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UPPER QUATERNARY DEPOSITS OF THE NADYM OB AREA: STRATIGRAPHY, CRYOGENIC FORMS, AND DEPOSITION ENVIRONMENTS

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The paper presents new data on the stratigraphy, lithology, paleopedology, geomorphology, and radiocarbon geochronology of Late Pleistocene and Holocene deposits in the Nadym Ob area of the West Siberian Plain. The study reveals several distinct events in the Late Pleistocene and Holocene climate and deposition history of the area. Fluvial deposition during the first stage corresponding to the end of MIS-3 (Karga interstadial) produced the second river terrace. During the next stage, in the Last (Sartan) Glacial (MIS-2), primary sand wedges formed as frost cracks became filled with aeolian sand. The presence of sand wedges is inconsistent with the existence of ice sheets in the area during MIS-2. The first terrace of the Nadym River and its tributaries accumulated during the third stage (from about 10.7–10.3 Kyr BP), and peatbogs appeared in the Holocene. The latest stage began in the late Holocene after a long deposition gap and produced thick aeolian sands upon the second and first river terraces. The aeolian sand deposition for the past 1200 years was punctuated by short episodes of soil formation and vegetation growth in a slightly warmer and moister climate.

Upper Quaternary deposits, sand wedge, Nadym Ob area, aeolian processes, West Siberian Plain

INTRODUCTION

Although a wealth of evidence has been collected on stratigraphy, lithology, and geomorphology of Quaternary deposits in the northern West Siberian Plain, they remain quite unevenly studied. Shortage of data leads to controversy in interpretations of the origin, stratigraphic division, ages, and deposition history of specific sequences, as well as on the history of regional paleogeography. The Nadym Ob area is among underexplored parts of the West Siberian Plain. Few publications address Quaternary deposits of the area [*Ivanovskiy, 1939; Lazukov, 1960; Reinin, 1960; Lazukov and Reinin, 1961; Zemtsov, 1976*] but lack detailed descriptions of sections. According to a popular hypothesis, though based on deficient knowledge of local geology in areas distant from sections along the Ob River sides, the northern West Siberian Plain was covered by ice sheets during the Last Glacial.

Studies of Upper Quaternary sediments in the Nadym River valley near Nadym city in 2012 revealed primary sand wedges in Late Pleistocene fluvial deposits, as well as abundant Holocene aeolian deposits. The wedge structures are of special interest because they are highly informative tracers of climatic and especially cryogenic settings of deposition and thus have important paleogeographic implications [*Romanovskiy, 1993*]. Their presence is inconsistent with the extent of ice sheets over the area during the Last (Sartan) Glacial. Radiocarbon dating shows late Holocene ages of buried soils in aeolian deposits. The new data allow reconstructing the Late Pleistocene and Holocene deposition and environment history of the Nadym Ob area.

QUATERNARY STRATIGRAPHY AND GEOMORPHOLOGY OF THE NADYM OB AREA

The Nadym River valley is very young. It is incised into an alluvial-lacustrine plain deposited during the Early Zyryanian glacial event, which consists of a floodplain and two terraces above it. The river water table is about 9 m asl near Nadym city. The first terrace is fragmentary and has its surface at elevations of 15–18 m asl. The second terrace deposited during the Karginian interstadial [*Lazukov and Reinin, 1961*] grades into a lacustrine-alluvial plain and has a width of ~3 km, elevations of 20.0 to 23.6 m, and the 4–5 to 10–15 m total sediment thickness near Nadym [*Melnikov, 1983*]. According to *Nazarov* [*2015*], this terrace structure is common to whole northern West Siberia. The Karginian age of the terrace has been confirmed by hundreds of OSL (optically stimulated luminescence) dates obtained from its alluvium showing ages in the range from 42 to 25 Kyr BP and the ages of the overlying sediments from 20 to 12 Kyr BP [*Nazarov, 2015*]. Thus, the second terrace and the sediments above it formed, respectively, during the third and second stages of the marine oxygen isotope stratigraphy (MIS-3 and MIS-2) [*Bassinot et al., 1994*]. In the Nadym Ob area, aeolian deposits are widespread upon both first and second terraces, as well as on older surfaces [*Ivanovskiy, 1939; Zemtsov, 1976*], and often make up large sand sheets, but their age and stratigraphy remain poorly constrained.

The Upper Quaternary stratigraphy of the area is exposed in the left side of the Nadym valley, 105 km upstream of the river mouth and 2.4 km southwest of the main channel, in a sand quarry (65°21.020′ N, 72°58.248′ E) that strips the upper part of the second terrace and the overlying aeolian sands. The terrace section, from top to bottom, is as follows.

