Late Pleistocene–Holocene environmental changes in ultra-continental subarid permafrost-affected landscapes of the Terekhol' Basin, South Siberia

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1. Introduction

Environmental changes and related evolution of soils in the late Pleistocene and the Holocene in South Siberia have not been studied satisfactorily yet as far as the region is complicated and diverse in respect to landscapes and soils, and hardly reachable in some parts. Soils and pedosedimentary sequences of small intermountain basins of the South Siberia are one of still insufficiently developed and highly promising archives of the Late Pleistocene and Holocene environmental changes. Advantages of soil-sedimentary sequences for paleoenvironmental reconstructions in small inter-mountain basins were closely discussed by Vorob'eva (2010). Surface soils of such basins, as a rule, have got obvious evidences of polygenesis (recording more than one set of soil forming environmental conditions). Buried soils related to different periods and environments are widespread in intramountain basins due to dynamism of fluvial, lacustrine, slope sedimentation (interchanging intensive sedimentation and relatively continuous hiatuses) during Late Pleistocene and Holocene. There are only few studies on Holocene soil and environmental evolution based on the analysis of soil (or soil-sedimentary) records of the South Siberia (Dergacheva et al., 2006; Desjatkin, 1984, 2008; Vorob'eva, 2010). Some of these studies analyze local sources not correlating them with earlier produced data on environmental changes in a wider region or the data obtained from other environmental archives. Studies of different sedimentary Late Pleistocene and Holocene archives in the South Siberia and, taking a broader region, in arid sector of Central Asia are more in number (Blyakharchuk et al., 2004, 2007, 2008; Huang et al., 2009; Rudaya et al., 2009; Schwanghart et al., 2009; Vipper et al., 1976 and others). However the data on Late Glacial and Holocene obtained for different localities and applying different methods are often contradictory. Generalizations of data accumulated at the moment are still rare (Blyakharchuk et al., 2004; Zhao et al.,...
Despite the growth in understanding of the Late Glacial and Holocene climate in the South Siberia and generally in arid/subarid parts of Asia a further work is needed. In editorial to the special issue of Quaternary International “Holocene climate variability in arid Asia: Nature and mechanisms” necessity to extend a net of study sites across the region was emphasized, in order to escape difficulties in the identification of regional patterns. Studies focused on climatically sensitive areas (such as ultracontinental arid permafrost affected areas) and inter-archive comparisons are among first-priority tasks (Chen et al., 2009).

Usually there are a number of paleoenvironmental archives available in local landscapes to access information on environmental changes. There could be independent sedimentary records of various origins (fluvi-al, limnic sediments, loess, peat etc.) and soil record in polygenetic surface soils and buried paleosols (soil memory). Different kinds of paleo-archives in most cases are studied independently because of narrow specialization of researchers and common difficulties of interdisciplinary studies. Meanwhile each kind of paleo-archive each method used to extract palaeocological information has its own approaches, limitations, advantages and disadvantages. Therefore a comparative study of different sedimentary and paleosol archives in a single local geosystem seems to be the most fruitful and reliable for environmental reconstructions. Data obtained from independent environmental archives of the same age are complementary and verifying each other. Meanwhile such comparative studies of different local paleoenvironmental archives are not a common practice in paleopedology. Only some rare studies can be cited in this field (Sedov et al., 2003, 2009, 2010; Solleiro-Rebolledo et al., 2006).

This study is an attempt to use closely related complementary paleo-archives of a local landscape – a small intermountain basin – for most comprehensive understanding of Late Pleistocene–Holocene environmental changes in the region. The following archives were studied as sources of paleoenvironmental information:

- soil-sedimentary sequences on a delta-alluvial fan of the Ajyl River – a small river entering the Terekhol’ Basin from its south-western side;
- sediments of the Terekhol’ Lake in bottom cores and on palsa-islands;
- soils of palsa-islands.

