EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Earth`s Cryosphere, 2018, vol. XXII, No. 6, pp. 3–14 **http://earthcryosphere.ru/**

REGIONAL AND HISTORICAL GEOCRYOLOGY

DOI: 10.21782/EC2541-9994-2018-6(3-14)

LATE QUATERNARY DUNE FORMATIONS (D'OLKUMINSKAYA SERIES) IN CENTRAL YAKUTIA (Part 1)

A.A. Galanin, M.R. Pavlova, I.V. Klimova

Melnikov Permafrost Institute, SB RAS, 36, Merzlotnaya str., Yakutsk, 677010, Russia; agalanin@gmail.com

The data inferred from a new key section in the Vilyuy river basin allowed us to examine the structural-faces features and absolute age of cross-layered sandy-loam sediments of the D'olkuminskaya series distributed in Central Yakutia in a wide hypsometric range. These deposits had formed in the period from the latest Kargin thermochron to the beginning of the Holocene (between 35 ka and 12–10 ka BP) under the overwhelming conditions of severe desiccation and desertification of the area. During the Boreal optimum of the Holocene, the soil-vegetation cover had largely provided for the stabilization of dune covers. The formation of the contemporary moving-dune massifs took place not more than one thousand years ago and had been directly linked with the climatic events of the Little Ice Age.

Dunes, eolian formations, grain size distribution, dunes mineralogy, absolute age, palynology, permafrost, D'olkuminskaya series, Pleistocene, Quaternary period

INTRODUCTION

The areas of dune massif evolution are widely spread in high latitude regions of the northern hemisphere, including Canada, Alaska, Europe and Russia. *R.F. Black* [*1951*] points out that Quaternary eolian sediments which consist for the most part of wind-blown sand and loess cover more than half of the areas of Alaska and Canada. Within the Arctic coastal plain of Alaska alone, the area covered by Late Quaternary dune massifs exceeds 12,000 km^2 [*Wolfe et al., 2011*]. A considerable expansion of the coeval dune massifs into the North Eurasian cryolithozone is observed within the areas of the Polar Urals framing [*Astakhov and Svendsen, 2011*], the West Siberian plains [*Velichko and Timireva, 2005*], Transbaikalia and Baikal [*Ivanov, 1966; Ufimtsev et al., 1997; Vyrkin, 2010*].

Vast massifs of undulating and cross-bedded quartz loamy sands (sand partcles >90 %) (D'olkuminskaya series) reaching 15–25 m in thickness are known in the Lena, Vilyuy basins and their tributaries; in Central Yakutia, they occupy up to 30 % of some regions [*Pavlov, 1981; Kolpakov, 1983; Kut, 2015*]. Due to the 250–400 m-thick continuous permafrost with temperatures of –4...–5 °C along peryphery of the area of their distribution, these are characterized by a unique presence of intrapermafrost taliks reaching magnitude of several tens of meters in thickness, whose discharge area represents high-quality drinking water sources [*Shepelev, 2011*] and favors the formation of thermo-cirques, a product of the suffosional (subsurface erosion) processes and icing. In the lower reaches of the Vilyuy river basin, the most well-known are the year-round Makhatta springs with a flow rate of about 760 L/s.

Both the age and origin of the D'olkuminskaya series has been a disputable question for over half a century. A number of researchers interpret them as dune covers formed as a result of drastic and rapid desertification during the last Late Pleistocene cryochron [*Kolpakov, 1983; Alekseev et al., 1984; Kamaletdinov and Siegert, 1989; Kamaletdinov and Minyuk, 1991; Waters et al., 1999; Galanin et al., 2016; Pavlova et al., 2017*]. Others believe them to be of alluvial-lacustrine origin, which is indicative of their deposition in pluvial (moderately wet) environments [*Soloviev, 1959; Alekseev, 1961; Ershov, 1989*; *Bolshiyanov et al., 2016; Spector et al., 2017*]. According to the most extraordinary hypotheses, these landforms provide evidence of glacial-hydrogenic catastrophes (floods) – severe flooding events (surges) associated with bursts of barrier-glacial basins at the turn of the Late Pleistocene and Holocene [*Spector et al., 2017*]. It is also suggested that cross-bedded loamy sands formed as a result of late Pleistocene marine transgressions [*Pomortsev et al., 2017*].

The accumulated to date results of absolute age determinations unambiguously indicate to the Late Pleistocene (MIS-2) age of the D'olkuminskaya series [*Alekseev et al., 1984; Kamaletdinov and Siegert, 1989; Kamaletdinov and Minyuk, 1991; Waters et al.,*

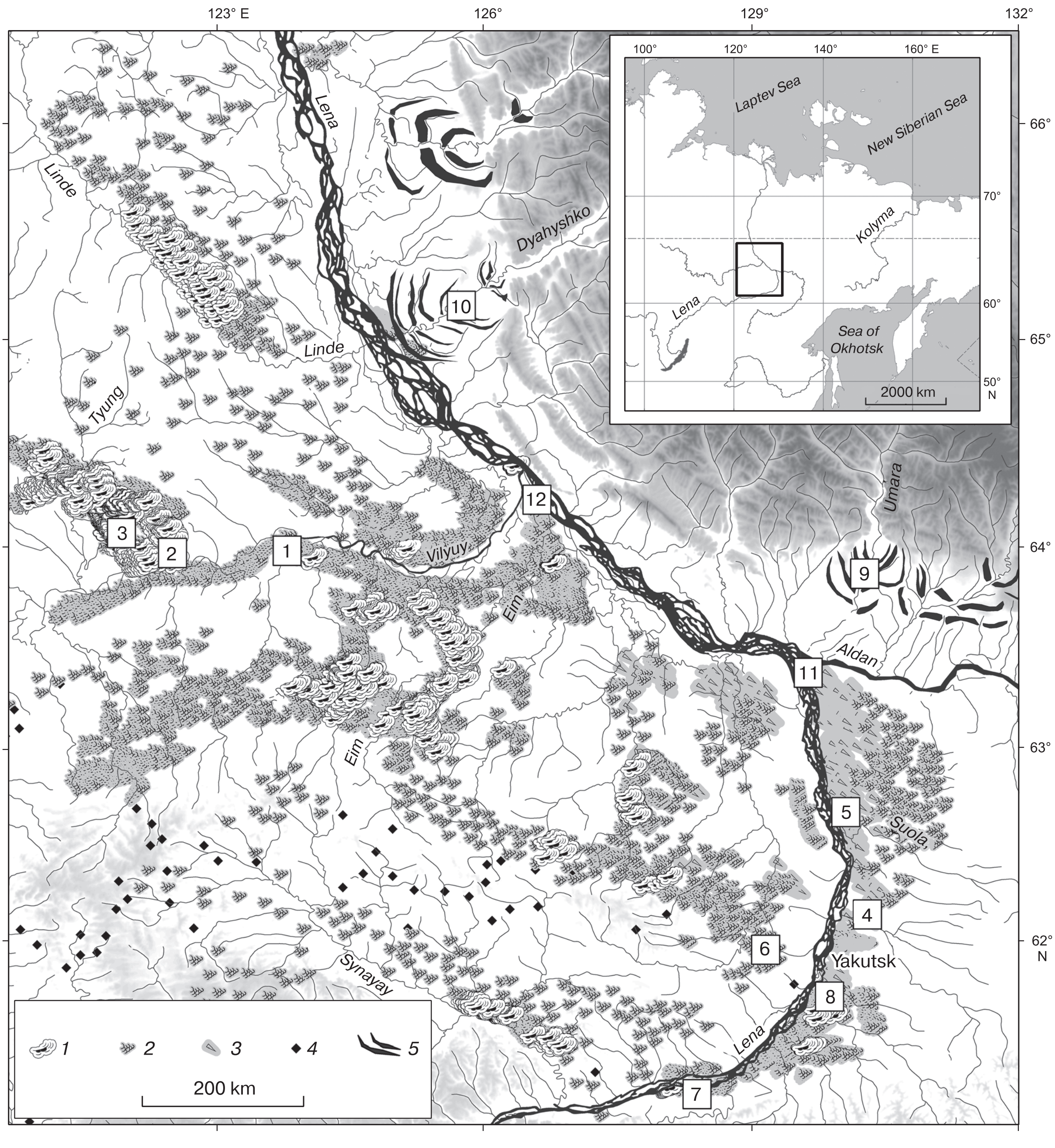

Fig. 1. Schematics of Late Quaternary and modern dune covering formations expressed in the relief of Central Yakutia and location of the key reference outcrops.

