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MICROMORPHOLOGICAL FEATURES OF QUARTZ GRAINS FROM THE KYSYL-SYR DUNE MASSIF, CENTRAL YAKUTIA

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The micromorphological study of quartz grains from the Kysyl-Syr dune massif in the lower reaches of the Vilyuy river included analyses for roundness and dullness and determinations of genetic groups of diagnostic elements on the quartz grain surface. The research results presented in this paper allowed to establish two stages in the formation of the Kysyl-Syr dune complex. Fluvial processes predominated during the first stage of sedimentation which began about 40 ka BP. The second stage (Late Pleistocene–Holocene) is characterized by eolian sedimentation.

Eolian sediment, Late Pliestocene, Holocene, micromorphological analysis, Central Yakutia

INTRODUCTION

The widespread actively moving eolian sands which occupy extensive areas and forming thereby sand dune massifs of complex structure is a unique feature of the cryogenic landscapes of Central Yakutia.

The morphosculpture of dune massifs is described as the closest to arid (desert) types produced by eolian processes, and are dominantly represented by dunes having different size. However, by comparison with the modern dune deserts in lower latitudes, these develop within areas underlain by permafrost of continuous type and encircled by ice-rich cryogenic formations collectively termed the Ice Complex (IC) which contain thick ice wedges classified into two main types: epigenetic and syngenetic.

One of such dune massifs, the Kysyl-Syr, is located in the basin of the Vilyuy river (lower reaches), 30 km from the Kysyl-Syr village. The section was thoroughly sampled and studied (including lithologic, mineralogical and palynological analyses of sediments) during the 2012–2016 expeditions [*Galanin et al., 2015b*; *Kut, 2015*].

The paleogeographic reconstructions were derived from the results of radiocarbon dating [*Galanin et al., 2015a*], spore-pollen [*Pavlova et al., 2016*] and cryofacies analyses, as well as from the data on the composition of buried peatlands. In addition, these allowed to identify the main stages of the Kysyl-Syr massif evolution and vegetation growth in the Vilyuy river valley (lower reaches) [*Galanin et al., 2016*]. Despite the large amount of the data accumulated, several topics still remain disputable, e.g. the issue of facies division of deposits in the section. This also requires establishing deposition conditions and the processes involved. In this paper, the author has attempted to classify the facies of sand deposits of the Kysyl-Syr dune massif and reconstruct its formation conditions during the period from the end of Late Pleistocene and throughout the Holocene.

OBJECT OF STUDY

The Kysyl-Syr dune complex is located in the lower reaches of the Vilyuy basin (63°54′ N, 123°16′ E), Central Yakutia, where the massif is confined to the surface of the first (1st) floodplain terrace (height: 8–10 m) composed of lacustrine-alluvial sand-loamy bed topped with multi-layer dunes containing buried peat layers, soil horizons, and vertically buried trees. The types of terrain of different age distinguished within the terrace are related to: the low-lying surface (lake marsh phase) with absolute elevations 84–90 m, stretching south of the studied massif; slightly undulating sandy surface (absolute elevations: 90–110 m) exhibiting smoothed elements of the ancient dune relief and vegetated with pine forest; a sandy massif, the youngest formation, which is the highest-order dune formed by smaller dune clusters and inter-dune depressions [*Urban et al., 2013*].

The base of the section is composed by alternating layers of gravel and pebbles and cross-bedded sands and loamy sands overlain by peat layer dated 44 670–35 720 yrs (MPI-29) (Fig. 1). A unit of sediments of various composition and origin is located in the upper part of the section, where sandy sediments are succeeded by the interbedding well-sorted coarse-grained sand, fine sand, sand loams and humus-rich clay loams. In the upper parts, the section is marked