1. Plane-parallel laminated gray mainly quartz fine silty sand containing abundant brownish-yellow nearly vertical elongate iron hydroxide precipitates along plant roots. Their vertical orientation and the absence of branching suggest growth over roots of aqueous plants. The top surface is rough and dissected by sand wedges (lighter-color sand filling thermal-contraction frost cracks in darker sediment). One wedge encloses a silicic ventifact in its upper part. Layer thickness: 0.6 m.

2. Gray polymictic fine sand, with uneven plane-parallel lamination (2–20 mm thick laminas) produced by alternation of silt and well washed sand; wave ripples. Layer thickness: 1.1 m.

3. Unconsolidated well washed light gray to brownish polymictic sand with platy cross lamination and with small lenses (to 2 cm) of coarse polymictic sand and scarce grains of fine gravel, as well as with isolated small pebbles in the upper part. Visible thickness: 0.6 m.

The lithology and structure of sediments, and the succession of layers in the section show distinct changes from the facies of a meander bar of a large river (layers 2 and 3) to an overgrown floodplain water body (layer 1), which fits the general deposition model of a slow meandering plainland river [*Shantser, 1951; Allen, 1970*].

The uneven eroded surface of the second terrace, the absence of the uppermost sediments, and the presence of a ventifact in a sand wedge indicate that the alluvium has been deflated. The sand wedges and the deflation surface are conjugate in space and related genetically. The second terrace cut by sand wedges is overlain by younger aeolian sand layers found throughout the Nadym Ob area. The sharp and rough contact between terrace alluvium and aeolian sands suggests a deposition gap. Aeolian sands total a thickness of 12 m, are light gray, with a yellowish-brownish hue, and have platy lamination produced by alternation of parallel laminas (within 20 mm) that differ in grain sizes from fine to medium or rarely coarse and make up 1.5–2.0 m thick inclined sets. Occasionally there appear up to 10 cm convolutions and swale-like laminated lenses reaching 3 m in thickness and 25 m in length. The sand unit encloses several paleosols. Aeolian deposits upon the second terrace stripped in the sand quarry form a 12 m high sheet extending for 2 km in the N–S direction and 1 km from west to east. It is located on the left side of the Kheigiyakha River, 8.5 km upstream of the mouth, northeast of the Nadym–Beloyar road. The sand sheet has a complex surface topography. It is bounded by sand ridges, from 4 to 12 m high, in the north, west, and south; in the east, the sand lies over the Nadym floodplain and first terrace. Upon the sand surface, there are dune-like elongate sand ridges, mainly 1.5–2.0 m high or exceeding 4 m in the south. The dunes keep moving along the surface of the second terrace. Erosion cutouts strip a polygonal network of thermal-contraction cracks in 50 m wide depressions between dunes on the surface of the second terrace, which are often buried under aeolian deposits. The orientation of dunes, depressions between them, and their slopes shows that the present aeolian topography is forming under the effect of northern and northwestern winds.

SAND WEDGES

Well pronounced polygonal structures of sand wedges, which formed as sand filled large frost cracks, cut the surface of the second terrace deposited earlier during the Karga interstadial. The climate in West Siberia of that time was slightly colder than now [*Zykina and Zykin, 2003, 2012; Astakhov, 2006*], but the temperatures were warmer than required for the formation of thermal-contraction cracks at the respective latitude. This is implicit evidence that the sand wedges are of epigenetic origin. The wedges are locally exposed but are buried under aeolian sands over a large part of the deflated surface. Sand wedges occur in the central part of the sand sheet, in ~50 m wide depressions between dunes (Fig. 1). They are spaced at 6–7 m and reach depths of 2.6 m and 0.4–0.6 m widths on the top. The wedges have nearly triangular shapes and show distinct vertical layering, with the layers consisting of 2–3 cm elementary veins of different grain sizes, gray or brownish-yellowish on the margins (due to iron hydroxide staining). The sediments that host the wedges are bent upwards, especially strongly near the wedge tops, and make swells around the wedges. There are remnants of ferruginous illuvial horizons of paleosols between some swells. One sand wedge encloses a ventifact which

Fig. 1. Large polygons of primary sand wedges on the deflated sand surface of the Nadym River second terrace.

could form in a desert setting only [*Glennie, 1970; Kolpakov, 1979*] and thus provides evidence for aeolian genesis of sand that fills the wedges. The wedges may have acquired convex tops as finer material was blown out from the polygon interior. The swells are often covered with reddish-brownish crusts of iron hydroxides stable to weathering, which has preserved the contours of large polygons till the present.

