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LATE QUATERNARY DUNE FORMATIONS (D'OLKUMINSKAYA SERIES)  
IN CENTRAL YAKUTIA (Part 2)

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The study of generalized geologic section of the Kysyl-Syr dune massif (tukulan) in the lower Vilyuy river basin (Central Yakutia) on the basis of new  $^{14}\text{C}$  dates from 27 samples and biostratigraphic data allowed new insights about the Late Quaternary evolution of paleogeographic conditions of dune-forming processes in the region. Based on the previously published results of the studies of key-sections of dune sediments in different parts of Central Yakutia and new absolute age dates, the authors have concluded that the widespread in Central Yakutia dune sediments (D'olkuminskaya Series) formed at different hypsometric levels (river terraces, watersheds) over a time spanning from the latest Karginsky termochron (late MIS-3) till the beginning of the Holocene (between 35 and 10 ka BP) under conditions of severe aridization and desertification of the area. The dune stabilization by soil-vegetation cover occurred during the Boreal optimum of the Holocene (12–6 ka). The modern unvegetated dune massifs are interpreted to have formed not more than 1 thousand years ago, due to dramatic climatic changes associated with the Little Ice Age.

*Dunes, eolian formations, grain size analysis, mineralogy, absolute age, palynology, cryolithozone, D'olkuminskaya Series, Quaternary period*

## INTRODUCTION

The contemporary views on the origin and age of Quaternary sand-dune deposits widespread over Central Yakutia, have been disputed for more than half a century. The topmost layer of these deposits is often formed by eolian landforms within extensive areas and is represented by vegetated and unvegetated dunes differing in morphology (parabolic, spear-shaped, longitudinal, etc.) and oriented southeastward (Fig. 1). However, the origin of these deposits was interpreted as aquatic and(or) fluvial-glacial, while the dune relief was a product of low wind-windwinning activity [Soloviev, 1959; Alekseev, 1961; Ershov, 1989]. Besides, this approach eliminates the paleoclimatic significance of eolian formations as indicators of extreme-arid depositional environments.

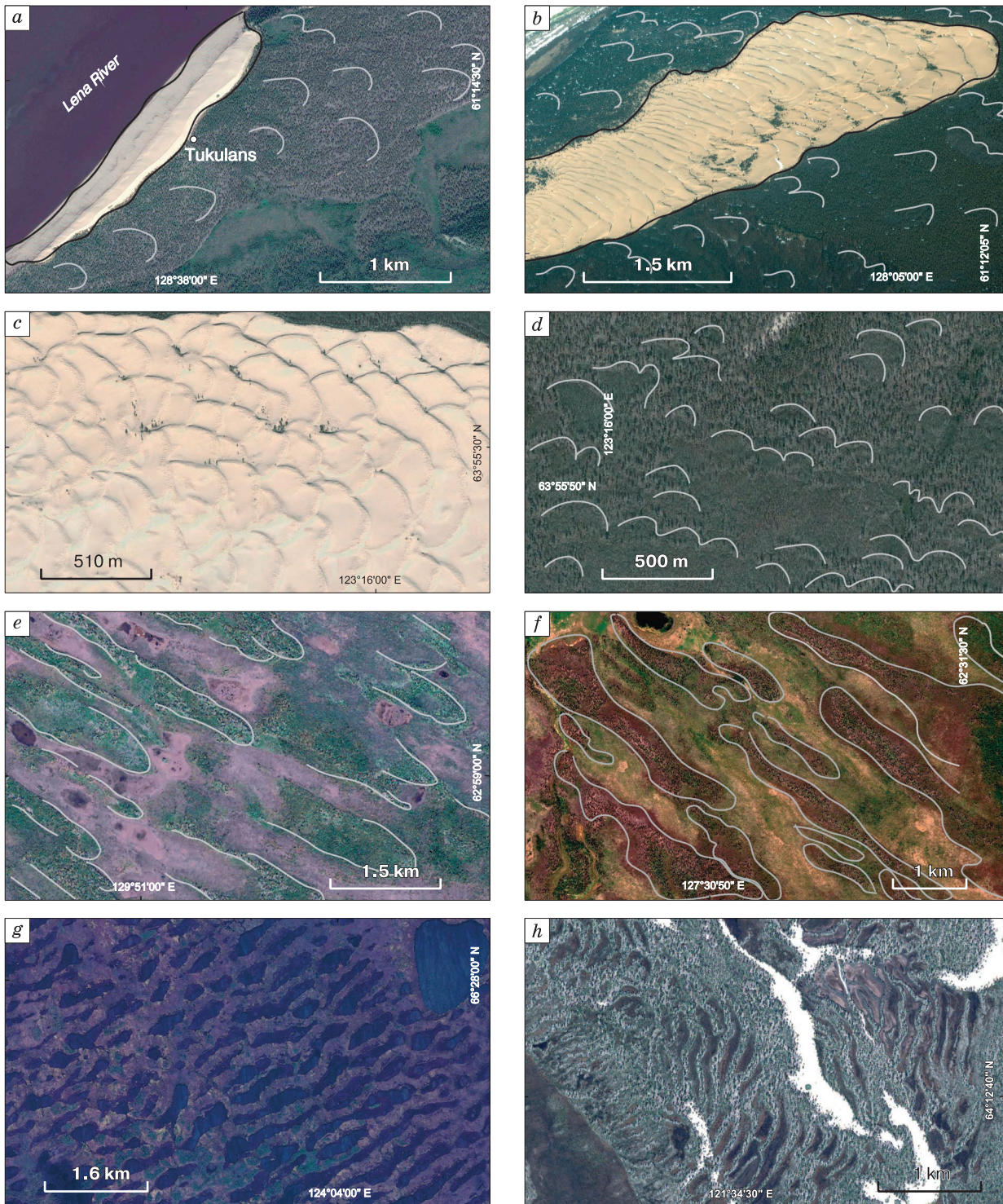
Actually, in the generally accepted theories emerged in the second half of the last century, the Quaternary history of Central Yakutia and entire Eastern Siberia was by all means associated with cold, but moderately humid (semi-humid) climates [Katasonov, 1979], which favored the development of large glaciation episodes throughout the cryochrons, along with full-flowing rivers and extensive ice-dammed basins in periglacial regions. Origination of the widely spread yedoma formation (ice-rich clay-loamy deposits with massive polygonal ice wedges) was associated with the fluvial processes [Katasonov, 1979; Ershov, 1989]. These hypotheses however almost totally ignored ventifacts, numerous deflation outliers and other eolian formations, which were

common in the region of dune massifs with extensive deflation basins and bearing evidence of extreme aridity and large-scale Quaternary desertification (Fig. 1). The key issues in the history of paleogeographic representations of the region have been repeatedly discussed [Galanin, 2016, 2017; Galanin and Pavlova, 2018].