1 – modern unfixed dune massifs (tukulans); *2*, *3* – fixed (in the Holocene) massifs of spear-shaped and parabolic dunes, respectively; *4* – destribution of ventifacts and faceted rocks after [*Kolpakov, 1983*]; *5* – moraines of channel glaciers of the Verkhoyansk glaciation. Digits in the squares – key sites and reference sections of the D'olkuminskaya series: 1 – Kysyl-Syr tukulan [*Galanin et al., 2016; Pavlova et al., 2017*]; 2 – southeastern part of the Makhatta tukulan [*Pavlova et al., 2017*]; 3 – central part of the Makhatta tukulan; 4 – the Megin location of the mammoth fauna finds in the low reaches of the Suola river; 5 – Peschanaya Gora outcrop [*Alekseev et al., 1984; Kamaletdinov and Minyuk, 1991; Spektor et al., 2017*]; 6 – Shestakovka river basin and Lake Chabada; 7 – Ust-Botuoma outcrop [*Alekseev et al., 1984*]; 8 – Diring-Yurakh outcrop [*Kamaletdinov and Siegert, 1989; Waters et al., 1999*]; 9, 10 – end-moraine complexes of the Verkhoyansk glaciation overlapped by eolian sediments [*Siegert et al., 2007*]; 11, 12 – deflation-truncated sites of low terraces and dune-blocked arms of the Lena and Vilyuy rivers [*Kolpakov, 1983*].

1999; Siegert et al., 2007; Galanin et al., 2015, 2016; Bolshiyanov et al., 2016; Pavlova et al., 2017], however, viewpoints on its origin differ drastically. The study of the covering loamy sands is essential to full understanding of the Late Glacial history of Yakutia and Eastern Siberia. This paper discusses the results of biostratigraphic studies of the new Kysyl-Syr reference section of Late Quaternary dune formations in the lower reaches of the Vilyuy river basin (Fig. 1) obtained during the 2012–2015 field works.

RESEARCH METHODS

The approaches to facies analysis and stratigraphy used in the study of the Kysyl-Syr dune massif (Fig. 2) included: geomorphological inspection; search, clearing and description of outcrops; the study of lithology, sedimentation and cryogenic textures; sampling for various types of analysis, including absolute dating of sediments, etc.

Particle-size distribution analysis of silt samples (117 pcs.) was performed by standard sieve analysis [*Shvanov, 1969*] and aerometric methods in the Melnikov Permafrost Institute (MPI) SB RAS Granulometric laboratory. The statistics processing of the results was performed with the Gravistat software [*Blott and Pye, 2001*] using geometric (modified) Folk and Ward graphical method [*Folk, 1980; Blott and Pye, 2001*]. The medium (x) and median (Md) grain sizes were calculated in micrometers (μm). Other indicators include: grain sorting coefficient (σ), skewness (asymmetry) (α) and kurtosis (τ) in non-dimensional units on logarithmic scales [*Folk, 1980; Blott and Pye, 2001*]. Within frames of the used method, the sorting coefficient takes integer values for sediment sorting described as: $\sigma < 1.27$ (high, i.e. well-sorted), $1.62 < \sigma < 2.0$ (moderate), $\sigma > 2.0$ (poor, or poorly sorted).

The skewness coefficient α can take values from −1 to +1, suggesting either symmetric distribution (zero values), the presence of "tails" of small fractions (negative values) resulting from their removal and accumulation of coarse fractions, or accumulation of fine fractions (positive skewness).

The kurtosis (peakedness) τ being a measure of the contrast of grains sorting between the average of the extremes of the size distribution and the center, can take only positive values. Higher kurtosis describes highly peaked distributions typical of very well sorted samples, while its low values (<<1) are characteristic of flat and flat-topped distribution. A normal distribution has a kurtosis of 1.

Results of particle-size analysis and calculated statistical characteristics were plotted and grouped by facies with the estimation of average values (Table 1).

Mineralogical analysis of samples (38 pcs.) was performed in the laboratory of MPI SB RAS using a binocular microscope and a polarization mineralogical microscope, and immersion oil. Mineralogical analysis was carried out for the modal fraction (100–250 μm), which was extracted using sieves from the elutriated (pre-washed) sample.

The absolute age of deposits was derived from ^{14}C dating (28 dates) and by applying the optically stimulated luminescence (OSL) method (2 dates). The radiocarbon analysis was performed by the authors using the liquid scintillation counting (LSC) method [*Kovalyukh and Skripkin, 2007*] on the Quantulus 1220 spectrometer-radiometer in the MPI SB RAS Radiocarbon Lab. (Yakutsk).

The obtained ^{14}C dates were calibrated using the OxCal 4.3 software [*Bronk, 2009*] for a 95 % significance level. A series of cross-dating was performed by the LSC method at the Radiocarbon Laboratory of GIN RAS (Moscow) and accelerator mass spectroscopy (AMS) method at the Center for Isotope Research of the University of Groningen (Netherlands). When compared, the results showed high convergence (98 %) of the dates.

The infrared and OSL dating of two samples of dune quartz loamy sands was performed at the Tallinn Research Laboratory for Quaternary Geochronology, Institute of Geology, Estonia.

A complete list of dates obtained for the Kysyl-Syr reference section and other exposures of the D'olkuminskaya series, along with history of its evolution, will be accomplished in the second part of the article. Some cross dates were discussed earlier in [*Galanin et al., 2015, 2016*].

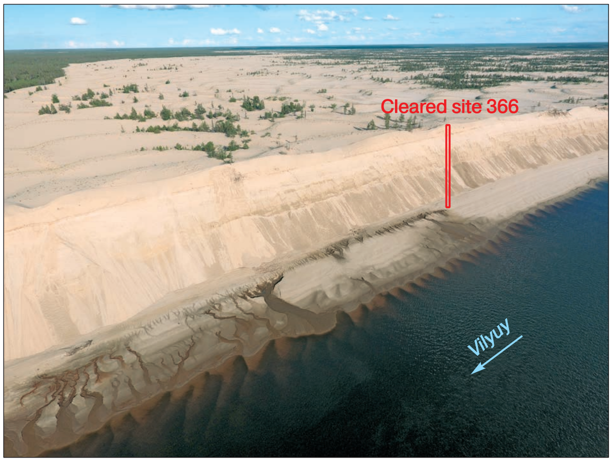

Fig. 2. Kysyl-Syr reference section of Late Quaternary dune formations in the scarp of the 30–35-meter terrace with intrapermafrost sources discharging into the channel of the Vilyuy river (Central Yakutia) and the position of reference Cleared site 366.

