed by the snowmelt and soil moisture. Of course, the water-logging effect of shallow permafrost had crucial importance for this soil moisture supply. This means that reconstructed soil hydrological status could support some cold-tolerant vegetation and does not agree with the "glacial desert" hypothesis (Velichko et al., 2011).

Finally, it should be highlighted that both hypotheses of the origin of observed polygonal wedge structures are not compatible with the presence of glacial ice and/or large ice dammed water bodies in the north of West Siberia during MIS 2. We propose to take this conclusion into account when revising the meaning of the Sartanian Horizon within the Quaternary stratigraphic scheme of the West Siberian plain for the northern part of this territory – where this Horizon is still attributed as "glacial" (Unifitsirovannaya…, 2000).

5.3. Terminal Pleistocene in the north of West Siberia: paleopedological and paleobotanical record from the ice wedge pseudomorph fill

Before paleoecological interpretation of the pseudomorph fill record we again should first understand its formation processes. The following features indicate that the ice wedge melting and deposition of pedosedimentary material in the resulting hollow occurred when permafrost was still present in the host sediment: first, surprisingly good preservation of the pseudomorph outline suppose that the walls of the wedge (quite steep) during the ice thawing were firm enough to avoid collapse or slumping. However, the loose sandy host sediments could hardly maintain such steep slopes. Only if the sand is consolidated by the ice cement of permafrost the material could be firm enough to avoid collapse. Second, morphological pattern of the pedosediments within the pseudomorph fills indicates strong gleyzation (redoximorphic processes) which had affected the soil material. These processes could develop only in the case of anoxic soil environment caused by overmoisturing. How could saturation with water occur in the profiles located in a well-drained geomorphic position of high river terraces and developed in a sandy substrate with high porosity and easy percolation? This could be possible if impermeable permafrost was blocking the downward water movement. We thus conclude that the gleyic palaeosol material that fills the ice wedge pseudomorphs was a Cryosol in which redoximorphic processes took place due to waterlogging by permafrost. Further gleyzation proceeded already within the pseudomorph fill producing specific colour differentiation, in particular – rusty oxidized rim outlining the wedge contour. It should be stressed that these palaeosols differ sharply from the recent surface soils. The latter are Podzols typical for pedogenesis under boreal forests on sandy sediments in the well-drained positions and in the absence of permafrost observed at present.

Already Romanovskiy (1977) stressed that melting of ice wedges and development of pseudomorphs does not imply necessarily degradation of permafrost: these two processes are independent. This could occur already in the beginning of the warming which took place towards the end of MIS 2 – Sartanian cryochron, when the climate was still rather cold. Vasil'chuk (1992) inferred winter air temperatures at the end of MIS 2 (14–11 ka BP) 3–5 °C lower than present day ones from the isotopic composition of wedge ice in the Gydan Peninsula, to the north of the studied region. Additional evidence of rather cold soil environment and cryogenic processes affecting soil matrix in the pedosediments of the studied ice wedge casts is provided by the data on the quartz sand grains surface morphology (Sheinkman et al., 2021b) which showed strong features of fracturing and breakdown by frost action. More information about the landscape setting in which ice wedge degradation took place could be obtained from the paleobotanical results.

As shown in the Fig. 6, there were highly significant differences between pollen spectra of the pedosediment fill of the polygonal wedge structure (sample 2) and the recent soil (sample 1) at the Pyul'ky site. Sample 2 was characterized by a manifold (by 14 times) reduction of the AP/NAP value, which indicates a sharp decrease in the cover of arboreal vegetation within the region at the end of MIS 2. The composition of the pollen spectrum of sample 2 is also indicative of an active development of sedge-sphagnum bogs, which was accompanied by a wide distribution of characteristic species of both tundra and steppe biomes (Prentice et al., 1996; Müller et al., 2010; Kobe et al., 2020). Such sedge-sphagnum bog communities included sedges (Cyperaceae), bog moss (*Sphagnum*), grasses (Poaceae), buttercups (Ranunculaceae), Jacob's-ladder (*Polemonium* sp.) and Lycopodium (*Diphasium apressum*). The presence of pollen (*Betula* sect. *Nanae*, *Salix* sp., *Alnaster fruticosa*) allowed for a suggestion that small areas of shrubby tundra communities existed in favorable positions within valleys around the Pyul'ky site. At the present time, such species of shrubs preferably occupy areas, where a quite deep snow cover protects soils during the winter and provides for an increase in soil microbial activity and available nitrogen content (Sturm et al., 2005). Such habitats could also support tree species (*Picea* and *Betula* spp.) under conditions of a still very cold, continental climate at the end of MIS 2. Apparently, those species had a sufficient water supply in the Pyul'ky region. However, the composition of the reconstructed plant communities implies the predominance of soil moisture (resulted from permafrost thawing during the summer) over the atmospheric moisture. This conclusion is supported by the combination of high frequencies of shrubs, buttercups, sedges and grasses in the pollen spectrum, which is indicative of the presence of permafrost close to the soil surface (Gravis and Lisun, 1974).