These structures can be interpreted as primary sand wedges [*Péwé, 1959; Romanovskiy, 1977; Murton et al., 2000*] proceeding from several criteria: wedge-like morphology; vertical orientation; sand lithology of wedge hosts; filling material; sizes of wedges and polygons; the presence of a ventifact near the top of one wedge. The features of sand wedges and veins in the study area perfectly agree with the published criteria [*Péwé, 1959; Romanovskiy, 1977; Murton et al., 2000; Murton and Bateman, 2007; Bockheim et al., 2009*]. They result from multiple events of frost cracking and filling of cracks with aeolian sand, in a continental climate with strong winds. Present primary sand wedges occur mainly in polar deserts, especially in strongly continental conditions, with an active layer (seasonal thaw) above permafrost, in coarse sediments deposited in different environments [*Berg and Black, 1966; Pissart, 1968; Romanovskiy, 1977; Murton et al., 2000*]. In present Antarctica, sand wedges form only on ice-free ground [*Berg and Black, 1966*]. In the Pleistocene, such wedges were widespread in Central and Northern Europe at the edge of ice sheets [*Goździk, 1973; Murton et al., 2000*]. In West Siberia, they existed in the Pavlodar Irtysh area during the Last Gacial [*Zykin et al., 2003*]. They commonly appear in the conditions of low-snow winters with strong winds and intense aeolian processes [*Romanovskiy, 1977*], which is confirmed by the presence of the ventifact.

Large polygons and convex surfaces of large sand wedges enclose a system of small sand-filled veins spaced at 0.2–0.3 m (Fig. 2), 0.05 m wide on the top and 0.2–0.3 m deep. Downward bending of the sediment layers that host the sand veins indicates their origin by thermal contraction (cracking).

Fig. 2. Small sand vein structures inside large polygons.

The location of the deflated surfaces on the second terrace which was deposited between 42 and 25 Kyr BP [*Nazarov, 2015*] during MIS-3, as well as the sequence of climate events in West Siberia [*Zykina and Zykin, 2012*], allow attributing the sand wedges to the Last (Sartan) Glacial, or MIS-2.

HOLOCENE BURIED SOILS

Aeolian sands contain fragments of three buried soils at different stratigraphic levels in the lower part of the section, but they have been deflated over the greatest part of the sand sheet. Soil fragments lie on eroded surfaces and mark deposition gaps. The genetic soil horizons are labeled according to the classification used currently in Russia [*Shishov et al., 2004*].

The oldest soil, with a 0.6 m thick well differentiated profile, lies near the base of aeolian sands at a depth of 11.4 m below the present sand surface. The humus horizon (OA), 11 cm thick, has a deflated top surface, and consists of four 2 cm layers of black silt, with pieces of coal and poorly degraded plant remnants, thinly intercalated with yellowish-gray fine sand stained with organic and coal matter. The base of the OA horizon is sharp and wavy. The 34 cm thick podzol horizon (E) is composed of whitish unconsolidated fine non-carbonate quartz sand and has a flat base. The 15 cm thick ferruginous illuvial horizon (Bf) is grayish-brownish sand, denser than the sediments above, rich in secondary iron phases (precipitates), and dark gray sand in the lower part. Coal pieces (sample SOAN-8777) from OA gave an AMS ^{14}C age of 1240 ± 65 yr BP (calibrated age of 760 ± 70 AD).

The second buried soil lies 1.2 m above the base of aeolian sands, at a depth of 10.7 m below their present surface and 0.7 m above the lowermost soil. It is a 0.7 m thick ferruginous podzol-illivial soil with a differentiated profile. A 5 cm coarse humus horizon (OA) has an eroded top and consists of a dark gray or black poorly degraded material with a minor amount of sand and abundant pieces of coal. The podzol horizon (E), 10 cm thick, is whitish unconsolidated fine sand with a sharp base. The ferruginous illuvial horizon (Bf), 55 cm thick, is composed of grayish-brownish sand, denser than all other horizons, with abundant iron precipitates and holes of shrub rootlets filled with poorly degraded black plant remnants. At the top, the horizon is contoured by a 7 cm ferruginous pseudofiber interlayer with wavy top and base surfaces. Coal pieces (sample SOAN-8774) from the OA horizon gave a ^{14}C date of 830 ± 25 yr BP corresponding to a calibrated age of 1230 ± 25 AD.