For the lack of sufficient number of absolute dates, sands and loamy sands composing the sedimentary blanket of Central Yakutia, located at various hypsometric levels and almost identical in composition, structure and facies characteristics, have long been thought to belong to completely different genetic types. Their origin was thus assumed to be either alluvial-lacustrine (on river terraces of large rivers, such as the Lena, Vilyuy, Sinyayay, Tyung, Linde rivers, etc.), or “deluvial-proluvial and solifluction-driven” (on gentle slopes of interfluves), and eluvial (on watersheds) [Ganeshin, 1959; Kolosov, 1982; Ershov, 1989].

Dune deposits of Central Yakutia  
(D'olkuminskaya Series)

Researchers advocating an alternative hypothesis [Katasonova and Tolstov, 1963; Pavlov, 1981; Kolpakov, 1983; Kamaletdinov and Siegert, 1989; Kamaletdinov and Minyuk, 1991; Waters et al., 1999; Siegert et al., 2007] related sand-dune deposits blankets to the eolian formation, represented in Central Yakutia by variegated facies cluster of sandy (dune massifs),



**Fig. 1. Some types of eolian morphosculpture of Central Yakutia in satellite imagery.**

*a* – embryonic piled-up dune (Kysyl-Elysin tukulan) 140 m in height on the Bestyakh terrace surface (right-bank area of the Lena River in the vicinity of the Botuoma River mouth); *b* – unvegetated dune massif – Saamys-Kumaga tukulan (*ibid.*); *c, d* – unvegetated (*c*) and vegetated (*d*) by pine forest parabolic dunes of the Kysyl-Syr tukulan (lower reaches of the Vilyuy river); *e* – deflation-accumulation surface of the Bestyakh terrace with spear-shaped dunes and ellipsoidal deflation basins on the right bank of the Lena River, 100 km to the north of Yakutsk; *f* – vegetated deflation basins and troughs and longitudinal dunes at the Lena and Vilyuy rivers watershed; *g* – transverse dunes epigenetically inundated by groundwaters (right bank area of the Lena River); *h* – syngenetically inundated semi-vegetated dunes (Makhatta sand massif, Tyung river basin).

rocky (bedrock deflation outliers and ventifacts fields) and loess (loamy sand) deserts [Kolpakov, 1983; Pewe and Journaux, 1983].

As the absolute dates and data on the structure of new key sections progressively accumulated, it has become obvious that the blanket sand deposits with horizontal, rather than cross-bedded stratification, composing the upper parts of both the low-sitting and the highest terraces in the middle reaches of the Lena river, are coeval and syndeposited throughout the Sartan cryochron (MIS-2).

Proceeding from this, V.V. Kolpakov [1983] identified the D'olkuminskaya Series, whose reference stratotype section is located in the bluff of the 25-metre terraces of the Lena river (Peschanaya Gora outcrop), 100 km north of Yakutsk (Fig. 2). Later, both the eolian origin of sediments of Peschanaya Gora and age of the D'olkuminskaya Series were acknowledged by other researchers [Kamaletdinov and Siegert, 1989; Kamaletdinov and Minyuk, 1991; Waters et al., 1999; Siegert et al., 2007].

However, it was only in 2009 that the presence of dune deposits of the D'olkuminskaya Series within the chronological boundaries of MIS-2 was validated by a new edition of regional stratigraphic scheme [Volkova et al., 2010], and a new map of Quaternary deposits published in 2014 [Map of Quaternary..., 2014], which have accentuated many drastic changes that have taken place in Central Yakutia. Thus, dune deposits were first mapped (to replace alluvial-lacustrine deposits) on the Bestyakh, Tabaga and Tyung terraces and in other related areas, whereas their coeval ice-loess sediments (yedoma formation) were assigned to the eolian formations [Volkova et al., 2010; Map of Quaternary..., 2014].

Despite the publication of the updated map, many researchers, while agreeing with the absolute dating and chronological range (MIS-2) of the

D'olkuminskaya Series, disacknowledge its eolian origin. Incidentally, the attempts have been made by some researchers to explain the syndeposition of sands with cross-bedded structure at different hypsometric levels as a result of river floods [Bolshiyarov et al., 2016] or catastrophic floods due to the breakthrough of ice-dammed lakes at the turn of the Late Neopleistocene and Holocene [Spektor et al., 2017]. While others associate its formation with the marine transgression in the late Pleistocene [Pomortsev et al., 2017]. Unfortunately, most of these works do not provide any new factual material that would throw light on the facies composition, origin and age of sand-dune deposits.

Therefore, dunes and other eolian formations of Central Yakutia has thus far remained the least studied genetic types of Quaternary deposits in the region. Likewise, their facies composition, main features, age and areas of distribution are largely underexplored. Even more vague are the characteristics of climatic, hydrological and geocryological conditions, as well as paleolandscapes, which could produce (in the immediate vicinity and coincidentally) combinations of extremely arid conditions of accumulation of dry-frozen ("frost-affected") dune sands and extremely ice-poor and excessively water-saturated sediments with massive polygonal ice wedges.

### The Kysyl-Syr outcrop

The Kysyl-Syr sand-dune massif represents thus far best studied and informative key sections of the Late Quaternary dune deposits in Central Yakutia (Fig. 1, c, d), as well as the eponymous outcrop discovered by the authors in 2012 on the right bank of the Vilyuy river 20 km below the village of Kysyl-Syr, where a section of sandy sediments dated from 50 ka BP to the late Holocene is exposed in the river bluff (height 35 m; length >3 km), which comprises alluvial and dune facies, buried soil horizons, peat layers, etc.