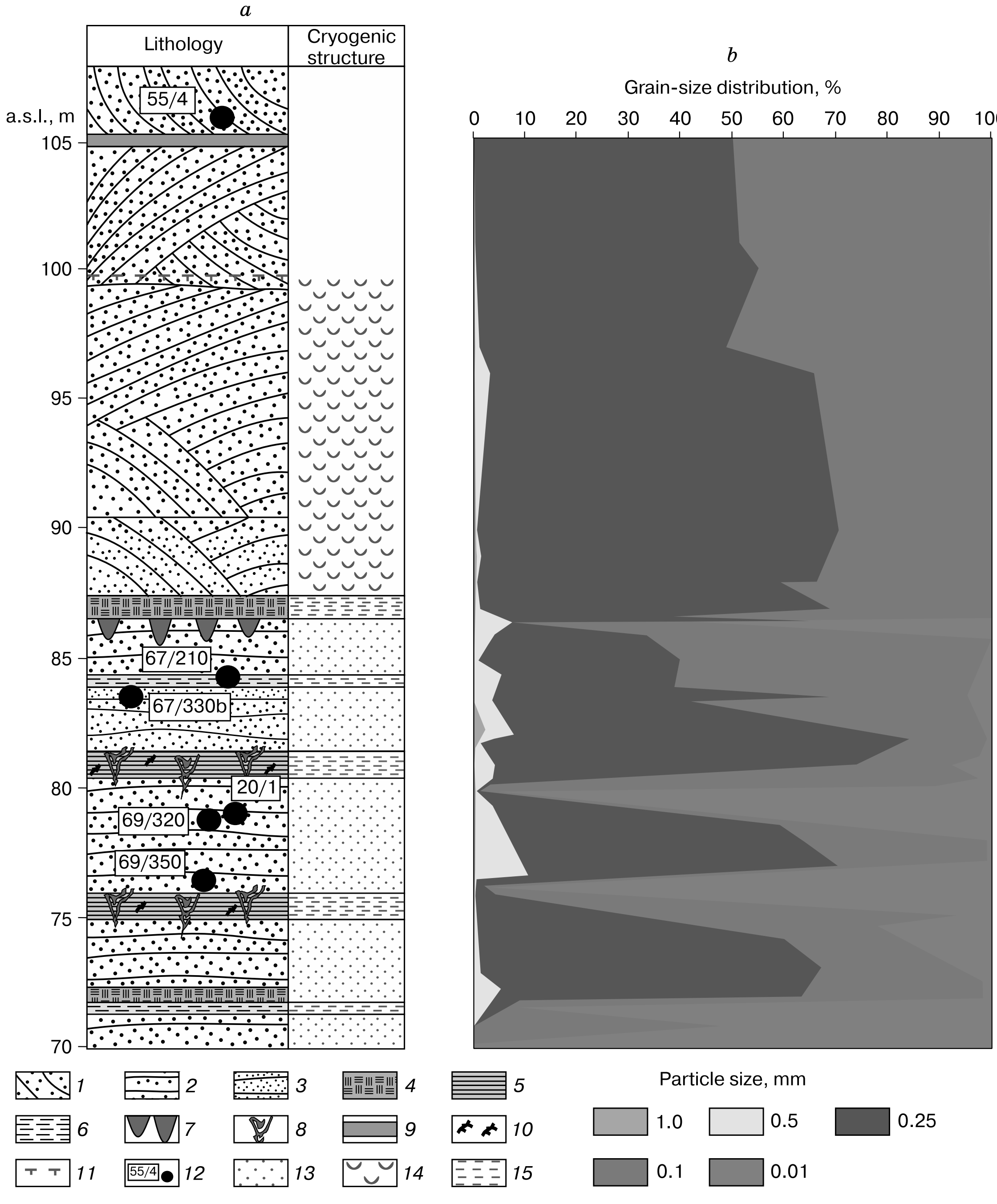

Fig. 1. Composite section of the Kysyl-Syr dune massif with sampling points:

a – composite section; *b* – particle size distribution over the section. *1* – cross-bedded medium-grained sands; *2* – horizontal-layered medium-grained sands; *3* – fine-grained sands; *4* – peat; *5* – sand-loams; *6* – clay-loams; *7* – soil-ice veins; *8* – soil veins; *9* – buried soil horizons; *10* – woody residues; *11* – permafrost table; *12* – sampling point. Cryogenic structures: *13* – massive, *14* – contact, *15* – schlieren.

by alternation of light fine-grained sands and horizontally layered clay-loams with sporadic inclusions of woody residues. This part of the section is crowned by the marker horizon of peat, whose age varies from 9440–8640 to 3825–3370 years (MPI-42 and MPI-43, respectively). The water infiltration zone is characterized by ice-cemented pore space, which prompted the formation of massive cryo-structures in sandy sediments. Clay-loams, sand-loams and peat are typically characterized by schlieren cryostructure. A 20-meter high pack of well-sorted medium-grained sands with buried Holocene soil horizons and trees rests above the peat horizon. This part of the section is characteristically ice-poor, with developed contact-type cryostructure alone (ice forms only at the contact of individual sand particles, edges, and vertices).

