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LITHOLOGICAL AND GEOMORPHOLOGICAL INDICATORS OF GLACIAL GENESIS OF THE UPPER QUATERNARY STRATA IN THE LOWER COURSES OF THE NADYM RIVER

Short title: Glacial genesis of upper Quaternary strata in Nadym

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Highlights:

Sediments in area of the Nadym River formed during glaciation
Continental glaciation evidently occurred during the Pleistocene

Abstract
Analysing the genesis of Quaternary sediments is important for understanding the glaciation history and development of marine sediments in the northern part of the Western Siberia. The key features of sedimentation and landform formation have been characterized for the first time in an example of a lithological column from the lower sources of the Nadym River. A

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comprehensive analysis was performed on the lithological, petrographic, and geomorphological data from the upper stratum of Quaternary sediments of the column. Based on the shape and morphology of quartz grains, some features of glacial processes for some layers of the studied sections were identified and analysed with special attention to the environmental history. A petrographic study of the boulder samples was carried out, which showed that the majority of samples are boulders of glacial origin according to their shape and texture. For the first time, digital terrain models were applied to study of the key plot where the lithological column is situated, which made it possible to identify the specific terrain areas that were most likely formed by glaciation. It is suggested that extensive lacustrine-alluvial plains existed in the Nadym River Basin, which was represented by postglacial sites. Such a concept provides a lithological basis for understanding the reasons for the formation of the present and recently formed environments and landforms. Therefore, it could be possible that local glaciation in the region of the Nadym River's lower course had an effect on the formation of the stratification of the layers of Quaternary origin.

1. Introduction

The history of geomorhology development in the northern part of Western Siberia has been a subject of intensive discussion during the last part of XX-th century. The stratigraphy of Enisey river estuary is a key factor of West-Siberian lowland quaternary evolution. The problem of the presence and distribution of cover glaciations in the Pleistocene is the most problematic for current geomorphology of North part of Western Siberia. Numerous examples of sedimentation alternation, induced by various cover glaciations of different ages and thicknesses are presented here in different geomorphological levels and landforms. These series of sediments has been used as a background reference points for geological interpretation of the history of Western-Siberian lowland. A certain compromise between the opposite point of views on glaciation presence on the territory of Western Siberia was proposed by scientists of the Tyumen complex expedition of the geographical faculty of Moscow State University, who prepared in 1971 Atlas of the Tyumen region. G.I. Lazukov and M.E. Gorodetskaya developed a geomorphological regionalization scheme, which shows limited areas of maximum Samara glaciation along the periphery of Western Siberia without formation of a single ice shield, while the main territory is presented in the form of a series of different-altitude sea terraces of different degree of dismemberment (Lazukov, 1972). Numerous discussions at geological plenary and commissions did not lead to the formation of a single representation, so the second edition of the Q-42-43 of the State Geological map of scale 1:1000000 (an edition S.B. Shatsky, 1995). Thus, a number of contradictions at the general prevalence of the glacial concept contains - on the map simultaneously with glacial, fluvial and glacial deposits are specified marine and glaciomarine, borders of large stages the late Pleistocene of gaciations are allocated. At the present stage (including the period from the second half of the 1990s) with the general reduction of geological surveys intensity, the work on harmonization of contradictory points of view was continued. In 1999, the Legend of the Tyumen-Salekhard Subseries of the West Siberian Series map was approved to the sheets of Gosgeologocal map-200, based on a stratigraphic approach, which allows to more objectively dismount and correlate cuts on the basis of complex paleogeomorphological analysis taking into account the results of all available methods of research (paleontological, physical, first of all paleomagenic).

The state geological map of Russia Q-43 for this region indicates the dominance of glacial and fluvioglacial types of the surface sediments (Alyavdin, Mokin, 1957). The possible existence of ice sheets and related permafrost sediments was identified as a key issue

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in the beginning of the systematic geological study of this territory in the 1960s. Some researchers (e.g., Svendsen, 2004) have suggested that there were extended glaciations that resulted in blocking of the river or parts of rivers at certain stages, leading to the formation of large glacier-dammed lakes (Grosvald, 1999). Another point of view is related to the possible existence of glaciation on the plain (Generalov, 1986). That is why the landforms present as a sequence of terraces formed by marine transgressions of various ages. There is also an opinion that the glaciation was localized in the form of ice caps on separate watersheds and that the river flow unblocked (Velichko, 1987; Velichko et al., 1997). Bolshiyanov (2006) have argued this opinion and have implemented the term “passive glaciation”. In this context, it is assumed, that the sea level fluctuations might have created extended abrasion platforms. Also, there is a point of view that those forms of relief, which previously were considered as glacial and fluvioglacial (morains and easkers) were not originated from cover glaciations, but resulted form erosion, abrasion and thermokarst outcrops related to permafrost-erosion and tectonic processes of the late Pleistocene. It was suggested, that isolated parts of Smarovskoye glaciation was presented in some parts of the Tyumen region in combination with relics of ancient marine terraces (Lazukov, 1972). Later, the intensive discussion was between geologists regarding the nature of possible glaciations and sedimentation history on the territory of Western Siberia. It was suggested that glaciations has been extended till Siberian ridges where it was continued by ancient periglacial Mansyiskoye lake (Grosvald, 1999). Bolshiyanov (2006) suggested that the glaciations was passive, without formation of discontinuous cover and without blocking of the preferential flow in topography. At the same time, the abrasion relief with extended ledges has been formed in late Pleistocene period. In the region of Nadym river the investigations of sediments stratigraphy and landforms development was started in 1960-th. As result of theses, works 3 generation of geological maps were created. Here, there numerous geomorphological levels are presented. But, this region was ont covered by Russian-Norvegian project “Queen”. It was suggested on the sheet of the state geological map Q-42-43 that there is a combination of glacial and marine glacial sediments and numerous lake terraces on the territory of Western Siberia. Nowadays, the glacial sediments are excluded form the current version of the state geological map (Babushkin, 1995) which is in contradiction to the results, obtained by Zastrozhnov (2011) and Fredin et al. (2012). Nowadays, there is not uniform concept of the landforms genesis in Western Siberia. The basing of the Nadym river is considered as most important for quaternary interpretation of this region history in Pleistocene. The topography and sediments of the Nadym River is one of the must informative key territories where numerous field investigations and remote sensing operations have carried out by numerous generations of researchers. The results of studying the Nadym River and adjacent areas, among other data, have served as a basis for classification of the Quaternary deposits in West Siberia (Maslennikov, 1998, Sedov et al, 2016, Sheinkman et al, 2016, Rusakov et al, 2018). Sheinkmann et al (2016) use to deny the presence of glaiation and their role in landform formation. In opposite, Bolshiyanov (2066) suggest that glaciation has existed and was important for geomorhological history of the surrounding of Nadym river. Nevertheless, the current geological map (Faibusovic, Abakumova, 2015) involves unsolved issues that are manifesting as new geological and geomorphologic data obtained. Thus, the objective of this study is to conduct detailed lithological, petrographic and geomorphologic analyses in the lower course the Nadym River with special reference to indicators of the key factors, affecting the sedimentation and landform formations.