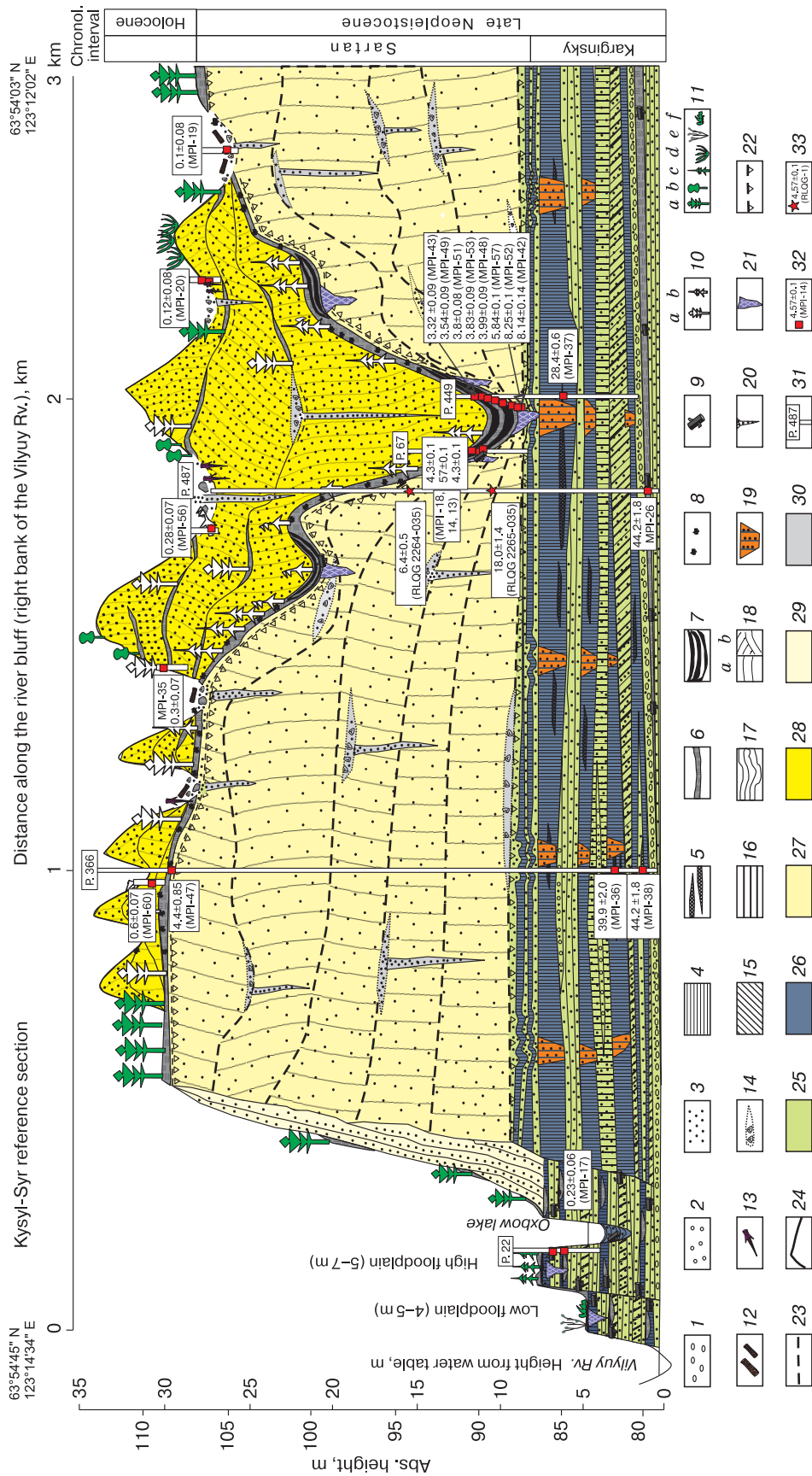
**Fig. 2.** Peschanaya Gora reference outcrop (D'olkuminskaya Series) in the bluff of the 25-m terrace on the right bank of the Lena river (100 km from Yakutsk).

The outcrop shows units of dune sands as steeply sloping cross-beds representing head facies of spear-shaped dunes (see Fig. 1, e). Photograph by A.A. Galanin.



**Fig. 3.** Kysyl-Syr outcrop (D'olkuminskaya Series) in the bluff of the 35-m terrace on the right bank of the Vilyuy river (20 km from Kysyl-Syr village).

Locations and numbering of key sites in the composite section are given in Fig. 4. Photograph by A.A. Galanin.



**Fig. 4. Composite section of the Kysyl-Syr reference outcrop.**

Lithology: 1 – pebble; 2 – fine gravel; 3 – medium-grain sand; 4 – fine loamy sand; 5 – alluvial plant detritus; 6 – soils; 7 – peat lenses; 8 – char coal; 9 – wood fragments; 10 – vertically buried pine-trees with the root systems (a) and larch-trees (b); 11 – woody vegetation cover formed by pines (a), birch (b), spruce (c), dwarf Siberian pine (d), willow stands (e), low heath shrub (f); 12 – accumulations of ortsteins and pedotubules; 13 – fulgurites; 14 – small-sized ventifacts. Sediments structure: 15 – cross-stratified; 16 – horizontally-stratified; 17 – plicated (cryoturbated); 18 – gentle (a) and steep (b) cross-stratified. Vein-shaped sedimentary formations: 19 – sand wedge polygons in alluvial deposits; 20 – sand-filled veins (wedge casts) in detached cracks in sand-dune deposits; 21 – frozen veins of water infiltration in the humus. Facies boundaries: 22 – major deflation unconformities; 23 – minor deflation unconformities; 24 – exposed relief of modern sand-dunes. Sedimentary facies: 25 – river channel; 26 – floodplain-oxbow; 27 – dunes of Sar-tan cryochron; 28 – Late Holocene dunes; 29 – deluvial-talus slope of terrace; 30 – deflation basin facies. Other notations: 31 – Key (cleared) sites and their numbering; 32 – uncalibrated radiocarbon dates and their lab codes; 33 – IR–OSL dates and lab codes.

During the 2012–2016 field studies, the authors obtained a significant amount of new evidence, including the results of geomorphological observations and descriptions comprising the full thickness of Key sites 366, 449, 487 and a series of shallow pits, which served as a basis for building a composite section (Figs. 3, 4). Particle size composition of sediments was studied from 117 samples from different segments of the surface of the modern dune massif: from the Vilyuy river channel (80 specimens), and from Key site 366 (37 specimens) [Galanin and Pavlova, 2018, Fig. 3]. A quantitative mineralogical analysis of 38 samples (assumably from dune and alluvial facies) was performed for modern and Late Pleistocene sediments [Galanin and Pavlova, 2018].

The data on the permafrost-geological conditions of the Kysyl-Syr massif were obtained from the two year-long geothermal monitoring in three wells, as well as from the results of GPR (ground penetration radar) and ERT (electrical resistivity tomography) surveys [Galanin et al., 2018]. The information on sediment age and depositional history was inferred from 27 absolute dates and palynological characterization of the section of Key site 449 which includes a peat layer (about 2 m in thickness) buried in the dunes.

Given the significant amount of the actual material, the methods used by the authors, which includes geomorphological characteristics of the Kysyl-Syr tukulan, description of its internal structure, particle size and mineralogical composition, permafrost properties are discussed in Part one [Galanin and Pavlova, 2018].