The data on the alluvial soil-sedimentary sequences are a major focus of this paper. Data on lake and island sedimentary sequences (Panin et al., 2012) and island soils (Bronnikova et al., 2010) were published earlier in details. In the present paper these results are generalized and discussed as a complimentary source of paleoenvironmental information.

2. Materials and methods

2.1. Study site: contemporary environment and study objects

The Terekhol’ Basin is a small intermountain depression located at the north-east slope of the Sangilen Upland, the south-east part of Tyva Republic, South Siberia (50°N, 97°E, about 1300 m above sea level) (Fig. 1A).

The climate of the study area is ultra-continent subarid, with extremely severe winter and relatively hot short summer (the frost-free season is only 32 days long). The mean annual temperature is −6.1 °C, the amplitude of annual temperature variation reaches 55.5 °C, and the sum of temperatures above +10 °C is 1000–2000 °C. The mean annual precipitation is 230–323 mm, and only 11% of annual sum falls in a form of snow (Agroclimatic..., 1961). There is no published data available on the seasonal freezing–thawing processes. But it is clear from distribution of annual precipitation sum that soil gets frozen while being dry and doesn’t get much water due to thawing because of autumn–spring water deficit.

Continuous relic permafrost is found in the bottom of Terekhol’ Basin. It is up to 170 m thick according to geophysical data (Koshurnikov et al., 2008). Active layer is 120–300 cm deep in July–August in well drained conditions. In most of sections it varies around 200 cm.

Steppe landscapes prevail in the basin’s bottom. They occupy all areas with the exception of the alluvial–lacustrine–thermokarst area surrounding the Terekhol’ Lake and narrow strips of larch taiga along transit streams. The never plowed areas are now occupied by dry steppe communities (Stipa sp., Psathyrostachys hylantha (Rupr.) Tzvel., Poa argunensis Roshev., Bupleurum scorzonerfolium Willd., Veronica incana L., and Orostachys spinosa (L.) C.A. Mey) and communities of meadow steppes (Stipa sp., Bonghrosc i n erins (Leyss.) Holub., Potentilla bifurca, P. argunensis Roshev., Thermopsis mongolica Czefr., Heteropappus alticus (Willd.) Novopokr., and B. scorzonerfolium Willd.). Previously arable lands have lost Stipa sp. and got some ruderal species such as P. hylantha (Rupr.) Tzvel., Elytrigia repens (L.) Nevski, Potentilla tanacetofolia Willd. ex Schlcht., Artemisia glauca Pall. ex Willd., Chenopodium album L., Descurainia sophia L. Larch taiga communities cover mountain slopes of the basin. Lake terraces and low islands are occupied mostly by meadows and meadow-steppes, the highest positions of the terraces and high islands are covered with normal steppe vegetation with Stipa sp.

Cryosols are the major and the most widely spread soils of the Terekhol’ Basin. Soil cover of steppe landscapes, particularly the surface of the delta-alluvial fan, mostly consists of Turbi-Natri-(Sali)-Molliglossi-Calci Cryosols and Turbi-Protonatri-Molliglossi-Calci Cryosols. There are two general options of surface soil formation which proceeds at the background of numerous evidences of cryogenesis: (1) all the variety of solonization–solodization and alkalinization–dealkalization processes in its different stages (from its initial phase through the mature, sodic stage and later secondary salinization up to residual morphological features of Natric horizon), and (2) chernozemic process including formation of the Mollic horizon (with initial signs of solonization) and accumulation of secondary carbonates in Bk horizons. The specific contemporary soils of the alluvial fan were earlier described in details (Bronnikova et al., 2011). A variety of Cambic Cryosols is formed under taiga ecosystems, and Histic and Calci-Mollic Cryosols prevail on the lake terraces and islands.

