Reconstruction of Late Pleistocene sedimentation environment from data on catenary differentiation of soils and sediments along the northern slope of the Klin-Dmitrov Ridge (Russia)

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Abstract. Based on analyzing the catenary sequence of soils and parent materials down the northern slope of the Klin-Dmitrov Ridge adjacent to the Upper Volga Lowland (formerly the periglacial zone of the Russian Plain), it was revealed that sediments including sandy loams, clay loams and clays, which constituted slope terraces at heights from 130 to 180 m a.s.l. and often accounted for lithic discontinuities in soil profiles, had glacio-lacustrine genesis, i.e., they had accumulated during the existence of a periglacial dammed lake at the final stages of the Late Pleistocene.

1. Introduction
The Klin-Dmitrov Ridge in the center of the Russian Plain is known as the marginal zone of the Moscow (Saalian) Glaciation and the southern border of periglacial dammed lakes during the Valdai (Würm) Glaciation [1]. However, there is a lack of data on geomorphological and lithological structure of the northern slope of the Klin-Dmitrov Ridge and, therefore, the genesis of sediments on slope terraces is poorly understood.

The aim of the present study was to analyze the morphogenetic features of Holocene soils and the spatial distribution of their parent materials of different ages on conjugated topographic levels of the northern slope of the Klin-Dmitrov Ridge and the adjacent surface of the Upper Volga Lowland, which can help to improve our understanding of the Late Pleistocene landscape development history.

2. Materials
Field studies were conducted in the northern part (Dmitrov District) of the Moscow Region, Russia. The studied catena was 8 km long (from 56°23.0' to 56°19.5' N; 37°25.5') and crossed six “topographic levels” within the altitude range from 130 to 230 m a.s.l., which included several terraces of the northern slope of the Klin-Dmitrov Ridge and the adjacent surface of the Upper Volga Lowland (figure 1). Textural classes of minerogenic sediments given in the caption to figure 1 and further
correspond to the classification widely used in Russian Federation and former USSR [2]. This classification is based on the weight percentage of particles smaller than 0.01 mm in size and the prevailing textural fraction as presented in table 1. The classes listed in table 1 are combined at the coarser hierarchical level into the classes presented in figure 2.

**Table 1.** Textural classes mentioned in the paper, the corresponding percentages of particles smaller than 0.01 mm in size and the prevailing textural fractions, i.e. sand (0.05–1.0 mm), coarse silt (0.01–0.05 mm), silt (0.001–0.05 mm), clay (<0.001 mm).

| Textural class name                             | Percentage of particles < 0.01 mm, range | Prevailing textural fraction |
|------------------------------------------------|----------------------------------------|------------------------------|
| silty clay loams                                | 22–44                                  | coarse silt                  |
| layered silty clay loams                       | 24–34                                  | coarse silt                  |
| coarse silty-sandy clay loams                   | 20–24                                  | sand                         |
| silty clays                                     | 50–52                                  | coarse silt                  |
| sandy-coarse silty loams                       | 9–18                                   | sand                         |
| coarse silty-sandy loams                       | 13–14                                  | sand                         |
| clays                                          | 49–62                                  | clay                         |

**Figure 1.** Morphological features of soil profiles on conjugated topographic levels of the Klin-Dmitrov Ridge and the adjacent Upper Volga Lowland used for interpreting the Late Pleistocene sedimentation processes. Minerogenic sediments: 1 – silty clay loams; 2 – layered silty clay loams; 3 – coarse silty-sandy clay loams; 4 – silty clays; 5 – sandy-coarse silt loams; 6 – coarse silty-sandy loams; 7 – clays. Eutrophic peats: 8 – hypnum; 9 – sedge-wood; 10 – wood-sedge composition. Other conventional signs: 11 – charred particles of ancient aquatic plants; 12 – small boulders and pebbles; 13 – soil profile numbers; 14 – height, m a.s.l.

In the nearby part of this lowland, the Yakhroma River broadened its course within a depression that remained from the former periglacial lake. The study area corresponded to the south-eastern
margin of the Tver Lake, which was one of the Upper Volga periglacial lakes during the final stages of the Late Pleistocene, i.e., from the Last Glacial Maximum (18–20 kyr BP) to the Late Valdai Cryochron (10–12 kyr BP).

3. Methods

Within the studied catenas, a total of 12 soil pits at different topographic levels were described in detail. These pits were excavated in the most representative locations, which were selected based on preliminary surveying (coring, digging of test pits and applying rapid techniques of field soil electrophysics). Most of the soil profiles were characterized by lithic discontinuities due to the presence of different parent materials. Soils were described according to the international guidelines [3] and classified according to the WRB [4].