This paper presents data on the absolute age of the Kysyl-Syr reference outcrop, including 27 dates (Table 1), as well as its composite section (Fig. 4) and the spore-pollen characteristics derived from Key site 449 [Galanin and Pavlova, 2018, Fig. 4]. The other part is devoted to the discussion of the age and evolution history of Late Quaternary dune deposits (D'olkuminskaya Series) in Central Yakutia, with account of all available evidence.

#### **Facies composition of the Kysyl-Syr outcrop**

The Kysyl-Syr key section (63°54' N; 123°16' E) is located 20 km below the eponymous village and represents a natural outcrop (length: more than 3 km, height: up to 35 m) on the right bank of the Vilyuy river (Fig. 3). Its lithology and sedimentary facies at Key sites 366 and 449 are described in [Galanin and Pavlova, 2018]. The section structure inferred from the results of the study of all key (cleared) sites and a series of shallow pits is presented below.

*The alluvial member* (thickness: 10–12 m) occurring at the base of the section in the range of absolute heights of 76–88 m is essentially persistent and represented by interbedded packages (members) of unfro-

zen cross-stratified yellowish and slightly ochre sands and sand-loams with dark grey and grey horizontal-layered silty sand loams with inclusions of interlayers and lenses of fine gravel, plant detritus and drift wood. A gravel-pebble horizon abounding with pieces of wood and rare large boulders are exposed at the base of the alluvial pack in the low-water period. The alluvial member is crowned by essentially persistent package of frozen bluish (gleyed) thin-layered silty sand loam with interlayers of clay-loams and alluvial plant detritus. The top of alluvial deposits is distinctly persistent throughout the section and is disturbed by systematic wide wedge casts filled with coarse ochre-colored quartz sand.

Maximum thickness of *dune deposits* occurring in the 88–115 m interval of absolute heights is up to 22–24 m. These are represented by members of horizontally-undulating layered, rarely cross-bedded, medium and fine-grained quartz sands separated by deflation surfaces with thin beds of coarse quartz sand and sporadic inclusions of fine gravel (grain size: 3–4 mm). In the lower part, dune sediments are frozen and have a massive cryostructure.

Dune sediments are represented by two members partitioned by a well-developed soil horizon, clearly traceable throughout the outcrop. The horizon marks the buried paleorelief surface and serves as the top to the lower member of dune deposits. This marker soil horizon is buried only within unvegetated parts of the Kysyl-Syr dune massive, while beyond its bounds it shows up on the surface, merging with the soil-vegetation cover of the 30–35-m-high terrace of the Vilyuy river.

The top of the uppermost dune sediment forms the modern relief of parabolic dunes of the Kysyl-Syr tukulans. The upper and lower packages of dune sands are very similar in particle size composition, mineralogy and structure, but are strongly differentiated by the nature of plant residues, whose presence in the lower member range from negligible to non-existent, with filamentous roots of herbaceous plants encountered only occasionally; while the upper member abounds with underdeveloped soil horizons up to 3–4 cm thick, where fragments of shrubs and even whole bodies of vertically buried trees (sometimes with the root system) are encountered.

#### **Absolute dates and biostratigraphy of the Kysyl-Syr outcrop**

*Underlying alluvial deposits.* The data on the spore-pollen composition of the alluvial member was obtained from Cleared site 449, whose detailed section and description are provided in [Galanin and Pavlova, 2018, Fig. 4]. The pollen column described in full and supplemented with a diagram were also earlier published by the authors [Pavlova et al., 2017]. Results of the pollen analysis of alluvium revealed the predominance of conifers, which are dominated by

Table 1. Absolute dates within the Kysyl-Syr reference outcrop of dune deposits in the lower reaches of the Vilyuy River basin

No.	Lab label	Coordinates, degr. N; E	Depth, m	Sampled material	Age	
					$^{14}\text{C}$ , yrs	Cal. yrs. ( $\alpha > 95.4\%$ )
<i>Freestanding stumps and dead trees in modern deflation basins</i>						
1	MPI-15	63.9262; 123.2677	0.55–0.85	Dead trees buried vertically in modern unvegetated (unfixed) dunes	Modern	
2	MPI-19	63.9105; 123.2278	2.9		100 ± 80	290–0
3	MPI-20	63.9104; 123.2277	1.0		120 ± 85	295–0
4	MPI-35	63.9161; 123.2337	0.8		325 ± 65	510–155
<i>Key site 20 in the bluff of modern high floodplain (5–7 m) overgrown by spruce forest</i>						
5	MPI-16	63.9276; 123.2372	0.75	Shrub fragments (driftwood)	Modern	
6	MPI-17		2.5–3.0	Larchwood (driftwood)	230 ± 60	470–0
<i>Key site 487</i>						
7	MPI-56	63.9243; 123.2374	0–0.3	Vertically buried dead tree	280 ± 65	500–265
8	RLQG 2264-035		2.0	Quartz sand, IR–OSL	–	6400 ± 500
9	RLQG 2265-035		23	Quartz sand, IR–OSL	–	18 000 ± 1400
10	MPI-26		32	Shrubby-grassy peat	44 200 ± 1800	>45 200
<i>Key site 366</i>						
11	MPI-60	63.9269; 123.2380	1.4–1.6	Vertically buried dead tree	600 ± 75	675–510
12	MPI-47	63.9194; 123.2677	1.0	Carbonized wood and coal in the buried soil horizon	4400 ± 85	5290–4840
13	MPI-29	63.9186; 123.2340	32	Small fragments of wood	35 600 ± 1500	43 200–36 800
14	MPI-36	63.9162; 123.2331	30	Dispersed detritus	39 900 ± 2000	49 000–41 000
15	MPI-38		33		44 200 ± 1800	>45 200
<i>Key site 449</i>						
16	MPI-43	63.9029; 123.2113	0.1–0.2	Moss-sedge peat	3320 ± 90	3825–3370
17	MPI-49		0.5–0.6	Sedge peat	3540 ± 95	4090–3590
18	MPI-51		0.8–0.9	Moss peat	3800 ± 75	4415–3980
19	MPI-53		1.0–1.1	Sedge-moss peat	3830 ± 90	4515–3975
20	MPI-48		1.2–1.3	Shrubby peat with leaves of <i>Elaeagnus</i> growing on bogs	3990 ± 90	4815–4155
22	MPI-52		1.3–1.4	Shrubby peat with wood fragments	5840 ± 100	6890–6410
23	MPI-57		1.6–1.7	Peat admixed with humus	8250 ± 100	9470–9010
24	MPI-42		1.7–1.8	Humus from strongly humous sand-loam	8140 ± 135	9440–8640
25	MPI-37		7.0	Dispersed detritus	28 400 ± 600	33 800–31 200
<i>Key site 67</i>						
26	MPI-13	63.9042; 123.2159	1.0	Carbonized larchwood	4300 ± 90	5280–4580
27	MPI-14	63.9243; 123.2374	0.95	Weakly decomposed moss-sedge peat	4570 ± 110	5580–4880
28	MPI-18	63.9186; 123.2348	0.7–1.0	Twigs of dwarf birch	4120 ± 110	4880–4200