July 2016, the summer low-water period. Photograph by A.A. Galanin.

Table 1. **Generalized characteristics of grain-size distribution in some facies (Late Pleistocene and modern) from the lower reaches of the Vilyuy Rv. basin calculated by geometric (modified) Folk and Ward graphical method [*Folk, 1980; Blott and Pye, 2001*]**

Facies (number of samples)	Mean grain-size statistical parameters				
	Average grain size (x, μm)	Grain sorting coefficient (σ)	Asymmetry (α)	Kurtosis (τ)	Median (Md, μm)
Modern unvegetated dune masiffs					
Transit-accumulation segment of dune (32)	295 ± 29	1.56 ± 0.08	–0.28 ± 0.09	1.12 ± 0.21	315 ± 19
Leeward slope of dune (13)	299 ± 48	1.50 ± 0.15	–0.17 ± 0.14	0.95 ± 0.18	312 ± 37
Deflation basin (10)	284 ± 153	1.62 ± 0.11	–0.28 ± 0.08	1.06 ± 0.13	310 ± 13
Deflation basin (2)	238 ± 3	1.73 ± 0.06	–0.07 ± 0.04	0.78 ± 0.05	248 ± 3
Deflation basin with gravel (4)	819 ± 62	2.69 ± 0.36	–0.47 ± 0.08	0.71 ± 0.12	1160 ± 215
Modern semi-vegetated dune masiffs					
Deflation basin populated with single trees (1)	206	1.64	0.12	0.78	198
Leeward slope of active dune with single trees (2)	256 ± 7	2.02 ± 0.18	–0.01 ± 0.11	1.14 ± 0.13	277 ± 14
Biogenic-eolian mounds, small (12)	257 ± 12	1.62 ± 0.03	–0.27 ± 0.05	0.82 ± 0.09	281 ± 15
Biogenic-eolian mounds (2)	209 ± 0.3	1.63 ± 0.01	0.11 ± 0.01	0.78 ± 0.01	201 ± 1
Suffosional-proluvial (1)	270	1.76	–0.19	0.97	299
Modern alluvial sediments of the Vilyuy Rv. within the dune massifs areal					
River-channel (4)	343 ± 261	1.50 ± 0.03	–0.10 ± 0.15	1.42 ± 0.11	347 ± 18
Midstream, stratified (3)	376 ± 161	1.46 ± 0.18	0.12 ± 0.07	1.17 ± 0.15	370 ± 5
Late Pleistocene dune sediments from the Kysyl-Syr key section					
Gently-laminated and cross-bedded dune loamy sands (the Sartan cryochron) for Cleared site 366 (12)	300 ± 40	1.6 ± 0.1	–0.22 ± 0.08	1.03 ± 0.2	318 ± 32
Alluvial Late Pleistocene sediments at the base of the Kysyl-Syr key section, Cleared site 366					
Midstream lenticular and cross-stratified sands (5)	340 ± 33	1.7 ± 0.2	–0.08 ± 0.20	1.5 ± 0.26	338 ± 21
River-reach horizontal-stratified fine loamy sands interbedded with silt clays (5)	204 ± 60	1.92 ± 0.2	–0.20 ± 0.16	1.1 ± 0.27	216 ± 33
Flood-plain horizontal-stratified fine loamy sands (4)	160 ± 37	1.66 ± 0.04	–0.10 ± 0.06	0.92 ± 0.11	225 ± 75
Oxbow horizontal-stratified, strongly-gleied silt clays (5)	37 ± 22	5.11 ± 1.15	–0.37 ± 0.06	1.14 ± 0.19	52 ± 35

RESEARCH RESULTS

Geomorphology and landscapes of the Kysyl-Syr massif

The Kysyl-Syr dune massif (63.9° N, 123.3° E) was selected as a key research object (Figs. 1, 2) proceeding from the characteristics listed below.

1. Geomorphological conditions. The massif (tukulan) surface is characterized by a remarkably complex dune relief, whose total area of fixation is not more than 10 %. The massif is compact in size (6 × 4 km) and has elliptical shape extending southwest.

2. Both the natural exposure and high informativity of the section being most representative in the bluff (35 m in height and about 2 km long) allowed establishing the following illustrative characteristics: the variegated facies of alluvial and eolian deposits are rich in marker horizons, erosion and deflation surfaces, layers with alluvium organic matter, buried soils with lenses of peat and vertically buried trees; some sedimentary units contain rich organic material perfectly suitable for ^{14}C dating and stratigraphic analysis.

3. The massif's compactness (size: 6 × 4 km; area: about 19 km^2) facilitates the landscape-geomorphological studies and provides an opportunity for investigating the study area by walking routes.

4. The accessibility of the Kysyl-Syr reference section by vehicles and water transport allows its surveying repeatedly in order to update the results.

From the morphometric perspective, the dune massif is asymmetric (skewed). Being exposed in the river bluff, its the northern part has the absolute elevation marks up to 110–116 m and rises above the river Vilyuy water line (79–80 m) in the form of a terrace 30–36 m in height. In the south-easterly direction, the massif surface gradually reduces to the absolute marks of 85–90 m in the marginal part, and practically becomes aligned with the modern floodplain elevation at the level of 5–10 m.

Small islands of sparse pine and birch growth with lichen-bearberry cover and admixture of crowberry, cranberry, willow shrubs, and sporadic poplar and larch trees (*Pinus sylvestris*, *Betula platyphylla*, *B. alba*, *Salix bebbiana*, *Populus suaveolens*, *Larix gmelinii*, *Arctostaphylos uva-ursi*, *Vaccinium uligino-*

sum, *V. vitis-idaea*) developed within the vegetated segments of the Kysyl-Syr tukulan, with their total area not exceeding 10 %. The plant species encountered in the waterlogged sodded depressions (southern part of the massif) are: dwarf birch, swamp ledum, sweet gale, and rarely spruce, Siberian dwarf pine, cranberry, horsetails, etc. (*Chamaedaphne calyculata*, *Betula exilis*, *Ledum palustre*, *Oxycoccus microcarpus*, *Equisetum fluviatile*, *Picea obovata*, *Pinus pumila*). Siberian dwarf pine is found only in the southern part of the Kysyl-Syr tukulan, where it forms large groups on biogenic-eolian mounds and low ridges composed dominantly by sand.

At least 90 % of the Kysyl-Syr massif surface is made up by moving active parabolic dunes, deflation basins and corridors grouped into several hierarchical orders. A piled-up dune, which develops only on the edge of the Vilyuy river bluff (northern part of the dune massif), has a length of more than 2 km (Fig. 2). It consists of a system of partially closed narrow sinuous ridges up to 10–12 m in height, with the deep- and narrow-most deflation basins and funnels tending to form in their leeward part.

Scale-shaped parabolic and asymmetric (skewed) polysynthetic dunes are commonly spread in the inner part of tukulan (Fig. 2). The smallest (elemental) dunes average from 100 to 150 m in length, while their crest height is usually 4–6 m; these parameters can locally reach 250 m (length) and more 20 m (height). The windward face of active sand dunes that begins in the elemental deflation basin is usually gentle (2–4°) and, as a rule, completely devoid of vegetation. A leeside slope of elemental dunes is steeper, crumbly, with slipface angle close to natural angle of repose of sand (25–30°).