METHOD OF MICROMORPHOLOGICAL ANALYSIS

The micromorphological analysis of the quartz grains surface was applied to study sedimentation conditions of the dune sand sequence. The method is based on the assertion that each medium through which the material passes, leaves its characteristic traces on the particle surface as a result of mechanical and chemical processes.

The micromorphological approach has been known since the end of the 19th century [*Sorby, 1880*], but its development gained most significant traction with the advancement of electron microscopy in the 50s of the 20th century. In 1951, geologists R. Folk and K. Wever pioneered the application of an electronic microscope to the study of shales' structure and composition [*Krinsley and Doomkamp, 1973*]. In the next few years, sedimentologists, paleontologists, and geologists began using this method for various geological purposes [*Bull, 1978; Helland et al., 1997; Woronko et al., 2015*].

The micromorphological techniques were also used by Russian geologists: V.P. Baturin [*1947*], V.P. Chichagov [*1961*], L.B. Rukhin [*1962*], E.V. Rukhina [*1973*], L.R. Serebryaniy [*1980*], A.A. Velichko [*Velichko et al., 1997*], V.V. Rogov [*2000*], V.N. Konishchev [*Konishchev et al., 2005*], S.N. Timireva [*Timireva and Velichko, 2006*] and others, primarily, for determining the origin of Quaternary deposits. In this paper, quartz grains were studied from six samples of sandy sediments. The sampling points and description of samples are shown in Fig. 1 and in Table 1. The samples were preliminary subjected to the particle size distribution test (with statistical processing of the results) and mineralogical analysis [*Kut, 2015*].

The applied particle-size range was 0.25–0.5 mm. Grains shape and degree of dullness were studied with Carl Zeiss Jena binocular microscope. Prior to the microscopic analysis, the sampling was boiled in a weak hydrochloric acid (HCl) solution for 10 minutes, to remove ferrous and carbonate films that may produce masking effect on the surface elements. Then the samples were washed in distilled water and dried at room temperature. Of them, 30–40 grains were selected from the sample and affixed using double-sided adhesive tape on individual aluminum conductive SEM stubs. The surface of grains was sputter coated with a thin layer (10 microns) of conductive material (gold, in this case).

Once all the all preparatory work was completed, the selected grains were examined under electron microscope (JEOL JSM-6610LV (Japan) in the mode of secondary electrons at an accelerating voltage of 15 kV). A 150–300-fold enlargement was applied to view whole grains. The most interesting regions were examined with a 500-fold magnification.

The surface of samples was visually examined under an electron microscope with subsequent fabrication of micrographs (performer: V.A. Shishkov, Ph.D) at the Collective Use Center of Laboratory of Radiocarbon Dating & Electron Microscopy (Institute of Geography RAS). The obtained micrographs enabled descriptions of the most characteristic and frequently encountered features, identification and classification of diagnostic signatures, proceeding from their genetic groups.

RESULTS OF MICROMORPHOLOGICAL STUDY OF GRAINS

The degree of roundness and dullness of quartz grains surface of the depositional environment represent critical parameters, determining its dynamics. Roundness characterizes alterations in grains shape affected by the abrasion while being transported and during their accumulation. The degree of roundness

Table 1. **Sampling points and description of samples**

Item	Sample No.	Section No.	Sampling interval, m	Description
				Modern floodplain
1	20/1	20	77.5–77.4	Sand, fine-grained, yellow, well-washed, with rare inclusions of pebble (up to 5 mm in diameter)
				Cross-bedded unvegetated dune sands
2	55/4	55	106.0–105.9	Sand, fine-grained, grey, with rare ochre stains
3	67/210	67	85.6–85.4	Sand, light grey to whitish, medium-grained, well-sorted
4	67/330b	67	84.4–84.3	Sand, light brown, medium-grained, with spherical inclusions of clay-loam and admixture of undegraded organics
				River-channel sands underlying eolian cross-bedded sands
5	69/320	69	77.2–77.0	Sand, light brown, medium-grained
6	69/350	69	76.7–76.6	Sand, medium-grained, whitish; well-sorted

was studied using the A.V. Khabakov visual scale [*Ananieva, 1998*]. Analysis of grains from six samples showed that their sediments are ranked as the II, III and IV grain roundness classes: moderately rounded, well rounded, and perfectly rounded, respectively, suggesting thereby a fairly dynamic and motional sedimentary environment. There are practically no unrounded grains. Grains with half-matt and glossy surface tend to be prevailing, whereas grains with glossy surface are rare. Average distribution of quartz grains over roundness and dullness classes is shown in Fig. 2.