*Picea* (73.9–94.5 %) and *Pinus sylvestris* (1.3–6.6 %). Shrubs and low shrubs (1–2 %) are represented by the genera *Betula*, *Ericales*, *Alnaster*. The herbaceous group (0.6–17.8 %) is dominated by *Artemisia*, Chenopodiaceae and Poaceae, while Rununculaceae, Chenopodiaceae, Poaceae etc. are rare species. Spores are dominantly represented by *Botryococcus* (3.8–8.9 %). The concentrations of pollen and spores appear negligible in the lower parts of the palynozone (crossbedded sands of the river channel facies), which are statistically differentiated for trees (91.3–357.8 grains/g), herbs (2.3–19.8 grains/g), spores (8.5–18.7 grains/g); while in the upper part (floodplain facies) pollen productivity has increased (2794.2 grains/g).

The plant species identified in the lower part of the alluvial member in the vicinity of Key site 366 are: spruce, larch, dwarf birch (*Picea* sp., *Larix* sp., *Betula exilis*). This locality is noted for the find of a bison rib (*Bison* sp.). Based on a series of radiocarbon date determinations on wood and plant detritus at Key sites 366, 449 and 487 (Fig. 4; Table 1), the age of the formation of deposits is interpreted to be in the range of 45–30 ka BP (end of the Karginsky Thermochron, MIS-3).

The dates yielded by optically stimulated luminescence (OSL) for the *lower member* of dune-sands (Fig. 4; Table 1) near the base ( $18.0 \pm 1.4$  ka BP) and top ( $6.4 \pm 0.5$  ka BP) from Key site 487 are referred to the Sartan cryochron (MIS-2). The data are also confirmed by almost totally missing pollen in the sediments and very few remains of vegetation, represented by layers of filamentous roots of herbs only in the upper part of the member.

The *marker soil horizon* separating the upper and lower dune sand packages, based on a series of radiocarbon dating (Table 1; Fig. 1) has been assigned to the boreal optimum of the Holocene. This soil was dated in the greatest detail in the area of the occurrence of a peat lens (Key site 449), which formed within the interval spanning from 9 to 3.5 ka (calib.) BP [Galanin and Pavlova, 2018, Fig. 4]. The peat layer is distinctly differentiated by the finds of plant residues: abundantly encountered partially carbonized fragments of larch and dwarf birch (lowerpart), remains of mosses and sedges (middle part), prolific Ericaceae twigs, including *Myrica gale* (upper part).

Beyond the peatland bounds, pieces of coals and carbonized wood fragments were revealed in the same soil horizon (Key site 366), as well as on the surface of some deflation basins in interior parts of the tukulans. This may be the evidence of a major fire that preceded the formation of the upper (modern) member of dune sediments. Absolute dating 5.29–4.84 ka (calib.) BP (MPI-47) of coals in the upper part of Key site 366 (Fig. 4; Table 1) indicates that the event probably occurred at the end of the boreal optimum.

The two palynozones established in the pollen columns within the *peatland* (Key site 449) [Pavlova et al., 2017] are the lower and upper zones. The lower zone (birch-tree stand) dated at the 9.9–6.7 ka (calib.) BP is dominated by woody species (83.9 %) with predominance of *Betula* sp. (24.2–68.2 %), locally admixed with *Picea*, *Pinus*. Shrubs and low shrubs (1–2 %) are represented by the taxa *Salix* sp., *Ericales* sp., *Alnaster* sp. and *Selaginella rupestris*. Herbaceous pollen (16.1–48.7 %) is dominated by Cyperaceae, Poaceae and *Artemisia*; spores (0.9–10.6 %) are represented by *Botryococcus*. By comparison with the underlying sediments, the concentration of pollen and spores in this palynozone has shown an increase described as 6–9-fold (trees) 40-fold (herbs) and 12-fold (spores).

The upper palynozone (pine-tree stand), dated within the interval 6.7–3.3 ka (calib.) BP is characterized by the dominance of tree taxa (98 %), overwhelmingly represented by *Pinus sylvestris* (43.0–63.6 %). It is distinguished by the appearance of pollen *Pinus* s/g *Haploxyton* (2.0–13.0 %), probably represented by dwarf Siberian pine (*Pinus pumila*), whose prolific groups are established in the composition of modern vegetation in the southern part of the Kysyl-Syr tukulan. The zone is characterized by a sharp decrease in the concentrations of pollen of shrubs (2–3 %) and herbaceous (2.3–9.2 %) layers, as well as by disappearance of mosses.

The marker soil horizon, which includes the investigated lens of the peat, has regional distribution, and is often exposed to a depth of 1–10 m below the surface of modern dunes, coming out onto the surface beyond the Kysyl-Syr tukulans, to merge with the soil-vegetation cover of 30–35-meter-high terrace of the Vilyuy river. In the studied section, the landscape-climatic processes of soil formation at regional scale and vegetation of tukulans of Central Yakutia are thus distinctly recorded in the Holocene climatic optimum, which can be used as a climatostratigraphic reference marker.

The *topmost (modern) package of dune fine-sands* of the Kysyl-Syr tukulan contains a lot of vertically buried trees, layers of poorly developed soils and coals. Several dates (Fig. 4; Table 1) obtained for stumps and wood fragments from the deflation basins indicate that modern unvegetated dunes were formed not earlier than 500–600 years and during the last Holocene cooling (Little Ice Age).

#### The age of loamy sand blanket deposits of Central Yakutia

For a long time, the views on the Late Quaternary sand blanket deposits in Central Yakutia were based on few reference sections (Peschanaya Gora, Ust-Botuma and Diring-Yuryakh) in the middle reaches of the Lena river [Alekshev et al., 1984; Kamaletdinov and Siegert, 1989; Kamaletdinov and Minyuk, 1991;

*Waters et al., 1999*]. The exposed in the river bluff crossbeds of well-sorted sands with unusually low moisture content are attributed to the Late Pleistocene D'olkuminskaya Series (MIS-2) [*Kolpakov, 1983*].

Despite the exhaustive paleontological and palynological studies its chronological volume remained highly disputable. Initially, loamy-sand crossbeds, composing the section of the 20–25-meter (Kerdem) terrace outcrop (Peschanaya Gora), were attributed to the second half of the Neopleistocene. Then *V.V. Kolpakov [1983]* assigned them to the Middle Pleistocene Samara glaciation. The first radiocarbon dating ( $17.2 \pm 0.5$  ka BP, IM 760) of buried soils in the Peschanaya Gora exposure unambiguously referred to the Sartan time (MIS-2) [*Alekseev et al., 1984; Kamaletdinov and Minyuk, 1991*].