Particle-size distribution was determined by sieving and the pipette method (using Na_2P_2O_7 as a dispersant) for the Russian system of particle-size fractions [2]. Each sample was analyzed in 3 replications with the subsequent statistical data processing [5]. The least significant difference (LSD_0.05) between sample averages was determined by comparing actual values of Fisher criterion (F_0.05) with the theoretical criterion of $\alpha = 0.05$ ($F_{0.05}$). Before dispersion analysis, all data were converted using Fisher’s angular transformation, i.e., percentages were converted to values of the central angle measured in radians [6]:

$$\varphi = 2 \cdot \arcsin \sqrt{P},$$

(1)

where $P$ is the percentage, expressed in part of an identity element.

The above-mentioned techniques of field soil electrophysics allowed identifying spatial distribution patterns of soil-sedimentary strata within Topographic Levels II–VI and helped to solve a range of soil genetic problems [7]. The method of horizontal electrical profiling (HEP) was applied for measuring soil electrical resistivity (ER). According to [8], this method is based on the use of four (AMNB) electrodes inserted into soil at fixed distances, which predetermine the measurement depth, i.e., the longer the distances, the deeper the measurements. The electrodes are moved step-by-step along grid lines within survey plots. The electrical field applied to the heterogeneous soil-sedimentary strata is non-uniform, therefore, the electrical resistivity measured with this method is termed apparent [9] and the measurement depth – pseudo depth [8]. We surveyed 40–60 ha plots using a LandMapper-01 device with equal distances between electrodes (AM = MN = NB were 0.3, 0.5 and 1.0 m for three survey grids). Electrical resistivity measurements were taken with a 5 m step along grid lines, with GPS co-ordinates recorded in each measurement point for the subsequent mapping of surveyed plots. It is known [7, 9] that electrical resistivity values depend on many factors specifically, soil moisture can overlap with soil texture effects. Therefore, to ensure a correct interpretation of data, we conducted the HEP survey within a short rain-free period (several days), which implied that soil moisture could be regarded as a constant “background” factor.

4. Results and discussion

4.1. Analysis of the morphogenetic features of soils and parent materials within the catena

The studied soils included Retisols on the terraced slope of the Klin-Dmitrov Ridge and Histosols on the adjacent surface of the Upper Volga Lowland. Most of those soils were arable.

As shown in figure 1, there was a great diversity of parent materials in the 12 soil pits studied on Topographic Levels I–VI. Eutrophic peats were parent materials of Histosols at Topographic Level I (130 m a.s.l.). Parent materials of Retisols of the slope terraces were represented by various minerogenic sediments, which often accounted for lithic discontinuities in soil profiles. Level II (up to 145 m) was dominated by sandy loams underlain by clays. Level III (up to 160 m) consisted of silty clay loams with a fragmentary cover of sandy loams. Level IV (up to 170 m) was also composed of silty clay loams with a thin cover of sandy loams. Level V (up to 180 m) included both stratified and non-stratified clay loam sediments and Level VI (up to 230 m) consisted of non-stratified clay loams only.
Generally, parent materials of soils at Topographic Levels II-V were characterized by the presence of stratification features, inclusions of small boulders and pebbles as well as charred particles of ancient aquatic plants, which were indicative of the glacio-lacustrine genesis of the sediments. According to [10], layered mantle loams sporadically occurring within the slope terrace at Level V (up to 180 m a.s.l.) are direct markers of the highest water level of the periglacial lake in the Late Valdai.

4.2. Particle-size distribution in soils and parent materials within the catena

The particle-size distribution (proportions of sand, silt and clay fractions) in the glacio-lacustrine sediments studied on the slope terraces of the Klin-Dmitrov Ridge depended on the sediment texture classes (sandy loam, clay loam and clay) and the terrace altitudes (topographic levels, a.s.l.). Specifically, the contents of sand (0.05–1 mm) and coarse silt (0.01–0.05 mm) were analyzed in two groups of soils with lithic discontinuities: (1) soil profiles with parent materials of three texture classes (sandy loam, clay loam and clay) and (2) soil profiles with parent materials of two texture classes (sandy loam and clay loam) (figure 2).