The reconstruction of sand dune deposits transport and accumulation conditions of dune massifs was performed on the basis of 15 diagnostic signatures deduced from the quartz grains surface (Table 2), most of which are mechanical in nature and represent either separate elements or their combinations. Analysis of the diagnostic signatures distribution over the surface of quartz grains in the samples showed a pro-

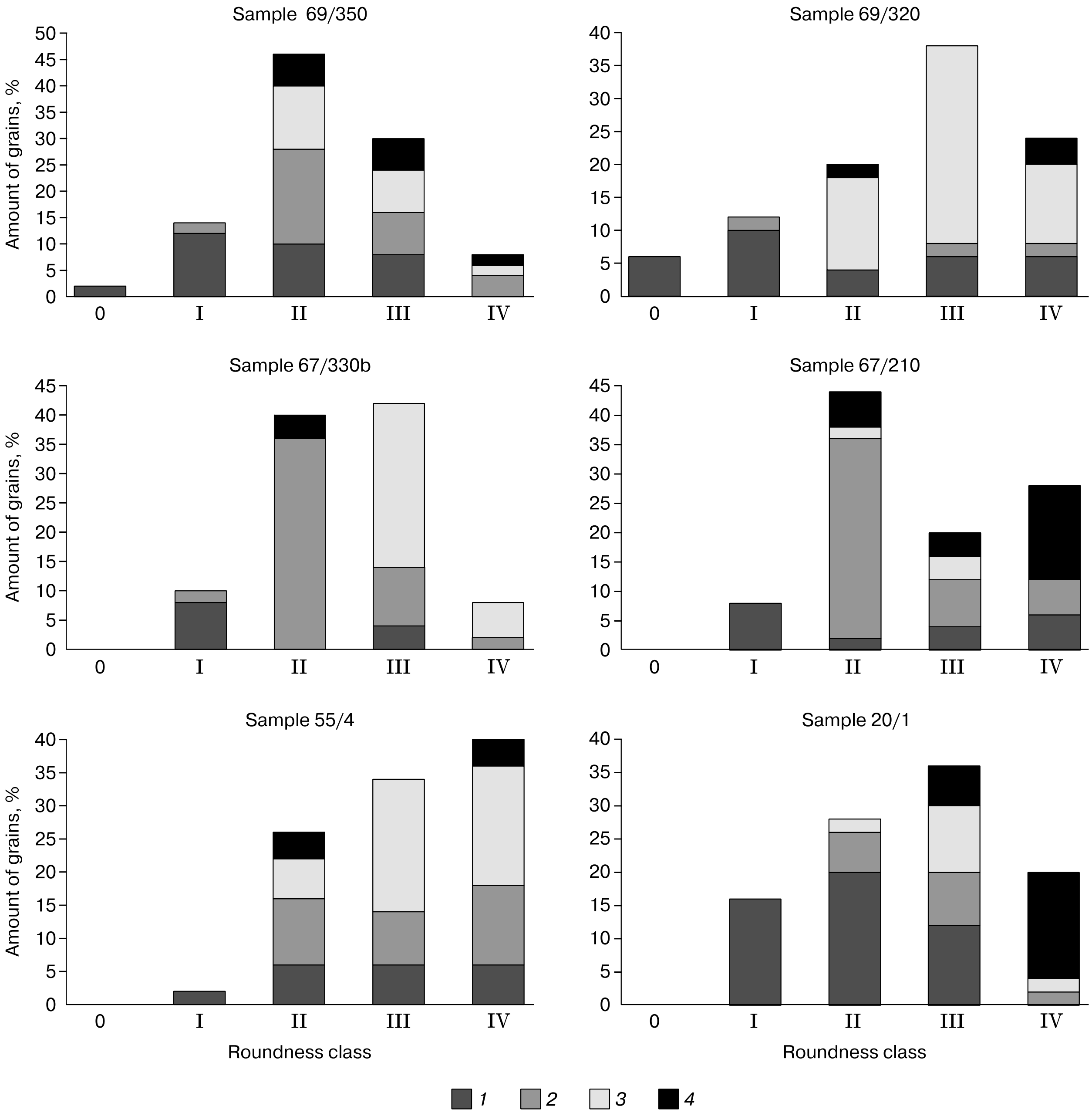

Fig. 2. Distribution of quartz grains according to the roundness classes and the degree of surface dullness (after A.V. Khabakov [*Ananieva, 1998*]).