Later, within eolian deposits of the D'olkuminskaya Series were included sand blanket deposits covering the Bestyakh and Tyungyul terraces on the right bank of the Lena river. Their facial composition and absolute age were found to be identical to the Peschanaya Gora outcrop [*Kamaletdinov and Siegert, 1989; Waters et al., 1999*]. Recent  $^{14}\text{C}$ - and OSL-dates have proved the same age of deposits in the areas of the D'olkuminskaya Series distribution in the vicinity of Nizhny Bestyakh village, as well as in outcrops of thermo-suffosional cirques Ulahan-Taryn, etc. [*Bolshiyarov et al., 2016*].

In this paper, the authors show that the diverse sand blanket deposits in the basin of the lower reaches of the Vilyuy river have eolian (dune) origin and formed under of severe climatic conditions experiencing extreme aridization in the second half of the Late Neopleistocene. Their cryofacies and stratigraphic characteristics correlate well with dune sands in the identical Peschanaya Gora outcrop and should be considered as part of the D'olkuminskaya Series.

#### **Alternative hypotheses on the origin of loamy sand blanket deposits in Central Yakutia**

The origin of the D'olkuminskaya Series has been under discussions for more than half a century. Advocates of the eolian origin believe that its formation is associated with cold cryoarid conditions and the region's large-scale desertification in the second half of the Neopleistocene [*Kolpakov, 1983; Alekseev et al., 1984; Kamaletdinov and Siegert, 1989; Kamaletdinov and Minyuk, 1991; Waters et al., 1999; Galanin et al., 2016*].

Alternatively, the other group of researchers suggests that the loamy-sand cross-beds of the D'olkuminskaya Series were deposited from water flows and(or) within the ice-dammed basin, which formed as a result of the Lena river runoff dammed by Verkhoyansk glaciers [*Soloviev, 1959; Alekseev, 1961; Ershov, 1989; Bolshiyarov et al., 2016; Spektor et al., 2017*]. The attempts have been made to link the ori-

gin of sands with marine transgressions [*Pomortsev et al., 2017*].

The aquatic hypotheses generally provide reconstructions of more humid (semihumid) climates [*Ershov, 1989*] during the cryochrons with conditions favorable for the Verkhoyansk glaciers to feed high-water rivers transporting affluent sandy material, with the fluvial processes extending to all hypsometric levels.

The evidences of aquatic origin of the D'olkuminskaya Series include [*Bolshiyarov et al., 2016; Spektor et al., 2017*]: the presence of loamy sand facies with a specific fluvial microstructures; the mollusk fauna finds in peat and lacustrine clay lenses containing remains of bog vegetation, etc.

The monotonous structure, absence of loamy material and cross-stratification of deposits of the D'olkuminskaya Series and unconformably (south-eastward) dipping beds in relation to the modern flow of the Lena river are explained by the supporters of the fluvial concepts by the unique, having no modern analogues hydrological regimes of late Pleistocene rivers and water bodies.

In a recent publication another attempt has been made to associate the origins D'olkuminskaya Series and southeastward oriented dune relief of high terraces of the Lena river and Lena plateau with catastrophic breakthroughs (spillways) of the hypothetical ice-dammed glacial lake existing in the late Pleistocene [*Spektor et al., 2016, 2017*]. In keeping with the M.G. Grosvald's "hydrosphere disasters (mega-flood)" theory [*1999*] and its terminology, the authors interpret facies structure and relief orientation of the D'olkuminskaya Series as signs of either deluvial ("diluvium" means "flood") morphogenesis or "mega-flood" (catastrophic floods).

The authors believe these processes to have developed in Central Yakutia during the Sartan cryochron in the 20–11 ka BP interval, which led to the formation of a specific relief, called the *Siberian scabland* (channeled scabland). Its characteristic elements are signs of giant ripples, "...morphosculptures of flow (teardrop-shaped hills), drainage basins and traces of cavitation, etc." [*Spektor et al., 2016, p. 298*].

The finds of fragments of boulder-pebble glacial moraines on the left bank of the Lena river between the Aldan and Zhigan river mouths indicate that the Verkhoyansk glaciers reached the Lena river valley throughout the Quaternary and, hypothetically, could have dammed its flow. However, a series of 50 absolute OSL and AMS-dates obtained in 2007 by *K. Siegert and colleagues [2007]* in the Dyanyshko and Tumara rivers valleys, the Lena's right tributaries, showed a significantly older age of the glaciations in comparison with the D'olkuminskaya Series deposits. It has been established that the most ancient (external) moraines, which have reached the modern

Lena position, formed as late as 140 ka BP (Samara glaciation, MIS-6), followed by a well-defined moraine belt formed about 90–100 ka BP (MIS-5e), while glaciers did not extend beyond the Verkhoyansk ridge over the period spanning past 60 ka (MIS-3–2) [Siegert et al., 2007]. Thus, the age of the D'olkuminskaya Series deposits (MIS-2) does not correspond to a time (MIS-6), when the Lena river was probably dammed by glaciers.

In addition to the aforementioned chronological inconsistencies between the D'olkuminskaya Series and glacial events in Central Yakutia, the hypothesis of “catastrophic megaflood” has many other contradictions, whose discussion is beyond the scope of this paper.

At this, during the study of sections of terminal-moraine complexes in the valleys of the Verkhoyansk tributaries of the Lena river K. Siegert et al. [2007] revealed widely distributed of fine sands and loamy sands of the last cryochron (MIS-2), covering the Middle and Late Pleistocene moraine topped by the 5–15 m thick sediment blanket. In their composition and chronological volume, they similar to the formations of the D'olkuminskaya Series in the Peschanaya Gora reference outcrop [Kamaletdinov and Siegert, 1989; Kamaletdinov and Minyuk, 1991].

The currently available representative number of well-dated reference sections of the Lena river basin and its major tributaries, not only confirm the chronological scope of the D'olkuminskaya Series, but also point to its wide regional distribution (Fig. 1). Generally, this is in good agreement with the assumptions made by V.V. Kolpakov [1983] about the extremely underestimated volumes and areas of distribution of Quaternary eolian and, in particular, sand-dune deposits in Yakutia and Eastern Siberia.