**Figure 2.** Distribution of sand (0.05–1 mm) and coarse silt (0.01–0.05 mm) in sediments of different texture classes (sandy loam, clay loam and clay) at different topographic levels on the slope of the Klin-Dmitrov Ridge. *a* – sand and *b* – coarse silt in soils formed on sandy loams, clay loams and clays; *c* – sand and *d* – coarse silt in soils formed on sandy loams and clay loams.
The first group included three soil profiles within Topographic Level II. There were clear trends for increase in the coarse silt content and decrease in the sand content with increasing altitude of soil pit location (from 135.8 to 145 m a.s.l.) (figures 2a, b). Such trends were confidently established in clay loam and clay sediments. Sandy loams were characterized by insignificant differences in the contents of the analyzed particle-size fractions. Generally, all sediments belonged to a single phase of subaqueous sedimentogenesis in the Late Pleistocene.

In the second group, there were five soil profiles located within Topographic Levels II–IV. Like in the first analyzed group, there was a tendency for decreasing sand content with increasing altitudes (from 135.8 to 170.3 m a.s.l.) (figures 2c, d). In sediments of both texture classes (sandy loams and clay loams), sand content decreased with transition from Level II to Level III and then to Level IV.

Generally, there were close curvilinear relationships between the proportions of the analyzed particle-size fractions and the topographic levels of sediments of different texture classes.

4.3. Soil electrical resistivity and paleogeographical interpretation of parent materials
The horizontal profiling with the 0.3 m distance between the electrodes allowed to determine the electrical resistivity (ER) of the studied arable soils to the depth of the plough layer. At Topographic Level II, the ER of the plough layer was generally with the range of 200–300 Om·m, with only small areas characterized by higher values of 300–400 Om·m (figure 3). Topographic Level III was characterized by generally lower ER values of 50–150 Om·m, which was associated with the presence of silty loam and lower sand content within the plough layer. Level IV had a complex pattern of the distribution of ER values, i.e., different areas of this terrace were characterized by ER ranges of 150–200, 200–300 and 300–500 Om·m, with the highest values recorded in the rear part of the terrace dominated by sandy parent materials with occasional inclusions of pebble at the depth of the plough layer. At Level V, the ER range of 50–200 Om·m indicated the presence of a continuous cover of silty loam within at the plough layer depth. Low values of ER at Level VI were typical for arable soils developed on homogeneous silty loam sediments.

Generally similar distribution patterns of ER values were obtained by horizontal profiling with electrode distances of 0.5 m, with areas of higher resistance associated with sediments of coarser texture that contained higher proportions of sand fraction and occasional inclusions of pebble.

The ER values obtained by horizontal profiling with electrode distances of 1.0 m corresponded to 1.0 m depth. It was revealed that the lowest electrical resistance values were associated with the presence of sediment layers of clayey texture within the 1 m depth. The highest ER values (up to 600–800 Om·m) detected within local areas indicated the presence of thick layers of coarse-textured (sandy) sediments.

5. Conclusion
Based on the data obtained, it was established that sediments including sandy loams, clay loams and clays on the slope terrace levels up to 180 m a.s.l. had glacio-lacustrine genesis. The northern slope of the Klin-Dmitrov Ridge served as a dam, which prevented some glacial meltwater from leaving the valley. The slope terrace at 180 m a.s.l. (Topographic Level V) corresponded to the lake’s highest water level. As the water level dropped down in several stages, terraces were formed at heights of about 170, 160 and 140 m a.s.l. (Topographic Levels IV, III and II) on the slope of the Klin-Dmitrov Ridge. The slope terrace levels generally correlated with the regional data on the Late Pleistocene periglacial lake terraces within the Upper Volga basin.

Textural changes in sediment layers, which corresponded to lithic discontinuities in soils, were indicative of a dynamic development of the Late Pleistocene lacustrine sedimentation. The analysis of distribution of particle-size fractions (sand, silt and clay) within sediments of different textural classes (sandy loam, clay loam and clay), which formed the above-mentioned slope terraces, revealed the following general trend: the higher the terrace, the higher the coarse silt content and the lower the sand content in the sediments. Such pattern typically results from a rapid descend of water level in lakes, when sand initially deposited at higher topographic levels is subsequently moved down and re-
deposited at lower levels. In the study area, sand was re-deposited at the surface of clay sediments of the lower terrace (Level II).

Figure 3. Maps of HEP survey plots showing the spatial distribution of electrical resistivity values (Om·m) measured using different distances between the electrodes (0.3, 0.5 and 1 m) in soils and sediments at different topographic levels on the slope of the Klin-Dmitrov Ridge.

Thus, the present study has improved our understanding of the Late Pleistocene sedimentation paleogeography on the Russian Plain.

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