Catchment areas of the Terekhol’ Lake and the Ajyl River lie in the mountain surroundings of the basin. They are composed of Precambrian marbles cut by intrusions of early Paleozoic granitoids. Such geological conditions high carbonate content of fluvial and especially lake sediments. The Terekhol’ Lake is a fresh water body fed by groundwater, and by a number of small mountain rivers. The lake is drained by the Saldam River, left tributary of the Balyktug-Khem River (one of the sources of the Yenisey River). Terekhol’ Lake has a considerable area of 33.19 km², but it is extremely shallow: the average depth is about 0.6 m; less than 1% of the lake area is deeper than 1 m. Islands make up about 2.85 km² of the lake area. There is no permafrost below the lake (talik), but all islands have newly formed permafrost (Koshurnikov et al., 2008).

The basin bottom is the basis level for the Ajyl River which dissects its southern slope (Fig. 1B). Ajyl is a small mostly rain-fed mountainous river 14 km long draining a catchment area of 40 km². Seasonal floods, up to 7 in number, normally take place at the end of May – at the beginning of June. During low water phases between floods the river doesn’t reach the lake because of seepage into sediments in the eastern part of its vast Late Quaternary alluvial fan.

2.2. Applied approaches and methods

Topographic profiling was accomplished for the delta-alluvial fan, across the bottom of the lake and islands. Topographic surveying was done applying a high-precision Leica Smart Station. The last one includes a GPS base-station (which was set on a local reference point),
a GPS-rover and a digital tacheometer. Key soil-sedimentary and sedimentary sections were studied along the produced topographic profiles. Most of the pits were made within the active layer down to the top of permafrost. Litho-stratigraphic and morphological pedogenetic descriptions within the active layer were provided for the soil-sedimentary sequences of the alluvial fan and island soils.

Micromorphological studies of surface and buried soils were conducted for the key sections. Undisturbed soil monoliths were studied in thin sections under a polarizing microscope Nikon E200 Pol in plain polarized (PPL) and cross polarized (XPL) transmitted light at magnifications of 40×, 100×, and 400×. Terminology and approaches of G. Stoops were applied in micromorphological studies (Stoops, 2003).

Morphological results were supported by some analytical data on profile distribution of organic C, carbonates etc. Analytical studies were performed using the standard methods (Vorob’eva, 2006): pH was measured in water suspension by potentiometry; total organic carbon — by wet oxidation with dichromate potassium and concentrated sulfuric acid; carbonates were determined by alkaliometric titration; total soluble salts were estimated from electroconductivity measurements in water extract (soil:water = 1:5). After preparatory successive removal of carbonates by 10% HCl, and organic matter by 30% H2O2, data on particle size distribution of silicate residue of the sediment were obtained with vibroshaker Analysette 3Pro Frisch screen sizing of fractions >0.1 mm, followed with Analysette 22 Frisch laser granulometry of <0.1 mm part, which was dispersed with sodium pyrophosphate (Konert and Vanderberghhe, 1997).

Mineralogical composition of clay fraction (<1 μm) was analyzed by X-ray diffractometry (CuKα emission, Ni-filter) in scan mode (scanning pitch is 0.1°, exposure time is 10 s). Samples were pretreated with 10% hydrogen peroxide with water-bath heating to remove organic matter, then Mg-saturated with 1 N MgCl2 for 24 h and washed off the salt excess by centrifuging. Mg-saturated air-dry, ethylene glycol-saturated, 350 and 550°C heated oriented samples have been studied. Quantitative estimation of clay mineral groups based on areas of their reflections was done according to Biscaye (1965).

Radiocarbon analysis was used as a dating tool in soil-sedimentary sections and sedimentary columns. Radiocarbon dating was done in the Institute of Geography, Russian Academy of Sciences (lab index IGAN) by liquid scintillation counting and in Lund University (lab index LuS) by Accelerator Mass Spectrometry. Calibration of 14C dates was done in an on-line version of OxCal 4.1 (https://c14.arch.ox.ac.uk/oxcal/OxCal.html, Bronk Ramsey, 2009), using calibration scale IntCal09. The intervals of calibrated age are given with 95.4% probability. Age scale of the lake development and age of single events in its history were determined basing on age–depth diagrams as interpolation of sedimentation rates. Calculating error is estimated in ±200–250 years taking into account data scattering and the width of confidence interval.
3. Results