The third buried soil located 1.5 m upsection from the second soil, at a depth of 9.2 m below the present surface of aeolian sands, is likewise of ferruginous podzol-illuvial composition and has a 1.45 m thick differentiated profile. The horizon OA, 10 cm, is composed of dark gray, locally black, coarse silt with degraded plant remnants and scarce pieces of bark and coal. The top surface is uneven, deflated; at the base, small tongues penetrate downward into the horizon below. The horizon E, up to 55 cm thick, consists of whitish unconsolidated non-carbonate fine sand and a sharp, tongue-like base; the transition to the underlying layer is marked by color and density change. The horizon Bf, 0.5–0.8 m thick, is composed of grayish-brownish dense sand with abundant iron hydroxide precipitates. Coal pieces (sample SOAN-8776) from the lower layer of the OA horizon have a ^{14}C age of 510 ± 65 yr BP corresponding to a calibrated age of 1385 ± 65 AD. On the soil surface, there are standing (vertical) fragments of tree trunks or lying (horizontal) trunk fragments with the substrate of the lower horizons E and Bf, pulled out from their place together with the stump. The age of wood is 400 ± 50 yr BP (SOAN-8775), and the corresponding calibrated age is 1480 ± 40 AD.

The obtained radiocarbon ages of the buried soils indicate that the host sands were deposited in the late Holocene, since ~760 AD. The soils in aeolian sands record phases of slightly moister climate for the past 1200 years, when soils could form and maintain vegetation growth. The short wetting excursions punctuated quasi-periodically the mostly dry conditions of sand deposition. Comparison of the chronology of buried soils in the Nadym valley with global reconstructions of mean air temperatures for the Northern Hemisphere [*Mann et al., 1999*] and Subarctic areas of Eurasia [*Naurzbaev et al., 2001*] shows some similarity of climate events over a vast territory. The formation of soil with a ^{14}C age of ~830 yr BP falls within the peak of positive temperatures between 1150 and 1200 AD in the curve of *Mann et al.* [*1999*]. The uppermost soil dated at 510 yr BP formed in a slightly warmer climate from 1400 to 1550 AD within a cold period of another temperature curve [*Naurzbaev et al., 2001*]. The similarity of late Holocene soil profiles in the sampled section suggests similar biotic and climatic conditions of soil formation. The aeolian sands lying above the uppermost soil were deposited during the Small Ice Age which lasted from the middle of the 15th century to the latest 19th century [*Monin and Shishkov, 1998*].

MORPHOSCOPY AND MORPHOMETRY OF QUARTZ GRAINS

The surface textures of quartz sand grains from different depths of the section were studied by morphoscopy and morphometry with implications for deposition conditions. The results revealed main processes that acted upon the sand grains during their deposition and transport. Quartz grains of 0.5–1.0 and 1–2 mm sizes were examined under a binocular microscope following the method of *Velichko and Timireva* [*2002*] and on a Jeol *JSM-6510LV* scanning electron microscope. The roundness of grains was estimated according to a template [*Rukhin, 1969*] and rated on a five-grade scale [*Khabakov, 1946*]; the coefficients of roundness and matting were calculated for each sample. Matting was estimated visually and rated from glossy to matted.

