Soil-sedimentary sequences of lake depressions in the steppe zone of West Siberia (Russia)

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Abstract. Lakes are widely distributed in the steppe zone of West Siberia (Russia). These lakes experienced climate-related fluctuations of water levels and corresponding rhythmic changes in the lake basin landscapes throughout the Holocene. Location, structure and properties of soil-sedimentary sequences (SSS) were studied near the Lake Bolyshoi Bagan, where four SSS profiles were examined. The profiles were located on the lake beach ridges and were of different age. Two types of sediments were found in the SSS structure, namely lacustrine sand of the shore facia (top and middle layers) and subaerial-deluvial loam with gleic properties (lower layers). The studied SSS showed abrupt textural shifts between sandy deposits and loamy layers. The top part of the younger SSS also contains aeolian layers. The loamy layer, as compared with the sandy one, had increased contents of carbonates and dissolved salts. The lowest soil in all SSS was identified as Protosalic Relictigleyic Solonetz (Loamic, Columnic, Ochric). The surface and buried soils in all SSS were ascribed to the Reference Soil Group of Arenosols. Heterochronicity of surface soils is recorded in the different soil organic carbon content. The studied SSS reflect the interaction of environmental factors in the steppe zone of West Siberia during the Holocene: water level fluctuation in lakes, alternating aeolian and lacustrine sedimentation, and succession of pedogenesis and sediment accumulation periods.

1. Introduction
Soil-sedimentary sequences (SSS) have been successfully used for reconstructing paleoenvironment and climate in different geological periods [1, 2]. Such sequences show the periods of pedogenesis and decreased exogenous processes in their soil profile structure and individual soil horizons, whereas the intensification of erosion and accumulation processes are manifested as sedimentation layers. Thus SSS represent records of environmental rhythms, including climate changes, when favourable environmental conditions facilitated the pedogenetic stage, whereas the more adverse environmental conditions resulted in the lithogenic stage. Investigation of SSS allows revealing alternating stages of pedogenesis, exogenous processes and sediment accumulation and reconstructing climate and landscape changes. Climate fluctuations in The Holocene can be studied using various SSS, such as ravine slopes [3] and alluvial soils [4]. Such objects are well represented in research publications. However, publications about paleosols and SSS in fluvial, lacustrine, and mixed marine-continental depositional systems are relatively few [1, 5]. No research was carried out on SSS in lacustrine depressions in the steppe zone of West Siberia, and consequently the pertaining information is absent.

Lakes are widely distributed in the steppe zone of West Siberia. According to the multidisciplinary research carried in the area, the Holocene there saw significant changes in climate and environment,
which affected lake ecosystems [6, 7]. These lakes experienced climate-related fluctuations of water levels and corresponding rhythmic changes in the lake basin landscapes throughout the Holocene. During the humid climate phases, there occurred waterlogging and flooding of subaerial areas. During the arid phases, the lakes dried up partially or completely. Thus the SSS of lake depressions were formed. These SSS have been poorly studied in Russia. So the aim of the work was to study some properties and diversity of pedogenesis and sedimentation series in lake depressions in the West Siberian steppe zone and to reconstruct climate changes in the region.

2. Material and methods
We studied SSS in the Bolyshoy Bagan Lake area, situated in the steppe zone of West Siberia (figure 1, a, b). Currently the lake is 4 km by 2 km with an area of 5.6 km². In its southern part the lake has a dried roundish bay, representing a saline plain (SoR). The paleolake depression is much bigger than the current lake area as it includes adjacent areas, representing dry saline depressions and lakes (figure 1 c). The SSS are confined to the lake beach ridges, which have different ages and are located directly in the lake depression (figure 1d). We studied four SSS on the beach ridges at different distances from the current lake shoreline. The most remote lacustrine beach ridge is 900 m away from the current shoreline, its surface being 9 m above the lake water table (figure 1d, e).

The SSS research topics include morphology, physical and chemical properties, genetic attribution of soil horizons and sediments, all of which provide information about local paleoenvironments and paleoclimate. We started our studies of SSS structure and properties with examination in the field, which provided the basis for the subsequent procedures. We used pedolithogenic approach to study SSS [8], which involved characterization of both soil genetic horizons and all lithological layers. Surface and buried soils in the studied SSS were described in accordance with the Guidelines for soil description [9] and ascribed a taxonomy in accordance with the World Reference Base (WRB) of Soil Resources (2014) [10]. The SSS were characterized depending on the specific stratigraphy of soil genetic horizons and sedimentation layers.

The soils were sampled and analyzed using standard procedures in soil science to determine their physical and chemical properties [11]. Soil horizons and sedimentary layers were characterized by pH (1:5), soil organic carbon content (SOC) and carbonate content, electrical conductivity (ECe) and soil texture class by WRB [10].

The climate of the region is arid with precipitation to evaporation ratio of 0.69. Summer droughts occur often. Average air temperatures are –20°C (January) and 19°C (July). The annual average temperature is –0.2°C. Annual precipitation averages 310 mm, about one-third falling in winter. The snow cover persists for about 5 months.