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2. Materials and methods

2.1 The study sites

The field investigations were carried out in August 2016 on the left bank of the Nadym River near the confluence of the Kheigiyakha (Long Ugan) River, 40 km south-west of the city of Nadym (Yamalo-Nenets Autonomous Okrug, Russia). The area is well developed in terms of industry and includes main gas lines (the Urengoi–Pomary–Uzhhorod line, Nadym–Punga–Nizhnyaya Tura line, etc.), high-voltage power transmission lines (200 kV, 500 kV), an oil pipeline (CPF Yarudeyskoye oil field – OPS Purpe), and a hard-surface motorway (Nadym–Yagelnoye Road). Due to the lack of natural exposures, two quarries were chosen for this research (N65.350455°, E72.970881°, and N65.061417°, E72.943848°). Two sections were made in the quarry walls: K-1 and K-2, which are 5 m and 6 m high, respectively (Fig. 1). The area selected it best example for investigation Quaternary history in central part of Yamal region due to geomorphological pecularities and stratification.

The vertical sections were exposed on the high bank of the Nadym River. Sections K-1 and K-2 show the structure of a second terrace above the floodplain of the Nadym and Levaya Khetta Rivers. Section K-1 was made in the eastern wall of sand quarry N1 within the Aeolian massif (N65.350455°, E72.970881°, absolute elevation 20 m). The total thickness of the exposed stratum was 435 cm. A detailed description of each horizon is given in Table 1, and a general view of the section is shown in Figure 2(a).

Section K-2 was made in the northern wall of dormant sandy-gravel quarry N2, which is located near the Nadym–Yagelnoye Road (absolute elevation 50 m). The total thickness of the exposed stratum was estimated as about 421 cm. Detailed descriptions of each horizon and layer of the strata are given in Table 2, and a general view of the section is shown in Figure 2(b).

2.2 Methods

Samples of sediments were taken from each of the horizons for morphological analyses using grain morphoscopy. The chemical composition and grain size distribution were also identified. The main oxide concentrations using an X-ray fluorescence method and SEM photos were done in Analytical Center for multi-elemental and isotope research of the Sobolev Institute of Geology and Mineralogy of the Siberian Branch of the Russian Academy of Sciences (SB RAS). The grain-size distribution was determined using a dry screening method (a sieving test) with a vibratory sieve shaker (Analysette 3, Fritsch, Germany, https://www.fritsch.com.ru/podgotovka-prob/rassev/vibracionnye-grokhoty/detali/produkty/analysette-3-spartan/compare/ (page viewed 04.05.2019)). Fractions were quantified gravimetrically with a precision of 0.1 g.

Quartz grains of medium- and coarse-grained sand were studied using a binocular microscope according to the technique developed by the Institute of Geography of the RAS (Velichko & Timireva, 1995). Images of the grains were obtained by scanning electron microscope (Tescan MIRA 3 LMU). The roundness of the grains and their shapes were evaluated according to the method reported by Rukhin (1969) and the 5-grade scale reported by Khabakov (1946). The roundness coefficients and the degree of surface dullness were then calculated for each sample (Velichko & Timireva, 1995). In general, these methods are in good correspondence with the procedure for the preparation of samples described by Krinsley & Doornkamp (1973).

The surface shape and heterogeneity of the grains were determined visually on a gradient ranging from glossy to matte. This method was previously used when studying underlying sands under the peat deposits near the Siberian Uvaly, the Taz and Pur Rivers

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(Velichko et al., 2011), and Aeolian sediments in the south of West Siberia (Sizikova & Zykina, 2015).

Sampling was also conducted in the lowest horizon of section K-1 for absolute age dating using the optically stimulated luminescence technique (the analysis was performed by N. A. Molodkov at Tallinn University). In total, 15 samples were taken from one of the quarries for further petrographic study (coordinates N65.061368° E72.943045°). The samples were prepared into the form of thin sections in the perpendicular direction with transparent slices. Their micromorphology was then investigated under an optical microscope (Carl Zeiss AxioScope A1, Sobolev Institute of Geology and Mineralogy of the SB RAS, Novosibirsk).

Digital terrain models (DTMs) were used to characterize the geomorphic features of the studies sites. This was the first time that this was done for the investigated territory. The DTMs had spatial resolutions of 12 and 26 mpx and were created using satellite images from TerraSAR-X and TanDEM-X. The initial data were obtained within the framework of a research project supported by the Terrasar-X team for the purpose of studying possible applications of the TanDEM DTMs in scientific research (DEM_GEOL1378). Multispectral space images were used (10 mpx), which are generally available thanks to the Sentinel-2 mission (Copernicus Open Access Hub, n.d.).

3. Results

3.1. Bulk chemical composition

Data about the oxide content are given in table 3. Based on the main oxide concentrations, it is possible to evaluate main differences in sedimentation processes in various paleoenvironments. To clarify the differences of various stages of sedimentation, section K-1 was divided in two sub-layers and sampled. Data on the concentrations of SO_3, V_2O_5, Cr_2O_3, and NiO are omitted because they were lower than the detection limit in all samples.

All of the studied layers are characterized by a horizon with a high content of silica oxide. Aluminium and iron oxide were also dominant in the chemical composition of the samples. The silica content was higher in horizon 6, which also had very low contents of aluminium, titanium, magnesium, iron, manganese, calcium, and other elements. Therefore, this horizon can be attributed to olgomictous sands that sustained long-term exposure and could preserve only the most stable mineral, silica.

The exposed deposits are part of the second terrace located above the floodplain, and upon first glance, they demonstrate a transition zone from the channel and floodplain facies to a series of subaerial sediments. For horizon 6 of section K-1, absolute age dating was performed using the optically stimulated luminescence (OSL) method. The determined age was 24.3±1.7 thousand years (RLQG 2443-057, U_{ppm}=0,11, Th_{ppm}=0,45, $K_{\%}$=0,01), which corresponds to the interchange from the warm Karginsky Age to the last Sartan Ice Age.