1 – glossy; *2* – quater-matt; *3* – half-matt; *4* – matt.

nounced predominance of the following most common elements: upturned plates microrelief of the surface; chips (both conchoidal fracture and flat cleavage plates); silica impurities in the form of minute particles adhered to the surface of particles and chips.

Sample 20/1 from deposits of the modern floodplain represented by fine-grained sand (Table 1). The particles have a rounded shape with varying degrees of roundness (84 %) (Fig. 2), while angular-shaped grains are extremely rare. Grains with a matte and glossy surface have fairly equal proportion: 52 and 48 %, respectively. The surface of the particles is complicated by conchoidal fractures (Fig. 3, *a*). Most chips are small in size and occupy up to 10 % of the particle surface, with some of them having parallel striations. Upturned plates account for 60–70 % of the surface, where they are superimposed on the surface of chips and pits. Besides the above elements, curved scratches are developed on 20–30 % of the visible surface.

Sample 55/4 is represented by fine sand (Table 1) from the upper part of the studied massif (modern sand dune deposits). Most quartz grains (98 %) have rounded shape (Fig. 2). Of them, about 82 % have a matte surface. Both conchoidal fractures and flat cleavage plates are marked as primary dominant surface elements. Chips have developed on 20 % of the particle surface and differ in size. The upturned plates acting as a superimposed element, cover 90 % of the particle surface, including that of chips and pits (Fig. 3, *b*).

Sample 67/210 from the horizon underlying the buried peatland (Table 1) is represented by medium-grained sands, with grains having medium rounded (sub-angular) form (44 %) and matte surface (80 %) (Fig. 2). Their characteristic features also include chips with a conchoidal fracture and flat cleavage plates, occupying 40–50 % of the visible surface, and upturned plates. Chips are distinguished by their large size as compared to samples 55/4 and 20/1. The most widespread here are V-shaped micro-pits (60–90 %) and grooves (20–30 %) (Fig. 3, *c*).

Another *sample 67/330b* from the horizon underlying the buried peatland (Table 1) is represented by medium-grained sands. The proportions of grains of roundness class II and III in the sampling are 40 and 42 %, respectively (Fig. 2). Only 12 % of the particles have a glossy surface. A set of diagnostic elements is represented by chips and pits, and by superimposed upturned plates. No parallel striations were identified in sample 67/330b.

Sample 69/320 is represented by medium-grained sands from alluvial horizon dated to the Karginsky Thermochron (Table 1). The surface of quartz grains is characterized by the predominance of well-rounded grains (38 %) with a matte surface (56 %) (Fig. 2). The diagnostic elements on the surface are: conchoidal fractures with straight faces, fairly large size (up to 50 %), upturned plates relief (60–70 %) and V-shaped micro-pits (50–60 %). Along with the above elements, the locality is also noted for dish-shaped concavities (Fig. 3, *d*) commonly of irregular shape (20–30 %), steps (Fig. 3, *e*) and traces of parallel striations (Fig. 3, *f*). Silica particles are observed only on the surface of grains (Fig. 3, *g*), whereas they are totally missing from the surface of chips and pits on the particles.

Table 2. **Diagnostic signatures inferred from quartz grains surfaces**

Sample No.	Upturned plates (microrelief)	Chips: conchoidal fracture	Chips: with flat cleavage plates	Pits: V-shaped	Pits: dish-shaped concavities	Pits: irregular-shaped	Curved scratches	Grooves	Etch holes	Steps	Parallel striation	Chip splitting the particle into fragments	Fractures produced by chemical solution	Admixtures: on the surface of particle	Admixtures: on the surface of chips and pits
20/1	88	77	27	27	–	–	8	27	8	4	46	–	81	85	69
55/4	96	56	41	33	37	15	26	37	7	15	15	4	41	15	78
67/210	98	59	43	91	27	32	32	45	16	20	39	16	55	52	39
67/330b	92	46	17	88	29	42	8	13	13	13	33	–	50	58	42
69/320	85	54	58	81	19	46	38	38	19	15	62	8	38	81	8
69/350	80	52	60	68	20	56	44	40	12	40	36	20	44	8	84

Note. In percent (%) of the total number of the studied grains in a sample.