3.1. The delta-alluvial fan: stratigraphy and chronology

The main generation of the alluvial fan occupies an area of 2.5 × 4 km (Fig. 1C). Its surface is slightly (up to 2–3°) inclined towards the lake. General stratigraphy of the fan presented in Fig. 2, Fig. 3A, E demonstrates the major stratigraphic units in the key sections 6 and 233. Coarse-grained unsorted sandy-gravely alluvium at the basement (Fig. 2, Fig. 3A, E, Unit 6) is covered with 150–200 cm of clearly stratified silt loams and silts, sometimes intercalated with sands (the data on particle size distribution will be presented below). This upper facie resulted from overbank inundation during seasonal floods. It includes one or two buried soils, which are distinctively different in their absolute age and a degree of the development in the eastern and western parts of the fan (see details below). An approximate border between eastern and western parts of the fan is shown in Fig. 1C.

The coarse-grained basement of the Ajyl’s fan enters more than 1 km into the lake. It was found under the lake sediments in a number of bottom cores and on islands (Fig. 2). The roof of this layer under lake sediments is related to the Younger Dryas time, and it was dated at 11,395–12,837 (Table 1).

As it was mentioned above, there are two successive buried soils in subaerial soil-sedimentary sequences of the alluvial fan, within its stratified silt loams and silts of the delta-floodplain overbank facies. These soils in the eastern part of the fan are related to the Pleistocene–Holocene border. The older (deeper) of them is wider spread, and better developed (Fig. 3A, Unit 3). The younger (upper) one was found in 7 of the 10 studied sections (Fig. 3A, Unit 2). In the sections where both soils occur, they are delimited by 20–50 cm of bedded fluvial loams. Clear layering of this material testifies on high rates of sedimentation that means very short period of time between the two successive phases of pedogenesis. The dates obtained from these soils have given in some cases overlapping intervals of calibrated C14 age (Table 1). The overlapping interval of calibrated dates obtained from the older soil (IGAN-3407 and IGAN-3441) is 11,248–11,802. The narrowest, overlapping interval of three dates obtained from a younger soil is 10,565–11,220 (IGAN-3428, IGAN-3865, IGAN-3976) (Table 1). Thus the older soil falls exactly on the Pleistocene–Holocene border. The younger soil was formed at the very beginning of the Preboreal period of the Holocene. Though these two soils are very close in age, they are highly different in their genesis as it will be demonstrated below.

Soil-sedimentary sequences located to the east from the central axis of the fan have the same general stratigraphy: coarse Pre-Holocene basement (Fig. 3E, Unit 6) overlaid with stratified silt loams and silts of the overbank facie usually containing one buried soil (Fig. 3E, Unit 5). The C14 dates obtained from the 2 cm roof layer of its Ab horizon get in the interval from 3702 to 4869 cal years ago (IGAN-3967, IGAN-3819 in Table 1). We consider this time span as an approximate date of the soil’s burial due to shortly re-established overbank sedimentation. Surface soil was formed on this last phase sediment (Fig. 3E, Unit 4).

The paleosol buried in the eastern part of the fan between 3700 and 4870 cal years ago has much more developed, mature profile in comparison to the soils buried around the Pleistocene–Holocene border in the western part of the fan. In addition to the dates from the roof of Ab horizon, the 2 cm layer at the bottom of organo-accumulative horizons was dated in some eastern sections with mature buried profiles. Overlapping interval for these dates is 8322–8518 cal yrs BP.