3.2. Grain size composition

The particle size distributions are given in table 4. Horizon 6 of section K-1 clearly demonstrates a predominance of medium- and coarse-grained sand fractions, while finer fractions are in smaller quantities, and silt and clay particles are almost absent. Horizon 6 of section K-2 is also marked by a minimal content of silt and clay and a very high content of medium-grained sand. This could be interpreted as the result of high fluvial velocity and sufficient washing of the sediment matter. In the top sediment layers, the silt and clay content were high, which is characteristic of Aeolian sediments.

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3.3. Morphoscopy of the quartz sand-grains

The micromorphology data of the quartz grains are given in table 5. For section K-1, a low roundness coefficient is clearly observed from horizons 2 to 6/2, while the degree of surface dullness drops at horizon 3 and remains within 33-44.5% from horizons 3 to horizon 6/2 (Table 5). The coefficients and distribution of the sand grains according to their roundness in the sequence of horizons 1–3 suggest a significant influence of Aeolian processes on the transport of sand. The possible presence of intensive aeolation is also supported by the morphoscopic data, where grains with micro-pitted texture are observed in the samples, which is an indicator of subaerial impact (Velichko & Timireva, 1995; Vos et al., 2014; Krisley & Doornkamp, 1979).

In addition to micro-pitting, signs of fluvial transport are rather distinct (fine-pitted and smooth surfaces, V-shaped pits, and crescentic percussion marks). Therefore, these sand grains were shaped due to the following process: first, they were transported by water flow, and then they were eroded from river valleys and transported by wind for a short distance. This is indicated by the prevailing micro-pitted texture of the protruding edges of the grains.

For horizons 4 and 5, high roundness coefficients and low degrees of surface dullness are typical, which is an indicator of significant subaqueous impact. This is also supported by the prevailing number of well-rounded and perfectly rounded grains (Figure 3), as well as the frequency of fine-pitted surfaces and subaqueous V-shaped pits (Vos et al., 2014; Krisley & Doornkamp, 1979). Some grains show the indications of Aeolian processes in the form of micro-pitted texture.

In horizons 6/1 and 6/2, glossy grains are notably abundant regardless of the roundness (Figure 3), which suggests aqueous transport. The prevalence of glossy grains among the subangular and perfectly rounded grains (Figure 3) can be attributed to the presence of two washout sources, one of which could have brought in unaltered material. Morphoscopy data also illustrate that the fluvial nature was one of the key factors of this horizon.

In terms of roundness, the sand grains from both layers can be divided into two groups. The first group includes grains of grades III and IV, which are often glossy unless damaged by chemical processes, and their main features are fine-pitted surfaces (Figures 4 (a)–(d)) and crescentic percussion marks (Figures 4 (a), (d), (f), (h)). Most frequently, these grains are characterized by spherical or nearly spherical shape, which could be connected with long-lasting subaqueous impacts.

Group 2 includes sub-angular and sub-rounded grains of irregular shape and smooth surface texture (Figure 3). The main feature of these grains is crescentic pits (Figures 4 (f)-(h)). The ground-down flat faces (Figures 4 (a), (e)) and elongated form (Figures 4 (a), (c)) support the idea that the grains were not exposed to subaqueous impact for enough time to obtain a regular shape. Some grains are characterized by various grooves and scratches, which often appear due to intense mechanical alteration, as well as conchoidal fractures (Figures 4 (f), (j)), which are caused by frost weathering. If water or other liquids penetrate a crack and then freeze, the grain splits (Velichko & Timireva, 1995). Such flat faces, grooves, scratches, and fractures have rounded edges, and textures that are typical for aqueous impact can be often detected on them. Therefore, a post-sedimentation origin appears impossible.

Presumably, the glacial deposits were washed down the course of the flow that collected and transported part of this material. It should also be noted that the amount of subangular material in horizon 6/2 is higher than in horizon 6/1, which could indicate that during the sedimentation of horizon 6/2, the deposits represented by grains from group 2 were washed down more intensively. All horizons of the section were subject to post-sedimentation chemical erosion and frost weathering.

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According to the morphoscopy data and quartz sand grains from horizons 1–3 in section K-2, we can conclude that both alluvial and Aeolian transport was critical for the formation of these sediments, which is demonstrated by the high roundness coefficients, medium degree of surface dullness (Table 6), and good roundness of the material (Figure 3). Fine-pitted surfaces, crescentic texture, and V-shaped pits are indications of fluvial transport of the sand (Vos et al., 2014; Krinsley & Doornkamp, 1979). Micro-pitting that results from Aeolian transport is found on such marks or on the grain surfaces (Velichko & Timireva, 1995).

For the content of the grains of subaerial origin in horizons 4 and 5, transport is not high, and the principal factors in the sedimentation of these layers were subaqueous processes. Horizon 6 was also formed by alluvial sedimentation but differs considerably from the above horizons in terms of the sand-grain distribution and prevailing low grades of roundness (Figure 3). Horizon 6 includes a significant number of grains with post-sedimentation conchoidal fractures and flat faces. These features could be related to the flow-collected material being exposed to the frost and mechanical impacts typical of glacial deposits.

In general, the morphoscopy of grains from horizon 6 and the mechanism of their sedimentation appear similar to those of layers 6/1 and 6/2 in section K-1. Horizon 6 in both examined sections is distinguished by the morphology of the sand grains. They are characterized by the lowest roundness coefficients (63-65%) and degrees of surface dullness (33-35%, Tables 5 and 6), the presence of the glossy grains at all grades of roundness, smoothed and ground-down flat faces, crescentic texture, and fine-pitting on the surfaces. Based on these characteristics, it can be concluded that horizon 6 was formed by fluvial processes, although it should be noted that it includes material typical of glacial deposits.

3.4. Petrographic analysis

The petrographic analysis of 15 samples taken in section K-2 clearly allowed us to revealed several groups of materials:

1) The first group (6 samples) is presented by grey, yellowish-grey, and greenish-grey fine-grained and very fine-grained sandstones and siltstones with slab jointing. They are usually moderately or poorly sorted and have primary foliation that is emphasized by the regular orientation of flattened grains, varying grain size, and matrix content. The matrix is hydromicaceous clay, sometimes with ferruginous cement, with a small portion of silica. The fragments are usually sub-rounded or sub-angular. The rock is composed of polymictic sandstones, similar to arkosic sandstones. Quartz and feldspar prevail among the mineral grains, composing ~30 vol% of the fragments, while another third is predominantly composed of siliceous rock fragments. Some samples contain significant amounts of muscovite (up to 5% by volume), chlorite (including pseudomorphs after the dark-coloured minerals), and epidote. The presence of muscovite could be an indicator of low weathering of initial sediments.