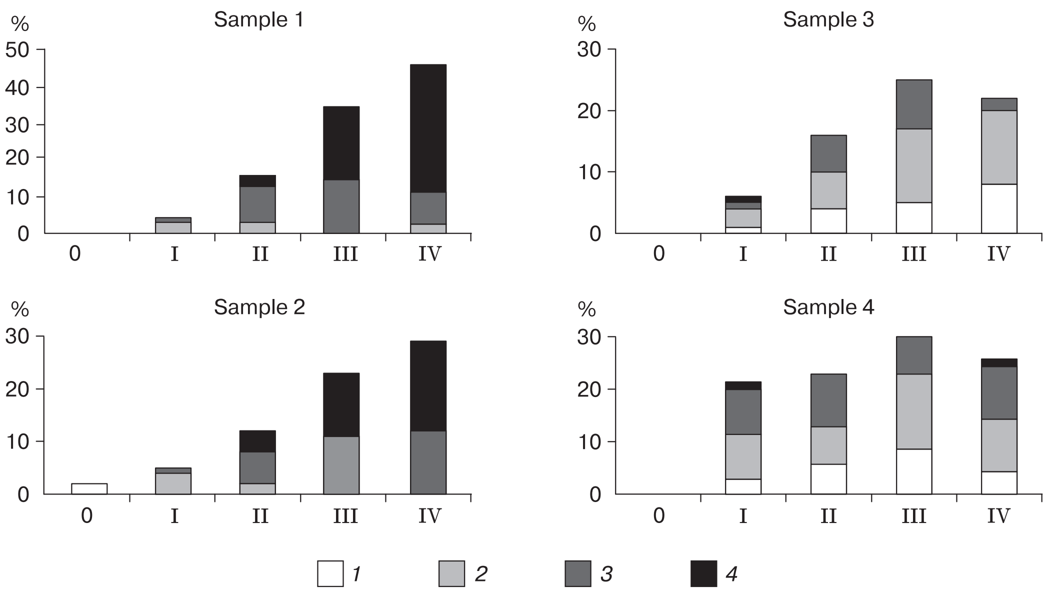

Fig. 3. Roundness and matting histograms of quartz sand grains.

1 – glossy surface; *2* – quarter-matted surface; *3* – half-matted surface; *4* – matted surface; 0, I, II, III, IV are roundness grades according to the scale of *Khabakov* [*1946*].

The quartz grains from the top of the sand sheet, which were exposed to aeolian processes (sample 1), are strongly rounded (80.4 %) and matted (76.5 %). Many grains are of roundness grades III and IV (34 and 46 %, respectively), within 4 % of grains are of grade I, while angular grains are missing (Fig. 3). Almost all grains have matted (57 %) or half-matted (34 %) surfaces; there are no glossy grains. The grains