We also obtained two dates from the bottom 2 cm of the surface A horizons (IGAN-3489, IGAN-3964). They are young and considerably different (Table 1). Generally these two dates testify on pretty high rates of humus rejuvenation in studied soils. This process is especially fast in soils with strongly developed contemporary Natric features (the surface soil in section 1), which supposes high mobility of humus in a profile. High rates of humus rejuvenation allow supposing that soil formation started at the Pleistocene–Holocene border both in the western and eastern parts of the fan. Pedogenesis at the Pleistocene–Holocene transition was twice interrupted by floodplain sedimentation in the western part of the fan, so that two environmentally different phases of pedogenesis are well documented in the western sections. At the same time in the eastern part of the fan pedogenesis was not interrupted by sedimentation at the Pleistocene–Holocene transition. Thus there are no separate buried soils related to that period in eastern sections. The same general stratigraphical pattern in eastern and western parts of the alluvial fan together with different age and maturity of buried soils in different parts of the fan could result from west to east...
shift of the river channel and the sedimentation zone of seasonal floods related to it. Thus the river channel was shifting to the west in the first part of Holocene, and over-bank inundations buried soils in the eastern part of the fan around 3700–4870 cal. of the first two thirds of the Holocene.

3.2. Buried soils of the Pleistocene–Holocene transition

Soil-sedimentary sequences on the delta alluvial fan in its western part will be examined with an example of section 6: N 50.60355° E 97.39338° (Fig. 1C). Based on field description and grain size analysis, a stratigraphy of section 6 is as follows. There is a coarse-grained layer in the basement of the section, right above the permafrost table (Fig. 3A, Unit 6). It is represented by unsorted gravelly sands (Fig. 4, 4Cf horizon). Both soils are developed within the delta-floodplain silts and silt loams (Fig. 4). Soil forming material for the lower paleosol is relatively homogenous weakly stratified silt loam. The upper paleosol is formed within fine and sharply stratified silts and silt loams (width of a strata is less than 2 cm). A stratification of the material above the younger paleosol is not that sharp and relatively coarse (width of laminae is 1–10 cm).

The over-permafrost soil sedimentary sequence 6 has the following horizontal arrangement (Fig. 3A): Anz@-2ABkz-2Bknz-2Anzb-2Bknb1-2Bknb2-2Ch-2C-2Bkb-2Bknb-2A@b-2Bkgb-2Bgb-3BCgb-4Cf. Surface soil (Fig. 3A, Unit 1) is classified as Calcic, Molliglossic, Salic, Natric, Turbic Cryosols (Calcric, Magnesic).

The upper (younger) buried profile (Fig. 3A, Unit 2) is classified as Protovertic Protocalcic Fluvisol (Calcric). The lower (older) soil...
Exchangeable complex of this soil contains up to 58.2% of Mg2+. Soda and NaCl prevail among readily soluble salts.

Deformations, disruption and partial or total destroying due to frost clustered and circular distribution pattern of coarse grains (Fig. 5A).