It is interesting to compare the pollen spectrum of the pedosediment of the wedge pseudomorph (sample 2) with spectra from the organic sediments of the preceding warmer stage MIS 3, i.e., the Karginsky thermochrone at the same site (samples 3 and 4). Sample 4 from the lower layer (dated to 43420–41877 cal BP, see Fig. 5b) was characterized by low values of the AP/NAP ratio, which are indicative of the existence of both open and forested landscapes within the Pyul'ky area. Communities of *Picea obovata* and *Betula* sect. *Albae* could develop in most favorable habitats such as river valleys. Taking into account the fact that *Betula* sect. *Albae* pollen can be carried by wind to significantly further distances than *Picea obovata* pollen (Bezrukova et al., 2010; Zhao et al., 2011), it should be suggested that the latter grew close to the studied profile, while the former probably reflects a wider regional distribution. Both samples 3 and 4 had low percentages of *Pinus sylvestris* (as compared to the recent soil spectrum of sample 1), despite that this species is known for its capability of dispersing pollen for tens of kilometers around the source trees (Birks and Birks, 2000). Therefore, Scots pine likely had an insignificant distribution within the study area and its pollen was possibly brought by wind from the areas to the south of the Pyul'ky site. In fact, *Pinus sylvestris* is known to be less tolerant of cryogenic soil conditions within the periglacial zone as compared to *Picea obovata* (Blyakharchuk, 2012). The composition of pollen spectra of samples 3 and 4 is also indicative of the development of mire communities of Cypeaceae-*Sphagnum* and *Salix* spp. together with a wide distribution species, which are attributed to steppe biomes (Prentice et al., 1996; Müller et al., 2010; Kobe et al., 2020). The steppe species (e.g., Poaceae, *Artemisia* sp., Chenopodiaceae/Amaranthaceae and Caryophyllaceae) developed mostly during summer seasons. Our reconstruction of MIS 3 vegetation within the Pyul'ky region showed the predominance of tundra-steppe communities with sporadic patches of woodlands under conditions of continental, cold climate. The wide distribution of steppe species could be explained by warm and dry summer seasons that provided for permafrost thawing to a great depth and for active evaporation. Our reconstruction agrees with the results of other studies on vegetation of the second half of MIS 3 in the north of Western Siberia (Sheinkman et al., 2016, 2021a). Therefore, the comparison of interstadial climate warmings of the second half of MIS 3 and the end of MIS 2 within the Pyul'ky region showed that continental permafrost landscapes developed in both cases, with the latter being characterized by a harsher climate, which caused an almost total suppression of woodland communities.

Relying on these results we conclude that the gleyic Cryosols which gave rise to the ice wedge pseudomorph pedosediments developed under swampy tundra vegetation and could be considered as Tundra gley palaeosols – similar to the "tundragleys" quite common in the European loess sections and corresponding to the warmer intervals of MIS 2 (Antoine et al., 2009; Terhorst et al., 2015).

The wide spread of the hydromorphic environments at the end of MIS 2, indicated both by swampy paleovegetation and strongly gleyed palaeosol materials could be due to certain increase of precipitation – when west-east transfer of moisture in Eurasia was re-established after degradation of the Scandinavian ice sheet. However, we would like to point to another possible factor – melting of the ice wedges itself promotes extension of hydromorphic environments. Kanevskiy et al. (2017) who studied the landscape consequences of the recent ice wedge degradation in Alaska showed surface water concentration in the thermokarst troughs and pits accompanied by growth of aquatic vegetation and accumulation of organic matter in water-filled troughs. We think that some similar tendencies could develop at the end of Sartanian cryochron in the north of West Siberia. Palynological indicators which show that soil source of moisture was more important than atmospheric one confirms the predominant role of ice wedge melting in generating hydromorphic conditions. We further speculate that the onset of peat accumulation on the northern part of the West Siberian plain could be also attributed to this enhancement of hydromorphism due to ice wedge degradation at the end of MIS 2. This could explain the fact that although majority of basal dates of the West Siberian peat deposits fits into the interval 11–8 ka cal BP, some of them yield ages of 12 ka cal BP and older (Kremenetski et al., 2003). Even as far to the north as on Belyi island in the Kara Sea peat horizons of 12 ka cal BP were found (Yurtaev et al., 2018). Kanevskiy et al. (2017) observed accumulation of organic materials associated with the recent ice wedge degradation in Alaska – this could be considered as a scenario for the beginning of peat accumulation in the West Siberian lowlands during the terminal Pleistocene.