2) Pebbles and boulders of the second group of quartzitic and quartz sandstone (6 samples) feature angular forms. The textures are usually massive and vary from poorly to well sorted. The cement is predominantly quartz or quartz-hydromicaceous, sometimes with goethite. The grain size varies greatly, but medium-sized varieties prevail. More than 95% of grains are quartz and siliceous lithoclasts, while muscovite, feldspar, epidote, zircon, monazite, and opaque minerals are also present. The quartzitic sandstones show regenerative incrustations around the primary rounded quartz grains. The grain boundaries are most often irregular and frequently saw-shaped, which indicates a notable meta-genetic alternation. Late veins of the fine-grained quartz aggregate are also rather frequent.

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3) The third group of samples was the least numerous yet the most informative. In this case, the first sample is a cobble of pinkish quartz trachyte–alkaline intermediate volcanic rock. Large pelitized phenocrysts of potassic feldspar (up to 1 cm) and rare fine quartz grains are distributed in the groundmass composed of pelitized potassic feldspar and quartz (Figure 5(a)). Furthermore, quartz-feldspathic myrmekites are rather frequent. There are small quantities of plagioclase, dark-coloured minerals that are substituted by aggregates of chlorite, epidote, and opaque mineral.

The second sample is dolerite with typical poikilitic texture (Figure 5(b)) formed by large poikilite clinopyroxene crystals (3-4 mm in diameter) with tabular plagioclase (up to 1-1.5 mm). There are large, separate hypidomorphic crystals of basaltic hornblende (up to 2 mm), which are substituted by hydrous ferric oxides, titanite, and chlorite. The main groundmass contains plagioclase and significant amounts of chlorite, which is presumably a product of substitution of the volcanic glass or clinopyroxene microliths.

The third sample is zoisite-amphibolite (zoisite-actinolite) metasomatic rock. Light-green idiomorphic grains of amphibole prevail over hypidomorphic crystals and sheaf-like aggregates of zoisite. Anhedral segregations of titanite and opaque ore minerals are also present. From a general chemical perspective, it can be suggested that the most probable protolith for this rock was a dolerite-like rock.

3.5. Relief

The study area is located in northern sparse taiga with vast wetlands. Thus, the relief structure was captured in great detail by the DTMs obtained with X-band radar data (with deep penetration capability). Analysis of the recent DTM revealed two typically glacial relief forms, which has been described previously on geological and glacilogical maps (Shatsky, Babushkin, 1996; Astakhov et al., 2016):

1) An area of the linear-ridged relief is located on the right side of the Yarudei River (left-side tributary of the Nadym River) near the Nadym–Salekhard transportation corridor, which was in process of construction (Figures 1 and 6). Two long, curved mountain ridges rising up to 55 m (the difference in relative elevation is 10-12 m) are well preserved. South of the ridges, there is an area of undulating, presumably kame relief. The ridges are composed of thermocast and erosional forms.

2) An area of the kame and easker relief is located on the right side of the Nadym River, south of the gas mainlines (Figures 1 and 7). The kames form a chain of hills rising up to 100 m (the difference in relative elevation is 30 m). The hills are well preserved, despite the fact that some formations were eroded by the fluvial network.

The studied areas of presumably glacial relief are located at different geomorphological levels and apparently belong to different ice ages. The good preservation of the relief indicates its stability during the warmer ages and periods of active erosion. In addition, these areas are not covered by marine sediments.

4. Discussion

Systematic geological studies of the Nadym River Basin began in the late 1940s, and since then, the problem of correlation between glaciations and marine transgressions has been under intensive discussion. Various stratigraphic schemes have been reflected in the state geological maps (http://webmapget.vsegei.ru/index.html). For example, map sheet Q-42-43 (Shchatsky, 1996) takes into account the complex interrelations between glacial, fluvioglacial, lacustrine-glacial, and marine sediments. However, further south, map sheet P-43 (Kovrigina, 2010) presents the entire variety of Quaternary sediments as steps of marine terraces, completely denying any evidence of glaciation. The marine concept of the territory development has also appeared in derivative works (field reports of a previous expedition).

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Thus, in detailed relief studies of the basin of the Nadym, Pur, and Polui Rivers, only marine and lacustrine-alluvial deposits were considered as lithological grounds for differentiation of the natural sites (Melnikov et al., 1983).

Recent works based on the extensive use of modern dating methods and actual ERS data point to widespread glacial sediments in the entire northern end of West Siberia (Astakhov, 2017). However, opponents of the glacial concept suggest that the glacier could not have filled such vast territories even during the coldest ages (Kuzin, 2013; Sheinkman, 2015). It is important to note an intermediate concept of localized (Velichko, 1997) or passive (Bolshiyanov, 2006) glaciation, where separate ice caps were formed on the watersheds instead a solid ice sheet, and the river flow remained unblocked. In this context, the problem of the deposit genesis at local sites could be solved with the help of various geological and geomorphological methods.

The most interesting phenomenon in the territory is a layer of supposedly fluvioglacial deposits, which lies at the base of the second terrace above the flood plain. It stretches vastly in the plane (more than 30 km) and differs significantly from the overlying layers in terms of thickness, lamination, and composition of sediments. The cross lamination and predominance of the medium- and coarse-grained material indicate high flow rates, and the sediments are characterized by a flushing regime, which resulted in poor chemical composition. This layer also contains inclusions of coarse clastic material, but large pebbles with longitudinal dimensions of up to 15-20 cm that occur at the bottom of the quarry were not found in the section.

At the base of section K-2, there were well-rounded pebbles of up to 10 cm in size and angular boulders, some of which had a flatiron shape or ground-down flat faces that were either bevelled or parallel to each other. The absolute age of the presumably fluvioglacial deposits (24 thousand years) allows us to attribute the time of their formation to the late Karginsky interstadial, which corresponds to numerous radiocarbon and OSL datings of the second terrace over the entire northern end of West Siberia (the dating range is from 42 to 25 thousand years) (Nazarov, 2015). On average, the age of the cover complex is lower and ranges from 20 to 12 thousand years (Astakhov, 2006; Zemtsov, 1976).