3. Results and discussion
The studied sequences consist of a regular alternation of buried soils and sediments of different genesis (table 1). Two main sediment types were found in the SSS: lacustrine sand from the shore facia (top and middle layers) and subaerial deluvial loam with gleic properties (lower layers). All SSS showed an abrupt textural change between the sandy sediments and the loamy layer. In the loamy sediments, the highest silt percentage was found in the top layer with features of the diagnostic natric horizon. The total thickness of the sand deposits increased towards the lake, being 60 cm in the BG2-19 profile, 89 cm in the BG4-19 and 146 cm in the BG5-19 profiles. The relative age of the sand deposits increased with the distance from the current lake shoreline. Besides these two sediment types, the top part of BG4-19 and BG5-19 had aeolian layers. The SSS sediment layers in the Bolyshoi Bagan Lake depression are separated by buried soil horizons and paleosols. The Profiles BG2-19 and BG3-19 contain four soils, including the surface one, whereas the Profiles BG4-19 and BG5-19 overall contain five soils. The lowest soil in all the studied SSS represents Protosalic Relictigleyic Solonetz (Loamic, Columnic, Ochric). The soil developed on loamy deluvial sediments and shows features of the relic hydromorphic pedogenesis. As presently the ground water can be found at the depth of 3-5 m , it cannot affect the layer. Surface and buried soils of sand sediments in all the SSS are identified as Arenosols. The grain
size distribution pattern is in good agreement with the SSS chemical properties. In sandy soils and sediments pH was predominantly neutral, whereas the loamy soil had alkaline pH (table 1). This is most likely due to the increased calcium carbonate content in the sand layers.

![Figure 1](image_url)

Figure 1. The study area and objects: (a) index map; (b) general view of the Lake Bolyshoi Bagan region; (c) enlarged view of the Lake Bolyshoi Bagan; (d) location of the study sites on the Google Earth satellite image; (e) hypsometric profile along the line A—B; (f) the studied soil-sedimentary sequences.

The loamy layer, as well as the buried soil in it, had high ECe (table 1), indicating soil salinity, i.e. significant content of dissolved salts. The hydromorphic features observed in the buried loamy soil
(Solonetz) and overall in the loamy sediments, high carbonate and dissolved salts content indicate their hydrogenic accumulation from the ground water; the latter could have occurred under arid conditions when the lake water table was low.

The heterochronicity of the surface soils was found to be a characteristic feature of the studied SSS. The closer to the lake, the younger the soils are. This is manifested by some features of humus horizons, as their thickness and SOC content positively correlate with the longevity of pedogenetic stage. The surface soil in the BG2-19 profile showed the most developed humus horizon and the highest SOC content (table 1). The buried horizons of the soil also had the highest SOC content as compared with the other studied SSS. The buried sandy humus horizons of the younger SSS had low SOC content (<1%). These differences in the properties of the buried and surface sandy soils of all SSS determine their taxonomy attribution. For instance, the sandy soil within the BG2-19 sequence is classified as Eutric Orthofluvic Arenosol (Endogeoabruptic, Humic); the one within the BG3-19 sequence is a Eutric Orthofluvic Arenosol (Epigeoabruptic, Humic); whereas within the BG4-19 sequence the sandy soil is Eutric Orthofluvic Arenosol (Epigeoabruptic, Ochric), and within the BG5-19 sequence the soil is classified as Eutric Orthofluvic Arenosol (Endogeoabruptic, Aeolic, Ochric). The depth of the boundary between sandy and loamy sediments, the presence of aeolian layers and SOC content [10] are the main Arenosol features bearing classification significance. Thus the studied SSS of the Lake Bolyshoi Bagan depression were characterized by a diverse set of properties and features.

Table 1. Structure and properties of soil-sedimentary sequences in depressions of lake Bolyshoi Bagan.