Based on the results of the study of the reference Kysyl-Syr section and other eolian formations of Central Yakutia [Galanin, 2016; Galanin et al., 2016, 2017; Pavlova et al., 2017; Galanin and Pavlova, 2018], the authors have made an inference about the eolian (dune) origin of blanket cross-bedded loamy sands deposits covering the terraces (of different-height) of the Vilyuy river and its tributaries. According to the geomorphological conditions of deposition, facies composition and age of these formations are identical to the D'olkuminskaya Series sediments (Late Pleistocene), which were characterized by the predecessors from the reference sections – Peschanaya Gora, Diring-Yuriakh and Ust-Batuoma – in the middle reaches of the Lena river [Kolpakov, 1983; Alekseev et al., 1984; Kamaletdinov and Siegert, 1989; Kamaletdinov and Minyuk, 1991; Waters et al., 1999].

### History of the formation of dune deposits in Central Yakutia

Proceeding from a fairly large number of dates accumulated by now, the history of the formation of

the D'olkuminskaya Series, by the authors' opinion, should include modern unvegetated dune massifs (tukulans). These provide fairly unambiguous reconstructions [Waters et al., 1999; Siegert et al., 2007; Galanin et al., 2015, 2016; Bolshiyakov et al., 2016; Pavlova et al., 2017] and stratigraphic descriptions of the D'olkuminskaya Series (Fig. 1). Besides, these formations were first shown on the new State Map of Quaternary deposits [Map of Quaternary..., 2014].

The authors admit that both dune-formation and desertification of Central Yakutia could be manifested in the earlier cryochrons rather than the Sartan time (MIS-2) alone, since the climate during the Quaternary time there was always ultracontinental, and throughout the cryochrons its continentality only intensified. The intense and long-lasting exposure to arid conditions of morphogenesis and sedimentation are evidenced by deflation-driven truncation of river terraces, and by deflation plains, ventifacts fields and Middle Pleistocene facet stones, diverse manifestations of eolian gold placers etc. after V.V. Kolpakov [1983]. The widespread Middle Pleistocene eolian deposits in the structure of high terraces the Lena river and Lena plateau were noted by many researchers [Kolpakov, 1983; Pewe and Journaux, 1983; Waters et al., 1999]. Moreover, all of the regional pollen spectra of Quaternary deposits abound in xerophytic taxa, while fossil biomes (including mammoth) are represented by species whose contemporaries are currently encountered only in steppes and deserts of cold climate.

The paleogeographic data in their entirety indicate that both the area of Central Yakutia and whole northern hemisphere were subjected to ultimate cooling and aridization events specifically during the last cryochron (MIS-2), which reduced drastically the diversity and number of mammoth biomes there, as compared to the Kargin time (MIS-3).

As a matter of fact, paleontological finds of mammoth fauna younger than 25 ka in Central Yakutia are extremely rare, while in the more northern areas they are more regular and numerous. The widely spread Late Pleistocene eolian relief is easily identified on satellite images of Central Yakutia, with its area occupying up to half of the entire territory, which is indicative of the catastrophically degrading soil and vegetation cover and, accordingly, pastures.

The authors believe that due to a decrease in cyclonic activity and the aggradation of the cryolithozone against the backdrop of the progressively developing climate cooling and aridization, a significant part of atmospheric precipitations was withdrawn from the runoff system, with the moisture accumulating in the form of ice shclieren, ice wedges and tabular ice. While their other part was subjected either to evaporation, and direct sublimation during winter season. The climate aridization and reduction

of fixing function of the vegetation firstly favored the formation of embryonic dune massifs on the edges of river terraces. In some cases, their formation might be contributed by wild fires.

Dune massifs oriented in the direction of the prevailing winds migrated southeastwardly and merged to form larger sand-dune deposit blankets crossing various topography elements (valleys' thalwegs, lake basins, etc.). The low position of the groundwater table in dunes basically precluded their fixation by vegetation.

Given that throughout the Sartan cryochron, the river flow in the region has dramatically reduced, and many minor streams even during high-water periods (spring floods) could not cope with the arriving eolian sediments, their valleys were divided into isolated drainage basins, producing thereby lacustrine-boggy facies. The runoff system of major rivers (Lena, Vilyuy, Aldan) and their main tributaries has also reduced significantly, which probably led to the obstruction of valley thalwegs by eolian sediments, to shallowing of watercourses and intensified their meandering.

The data obtained by the authors on the structure and age of the first terrace of the Suola river (Lena's right tributary, in 30 km from Yakutsk), whose valley is located within the Bestyakh terrace surrounded by dune massifs of the D'olkuminskaya Series [Galanin and Pavlova, 2018, Fig. 1], have thus shown that during the Late Neopleistocene-Holocene transition (12–10 ka BP) the riverbed was 6–8 m above the present position and was intensely meandering [Potapova et al., 2016]. There, in the exposure of a 10.5-meter terrace, the authors investigated the Megin location of mammoth fauna [Ibid.]. A lens of frozen peat abounding with mammoth fauna fragments remains was established within the 0–3 m interval above the modern water table of the river.

The species identified herewith are: *Bison prisus*, *Ovibos moschatus*, *Equus lenensis* and the archaic mammoth form (*Megin Mammoth*), dated 23.86–22.65 ka (calib.) BP (MPI-80), which approximates thermal minimum of the Sartan cryochron. Results of the paleoecological reconstruction of 60 fauna and 25 plant taxa identified in the peatland revealed that during its formation the mean July temperatures were not lower than +12 °C.

The vegetation cover was formed by a mosaic pattern of the combination of impoverished steppes, meadows, patches of larch forests and extensive areas unfixed by soil and vegetation cover [Potapova et al., 2016]. The remains of aquatic vegetation coupled with xerophytes suggest significant seasonal fluctuations in the level of water bodies and dominating evaporative environments. Up the section, within the 3–7 m interval from the modern water table of the river, the peatland is covered with crossbedded sands

of channel facies very rich in ice-cement (25–30 %) and massive cryostructure. These are dated as Early Holocene in the range of 12.4–11.2 ka (calib.) BP (MPI-109, MPI-104, MPI-105).

Higher up the section (the 7–9 m interval from the water table), the alluvial member is crowned with the floodplain sediments represented by thin-layered fine sand-loams with lenses of alluvial organic matter and peat, and dated as the beginning of the boreal optimum 9.95–8.74 ka (calib.) BP (MPI-103, MPI-108). Above it, in the 9.0–10.5 m interval from the modern water table of the Suola river, the section is crowned with a layer of light, locally ochre-colored loamy sands of late Holocene age (thickness: 1.0–1.5 m), including thin soil horizons and which overlap as sediment blanket all the terraces in the Suola river valley.