The sand quartz grain morphoscopy showed that the grains of this layer came from two different sources. One of the sources could be related to glacial deposits eroded by the water flow. This can be supported by the presence of angular grains with irregular shapes, smooth surfaces, and flat faces. The surfaces of grains often feature various grooves and scratches, which are formed by mechanical impact, and conchoidal fractures, which are the result of frost weathering.

Such morphology is typical of fluvioglacial sediments. Thus, in the Protva river basin in European Russia, Alekseeva (2005) points out "angular grains with sharp or slightly rounded edges and corners. The surface of grains is complicated by large and small chips with conchoidal fractures. Many grains have scratches and parallel striae in the factures, which is characteristic of glacial grains". According to Krinsley and Doornkamp (1973, p. 44-50), the same features (irregular curved shape, ground-down flat faces, and conchoidal fractures) are present on the grains from present-day Swiss glaciers, and sub-rounded and fine-pitted grains from a fjord delta are also located on the margin of a present-day glacier in Norway.

The subaerial origin of horizons 1–2 and the prevailing aqueous environment during sedimentation of horizons 3–5 in the sections correspond to the results obtained by Velichko et al. (2011). They studied of grains from the sands underlying peat bog deposits in the same territory. In addition, they point to angular grains with a low degree of surface dullness, which were discovered near the town of Noyabrsk and in the Pur River basin. These grain features are associated with glacial-marine sediments.

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The petrographic diversity of erratic boulders in West Siberia allows us to distinguish two or three paleoglacial regions that unite several dozen distributed provinces, each of which is characterized by a definite set of rocks and petrographic features. The first major generalization in this respect was made by Zemtsov (1976), who identified the guide boulders of the Ural region as ultramafic and mafic rocks of the Main (axial) Uralian zone, plagio-granites, and highly metamorphosed rocks (gneisses and shales). In the Central Siberian region, the prevailing boulders include dolerites and basalts of the Putorana Plateau, as well as various granitoids, quartzites, and Paleozoic sandstones of the Taimyr Region. These studies were substantially supplemented and detailed by a much more ambitious work by Sukhorukova et al. (1987).

Despite their small quantity, the petrographic analysis of pebbles and boulders sampled in quarry N2 led to the following conclusions. Firstly, high-silica alkaline effusive rocks (sample H-10, quartz trachyte) are indicative of both the Northern Taimyr Province (Troitsky & Shumilova, 1973) and many moraines of the Ural paleoglacial region (Sukhorukova et al., 1987), but they are never found in the Putorana Plateau and more southern regions. Moreover, there were only a small relative proportion of dolerites (sample H-14, dolerite) and other effusive mafic rocks, which are characteristic of Putorana and Nizhnyaya Tunguska regions. In contrast, there are no limestones that would be typical of the Central Siberian paleoglacial region (the Kulyumbinsk and Sukhaya Tunguska distributive provinces according to Sukhorukova et al., 1987). However, there are also no granites in the sample that are characteristic of the Northern Taimyr region.

Secondly, quartz and quartzitic sandstones are typical for the Ural paleoglacial region, but their share is usually within a few per cent. Quartzitic sandstones also described as Paleozoic were found 50 km north of Surgut within the tentative Central Siberian and Middle material outwash zones (Sukhorukova et al., 1987). The source of polymictic platy jointing sandstones could be the Paleozoic bordering of the eastern slope of the Urals (Sukhorukova et al., 1987) or the Mesozoic sandstones of the West Siberian Plate.

In general, the samples have a significant proportion of terrigenous rocks (sandstones and siltstones) and a low content of dolerites. On the one hand, this can be explained by poor representativeness of the samples. Nevertheless, the main zone of material washout could be located further north than the Putorana Plateau in the Taimyr area. In order to substantiate this point of view, further research is planned to determine the trace element composition and absolute dating and to expand the sampling.

The linear-ridged relief formed as a result of glacial impact in the north of West Siberia is marked on the Map of Quaternary Formations of Russia at a scale of 1:2,500,000 (Astakhov, 2016). In addition, the linear forms and glacial remains are marked on geological maps at larger scales, such as Map Sheet Q-42 (Zyleva at el., 2014). Detailed aerial photographs and space images of medium spatial resolution have often been used for the purposes of mapping the relief. However, the methodology for determining the glacial genesis was rather poor, and DTMs were not used much.

At the present stage, the most promising approach seems to be the use of DTMs obtained by radar interferometric and optical stereoscopic photography. In combination with high-resolution images under the conditions of sparse forest vegetation, it becomes possible to map the typical glacial forms in detail using methods that have already been verified in other areas of glaciation (Ely, 2016). In some areas, analysis of the DTMs obtained by the Tandem-X satellite identified dense forestation, a predominance of erosion processes, and well-preserved glacial forms, despite the plain relief of the territory. This is supported by large-scale field studies on the left side of the Levaya Khetta River (Vasiliev, 2007). These studies revealed two types of areas of the glacial relief and extensive sandurs on the surface of the second terrace above the floodplain.

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The zones of active modern Aeolian processes gravitate toward the sandur areas. It appears that the Aeolian relief occupied significantly larger areas in the north of West Siberia at the end of the Pleistocene Age. This is supported by the detailed studies of quartz grains from near-surface sediments that were carried out in the territory in the early 2000s. (Velichko et al., 2011).

DTMs and satellite images of the entire territory provided an opportunity to analyse it from the perspective of landscape indications of the sites exposed to glaciation. In this respect, the vast lacustrine-alluvial plains that reach their maximum area in the basins of the Nadym, Pur, and Taz Rivers can be considered as postglacial sites. Such an assumption, which was first made by Sacks (1940) for the lower reached of the Yenisei River, thus receives new factual support.

5. Conclusion

This research has shown that the integration of surface techniques and remote-sensing methods is highly efficient for analysing the Quaternary history of sediments that have formed in a region with a complicated geomorphological history and possible glaciation. The sediments of the high bank of the Nadym River can be attributed to fluvioglacial deposits for a number of reasons. The glacial impact resulted in indicative marks such as linear ridges and kame hills on the relief of certain natural sites in the territory.

Thus, it can be concluded that continental glaciation evidently occurred during the Pleistocene Age in the history of the development of the lower course of the Nadym River. It is difficult to conclude whether there was a common ice sheet or if there were several isolated centers of ice accumulation. The available data, especially the relief character on the DTMs, support the second option, at least in the late Pleistocene Age. There may be traces of more extensive glaciations in earlier ages in the extensive lacustrine-alluvial plains, which reach their maximum area in the basins of the Nadym, Pur, and Taz Rivers. In this case, they can be considered as postglacial sites that later underwent erosion transformations but retained the characteristic structure inherited by present-day landscapes.