The width of deflation basins is scaled with the size of elemental dunes and varies on average from 50 to 150 m, while its depth reaches 6–10 m. The encountered hypertrophied basins had a width of 300 m and more. The deflation basins are either crescent-shaped or ellipsoidal and are for the most part devoid of vegetation. Their bottoms are covered with coarse sand, rarely with fine gravel of exotic composition (garnet, agate, chalcedony, onyx). The encountered faceted polished pebbles and ventifacts, quartz fulgurites and Fe–Mn fine nodules and concretions (ortstein) are few in number [*Galanin et al., 2017*]. Horizons of stumps of dead trees (vertically standing and fallen) stripped of their bark by the deflation processes, are sometimes observed on the surface of unvegetated basins.

The vegetation cover of mobile (unfixed) dunes and deflation basins are presented by sparse tussocks and clumps of grasses and shrubs – fescue, sedges, timename, knot-weeds, sand sage, couch-grass, Alexandrian laurel, sorrel (*Festuca auriculata*, *Acetosella graminifolia*, *Aconogonon angustifolium*, *Artemisia commutata*, *Thymus asiaticus* Serg., *Carex vanheurckii*, *Equisetum arvense*, *Elytrigia villosa*, *Phlojodicarpus sibiricus*). Living dwarf biomorphs of pine, birch, poplar, whitebeam (*Pinus sylvestris*, *Betula* sp., *Populus* sp., *Sorbus sibirica*), up to 2–3 m high, are also occasionally found within unfixed dunes.

The lower order micro-reliefs are represented by mound-like landforms sized from a few centimeters to 10 m. These include a variety of eolian ripple marks on the dune surfaces. Larger landforms are eolian-biogenic mounds 7–8 m in diameter and 3–4 m in height, which form as a result of sand accumulation assisted by shrubby types of birch, poplar, willow (*Betula pubescens*, *B. cojanderi*, *B. exilis*, *Salix* sp.) etc.

In the areas of the Siberian dwarf pine (*Pinus pumila*) distribution, the mounds reach 10–12 m in height. The appearing sandy low-ridges whose crests are anchored by densely intertwined living and dead roots of this shrub have the length of several tens of meters.

Particle size distribution of unvegetated dunes

The granulometric composition of modern deposits of the Kysyl-Syr tukulan was characterized by 80 samples from different facies of the surface of unfixed dunes. The particle size distribution of samples from the Vilyuy river (modern channel and the floodplain) was also analyzed by their comparison (Table 1).

The established parameters of loamy sands accumulated within the limits of modern intensely-winnowed parabolic dunes are: average particle size (280 μm $< x <$ 300 μm), the degree of sorting ranking as good ($1.5 < \sigma < 1.6$), a weak negative skewness ($-0.28 < \alpha < -0.01$) indicative of the removal of small fractions (Table 1), and medium kurtosis ($0.7 < \tau < 1.1$) characteristic of the relatively peaked (normal) distributions.

Coarse sand fraction ($x = 800 \pm 61.93$ μm) admixed with fine gravel accumulate in large well-worked deflation basins, which is adduced by increased values for negatively-skewed distributions ($\alpha = -0.47 \pm 0.08$), deterioration of grain sorting ($\sigma = 2.69 \pm 0.36$) and by distributions tending to be flattened ($\tau = 0.71 \pm 0.12$). Surface sediments at sites characterized by the decaying deflation processes and semi-fixed dune topography are enriched with finer fractions (200 μm $< x <$ 210 μm) and show evidences of improved sorting and more symmetrical distribution (Table 1).

Particle-size distribution of modern alluvial deposits sampled from the submarine dunes (sandbars) and meander bar facies are characterized by a larger average particle size (340 μm $< x <$ 375 μm), a good sorting ($1.17 < \sigma < 1.50$) and seeply peaked ($1.17 < \tau < 1.4$) symmetric distributions. Modern floodplain facies have significantly smaller average grain size ($x = 160 \pm 37$ μm) and are characterized by symmetrical normal distribution (Table 1).

By comparison with contemporary dune deposits, modern alluvium facies are characterized by more contrast and significant grain size variability, which may be associated with the seasonal dynamics of the fluviomorphological process, i.e. deposition of coarser fractions during the flood and thinner in the low water period within the same site.

Mineral composition of unvegetated dunes

The mineralogical composition of modern dune facies is characterized by higher contents of light fraction (specific weight <2.9 g/cm^3), which is overwhelmingly dominated by quartz (85–97 %), while feldspar, sandstone fragments are encountered in smaller amounts (<10 %). Quartz grains are commonly clean, transparent, have a rounded shape, sometimes their surface is covered with brown drips and hydroxides. In some samples, perfectly rounded quartz grains were cemented with iron hydroxides.

Organic inclusions, Fe–Mn hydroxides, chlorite, clay minerals are common among the newly formed minerals in dune sediments, with rare exotic minerals from the heavy fraction (garnets, ilmenite, rutile) and rounded grains of stable minerals (kasper, chalcedony, opal, onyx). Beside these, the mineralogical analysis revealed sporadic diatom algae shells.

Fine gravel (1–5 mm) with the exotic mineralogical composition (garnet, epidote, jasper, chalcedony, etc.) is accumulated on the surface of some deflation basins. The roundness of mineral grains is usually reported to be from very good to perfect, with most of them polished. Wind-polished faceted pebbles and ventifacts are few in number, though. Focal accumulations of quartz fulgurites and Fe–Mn nodules and concretions (ortsteins) represent an exotic feature of the modern mineralogy of dune silts [*Galanin et al., 2017*]. The former are tubular forms 3–5 cm in length (less often, up to 30 cm) and 0.3 to 2 cm thick, formed by molten fragments of dune sand, tightly welded with white transparent quartz glass (refractive index <1.5).

Tubules of Fe–Mn fine nodules reach 5–6 cm in length and 3–10 mm in diameter and are composed by quartz sand cemented with Fe, Mn and oxygen compounds admixed with carbon in different proportions [*Galanin et al., 2017*]. Besides, the autogenous iron and manganese, the established in them high concentrations of cobalt, nickel, arsenic were, significantly exceeded these elements' amounts in the initial dune sands. Soil tubes (traces of biological activity), aka pedotubules form inside the profile of developed paleosol surrounding the root systems of woody vegetation, given good aeration. In the wake of the vegetation cover degradation and wind erosion of the soil tubular ferromanganese nodules, fulgurites (lightning tubes) and ventifacts accumulate accumulate on the surface of some deflation basins.

With respect to the mineralogical chracteristics, samples of modern silty alluvium show some affinity with contemporary dune silt, but have heavier mineralogical composition and more contrasting local variations. While modern alluvial sands are dominated by quartz (60–86 %), increasing amount of feldspars (5–20 %), and fragments of bedrock sandstones reported in some samples in large amount (up to 40 %). The content of heavy fraction (specific gravity >2.9 g/cm^3) in some alluvium facies increases to 1–2 %. A characteristic feature of alluvial silt is the constant presence of biotite, whose amounts in other mineral groups sometimes reaches 5–10 %. The mineralogical composition of modern alluvial sands and silts generally shows significant local-scale variations, which is associated with a more pronounced seasonal dynamics of the channel processes intensity, by comparison with the eolian ones.

Facies structure of the Kysyl-Syr outcrop

The Kysyl-Syr reference section was studied in right-bank bluff (35 m in height; and about 2 km long) of the Vilyuy river in the period from 2012 to 2016 (Fig. 2). During the summer low-water period 5–6 groups of groundwater sources were revealed at the bluff base, with visible flow rate of 3–4 L/s each, some of them outflowing as pressurized springs up to 30–40 cm in height. The maximum concentration of water outlets is observed in the interval 300–400 m in the north-western part of the exposure. In August 2016, prompted by the summer low-water, the exposure was enlarged by an area (at 75–76 m asl) composed by gravel-pebble with inclusions of small boulders and exhibiting wooden debris and single finds of bones of large mammals.