Table 1

<table>
<thead>
<tr>
<th>Lab index</th>
<th>Section number</th>
<th>Depth, cm</th>
<th>Areal and morpho-stratigraphic allocation</th>
<th>Median</th>
<th>Radiocarbon age, BP</th>
<th>Calibrated date, cal BP (probability 95.4%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGAN-3489</td>
<td>6</td>
<td>17-20</td>
<td>E. p, surface soil, Anz hor. (bottom)</td>
<td>832</td>
<td>910 ± 50</td>
<td>734-926</td>
</tr>
<tr>
<td>IGAN-3964</td>
<td>233</td>
<td>21-24</td>
<td>W. p, surface soil, A hor. (bottom)</td>
<td>2233</td>
<td>2240 ± 70</td>
<td>2046-2359</td>
</tr>
<tr>
<td>IGAN-3967</td>
<td>233</td>
<td>40-43</td>
<td>W. p, Abh hor. (roof)</td>
<td>3910</td>
<td>3600 ± 70</td>
<td>3702-4090</td>
</tr>
<tr>
<td>IGAN-3968</td>
<td>233</td>
<td>85-88</td>
<td>W. p, Ab@b hor. (bottom)</td>
<td>8116</td>
<td>7300 ± 90</td>
<td>7963-8322</td>
</tr>
<tr>
<td>IGAN-3975</td>
<td>233</td>
<td>93-99</td>
<td>W. p, Ab@bhor. (bottom in a wedge)</td>
<td>8316</td>
<td>7510 ± 90</td>
<td>8072-8518</td>
</tr>
<tr>
<td>IGAN-3819</td>
<td>214</td>
<td>90-92</td>
<td>W. p, Ab hor. (roof)</td>
<td>4701</td>
<td>4180 ± 80</td>
<td>4446-4869</td>
</tr>
<tr>
<td>IGAN-3441</td>
<td>1</td>
<td>110-120</td>
<td>E. p, the older buried Ab hor.</td>
<td>11,338</td>
<td>9870 ± 110</td>
<td>10,878-11,802</td>
</tr>
<tr>
<td>IGAN-3428</td>
<td>6</td>
<td>70-72</td>
<td>E. p, 2Anzb</td>
<td>11,951</td>
<td>10,270 ± 880</td>
<td>9541-14,471</td>
</tr>
<tr>
<td>IGAN-3407</td>
<td>6</td>
<td>118-128</td>
<td>E. p, 2Abp</td>
<td>11,731</td>
<td>10,120 ± 130</td>
<td>11,248-12,371</td>
</tr>
<tr>
<td>IGAN-3885</td>
<td>6</td>
<td>86-90</td>
<td>E. p, the younger buried A hor.</td>
<td>11,112</td>
<td>9730 ± 190</td>
<td>10,565-11,810</td>
</tr>
<tr>
<td>LuS-8398</td>
<td>M-6</td>
<td>705</td>
<td>Por-Bazhyn island, the roof of coarse-grained layer under lake sediments</td>
<td>12,241</td>
<td>10,460 ± 250</td>
<td>11,395-12,837</td>
</tr>
</tbody>
</table>

a All dates except LuS-8398 were obtained for specimens of humic acids, the date LuS-8398 was got for a stem of Comarum sp. extracted from the sediments.
b E. p. — east part of the alluvial fan, W. p. — west part of the alluvial fan.

(Fig. 3A, Unit 3) is classified as Protocalcic Protomolliglossic Turbic Cryosol (Calcric, Reductaquaic, Thixotropic, Endosceletic).

The surface soil has strong manifestations of solonization (alkalization, accumulation of exchangeable sodium and magnesium, consolidation and formation of massive prismatic or columnar structure in Bn horizons, redistribution of colloids), and salinization (accumulation of readily soluble salts) processes based both on soil morphology and analytical properties. Diagnostic features of Calcic, Natric and Salic horizons are overlapped here within 2ABknz and 2Bknz horizons. Distinctive morphological features of 2ABknz are dark grayishbrown color, highly consolidated (water dry), massive prismatic structure. There are dark colored, nearly isotropic clay-humus coatings found at microlevel.

pH values are strongly alkaline varying between 9 and 10 (Table 2). Content of organic carbon in the top horizon is 2.52%. That is really low compared with neighboring soils nearly untouched by solonization, where contemporary driving process is Mollic humus formation (6.62% in spite of very close intervals of calibrated age. The older soil (Table 1: the horizon 2A@b horizon at microlevel (Fig. 5B).

2A@b horizon has a thick platy to angular secondary cryogenic macrostructure obtained during diagenesis (Fig. 5C). At the same time there are zoogenic chambers containing welded excrements (Fig. 5D) referred to former biogenic activity. Zoogenic pores and excrements are sometimes deformed by later cryo-diagenesis. Microstructure of the first level is well developed, moderately separated granular (Fig. 5E).

B horizons have features related to seasonal over-permafrost waterlogging: diffuse gray or olive motting related with Fe oxide redistribution, and small Fe–Mn nodules. Besides that B horizons reveal accumulation of secondary carbonates: irregular micritic impregnation of the calcitic crystallothic b-fabric, and rare micritic nodules and coatings.

Only relatively stable analytical characteristics are under consideration here for paleosols: content of Corg, particle size distribution, content of CaCO3, total content of iron, contents of dithionite and oxalate extractable iron (where it was determined). At the same time pH values, exchangeable bases, and conductivity of water extract are not discussed for paleosols, as these parameters characterize contemporary soil conditions.