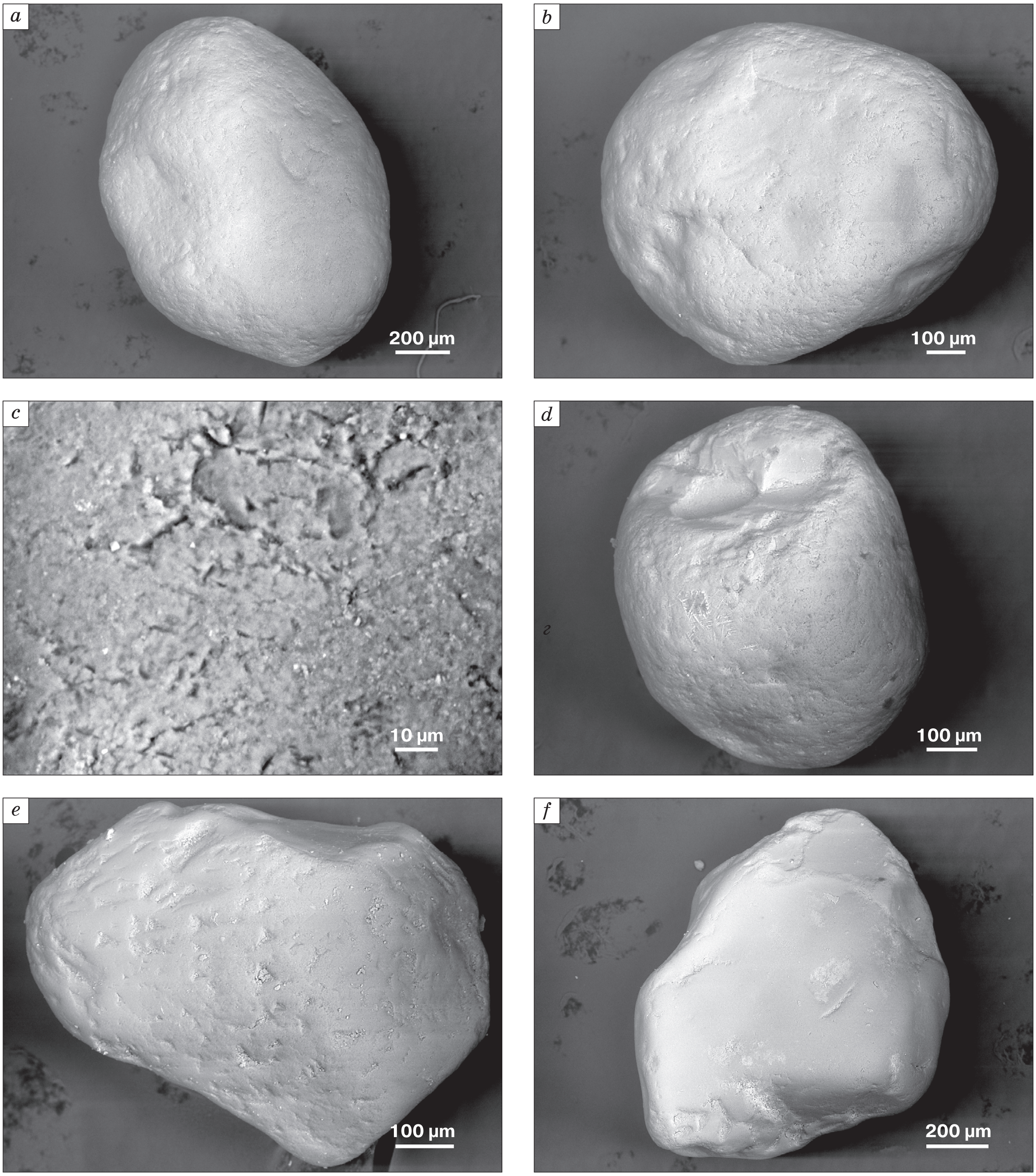

Fig. 4. Microtopography of quartz grain surfaces.

a: sample 1: matted grain with a pitted surface and traces of grain collisions; *b*: sample 1: scratches, grooves and collision traces on a matted grain surface; *c*: sample 1: pitted surface of the previous grain; *d*: sample 2: matted grain with a pitted surface, traces of collisions and concoidal fracture; *e*: sample 3: pitted surface with V-shaped pits on a quarter-matted grain; *f*: sample 4: rounded grain with a quarter-matted surface.

more or less strongly affected by aeolian transport have typical pitted surfaces (Fig. 4, *a*, *c*), sometimes with grooves and scratches (Fig. 4, *b*), which may be traces of dragging. Pits on grain surfaces, up to 150–200 μm in size, are traces of grain collisions in air flow at a high wind speed (Fig. 4, *a*). Some grains exhibit concoidal fracture indicating frost weathering [*Krinsley and Doornkamp, 1973*]: aqueous solutions that percolated along cracks inside the grains froze up and led to fracture [*Velichko and Timireva, 2002*].

Quartz grains from the lower part of the sand sheet lying immediately over the 830 yr BP buried soil (sample 2) have roundness and matting coefficients of 84.3 % and 75 %, respectively. Most of grains are of roundness grades III (33 %) and IV (41 %); 17 % of grains are of grade II, and 10 % are angular or subrounded (Fig. 3). Up to 88 % of grains are matted or half-matted. Most grains have pitted surfaces with traces of grain collisions during air transport (Fig. 4, *d*). Concoidal fracture is observed in grains of any roundness or matting (Fig. 4, *d*); their percentage is higher in sample 2 than in sample 1.

Aeolian genesis was inferred for quartz grains from the sand sheet surface, which is supported by high roundness and matting, predominance of grains with matted surfaces, signatures of collisions during airborne transport and dragging on the ground surface. The presence of concoidal fracture is evidence of frost weathering [*Krinsley and Doornkamp, 1973*].

The morphoscopy and morphometry results for grains from the sand sheet differ from those for the underlying alluvium. The roundness and matting of grains from layer 2 (sample 3) reach 71.8 % and 25.7 %, respectively. Most of grains are of roundness grades III and IV (74 % together), 17 % of grains are of grade II, 9 % are subangular; angular grains are absent (Fig. 3). The surfaces are quarter-matted in almost a half of all grains (48.5 %), glossy in 26 % and half-matted in 24 % of grains. The quartz grains typically have pitted surfaces, often with V-shaped pits produced by transport in water [*Krinsley and Doornkamp, 1973*]. Quite high roundness may indicate residence in quiet submerged conditions (Fig. 4, *e*).

Many quartz grains of layer 3 (sample 4) are rounded and matted (respective coefficients 65 % and 31 %); 30 % of grains are of grade III roundness; angular grains are absent; grains of other grades are in equal amounts (Fig. 3). The surfaces are mainly quarter-matted (Fig. 4, *f*) or half-matted. Pitted surfaces are well pronounced, which is common to fluvial deposits.

The surface textures of grains in samples 1 and 2 suggest aeolian origin of the sand sheet on the terrace surface. Concoidal fracture in grains from its base is evidence of cryogenic processes at the onset of its deposition about 1200 years ago and, hence, of a climate colder than now. The cryogenic processes of that time were more intense than now, judging by greater numbers of grains with concoidal fracture at the base of the sand sheet than at its top; some grains became redeposited from the upper fluvial deposits that froze up during the Last Glacial. Quartz grains from layers 2 and 3 indicate that aqueous settings differed either in stream speed or in residence time of grains.

LATE QUATERNARY CLIMATE HISTORY OF THE NADYM OB AREA

The Late Pleistocene and Holocene history of climate and deposition in the Nadym Ob area included four events separated by prolonged gaps.