The authors cleared several outcrop sites within the coastal bluff, of which the most informative are No. 366 and 449. The results of particle-size and mineralogical analyses and absolute dating are shown in Table 1 and in Figs. 3, 4, while the fullest list of absolute dates is presented in [*Galanin et al., 2015, 2016*]. A general description of the section with the thickness intervals indicated by absolute elevation marks (height above sea level) is given below.

Alluvial deposits. At the base of the section (the 75–88 m interval) a normal alluvial cycle occurring throughout its length and underlain by basal pebbles, is exposed only during the maximum low water. A unit of interbedding members of cross-stratified (underwater river dunes and sand bars facies) medium-grained sands and horizontally-layered sands (sand-spit facies) with interbeds of sandy silts (river reach and floodplain facies), with thin lenses of fine gravel (erosion and washover facies). The thickness of interbedded members varies from 3–4 to 40–50 cm, and the deposits color from pale yellow to dark gray. The cross-stratified sands composed by elementary laminae from 0.5 up to 2–4 cm thick, dipping at an angle of 35–45° in the direction of the streamflow of the present-day Vilyuy. These are characterized by visibly well-sorted material inside each elementary lamina formed as a result of the differentiation of heavy and light fractions. During the field survey, the alluvial unit was in the unfrozen state and intensely waterlogged at the level of the Vilyuy river bed.

The particle-size composition of the cross-stratified sands facies (Table 1) is represented by: average grain size x = 340 ± 33 μm, sorting coefficient σ = 1.7 ± 0.2, skewness α = –0.08 ± 0.20, kurtosis τ = 1.5 ± 0.26. While that of the facies of horizontally layered river-reach silts with thin-bedded sandy silts is characterized by: x = 204 ± 60 μm, σ = 1.92 ± 0.2, α = –0.20 ± 0.16, τ = 1.1 ± 0.27.

The alluvial cycle is crowned by the bed of thin, horizontally-layered, dark-gray to bluish fine silts (floodplain-oxbow facies), which in some areas, laterally grade into the light and occasionally into heavy clay silts with admixture of microconcretions of vivianite (oxbow facies) and dispersed with organics and fine plant detritus.

The top of the floodplain unit position leveled with the height of the modern Vilyuy river high floodplain (7–10 m) and traced throughout the length (2 km) of the coastal bluff, is gently subsiding (1–2 m per 1 km) towards the river. It is colored in ochre tones and broken by recurring short vertical veins (10–30 cm in width) filled with ochre sand from the overlying sediments. The floodplain fine silt facies having massive cryotecture, acts as an aquiclude, where moisture content (i.e. ice content) calculated on a wet-weight basis reaches 20–25 %.

The generalized granulometric composition of the floodplain facies is characterized by: average grain size x = 160 ± 37 μm, sorting coefficient σ = 1.66 ± 0.04, skewness α = –0.1 ± 0.06, kurtosis τ = 0.92 ± 0.11, and resultant values for the oxbow facies are: x = 37 ± 22 μm, σ = 5.11 ± 1.15, α = –0.37 ± 0.06, τ = 1.14 ± 0.19.

The alluvial deposits established in the lower part of the Kysyl-Syr section are therefore characterized by a variegated array comprising from river-bed to floodplain and oxbow of facies, which is adduced by a wide range of average grain sizes and contrasting variations of all particle-size characteristics (Fig. 3).

Mineralogical composition of alluvial facies experiencing strong variation even within one facies (Fig. 3) is dominated by quartz (60–85 %), feldspars (5–20 %), while some samples abound with fragments of bedrock quartz-feldspar with hydromicaceous cement of sandstones (1–40 %), whose nearest outcrops are revealed 15 km higher upstream on the left bank of the river. Feldspar grains are often cloudy, fractured, coated with Fe hydroxides. The heavy fraction content in some alluvial facies reaches 1–2 %, with magnetite, iron hydroxides, garnet, epidote, hornblende, pyroxene, ilmenite and leucoxene identified in its composition. High amounts of biotite, muscovite and chlorite (up to 50 %) in the group of minor minerals typify mineralogical composition of the alluvial facies.

The particle-size distribution and mineralogy of alluvial facies exhibit frequent cyclic variation bearing the evidence of seasonal fluctuations in the water level and flow rate in a water body (Fig. 3). While alternation of layers with oblique and horizontal stratification, and oblique laminae dipping down the Vilyuy river valley, complexed with erosion traces, thin layers of fine gravel and allochthonous plant detritus (driftwood) are indicative of the alluvial origin of sediments. The age of the alluvial deposits of the lower part of the Kysyl-Syr section determined from a series of radiocarbon dating (Figs. 3, 4) is attributed to the latter half of the Kargin Thermochron (MIS-3) [*Galanin et al., 2015, 2016*].

Dune sediments are represented by gently-laminated and cross-bedded sands and encompass the interval of 88–110 (116) m, composing thereby the upper two thirds of the Kysyl-Syr section (Fig. 3). They are divided into lower and upper units, distinctly separated from each other by the top of the paleorelief and horizon of buried soil, persistent throughout the exposure for about 2 km.

The lower unit (88–105 m) is represented by members of gently-laminated (3–5°) silts (the facies of gently sloping parabolic and spear-shaped dunes) which have thickness of maximum 10–12 m (Cleared site 366), separated by deflation surfaces. In the hypsometric plan beyond the modern (Kysyl-Syr) dune massif, the top of the unit delineates the above-floodplain terrace surface (height: 30–35 m) of the Vilyuy river, vegetated by the pine and bearberry forest. While the undulating top of the unit within the Kysyl-Syr tukulan is formed by a surface of intense deflation (with a persistent paleosol horizon), which is confined to 100–105 m elevation marks within Cleared site 366, subsiding to 89–90 m at Cleared site 449, to form a depression (Fig. 4). Dune sediments of the lower unit practically totally pinch out there, while the marking paleosol horizon tends to thicken and gradually evolves into a 2 m-thick peatland, resting directly on the underlying alluvium. The characteristic features of the lower unit sediments are: monotonously persistent structure; total absence of plant residues (except for few roots of herbaceous plants) and buried soil horizons.

Proceeding from the OSL dating and stratigraphic position (Fig. 3), the age of sediments composing the lower unit is related to the Sartan cryochron (MIS-2) [*Galanin et al., 2015, 2016; Pavlova et al., 2017*].