Content of organic carbon (Table 2) in 2A@b (the top horizon of the older soil) is relatively high for 11–12 thousand year old buried soil (1.21%), and it decreases gradually with depth.

Content of carbonates is relatively high. It demonstrates clear profile differentiation with the minimum content in 2A@b horizon and the maximum — in 2Bkgb horizon, where maximum of secondary carbonates is observed morphologically. It is clear that part of secondary carbonates is diagenic. But the distribution pattern allows one to suppose conditions favorable for eluviation of carbonates from the top horizon and their accumulation in 2Bkgb horizon (means enough atmospheric precipitation and satisfactory intrasoil drainage at a part of a year).

Particle size distribution within the older buried soil is mainly explained with variations of sedimentation processes. Sand fractions (2000–63 μm) have a tendency to increase gradually with depth at slow decrease of the clay fraction (<2 μm). Distribution of the clay fraction demonstrates a small rise in 2Bkgb and the upper part of 2Bgb horizons. This rise is considered to be also lithologically conditioned, taking into account absence of any illuvial clay coatings in these horizons.

There is no clear profile differentiation of clay minerals in the older of buried soils (starting with 2A@b horizon) (Table 3). Existence of physical splitting up at very low rates of chemical weathering is characteristic of permafrost-affected soils (Aleksseev et al., 2003). There is less than 1% of dithionite extractable iron in B and BC horizons at 7–8% of bulk Fe2O3 (Table 2) that also corresponds to the idea of very low rates of chemical weathering supported by possible spring lateral removal of reduced iron along the permafrost table.
3.3. Buried soils related to the first two thirds of the Holocene

Soils on the eastern part of the fan are represented by section 233, N 50.60443 E 97.40260 (Fig. 1C). It has the following over- and permafrost profile A-AB@-Bk-Ab@-2Bknb-2BkCg-2CF. Surface soil is Calcic Molliglossic Turbic Cryosol (Calcaric, Magnesic). The driving soil forming processes here Nowadays are accumulation of Mollic humus and redistribution of carbonates. As opposed to strong evidences of the actual solonization process in the surface soil of section 6, subangular blocky structure and enhanced density are residual in this profile. These features owing to a high share of sodium among exchangeable cations are not supported by contemporary environment. There are low contents of exchangeable sodium (0.3–1.2% of exchangeable bases) and slightly acid to slightly alkaline pH values in the surface profile (Table 2).

Buried soil starts from the depth about 40–55 cm. It is classified as Calcic Molliglossic Turbic Cryosol (Calcric, Re ductaquic, Endosclerotic). Coarse grained basic layer of the fan is found here at about 1 m from the surface (Fig. 3E, Unit 6). These sandy gravels were covered with very thin layer of early Holocene sandy and gravelly silt loams served as a parent material for the buried soil. The last one was overlaid by silt loams resulted from renewed seasonal overbank inundation over the alluvial fan in the middle of the Subboreal.

Buried soil here has well developed mature profile as opposed to the soils of the Pleistocene–Holocene transition. Its Ab@ horizon is very dark brown to black. Highly developed fine granular structure (Fig. 6A) is arranged here in moderately developed subangular blocks (Fig. 6B). At the same time in the surface Mollic horizon granular structure is not well shaped and there are no secondary aggregates (Fig. 6C). There is more than 5% of organic carbon (Table 2) in Ab@ horizon that is comparable to its content in the surface A horizon. Numerous features related to biological activities are registered in the humus accumulative horizons both in buried and surface soils (Fig. 6D).

Both upper and lower borders of the Ab@ horizon are wedged. There are involutions at the lower limit of the horizon (Fig. 3E, Unit 5). There are also strong turbations at the border of the coarse-grained basement and overlaying silt loams.