Thus, results of the study of the Suola river valley and the absence of typical channel facies of the Sartan age indicate a significant decrease in alluvial activity in Central Yakutia at this time. Whereas, the widespread Early Holocene channel and floodplain sediments and their occurrence 7–8 m above the modern channel and floodplain suggest drastically increasing precipitation and water flow there. During the second half of the Holocene most of the main rivers of Central Yakutia, up to 3–4-order minor streams, were able to "clear" their thalwegs of sand-dune deposits of the D'olkuminskaya Series, and subsequently experienced the intruding partially entrenched barrier with the formation of the 1<sup>st</sup> floodplain terrace 8–12 m in height (with minor watercourse) to 15–20 m (with the main rivers: Lena, Vilyuy).

The valleys of numerous minor-order watercourses due to the weak flow in the conditions of insufficient humidity of Central Yakutia (average annual precipitation: 240–300 mm/year) continue to remain till the present time in a non-equilibrium state inherited from the Late Pleistocene. Their thalwegs are very sinuous, and their channels often represent long chains of small pools connected by drying up streams. At this, no floodplains or low terraces have formed.

The extremely low fluvial activity at the end of the Sartan cryochron which involved even large main watercourses is evidenced by the intense deflation and wide distribution of spear-shaped dunes oriented southeastwards (Fig. 5) on the surface of the lowest (20–25 m) Lena river terraces at the mouth of the Aldan river (63°17' N, 129°47' E), and Vilyuy river (63°23' N, 128°44' E). These dunes not only truncate the terraces, but thrust over and partially block paleo-delta arms, whose bottoms only 12–15 m exceed the contemporary water tables of the Lena and Vilyuy rivers and are almost levelled with the high floodplain. This distinctly indicates that the level of Lena and Vilyuy rivers failed to have reached these marks

throughout the Holocene, while river arms did not function even during the flood periods. Otherwise, the dunes blocking these water channels would have been completely eroded.

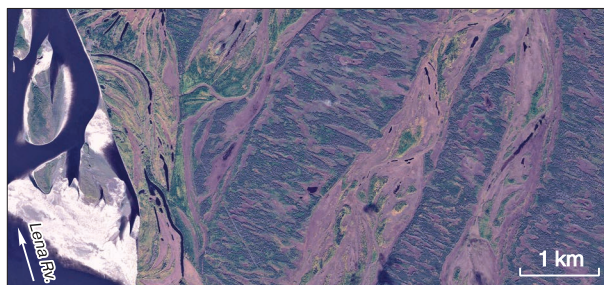
The inference the authors have made was that that by the beginning of the Holocene at least 40 % of the Central Yakutia area had been covered with a blankets of dune massifs and loamy sands, alternating with semi-closed deflation basins of eolian-dammed origin. The drainage network was fairly intensely breached by eolian processes. In the rest of the area, tundra-meadow-steppe depositional environments developed in the conditions of contrasting moisture content, which favored the formation of loess-like loamy sands with massive ice wedges. Woody and shrubby vegetation remained mainly along the shores of water bodies.

The Holocene warming, which began about 12.5 ka BP with subsequent dramatic increase in the precipitation, was accompanied by a decrease in eolian activity and progressively increasing influence of vegetation. The watercourses meandered across the dune sediment blanket, while the breached minor-order stream network was not coping with the runoff waters, and many drainage basins and valleys were therefore either partially flooded or water-logged.

Numerous lakes were common across a wide hypsometric interval. Their largest amounts are confined to extensive dune massifs, i.e. the areas of drainage system most strongly breached by eolian processes. The Boreal of the Holocene optimum is recorded in most sections at the top of the D'olkuminskaya Series in the form of peat mantles up to 2–3 m in thickness with the remains of freshwater molluscs and boggy vegetation [Kamaletdinov and Minyuk, 1991; Pavlova et al., 2017], interbedded with loamy sands and sands.

Fixation of dune massifs by soil and vegetation cove continued during the boreal optimum of the Holocene (9–5 ka BP) against the backdrop of increasing precipitation. The increased flow contributed to the thalwegs reworking by minor-order streams and clearing the valleys of eolian sediments. At the same time, the sediments of the yedoma formation with ice wedges in some areas were subjected to intense processes of thermokarst and thermoerosion. By the end of the boreal optimum the partially entrenched barrier was introduced into the hydrographic system at regional scale with subsequent formation of a 10–12 high terraces, giving rise to a considerable number of lakes in deflation and eolian-dammed basins.

Very young dates of soils and tree trunks, vertically buried in the modern dunes of the extensive Makhatta [Pavlova et al., 2017], Kysyl-Syr tukulans, etc., suggest that the fixation of most of the dune massifs of Central Yakutia by well-developed soil and vegetation cover had taken place by the beginning of the second half of the Holocene. Its last succession



**Fig. 5. Spear-shaped dunes oriented southeastwards composing the 1<sup>st</sup> above-floodplain terrace (Kerdem) 15–20 m in height on the right bank of the Lena river, 20 km to the south of the Aldan river mouth.**

Satellite image provided by Bing Maps Imagery (<https://www.bing.com>).

stage is represented by modern pine-bearberry-cowberry forests.

The last (modern) phase of activation of dune processes is associated with global cooling and climate aridization during the Little Ice Age (11–19 centuries), which actually is the age of all modern unvegetated dune massifs of Central Yakutia [Pavlov, 1981; Galanin et al., 2016], whose present-day area is about 3 thousand km<sup>2</sup> [Kut, 2015]. The Late Holocene dune-formation took place predominantly in the wake of major fires, through activation of individual sites of the ancient dune massifs. Note that the same time intervals during the last Pleistocene cryochrons and in the Late Holocene account for the global phases of the expansion of eolian formations throughout the Northern hemisphere: in Alaska [Black, 1951], in Canada [Wolfe et al., 2011], in Western and Eastern Siberia [Ivanov, 1966; Ufimtsev et al., 1997; Velichko and Timireva, 2005; Vyrkin, 2010].

## CONCLUSIONS

The accumulated to date amount of the absolute dates of sand-dune deposits in the Central Yakutia can be attributed to D'olkuminskaya Series formed since the end of the Karginsky Thermochron to the beginning of the Holocene (from 35 to 12–10 ka BP). The eolian formations is interpreted to have been the most extensive during the Sartan thermal minimum (21–18 ka BP). The eolian, slope, alluvial, lacustrine and glacial deposits of different ages at all hypsometric levels were subjected to eolian processes. The formation of modern unvegetated dune massifs intensified not earlier than 1 thousand years ago and is associated with the LIA drastic changes (climate cooling and aridization). The established chronological volume of sand-dune deposits blanket of the D'olkuminskaya Series of Central Yakutia is in good

agreement with the results of previous studies indicating a wide distribution of dune deposits dated as the last cryochron (MIS-2) and Late Holocene in Western Siberia, Northern Europe, Alaska and Canada.

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