| Horizon  | Depth, cm | Soil number/Reference Soil Group | pH (1:5) | SOC, % | CaCO₃, % | ECE, dS m⁻¹ | Soil texture class | Deposit origin |
|----------|-----------|----------------------------------|----------|--------|----------|-------------|-------------------|----------------|
| **Profile BG2-19** | | | | | | | | |
| Ah       | 0-10      | 1 Arenosol                       | 6.8      | 3.48   | 0.8      | 1.4         | LS                | Lacustrine       |
| AC       | 10-14     | 1 Arenosol                       | 6.7      | 1.53   | 0.5      | 1.2         | S                 | Lacustrine       |
| Ahb      | 14-24     | 2 Arenosol                       | 6.8      | 2.65   | 0.5      | 1.0         | S                 | Lacustrine       |
| C        | 24-45     | 2 Arenosol                       | 7.0      | 0.10   | 0.3      | 1.5         | S                 | Lacustrine       |
| Ahb      | 45-52     | 3 Arenosol                       | 7.2      | 1.82   | 1.0      | 1.4         | S                 | Lacustrine       |
| C        | 52-60     | 3 Arenosol                       | 7.5      | 0.21   | 1.5      | 1.3         | S                 | Lacustrine       |
| 2Btknb   | 60-75     | 4 Solonet                        | 7.9      | 0.23   | 9.8      | 6.8         | SCL               | Deluvial         |
| 2Bgkb    | 75-95     | 4 Solonet                        | 8.3      | 0.22   | 14.8     | 7.2         | SL                | Deluvial         |
| 2Cgk     | 95-120    | 4 Solonet                        | 8.5      | 0.18   | 12.2     | 11.0        | L                 | Deluvial         |
| **Profile BG3-19** | | | | | | | | |
| Ah       | 0-9       | 1 Arenosol                       | 7.0      | 1.21   | 2.1      | 1.2         | LS                | Lacustrine       |
| AC       | 9-21      | 1 Arenosol                       | 7.0      | 0.43   | 3.7      | 1.1         | S                 | Lacustrine       |
| Ahb      | 21-28     | 2 Arenosol                       | 7.3      | 0.51   | 0.2      | 1.2         | S                 | Lacustrine       |
| Ahb      | 28-33     | 3 Arenosol                       | 7.3      | 0.77   | 2.1      | 1.2         | S                 | Lacustrine       |
| AC       | 33-40     | 3 Arenosol                       | 7.6      | 0.61   | 2.5      | 1.3         | LS                | Lacustrine       |
| 2Btknb   | 40-58     | 4 Solonet                        | 8.5      | 0.67   | 10.8     | 6.2         | SCL               | Deluvial         |
| 2Bgkb    | 58-70     | 4 Solonet                        | 8.7      | 0.33   | 16.9     | 8.5         | SL                | Deluvial         |
| 2Cgks    | 70-95     | 4 Solonet                        | 7.9      | 0.25   | 16.5     | 10.8        | SL                | Deluvial         |
| 2Cgks    | 95-110    | 4 Solonet                        | 8.8      | 0.25   | 11.6     | 12.3        | L                 | Deluvial         |
| **Profile BG4-19** | | | | | | | | |
| Ah       | 0-12      | 1 Arenosol                       | 7.2      | 0.96   | 1.2      | 1.0         | LS                | Aeolian          |
| C        | 12-36     | 1 Arenosol                       | 7.4      | 0.16   | 4.6      | 1.4         | S                 | Aeolian          |
| 2Ahkb    | 36-46     | 2 Arenosol                       | 7.4      | 0.44   | 4.1      | 1.4         | S                 | Lacustrine       |
| 2Ck      | 46-57     | 2 Arenosol                       | 7.4      | 0.24   | 4.5      | 1.3         | S                 | Lacustrine       |
| 2Ahkb    | 57-60     | 3 Arenosol                       | 7.3      | 0.54   | 4.5      | 1.6         | LS                | Lacustrine       |
| 2Ck      | 60-72     | 3 Arenosol                       | 7.6      | 0.11   | 3.7      | 1.1         | S                 | Lacustrine       |
| 2Ahb     | 72-89     | 4 Arenosol                       | 7.2      | 0.26   | 1.8      | 0.6         | LS                | Lacustrine       |
Grain size distribution showed drastic sedimentation shifts: in the top part of the profile the subaerial-deluvial loams with relics of hydromorphic pedogenesis are replaced by the lacustrine-alluvial sands. Accumulation of lacustrine sands took place during the lake transgression. The process went stepwise, each step resulting in the formation of lake ridges. The most remote and the oldest shore ridge registered the level of the maximal lake transgression. Other lake ridges reflect the successive steps of water table fluctuations in the lake. Relatively prolonged periods of sedimentation alternated with shorter periods of pedogenesis. Poorly developed humus horizons of the buried soils in the sandy lithological layers confirm the short periods of pedogenesis, which were followed by intensive sedimentation and sediment accumulation, both lacustrine and aeolian sediments. The longest period of pedogenesis occurred in the surface soil on the ancient shore ridge. The SOC accumulation in this soil resulted from favourable (warm and moist) environmental conditions. Such conditions also stimulated highly productive phytocenoses, phytomass humification and accumulation of SOC. Aeolian deposits in the top part of the younger ridges formed during the arid periods with intensive winds. Substrate activity and climatic conditions did not favour SOC accumulation.

4. Conclusion

The soil-sedimentary sequences of the Bolyshoi Bagan Lake depression were found to have lithological layers of different genesis (deluvial, lacustrine, aeolian) that are separated by buried soil horizons and paleosols. Therefore we had identified these SSS as polygenetic pedolithocomplexes. The identified objects were characterized by a diverse set of properties and features depending on environment conditions. The pedolithocomplexes reflect landscape changes and intricate interaction of environmental factors in the steppe zone of West Siberia during the Holocene, such as water level fluctuation in lakes, alternating aeolian and lacustrine sedimentation, and succession of pedogenesis and sediment accumulation periods.

Environmental changes occurred due to dynamic climate conditions: the cold arid conditions were followed by the warm and humid ones during the periods of highest water level in the lake depression and then to the warm and arid conditions, which in the West Siberia have been persistent until present. Such conditions correlate with the lowest water level in the Bolyshoi Bagan Lake, as well as with aeolian activity, soil and sediment salinization in areas adjacent to the lake.

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