The upper unit (occurrence range: 88 (90)–116 m, thickness: from 2–3 to 20 m) is distributed only within the limits of the modern field of actively

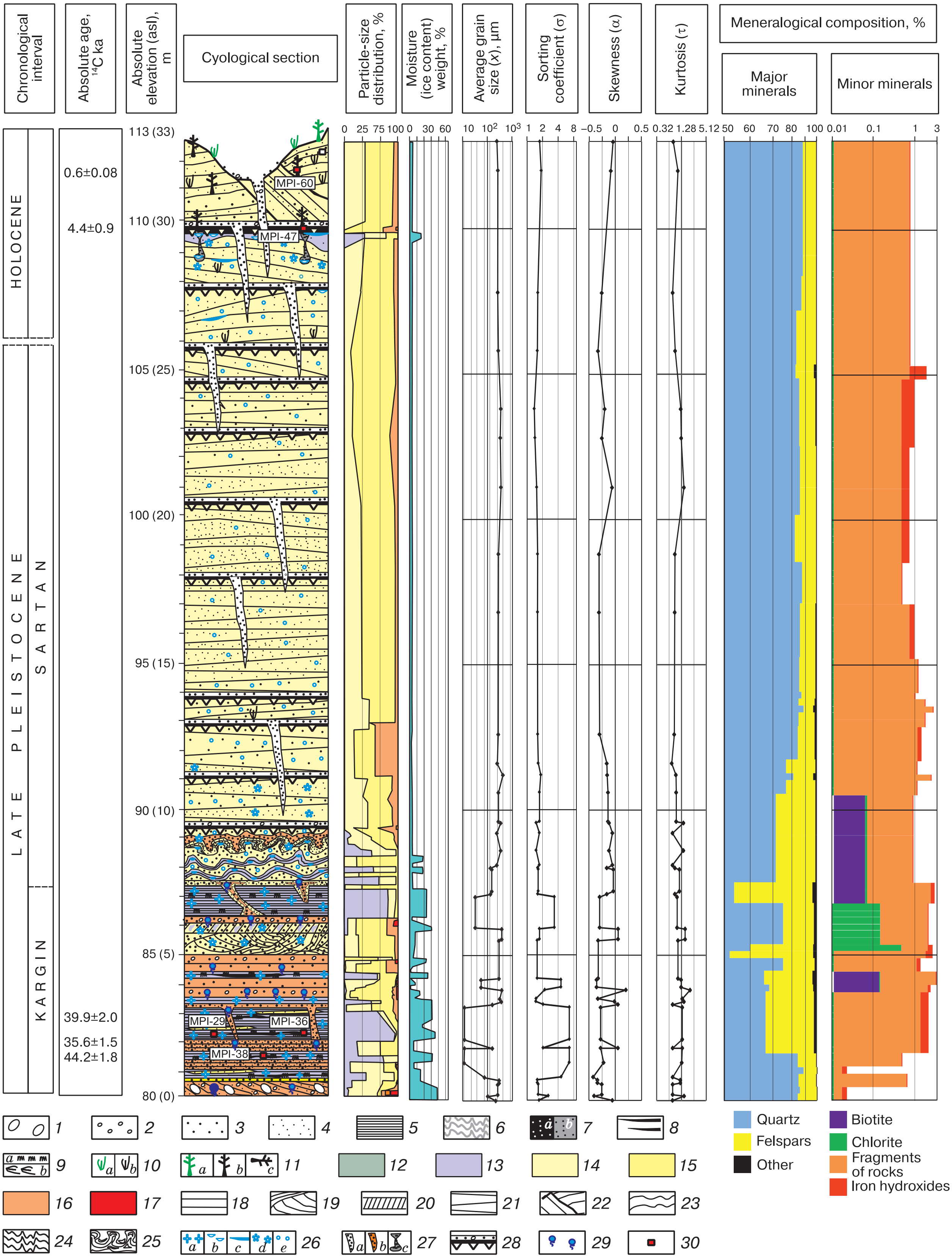

Fig. 3. Kysyl-Syr reference section of Late Quaternary eolian formations in the Vilyuy river basin; Cleared site 366 (63.9162° N, 123.2331° E).

Lithology: *1* – fine pebbles; *2* – fine gravel; *3* – medium sand; *4* – fine sand (loamy sand); *5* – mud (clay silt); *6* – loamy sand with thin (1 mm) rhythmic layers of clay silt; *7* – humus with admixture of sand (*a*) and sand with admixture of humus (*b*); *8* – thin layers and lenses of allochthonous plant detritus; *9* – shrub (*a*) and grassy (*b*) peat; *10* – living (*a*) and dead (*b*) vertically buried stems and clumps of cereals; *11* – living (*a*) and fossil trees: vertically buried (*b*), horizontally buried (*c*). *Particle size distribution*: *12* – heavy clay silt and clay (<0.01 mm); *13* – silt with clay silt, intensely-gleyed (<0.1 mm); *14* – fine sand (loamy sand) (0.1–0.25 mm); *15* – medium-grained sand (0.25–0.5 mm); *16* – coarse-grained sand (0.5–1.0 mm); *17* – gravel, fine pebbles. *Textures, fluvial syngenetic*: *18* – horizontal; *19* – lenticular; *20* – cross-bedded. *Textures, eolian*: *21* – gentle, cross-bedded (parabolic dunes) with the thickness variation of elementary layers from 1 mm to 30 cm; *22* – steep-dipping cross-laminated (piled-up dunes and barchans). *Postlithogenic involution and cryoturbation*: *23* – undulating; *24* – pluckered; *25* – diapiric. *Cryostructures of cementing ice* (*26*): *a* – massive, *b* – fine-cell, *c* – thin-schlieren and fine-lenticular, *d* – nestlike; *e* – contact. *Wedge formations* (*27*): *a* – dry (frost-desiccated) wedge-like syn- and epigenetic veins in the dune deposits, *b* – intensely ferruginized wedge-shaped sandy veins with massive cryotexture, *c* – clay silt-humus veins with massive cryotecture in the modern dune deposits. *Other elements: 28* – structural and sedimentary unconformities, surfaces of intense deflation with lenses of coarse sand and fine gravel; *29* – areas of self-effluent of inter-permafrost taliks; *30* – points of absolute age determination by radiocarbon method with laboratory dating codes.

winnowed dunes of the Kysyl-Syr tukulan, overlapping the surfaces of lower unit paleorolief and marking paleosol horizon. The top of the upper unit is formed by the exposed relief of modern migrating (unvegetated) dunes. The upper unit deposits are characterized by a more distinct cross-bedded stratification (facies of piled-up, embryonic and short parabolic dunes) dipping southwardly at angles from 5 to 30–40° in the south-east direction.

The modern dunes and the entire Kysyl-Syr sandy massif are oriented in the same direction. The upper unit is characterized by numerous vertically buried tree trunks (pine and, less frequently, larch) and interlayers of underdeveloped soils abounding with pieces of coals. Proceeding from the data from a series of radiocarbon dating (Figs. 3, 4) the time of the unit formation is estimated as the second half of the Holocene [*Galanin et al., 2015, 2016; Pavlova et al., 2017*].

The particle size distribution in the lower and upper units are alike and persistent throughout the section (Figs. 3, 4), which is characterized by the averaged (12 samples) values, as follows: average grain size $x = 300 \pm 40$ µm, sorting coefficient $\sigma = 1.6 \pm 0.1$, skewness $\alpha = -0.22 \pm 0.08$, kurtosis $\tau = 1.03 \pm 0.2$. Negative skewness and average kurtosis indicate normal distribution and presence of "tails" of small fractions, which is typical of modern dune deposits of the Kyzyl-Syr tukulan.

The mineralogical composition of dune silts composing both the units is also similar in many ways. The prevailing minerals of the light fraction are overwhelmingly dominated by quartz (85–97 %); feldspars and sandstone fragments are found in minor amounts (up to 10 %); quartz grains, as a rule, are clean, transparent, have a rounded shape, with their surface is occasionally covered with brown drips and hydroxides.

The heavy fraction is represented by few grains of garnet, rutile, ilmenite. The new formations are represented primarily by organic inclusions, iron and manganese hydroxides, chlorite, clay minerals. While polished grains of jasper, chalcedony, opal, onyx, diatom shells, fulgurites are rare [*Galanin et al., 2017*].