Stage I: formation of the second terrace during the Karga interstadial (MIS-3), from 42 to 25 Kyr BP, in a climate similar to the present conditions. Mean annual air temperatures in northern [*Astakhov, 2006*] and southern [*Zykina and Zykin, 2012*] West Siberia were slightly lower than now. Judging by the elevation of the terrace surface and its total sediment thickness of 4–5 to 10–15 m [*Melnikov, 1983*], the alluvium base near the Nadym mouth is slightly above the present river table.

Stage II: deflation in much more severe climate conditions compared to Stage I; thermal contraction and filling of frost cracks with aeolian sand. The presence of a ventifact found near the top of a sand wedge provides evidence for strong winds and a cold desert setting. Judging by the stratigraphic position of primary sand wedges above the second terrace and correlation of climate events in the Nadym Ob area with the respective sequence of Siberia [*Astakhov, 2006; Velichko et al., 2007; Zykina and Zykin, 2012*], the wedges formed during the Sartan Glacial (MIS-2). They began forming at the onset of strong cooling and drying in northern Siberia about 23 Kyr BP [*Astakhov, 2013*] and completed formation during the last deglacial transition since 15.7 Kyr BP, according to the marine $\delta^{18}O$ stratigraphy [*Stein et al., 1994*].

Primary sand wedges in sand and gravel commonly form at low mean annual ground temperatures: below –10 °C [*Romanovskiy, 1977*] or at least –12 to –20 °C, and a mean annual precipitation of <100 mm [*Karte and Liedtke, 1981; Karte, 1983; Bradley, 1994*]. They may form at more temperate conditions (mean annual air temperature of –10.9 °C and mean annual precipitation of 138 mm, as in the Mackenzie delta, Canada), at abundant sand inputs [*Murton et al., 2000*]. The difference of mean annual air temperatures during the cold event from the present values is 13–21 °C, which agrees with paleoclimatic [*Kutzbach et al., 1998*] predicting temperatures 10–15 °C colder than now in these latitudes about 21 Kyr BP. According to temperature measurements in boreholes drilled in Greenland ice at the Summit station [*Cuffey and Clow, 1997*], mean annual air temperatures were 15 °C colder than now, or even 18–20 °C colder in some periods. Northern West Siberia was an area of vast cold deserts and aeolian sand deposition [*Velichko et al., 2007*].

The presence of widespread polygonal structures with sand wedges filling frost cracks, as well as traces of active aeolian processes in the Nadym Ob area are inconsistent with ice sheets. This inference contradicts the view that ice sheets spread as far as 66°30′ N [*Saks, 1980; Arkhipov, 1997*] or 61° N [*Volkov, 1997; Groswald, 1999*] but agrees with recent evidence for the absence of Last Glacial traces in northern West Siberia [*Svendsen et al., 2004; Astakhov, 2006, 2013*].

Stage III: Accumulation of the first terrace of the Nadym and its tributaries; swamping and formation of peatbogs in the Holocene. Swamping in the area, as well as in whole northern West Siberia, began about 10.7–10.3 Kyr ago, according to ^{14}C dating [*Velichko et al., 2007*].