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Table Legends

Table 1. Description of section K-1
Table 2. Description of section K-2
Table 3. Total content of oxides in the sections (wt.%)
Table 4. Grain-size composition of the studied sections
Table 5. Morphometric properties of the quartz sand-grains from section K-1
Table 6. Morphometric properties of the quartz sand-grains from section K-2

Figure legends

Figure 1. Location map, where 1 is the area of linear-ridged relief; 2 is the area of kame relief; K-1 and K-2 indicate section K-1 and K-2, respectively (by TanDEM©DLR)
Figure 2. Sections K-1 (a) and K-2 (b), photo by Sizov O.S., 2016
Figure 3. Distribution of quartz sand-grains from section K-1 (a) and section K-2 (b) according to their roundness and dullness, where 1 is glossy, 2 is quater-matted, 3 is half-matted, 4 is matted; 0, I, II, III, IV are grades of roundness according to the scale of Khabakov (1946)
Figure 4. Pictures of quartz grains from horizon 6/2 section K-1: (a) glossy grain with smooth surface and flat faces; the faces feature crescentic pits, grain tops feature fine pits; (b) fine-pitted surface of grain 'a'; (c) glossy grain with smooth surface and sparse fine pits; (d) half-matted grain with fine-pitted surface and crescent pits; (e) glossy grain with flat faces and no evident texture; (f) glossy grain with post-sedimentation conchoidal fractures and crescentic pits; (j) conchoidal fracture of grain 'e'; (h) crescentic texture of grain 'e'.
Figure 5. (a) Sample N-10 – pinkish quartz trachyte, large inclusions of potassic feldspar (Kfs) with fine quartz grains (Qu) in the quartz-feldspathic matrix; (b) sample N-14 – greenish-brown dolerite, large poikilitic clinopyroxene crystals (Cpx) with thin plagioclase crystals (Pl), in the groundmass – plagioclase chlorite (Chl).
Figure 6. Area of the linear-ridged relief, DTM by TanDEM-X, 26 m/px. Map provided by O. Sizov.
Figure 7. Area of the kame relief, DTM by TanDEM-X, 26 m/px. Map provided by O. Sizov.

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Table 1

Layer	Thickness (cm)	Description
1	15	Podzolic horizon, ashy fine-grained sand, clear transition
2	35	Rusty horizon, fine-grained brown sand, unstratified, diffuse transition
3	111	Illuvial horizon, Aeolian sediments, fine-grained light-brown sand, cross-stratified, gradual transition
4	52	Alluvial horizon 1, cross-stratified, grey-brown, medium- and fine-grained, ferruginous, indications of cryoturbation, diffuse transition
5	47	Alluvial horizon 2, channel facies, parallely stratified, grey-blue, indications of minor cryoturbation, ferruginous layers available, medium- and fine-grained sand, clear transition
6	175	Fluvioglacial (presumably) horizon, thick, gray-blue, clear transition, cross inter-layers of coarse-grained material are visible, from (upper) unstratified to (lower) cross-stratified, coarse-grained, no indications of cryoturbation, no wedges, ferruginous inter-layers available, coarse pebbles (angular, scratched) occur

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Table 2.

Layer	Thickness (cm)	Description
0	18	Anthropogenic subsoil (removed overburden)
1	16	Podzolic horizon, thin, heterogeneous
2	94	Rusty horizon with cryoturbation and clay inclusions
3	66	Aeolian horizon, cryoturbated, unstratified or indistinctly stratified
4	79	Alluvial horizon 1, whitish, parallely stratified, ferruginous
5	48	Alluvial horizon 2, channel facies, distinctly stratified, clay inclusions
6	100	Fluvioglacial (presumably) horizon, ferruginous, cross-stratified, pebbles available

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Table 3.

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	BaO
Section K-1											
Layer 1	87.65	0.64	5.27	0.95	0.03	0.18	0.51	1.00	1.66	0.03	0.06
Layer 2	88.09	0.53	5.14	1.89	0.03	0.29	0.32	0.56	1.14	0.05	0.04
Layer 3	89.49	0.41	4.93	1.20	0.03	0.25	0.41	0.75	1.52	0.04	0.06
Layer 4	92.97	0.21	3.35	0.61	0.02	0.11	0.27	0.51	1.32	0.02	0.05
Layer 5	90.71	0.39	4.21	0.92	0.02	0.21	0.38	0.64	1.35	0.03	0.05
Layer 6/1	98.02	0.10	0.88	0.30	0.01	0.06	0.10	0.07	0.25	0.01	0.01
Layer 6/2	98.39	0.08	0.69	0.25	0.01	0.06	0.08	<0.05	0.20	0.01	0.01
Section K-2											
Layer 1	94.35	0.36	2.37	0.47	0.01	0.08	0.19	0.34	0.89	0.02	0.03
Layer 2	94.42	0.21	2.36	0.76	0.01	0.10	0.17	0.27	0.83	0.02	0.03
Layer 3	84.75	0.57	7.44	1.00	0.02	0.26	0.56	1.51	2.38	0.02	0.08
Layer 4	94.99	0.24	2.29	0.40	0.01	0.07	0.15	0.29	0.91	0.02	0.04
Layer 5	90.95	0.51	4.31	1.19	0.03	0.23	0.26	0.45	1.16	0.04	0.05
Layer 6	96.88	0.13	1.23	0.26	0.01	0.06	0.10	0.12	0.49	0.01	0.02

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Table 4.

Layer	Fraction size (µm) / Content (%)					
	very coarse-grained sand 1000-2000	coarse-grained sand 500-1000	medium-grained sand 250-500	fine-grained sand 125-250	very fine-grained sand 90-125	silt/clay <90
Section K-1						
Layer 1	0.08	0.73	9.51	28.74	29.24	31.70
Layer 2	0.30	4.20	32.19	32.08	12.54	18.70
Layer 3	0.06	1.20	11.92	35.61	32.29	18.92
Layer 4	0.04	0.95	16.39	56.70	20.06	5.86
Layer 5	0.03	1.58	19.75	59.89	13.12	5.62
Layer 6/1	1.93	23.75	71.53	1.78	0.45	0.56
Layer 6/2	1.73	46.89	46.27	4.21	0.45	0.45
Section K-2						
Layer 1	0.07	2.26	33.79	37.24	5.47	21.16
Layer 2	0.24	3.32	29.47	54.56	7.12	5.29
Layer 3	0.23	4.51	12.57	13.50	12.23	56.96
Layer 4	0.55	10.31	48.75	32.64	4.31	3.44
Layer 5	2.20	15.56	43.55	27.40	4.87	6.42
Layer 6	0.21	5.38	61.21	27.57	3.72	1.92

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Table 5.