It is clear that the proposed paleoenvironmental reconstruction for the end of MIS 2 in the north of West Siberia disagrees completely with the hypothesis of “late glacial desert” by Velichko et al. (2011). We should keep in mind however that the latter hypothesis is based mostly on the observations on quartz sand morphology which indicated strong reworking by wind of sand material directly below the Holocene peat. Similar observations were made also on the quartz grains from the studied ice wedge pseudomorphs: they also revealed the increase of the features of aeolian origin (Sheinkman et al., 2021b). However, we think that these results do not contradict our reconstruction of swampy tundra and forest-tundra with permafrost as a dominant type of regional landscapes at the end of MIS 2. Aeolian processes could develop locally within vegetated permafrost ecosystems, one of the examples are “tukulans” in Yakutia (Galanin et al., 2018). In the north of West Siberia recent windblown dune deposits are documented in some locations despite humid climate and well developed northern taiga vegetation, as observed at the Razduv site (Zykina et al., 2017). These deposits often develop in the areas where the plant cover was damaged e.g. by the wildfires. Shifting local aeolian processes could leave behind their signature on quartz grains of the surface layer traced on the regional scale – however not being a legacy of desertic vegetation-free landscape.

It is interesting that to the south of the study region in the upper Ob’ basin (Tomsk Priobye) sandy Late Glacial buried palaeosols are also found within the inland dunes (Konstantinov et al., 2019). However, these soils are not associated with the ice wedge pseudomorphs and are not gleyed – on the contrary they show incipient development of Cambic and even eluvial Albic horizons indicative of pedogenesis under the well-drained environment. The differences between the Late Glacial palaeosols developed at different latitudes could help to reconstruct the soil and ecosystem zonality as well as extension of permafrost in the West Siberian Lowland during the terminal Pleistocene.

5.4. Correlation with the European MIS 2 records

As mentioned above, within the scope of the official West Siberian stratigraphic scheme the studied ice wedge pseudomorphs belong to the Sartanian Horizon; however, their paleoenvironmental interpretation disagrees with the definition of this Horizon. We propose to use the data presented in this paper for actualization of this scheme in the part corresponding to MIS 2. Furthermore, we argue that the presented results support the definition of the specific Taz-Nadym cryopedogenic horizon that contains a combined archive of the regional environmental history during MIS 2, including the Last Glacial Maximum and Late Glacial. We propose this horizon as a representative regional geological unit that could be used as a tool for stratigraphic correlations on the continental scale, in particular – with the European Quaternary stratigraphies.

Concerning the official Quaternary stratigraphic scheme for the East European plain, the studied cryogenic and paleopedological objects could be correlated with the Ostashkov Horizon and to the Gololobovo loess-palaeosol complex (LPC) – both these units were developed during the MIS 2 (Shik,2014). More detailed correlation is possible with Russian loess-palaeosol stratigraphic column proposed by A. Velichko and his co-workers which pays major attention to the cryogenic and paleopedological phenomena. Indeed, horizons of the ice wedge pseudomorphs and other cryogenic features were observed in the loessic sections of the East European plain outside the area covered by the Pleistocene ice sheets and interpreted as the legacy of periglacial environments with permafrost (Velichko and Nechaev, 2009). Two distinct cryogenic horizons were defined for the Late Valday (MIS 2) period as part of the Russian loess-palaeosol stratigraphic scheme: Vladimir horizon (25–23 ka cal BP – early MIS 2) and Yaroslavl (20–18 ka cal BP – the coldest phase in the middle of MIS 2) horizon. It is important to stress that within this scheme the palaeosol units are defined separately from the cryogenic horizons; in particular within MIS 2 an incipient gleyic Trubchevsk palaeosol unit is identified, dated back to 16 ka cal BP (Velichko, 1990). Relying on the stratigraphic position and radiocarbon dates we suppose that Taz-Nadym cryopedogenic horizon could be provisionally correlated with both the Yaroslavl cryogenic horizon and Trubchevsk palaeosol.