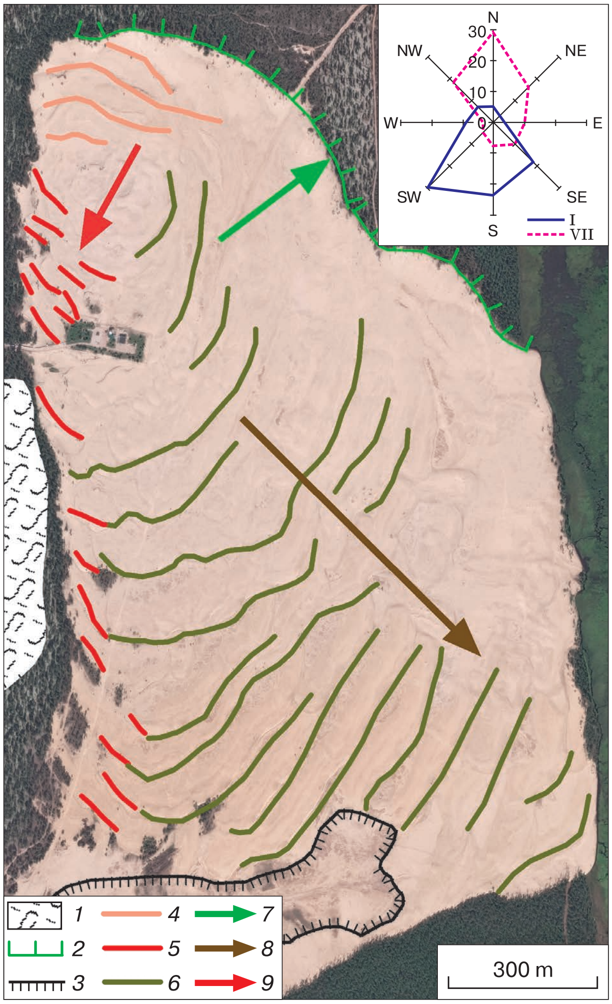

Fig. 5. Topography sketch of aeolian sands:

1 – hummocky aeolian topography; *2* – sand bar produced by southwestern winds; *3* – sand quarry; *4* – dunes, up to 1 m high, produced by southwestern winds; *5* – dunes, up to 1.5 m high, produced by southweastern winds; *6* – dunes, up to 4 m high, produced by southwestern winds. Arrows show wind directions: southwestern (*7*), northwestern (*8*), northern and northeastern (*9*), according to records of Nadym weather station (I is January, VII is July). *WorldView*-2 satellite image, 2014.

Stage IV: Aeolian deposition upon the first and second terraces in the late Holocene for the past 1200 years. The deposition was punctuated by brief episodes of warmer and wetter climate, which is recorded in alternation of aeolian sands and soils. Aeolian processes became more intense and sculptured the surface topography during cold and dry periods while soil formation and vegetation growth became possible in periods of slightly warmer and wetter conditions. Aeolian sand deposition in the area was coeval with the formation of late Holocene sand dunes in the Fore-Altai Plain in West Siberia [*Zykin et al., 2011*].

Detailed investigation into the morphology of aeolian landforms and deciphering of high-resolution satellite imagery suggest that aeolian sands formed in several steps (Fig. 5). First, southwestern winds caused extensive deflation of the Nadym fluvial deposits and formation of sand dunes which remain well preserved west of the sand sheet. The sand dunes are overlain by sands of the main aeolian sand sheet. The latter formed at the next stage, by northern and southwestern winds, and enclosed several buried soils. Later the sand sheet became split into asymmetric dunes, and polygonal wedge structures formed in depressions between them. Currently the dunes keep moving, being driven by northwestern winds. Furthermore, northeastern winds build small barkhans in the inter-dune depressions. Comparison of satellite images shot at different times shows that the sand sheet has not changed much its limits for the past 40 years.

CONCLUSIONS

The reported study of Late Quaternary sediments in the Nadym Ob area led to the following results.

1. Frost-induced primary sand wedges and veins making a polygonal framework on the second alluvial terrace of the Nadym River have been discovered and described for the first time. The location of the wedges on the surface of a terrace that formed between 42 and 25 Kyr BP constrains their origin to the Last Glacial (MIS-2), from 23 to 15.7 Kyr BP. That was the time of a very cold and dry (desert) climate when mean annual air temperature was in a range of –12 to –20 °C and the mean annual precipitation was less than 100 mm. The presence of sand wedges is inconsistent with the extent of ice sheets over the area during MIS-2.

2. We provide the first evidence for the existence of aeolian deposits in the Nadym Ob area in late Holocene time, since ~1200 yr BP. Morphoscopy and morphometry of sand grains confirms their aeolian origin and cryogenic activity at that time. The period

of active aeolian processes in the Nadym Ob area was coeval with the formation of Late Holocene sand dunes in southern West Siberia.

3. Mean annual air temperatures and humidity varied quasi-periodically during the aeolian deposition for the past 1200 years, which is recorded in alternation of aeolian sands and soils. Aeolian processes became more intense during cold and dry climate spells and produced aeolian sand deposits and topography features, while soils formed during short episodes of warm and wet climate and maintained growth of vegetation which fastened the sands. The climate changes were associated with changes in predominant wind directions.

4. The Late Quaternary history of the area included several stages. Fluvial deposition during the first stage (42 to 25 Kyr BP) produced the second river terrace. During the next stage (23 to 15.7 Kyr BP), primary sand wedges formed as frost cracks became filled with aeolian sand, in a desert setting of the Last Glacial. The first terrace of the Nadym River and its tributaries accumulated during the third stage (10.7–10.3 Kyr BP), and peatbogs appeared in the Holocene. The latest stage began in the late Holocene, ~1200 years BP, after a long deposition gap and produced thick aeolian sands and a hummocky topography upon the second and first river terraces.

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