Layer	Roundness coefficient (Q), %	Degree of surface dullness (Cm), %
Layer 1	66.5	61
Layer 2	89	80
Layer 3	83.5	44.5
Layer 4	76	44
Layer 5	73.5	38.5
Layer 6/1	70.5	28.5
Layer 6/2	65	33

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Table 6.

Layer	Roundness coefficient, Q (%)	Degree of surface dullness, Cm (%)
Layer 1	84	47
Layer 2	81	59.5
Layer 3	55.5	52
Layer 4	66	46
Layer 5	70	36.5
Layer 6	63	35

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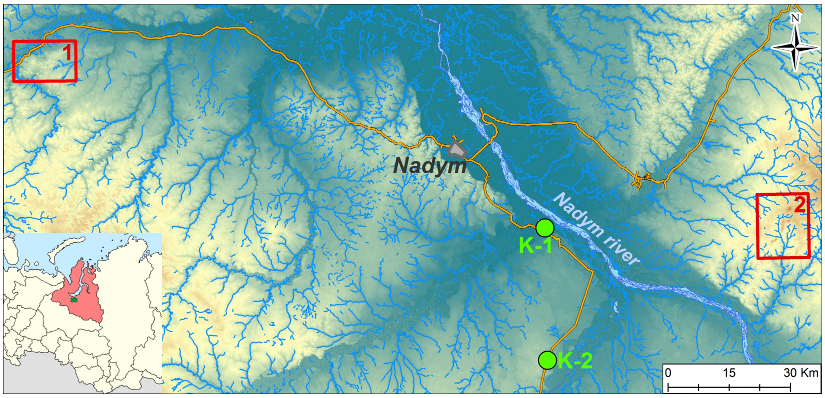

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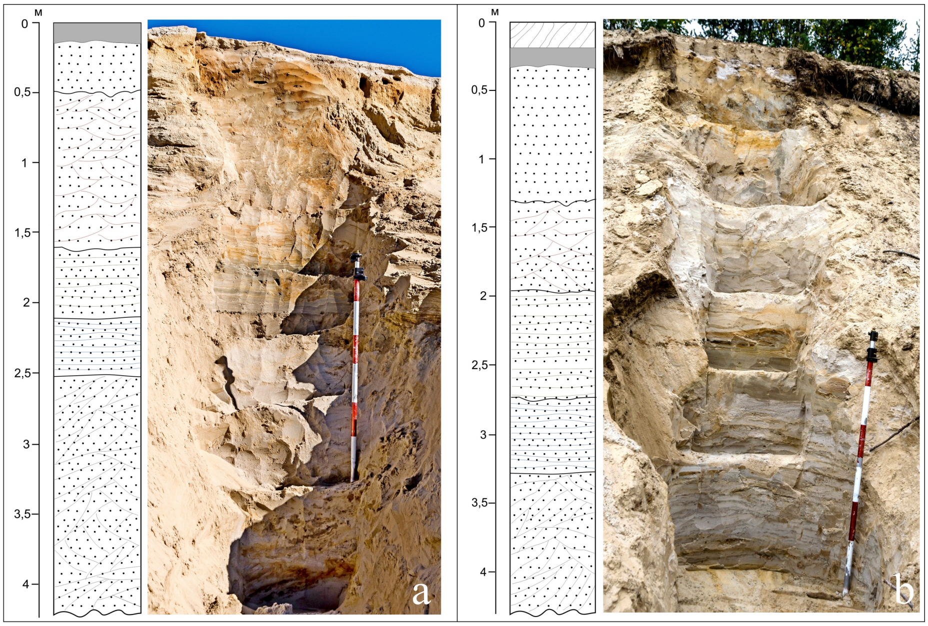

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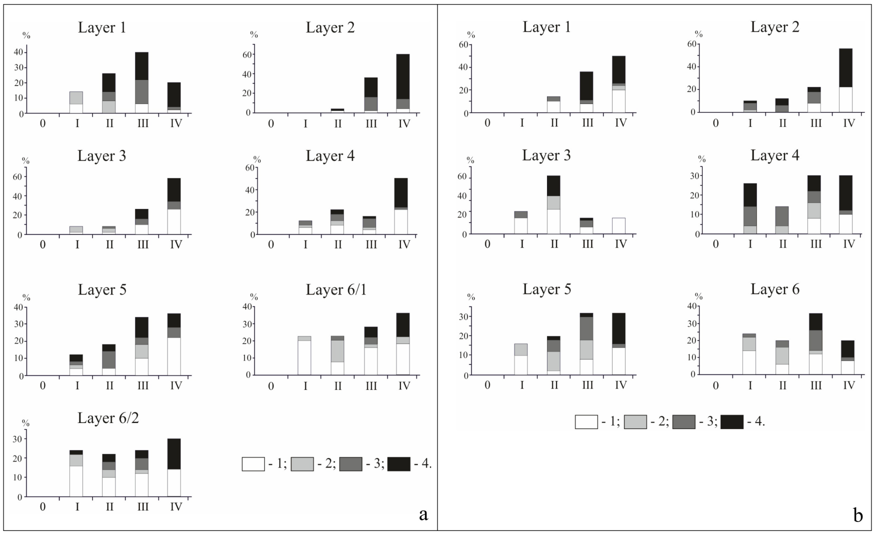