Sample 69/350 from alluvial sediments of the Karginsky horizon is represented by medium-grained sands (Table 1), whose particles are mostly of fairly well rounded shape (46 %) and have a matte surface (68 %) (Fig. 2). The identified diagnostic signatures include: conchoidal fractures and different sized flat cleavage plates faces (40–50 %), upturned plates and V-shaped micro-pits (100 %), dish-shaped concavities of irregular shape (10–20 %), straight and curved scratches (20–30 %), as well as chips splitting the particles (20 %) (Fig. 3, *h*).

The study of quartz grains revealed a fairly similar set of morphological elements of grains surface. This allowed the author to classify grains into the groups discussed below.

The glacial-cryogenic group comprises angular grains with fairly fuzzy or slightly smoothened outlines. The surface is glossy. This group is characterized by the development of various chips and flat cleavage plates of fractures. Many grains exhibit the

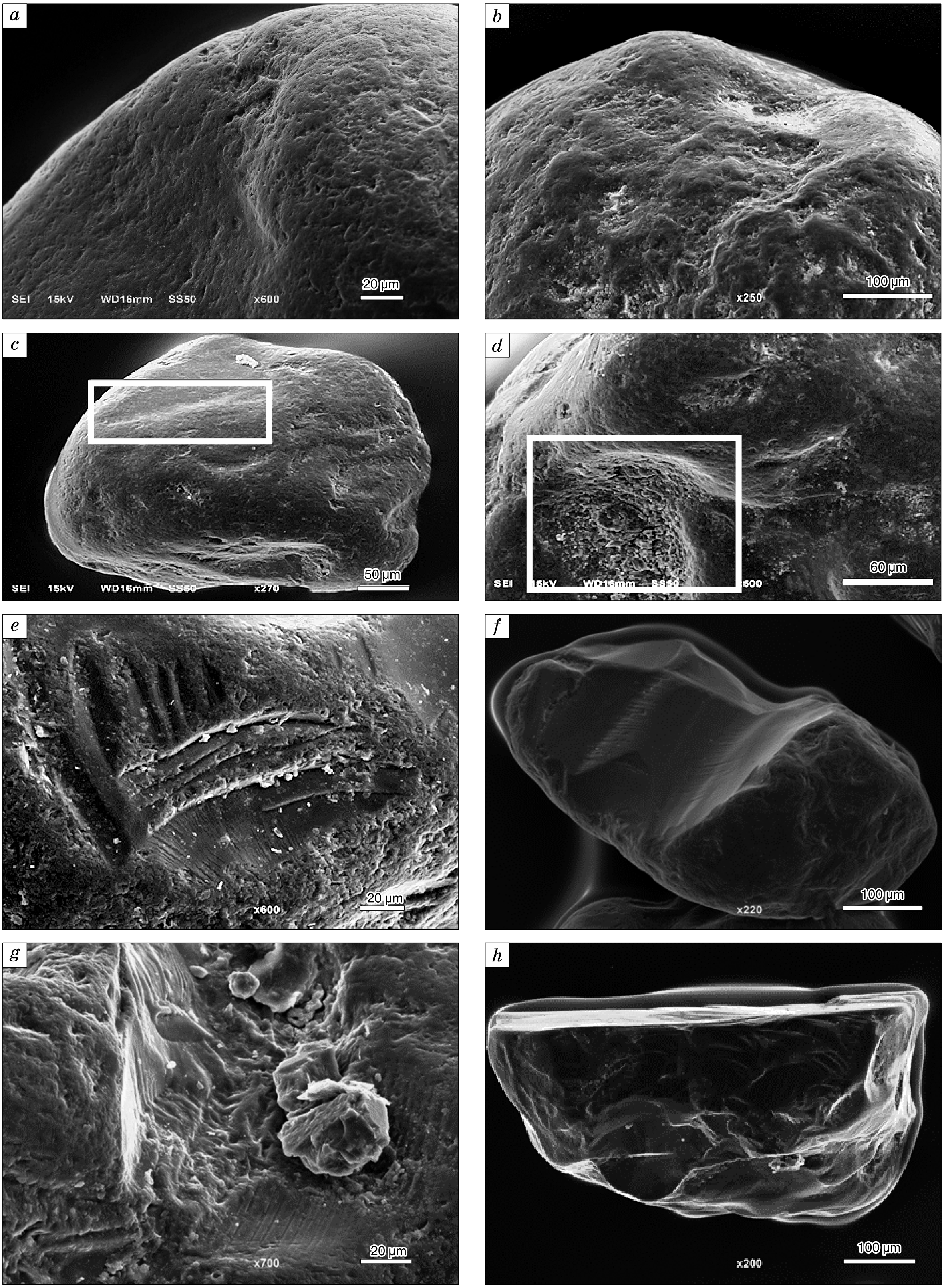

Fig. 3. Specific features of quartz grains surface:

a – conchoidal fractures; *b* – upturned plates; *c* – grooves; *d* – dish-shaped concavities; *e* – step structure with traces of parallel striation; *f* – parallel striation; *g* – adhered silica particles; *h* – chip that splits the particle.

presence of various cracks, scratches, steps, and parallel striations. As such, the combination of diagnostic elements on the surface indicates that their formation proceeded in glacial environments, and also as a result of mechanical destruction of bedrock debris, and cryogenic weathering.

Eolian group comprises rounded isometric-shaped grains, whose surface is commonly matte and complicated by upturned plates (60–100 % of the surface), various chips, and dish-shaped concavities.

Aquatic group includes rounded and angular grains with different degree of the relief smoothness; their surface is glossy. These are typified by V-shaped microrelief, small chips, and straight grooves on the surface resulting from the particles interactions in aqueous medium.

In addition, two more grain groups were identified: **aquatic-glacial** and **eolian-glacial**. These are represented by angular grains with fuzzy or slightly smoothed outlines, which were exposed either to aquatic or eolian medium, retaining, however, characteristic features of the original group.

In part, grains of this group have a matte surface, which is complicated by upturned plates, chips and pits (which is typical of eolian conditions); however, there are grains with a glossy surface with V-shaped microrelief (characteristic of the aqueous environment). In addition to the elements described above, all grains of these groups are also noted for parallel striation on their surface.

The traces of epigenetic transformations observed almost on all grains showed that their origination are associated with both chemical and cryogenic processes.

HISTORY OF THE KYSYL-SYR DUNE MASSIF EVOLUTION

Results of previous studies and this research allowed to identify two stages of the formation of the Kysyl-Sur dune massif in the Vilyuy basin.

The *first stage* is related to the latest Late Pleistocene, which is associated with the formation of a pack in the lower part of the section (height range: 70–86 m). The heterogeneous composition of this part of the section is indicative of the successive depositional events. The section is composed by the interbedding of coarse-grained alluvial sands, floodplain fine-grained sand and sand-loams, lacustrine and boggy humus-rich clay loams with traces of cryoturbation and well-sorted eolian quartz sand.

A pack of alluvial deposits (71–72 m), underlying the section, is characterized by cross-bedding and inclusions of gravel and fine pebbles. According to some data, these facies formed within the Paleo-Vilyuy river-channel in the Karginsky Interglacial [*Galanin et al., 2016*], which suggests that the hypsometric level of peatland overlying the alluvial sands occurs about 8–10 m below the present floodplain. This allowed an inference that the the Vilyuy water level during the Karginsky interglacial was much lower than the modern one.

The author has attributed the formation of the overlying deposits (72–86 m) to the period of Sartan glaciation (about 28 ka BP), which is characterized by drastic climate cooling and strongly reduced precipitation. The horizontally and weakly layered sands and thin layered sand-loam thus exhibit neither allochthonous nor autochthonous organic matter, which indicates a lack of vegetation cover both within the floodplain and on landscapes in the vicinities.

The results of comprehensive studies conducted earlier also suggest great similarity of facies composition to the modern sand dune deposits [*Kut, 2015*]. A pack of subhorizontal sands located up the section is well-reworked by wind and contains ochre inclusions and individual cemented particles, as well as iron hydroxides, thin layers of fine cartilage and gravel, and fine pebble of exotic composition.

Analysis of morphoscopic characteristics has shown that this horizon contains a large amount of grains (>50 %) bearing the evidence of wind-reworking, as well as grains from the glacial-cryogenic group (s. 69/350). It is also characterized by matte surface of grains, upturned plates, and dish-shaped concavities resulting from the particles collision in the air.