Further to the west a well pronounced Late Weichselian cryogenic horizon with large ice wedge pseudomorphs is traced in southern Poland and northwestern Ukraine (Jary, 2009). In the northwestern Ukranian loessic sections also Krasyliv palaeosol with strong gleyic features was described and dated to appr. 15–16 ka BP (Kusiak et al., 2012). These authors interpreted Krasyliv horizon as an ancient active layer, thus the redoximorphic pedogenesis of this palaeosol could be conditioned by permafrost waterlogging – as in case of synchronous pedosediments of the Taz-Nadym cryopedogenic horizon. Thus, also in this region the horizon of ice wedge pseudomorphs formed during the Last Glacial Maximum together with the Late Glacial cryohydromorphic palaeosol could be correlated to the Taz-Nadym cryopedogenic horizon.

The obtained results suggest that the Taz-Nadym cryopedogenic horizon had multiphase development. This is evidenced by the incised smaller wedges-pseudomorphs separated by the rusty rims within the larger wedge structures. We interpret this wedge sequence as a result of the following succession of events: first the larger ice wedges were formed during the coldest interval of the Sartanian/MIS 2 cryochron corresponding to the Last Glacial Maximum, then during the Late Glacial warming the ice of the wedges melted and the larger pseudomorphs developed. However afterwards during one of the strong coolings of the Terminal Pleistocene (presumably Younger Dryas) the fill of the pseudomorphs froze and was incorporated into the permafrost layer. New net of ice wedges was developed following the older wedge pattern but having smaller size. Finally, during the warming in the beginning of the Holocene these smaller wedges also melted giving rise to the second generation of pseudomorphs. Rather broad range of radiocarbon dates from the palaeosol humus agrees with this multiphase scenario. Thus, more detailed record especially for the Late Glacial paleoenvironmental fluctuations and correlations with the high resolution European loessic sections could be obtained for this horizon in future. However more detailed morphological investigations and instrumental dating are required for this purpose.

6. Conclusions

Polygonal ice wedge pseudomorphs in the north of West Siberia present a complex paleocryogenic and paleopedological record: the geometric parameters of wedge structures (size, shape, distance between wedges etc.) contain important information about processes and environments which controlled development of the polygonal ice wedges during the most part of the MIS 2 – Sartanian cryochron, whereas pedogenetic properties and paleobotanical materials of the wedge fill reflect the ecological conditions of the terminal phase of the Late Pleistocene and the transition to the Holocene when ice wedges melted and soil re-deposition towards the thaw basins took place. The chronological framework of this record is based on the radiocarbon dates of the soil organic matter encountered in the pedosediments of the pseudomorph fills.

Development of the studied former ice wedge structures took place following predominantly epigenetic pathway on the stable land surfaces of the alluvial terraces formed during the MIS 3 – Karginskiy thermochron. Growth of ice wedges required meltwater supply, thus supposing that the climate even during the coldest phase of MIS 2 could provide moisture for such a process; this conclusion casts doubt on the hypothesis of hyperarid “glacial desert” as a dominant type of landscape during the Sartanian cryochron in the north of West Siberia.

The period of polygonal ice wedge melting was marked by cryohydromorphic soil development within the seasonal-thawed layer above still persisting permafrost and predominance of swampy tundra ecosystems as evidenced by paleopedological and paleobotanical results. The spread of hydromorphic environments could result from quick climatic change at the end of MIS 2 and could be further prompted by surface water stagnation linked to polygonal ice melting.

Basing on the obtained results we propose to define the Taz-Nadym cryo-paleopedogenic horizon as a representative geological unit containing a complex record of MIS 2 – Sartanian cryochron; this horizon could be further correlated with the cryogenic and palaeosol units formed during MIS 2 in the periglacial regions of the Eastern Europe.

Author contributions

S.S., V.Sh. and A.Yu. studied and sampled the sections in the field, in particular S.S. and A.Yu described pedogenetic characteristics of soils and pedosediments whereas V.Sh. identified paleocryogenic features of ground wedge structures. E.B. carried out paleobotanical analysis of samples and its interpretation. E.Z. provided radiocarbon datings. S.S. contributed with the primary authorship of the text however all authors took part in the development of the manuscript.

Data availability

The data used to support the findings of this study are available within the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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