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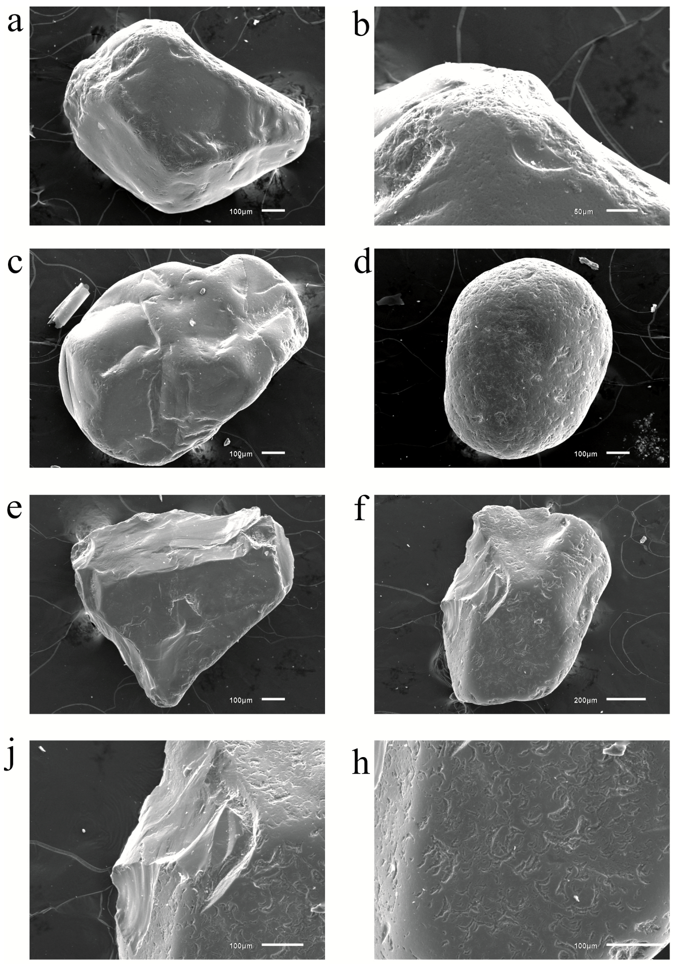

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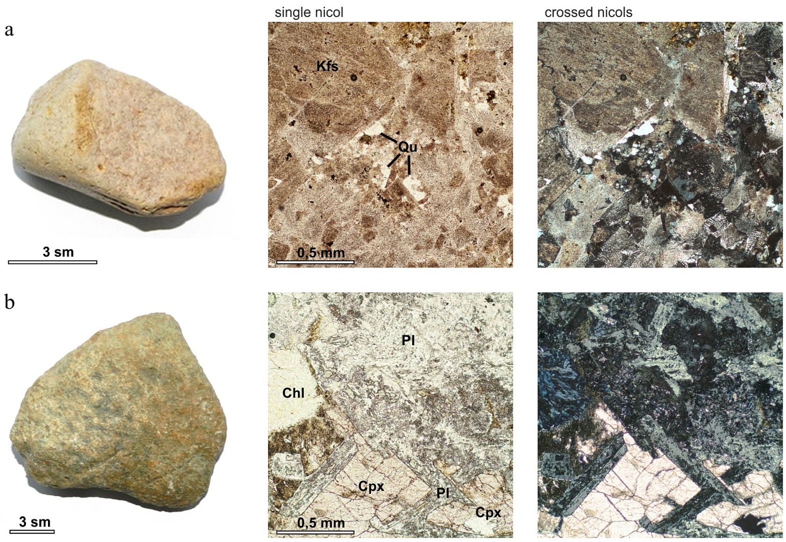

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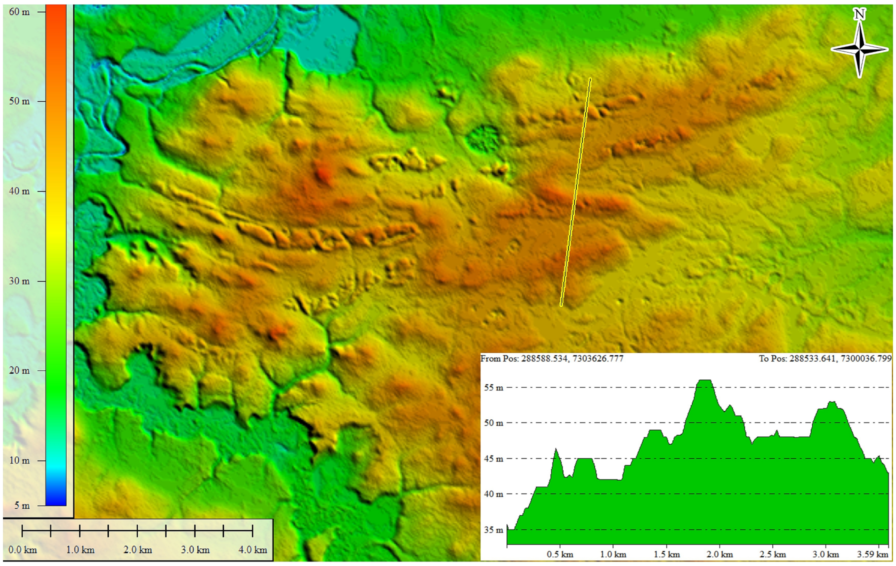

Figure 6. Area of the linear-ridged relief, DTM by TanDEM-X, 26 m/px. Map provided by O. Sizov.

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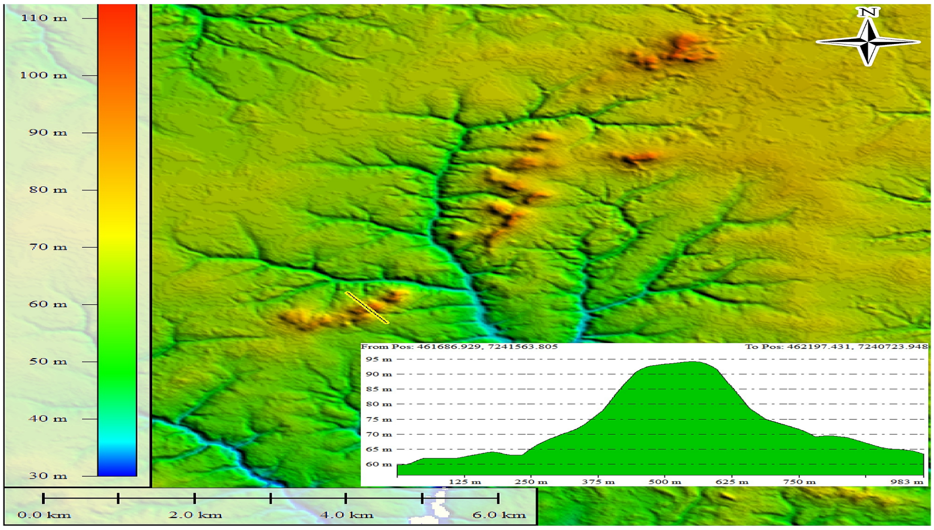

Figure 7. Area of the kame relief, DTM by TanDEM-X, 26 m/px. Map provided by O. Sizov.