By comparison with the underlying alluvium, the mineralogical signature of the dune sediments show dramatically decreasing amounts of biotite and muscovite. Probably the scaly grains of mica that accumulate abundantly in the alluvium tend to be readily blown off, once it is subjected to the wind processing and transformation into dune massifs. While minor contents of mica appear to be the most informative mineralogical signature of Quaternary dune deposits

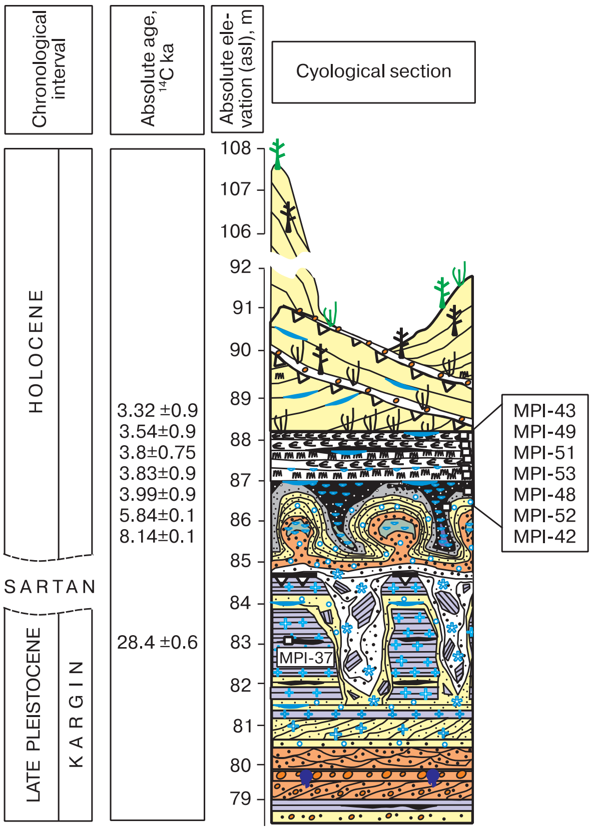

Fig. 4. Kysyl-Syr reference section of Late Quaternary eolian formations in the Vilyuy river basin; Cleared site 449 (63.9033° N, 123.2134° E).

For notations see Fig. 3.

in the region and can therefore be used as a genetic criterion for their diagnostics in the sections.

Sedimentary textures of dune facies are characterized by multilayered stratification [*Galanin et al., 2016*]. *Type one microstratification* (subparallel streamlining and undulating) is formed by alternating bleached quartz sands 2–3 cm in thickness (during summer-time) and thinner (1–2 mm) laminae of ochre loam sands with small amounts of dark dust (formed during winter). As such, the micro-stratification reflects the annual (seasonal) rhythm of eolian sedimentation, giving the sediments a specific striped appearance. *Type two micro-stratification* of dune sands is associated with diverse buried micro-deflation surfaces, composed by coarse bleached quartz sand, rarely by fine (2–3 mm) gravel. This stratification type (oriented either subhorizontally or gently sloping at angles of 3–5°) discordantly truncates the seasonal microstratification. Its origination is connected with continuous (cyclic) winnowing and moving elemental dunes in the direction of prevailing winds. *Type three*, the so-called cross-bedded stratification is similar to the previous type, but for larger inclination angles (15–20° or more). Reaching considerable sizes, this type stratification forms in the head parts of parabolic and spear-shaped dunes with enhanced thickness, as well as in the piled-up crest-shaped dunes tracing the edges of river cliffs.

Microtectonic deformations are widespread in dune sediments and tend to form during their natural gravity-driven compaction and cracking under dehydrated (arid) conditions. Most often these are microcracks with vertical and horizontal displacements with amplitude from a few centimeters to 1 m, as well as narrow vertical cracks up to 10–15 cm wide and 3–4 m long, filled with material from the overlying horizons [*Galanin et al., 2016*].

Ice content and cryogenic structure. The characteristic features indicative of the eolian origin are: low humidity/ice-content (<5 %) and high porosity and the absence of polygonal ice wedges [*Kamaletdinov and Minyuk, 1991; Shepelev, 2011*], bearing evidence of the landscape surface dehydration during sedimentation.

The dominance of sublimation cryostructures constitutes a characteristic feature revealing the syncryogenic freezing of dune sediments with very low moisture. As such, the cryostructures transpire as granular rime formed by water vapor condensation on the grain surface and in pores within the layer of zero amplitudes.

Among the sublimation cryostructures, most common are contact and thin schlieren and, less frequently, lumpy types [*Galanin et al., 2016*]. Thin-schlieren cryostructure is represented by thin horizontal layers and films of ice not more than 0.5 mm in thickness, separated by layers (1–5 cm) of dry (frost-desiccated) sand. During test pits excavation and shallow drilling in June 2012 and 2014 within the limits of the Kysyl-Syr tukulan, numerous schlieren of such sublimation ice were discovered by the authors at the base of the layer (depth from the surface: 2.5–3.0 m and below).

CONCLUSIONS

The results and findings of the study of the reference Kysyl-Syr section and other eolian formations of Central Yakutia [*Galanin et al., 2016; Pavlova et al., 2017*], allowed the authors to make an inference about the eolian (dune) origin of the gently-laminated and cross-bedded loam sands, composing the sedimentary cover (thickness: up to 20–25 m) on some terraces of Vilyuy river and its tributaries.

According to the characteristics of geomorphological conditions of the occurrence, the facies composition and age inferred from the numerous previous research into the Peschanaya Gora, Diring-Yuriakh and Ust-Botuoma sections in the middle reaches of the Lena river, these formations are identical to the sediments of the Late Pleistocene D'olkuminskaya series [*Kolpakov, 1983; Alekseev et al., 1984; Kamaletdinov and Siegert, 1989; Kamaletdinov and Minyuk, 1991; Waters et al., 1999; Spector et al., 2017*]. The key characteristics which attest to the eoloian (dune) origin of the D'olkuminskaya series include:

Lithological features: 1) loamy sand particle-size composition (average grain size is $x = 300 \pm 40$ μm), good sorting ($\sigma = 1.6 \pm 0.1$), the negative skewness ($\alpha = -0.22 \pm 0.08$), indicating minor content of silty fractions of narrow particle size range ($\tau = 1.03 \pm 0.2$); 2) lightweight mineralogical composition, low content of heavy fractions of mica, the presence of intra-soil formations (ortsteins, pedotubules, fulgurites), ventifacts; fragments of soil horizons, root organic matter, small pieces of coal, etc.; 3) light color (from white to yellowish-pale yellow and ochre tones), indicating good aeration and oxidative depositional conditions; 4) high porosity, the absence of layers of alluvial organics, driftwood.

Structural and textural features: 5) smoother and more persistent (locally, tens of meters) horizontal stratification, by comparison with alluvium; 6) the presence of multilayered stratification, due to the seasonal (winter and summer) micro-stratification of layers, microdeflation unconformity (alternation between periods of deflation and accumulation) and cross-bedded structures, sometimes dipping steeply (up to 40°) in the southeastern directions, opposite to the flow of modern watercourses; 7) the absence of fluvial cyclicity (interbedding of cross-stratified and horizontally-layered members), muddy floodplain facies, allochthonous organics and driftwood; 8) the presence of syngenetic vertical sand-filled cast wedges, microtectonic deformations.

Geomorphological features: 9) streamlining (blanket-like) occurrence and simultaneous formation at different hypsometric levels; 10) the presence in some sections of undulating surfaces of the buried relief, and those of the observed modern dune relief.