These deposits are therefore assigned by the author to eolian facies, which is justified by the fact that in this time period, the Paleo-Vilyuy's drainage capacity and water level fell dramatically, with subsequent drying of the river-channel. Inasmuch as cryogenic and eolian processes became major controls, the action of winds strongly reshaped the terrain, resulting in the formation of dunes and small local water bodies. It is in such depressions that two persistent beds of bluish clay-loam accentuated in the description of the sand massif (75–76 and 80–81 m) accumulated. These bear the evidence of the formation of polygonal patterned ground, as well as frost heaving and topmost layer disintegration. The appearing epigenetic ice-veins (wedges), which split the studied beds also attested to a significant cooling event and predominant wind action. Given the low moisture content, they formed while freezing, and emerging cracks were filling with sand from the overlying eolian ochre sands.

The redistribution of the region's hydrographic network is also evidenced by the sandy crossbeds with inclusions of fine pebbles (79.0–79.5 m), where the fraction of grains with traces of water-processing has increased from 16 to 35 % (s. 69/320). This may indicate short-term, but fairly dynamic aquatic environments.

The Sartan part of the section is terminated in the bed represented by eolian and assumingly eolian-floodplain facies (84–86 m). The bed is characterized by the alternation of persistent layers of dry-frozen quartz sand, humus-rich sand-loam, winnowed loamy sands and thin layers of cartilage and fine gravel (1–2 mm), as well as by rare inclusions of fine pebbles of exotic composition. The proportion of glacial-cryogenic grains with traces of wind processing (33 %) and eolian particles (33 %) tends to increase, within the quartz-sand crossbeds (s. 67/330b), suggesting thereby still ongoing eolian processes. In turn, the interlayers of medium-and fine-grained sand in the upper part of the pack (s. 67/210) are characterized by increased amounts of grains with traces of water-processing (45 %). Whereas sporadically encountered roots and a thin turf laminae are indicative of gradual climate mitigation. The eolian processes are increasingly fading. The surface of sand massif is fixed by vegetation. The Holocene Climatic Optimum is marked in the section by the formation of a two-meter thick peat blanket, whose age (according to radiocarbon dates) is from 8690–9440 to 3360–3830 years [*Galanin et al., 2016*].

The global climate cooling observed since the beginning of the second half of the Holocene is associated with the onset of the *second stage* of the formation (4.5–2.0 ka BP) of modern dune deposits with (thickness: 87–106 m), which was marked by climate cooling and increasing dryness. The sediments are dominantly represented by quartz sand and minor amounts of heavy fraction, which is localized in thin interlayers of deflation surfaces. The layers are arranged in subhorizontal, cross-bedded and locally enveloping (in areas of buried tree trunks) structures. The morphoscopic analysis revealed a sharp increase in the number of grains from the eolian group (up to 56 %, s. 55/4), which indicates the impact from highly intense eolian processes. A remarkable role of wind action in the formation of this part of the strata is confirmed by numerous thin soil horizons containing vertically buried trees. A series of radiocarbon dates has shown that the age of the oldest trees does not exceed 200–300 years (MPI-19, MPI-20), which suggests that the most active phase of the eolian processes development practically coincides with the global climatic events of the Little Ice Age during the 11^{th}–19^{th} centuries.

CONCLUSION

The micromorphological analysis of quartz grains has thus revealed that the formation of the Kysyl-Syr dune massif proceeded in the changing environment. The identified diagnostic signatures indicate both aquatic and eolian sedimentary environments, mechanical disintegration of bedrock fragments and cryogenic weathering. Among them, aquatic and eolian processes were predominant.

The results of micromorphological analysis fit in with the scenario of the evolution of dune massif, which comprises two stages. The first stage is related to the latest Late Pleistocene and characterized by significant climate changes (Karginskiy Interglacial and Sartan Glaciation) and redistribution of the hydrographic network of the Paleo-Vilyuy basin. The changes occurred in the hydrological regime during this period triggered the formation of a pack of alternating alluvial and floodplain beds at the base of the section, overlain by the horizon of eolian and lacustrine-boggy sediments formed during the Sartan Glaciation. The second stage of sediment accumulation in the section is marked a peat horizon, whose formation was attributed to the Holocene Climatic Optimum. The horizon is overlain by a thick sand dune deposits blanket accumulated during the second half of the Holocene in the course of climate cooling and activation of eolian processes. This is consistent with the widely accepted pattern of climate evolution at the end of the Late Pleistocene through the Holocene.

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