Permafrost-hydrogeological characteristics: 11) low ice content (<5 %) and the absence of polygonal ice wedges [*Kolpakov, 1983; Kamaletdinov and Minyuk, 1991; Shepelev, 2011; Galanin et al., 2016*], indicating extreme dehydration of the landscape surface during sedimentation; 12) the predominance of sublimation cryotextures, among which the most common are contact and thin-schlieren, less frequently, lumpy types [*Galanin et al., 2016*]; 13) anomalous thermal soil regime (soil temperatures: from –1 to 0 °C), deep thawing radius (3–4 m) coupled with high position of the base of layer of zero annual amplitudes (3–4 m); 14) widespread intensely waterlogged intrapermafrost taliks and subsurface watersources [*Shepelev, 2011*], widespread closed lake basins, poorly developed surface hydraulic network.

The authors thus believe that the numerous features discussed above attest to the dune (eolian) origin of the Late Quaternary sedimentary cover of Central Yakutia, composed of loamy sands, which was adduced by the compelling arguments of the previous researchers [*Kolpakov, 1983; et al.*].

The work was partially supported by the Integrated Program for Fundamental Scientific Research SB RAS II.1 and by the Russian Foundation for Basic Research (projects No. 17-05-00954, 18-45-140012).

References

Alekseev, M.N., 1961. Stratigraphy of continental Neogene and Quaternary sediments of the Vilyuy depression and Lower Lena valley. Izd-vo AN SSSR, Moscow, 120 pp. (in Russian)

Alekseev, M.N., Kamaletdinov, V.A., Grinenko, O.V., 1984. Cenozoic sediments of the Lena and Aldan rivers. In: Proceedings of the 27th Geological Congress. Yakut ASSR, Siberian Platform. Guidebook for excursions 052, 053, 054, 055. Nauka, Novosibirsk, pp. 21–42. (in Russian)

Astakhov, V.I., Svendsen, J.I., 2011. The Cover Formation of the Final Pleistocene in the Far Northeast of European Russia. Regionalnaya Geologia i Metallogenia, No. 47, 12–27.

Black, R.F., 1951. Eolian deposits of Alaska. Arctic 4 (2), 89–111.

Blott, S.J., Pye, K., 2001. Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surface Processes and Landforms, vol. 26, 1237–1248.

Bolshiyanov, D.Yu., Thiede, J., Savelieva, L.A., et al., 2016. To the study of the evolution stages of the Lena river valley. In: Proceedings of the All-Russian scientific conference "Geology and mineral resources of the North-East of Russia" (Yakutsk, April 6–8, 2016). SVFU Publishing House, Yakutsk, pp. 469–472. (in Russian)

Bronk, R.C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon, No. 51 (1), 337–360.

Ershov, E.D. (Ed.), 1989. Geocryology of the USSR. Central Siberia. Nauka, Moscow, 414 pp. (in Russian)

Folk, R.L., 1980. Petrology of sedimentary rocks. Texas, Hemphill Publ. Company Austin, 350 pp.

Galanin, A.A., Diachkovskii, A.P., Lytkin, V.M., et al., 2015. Results of absolute age dating of samples at the Radiocarbon Laboratory of Permafrost Institute SB RAS. Nauka i Obrazovanie, No. 4 (80), 45–49.

Galanin, A.A., Pavlova, M.R., Shaposhnikov, G.I., Lytkin, V.M., 2016. Tukulans: sand deserts of Yakutia. Priroda, No. 11, 44–55.

Galanin, A.A., Shishkov, V.A., Klimova, I.V., 2017. Fulgurites: the lightning marks in sandy dunes of Yakutia. Priroda, No. 5 (1221), 52–60.

Ivanov, A.D., 1966. Aeolian Sands of Western Transbaikalia and Prebaikalia. Buryat. kn. izd-vo, Ulan-Ude, 232 pp. (in Russian)

Kamaletdinov, V.A., Minyuk, P.S., 1991. The structure and characteristics of sediments of the Bestyakh terrace on the middle Lena river. Bulletin of the Commission of Quaternary Research, No. 60, 68–78.

Kamaletdinov, V.A., Siegert, K., 1989. Brief lithological characteristics of Cenozoic deposits of archeological site Diring-Yurakh (Middle Lena). In: The Pleistocene of Siberia. Nauka, Novosibirsk, pp. 126–131. (in Russian)

Kolpakov, V.V., 1983. Aeolian Quaternary deposits in the Lena area of Yakutia. Bulletin of the Commission of Quaternary Research, No. 52, 123–131.

Kovalyukh, N., Skripkin, V., 2007. Radiocarbon dating of archaeological ceramics by liquid scintillation method. In: Radiocarbon archaeological and paleoecological studies. IIMK RAN, St. Petersburg, pp. 120–126. (in Russian)

Kut, A.A., 2015. Aeolian-permafrost dune massifs (tukulans) in Central Yakutia: their structure, genesis, age and distribution patterns. Extended abstract of Cand. Sci. (geol.-mineral.) Dissertation. Yakutsk, 22 pp. (in Russian)

Pavlov, P.D., 1981. Geographical extent of aeolian sands in Central Yakutia. In: Aeolian Formations of Central Yakutia. IMZ SO AN SSSR, Yakutsk, pp. 18–30. (in Russian)

Pavlova, M.R., Rudaya, N.A., Galanin, A.A., Shaposhnikov, G.I., 2017. Structure and evolution of dune massifs in the Vilyuy River basin over the Late Quaternary period (by the example of Makhatta and Kysyl-Syr tukulans). Contemporary Problems of Ecology 24 (4), 411–422.

Pomortsev, O.A., Bolshiyanov, D.Yu., Popov, V.B., Pravkin, S.A., 2017. To the problem of Late Pleistocene marine transgressions and depositional environments in Central and Northern Yakutia. Vestnik SVFU, seriya "Nauki o Zemle", No. 4 (08), 5–13.

Shepelev, V.V., 2011. Suprapermafrost Waters in the Cryolithozone. Academic Publishing House "Geo", Novosibirsk, 169 pp. (in Russian)

Shvanov, V.N., 1969. Sand rocks and study methods. Nedra, Leningrad, 247 pp. (in Russian)

Siegert, K., Stauch, G., Lehmkuhl, F., Sergeenko, A.I., Diekmann, B., Popp, S., Beloliubskii, I.N., 2007. Evolution of glaciations of the Verkhoyansk Range and its foothills in the Pleistocene: the results of new research. Regionalnaia Geologiya i Metallogeniya, No. 30–31, 222–228.

Soloviev, P.A., 1959. Cryolithozone of the northern part of the interfluve between the Lena-Amga interfluve. Izd-vo AN SSSR, Moscow, 144 pp. (in Russian)

Spektor, V.V., Spektor, V.B., Boeskorov, G.G., et al., 2017. Periglacial alluvium of the Central-Yakutian plain according to the study of the bearing outcrop of Peschanaya Mt. Vestnik ZabGU, 23 (5), 45–59.

Ufimtsev, G.F., Janotta, A., Perevalov, A.V., et al., 1997. Aeolian landcapes of the Tunka valley. Geografia i Prirodnuye Resursy, No. 1, 65–70.

Velichko, A.A., Timireva, S.N., 2005. Western Siberia, the great late-glacial desert. Priroda, No. 5, 54–62.

Vyrkin, V.B., 2010. Aeolian formations in the Prebaikalia and Transbaikalia. Geografia i Prirodnuye Resursy, No. 3, 25–32.

Waters, M.R., Forman, S.L., Pierson, J.M., 1999. Quaternary geology and geochronology of Diring an early Paleolithic site in Central Siberia. Quatern. Res., No. 51, 195–211.

Wolfe, S., Bond, J., Lamothe, M., 2011. Dune stabilization in central and southern Yukon in relation to early Holocene environmental change, northwestern North America. Quatern. Sci. Rev., No. 30 (3–4), 324–334.

Received October 19, 2017