Bk horizon of the buried soil reveals a considerable accumulation of calcium carbonate: 16.5% comparatively to 4.8% in Bk of the surface soil. Morphological forms of calcite are numerous and variable here. These are micritic coatings (Fig. 6E) and infillings (Fig. 6D), very thin micritic coatings surrounding moderately developed and weakly separated granular aggregates (Fig. 6F). calcite-encrusted biogenic structures, and calcified plant tissues. Whereas in Bk horizon of the surface soil secondary carbonates are only represented by small (about 0.2 mm in diameter) micritic nodules (Fig. 6G) (carbonates of calcitic crystalloptic b-fabric are at least partly lithogenic).

There are relatively abundant redoximorphic pedofeatures (small impregnative nodules) found in all horizons of these buried soils (Fig. 6H).
between 3700 and 4870 cal years ago (IGAN-3967, IGAN-3819). It is

fl
decrease of high
Unit 2) was buried in the western segment of the fan.
above, by strati facie with the two successive buried soils of the Pleistocene
formation was re-established for a period of few centuries or even de-
strong aridization in South Siberia (Vorob'eva, 2010; Zykin et al.,
resulted (Panin et al., 2012). The Terekhol' Basin was characterized by

EDB gb 145 – EDB gb 128 – EDB gb 122 –

– not determined.

### 4. Discussion: Pleistocene–Holocene environmental changes in the Terekhol' Basin

#### 4.1. Fluvial activity

Retrospective analysis of the river Ajyl basin brought following results (Panin et al., 2012). The Terekhol' Basin was characterized by high fluctuations of river discharge at the end of the Late Pleistocene: during the Late (Sartan) chryochrone (MIS-2). During MIS-2 the Ajyl River accumulated a fan overlying the back side of the basin bottom (Fig. 1C). It is supposed to be related to the Late Glacial Maximum (LGM, 20–23 thousand years ago cal.) which is regarded as a period of strong aridization in South Siberia (Vorob'eva, 2010; Zykin et al., 2004), with characteristic drop of surface and river runoff and enhanced accumulation in river valleys (Spasskaya, 2009). This fan was eroded after LGM as a result of an enhanced river runoff in the Late Glacial (the event hasn’t been dated exactly). The only remnant of the Sartan fan has been preserved in the form of a narrow ridge parallel to the basin side.

The maximal intensity of fluvial processes in the basin was reached between LGM and the beginning of Holocene. Gravelly sands at the basement of the alluvial fan (Fig. 3A,E, Unit 6) were accumulated at that time. Termination of accumulation of coarse-grained material was imprint in buried soils of the Pleistocene–Holocene transition. This change is interpreted as a climatically conditioned decrease of the river runoff.

In the Holocene, fluvial sedimentation has never reached its Late Glacial intensity and was characterized by only few short and relatively weak impulses of seasonal flood activity. A very short sedimentation spike terminated the earlier phase of soil formation, and isolated the older soil in the western segment of the fan (Fig. 3A, Unit 3). Then soil formation was re-established for a period of few centuries or even decades, and again it was interrupted by a short period of sedimentation around 11,000 cal years ago, during which the younger soil (Fig. 3A, Unit 2) was buried in the western segment of the fan.

In subaerial soil-sedimentary sequences of the alluvial fan the decrease of high fluvial activity is indicated, as it was mentioned above, by stratified silt loams and silts of the delta-floodplain overbank facie with the two successive buried soils of the Pleistocene–Holocene border.

One more registered impulse of fluvial sedimentation took place between 3700 and 4870 cal years ago (IGAN-3967, IGAN-3819). It is important to mention that the dates obtained from the 2 cm roof layer of Ab@ horizon are considered to be approximate dates of re-established sedimentation. This impulse buried a soil being formed during the first 6–8 kyr of the Holocene.

#### 4.2. Pedogenesis

As it was already mentioned the Pleistocene–Holocene border was marked in the Terekhol' trough by the general climatically conditioned decline of fluvial processes. The transition period is characterized by confrontation between fluvial sedimentation and pedogenesis at general decrease of fluvial processes. Two successive short phases of pedogenesis left different paleosoils recording a contrast environmental change.

A set of morphological and analytical characteristics in the older paleosol of the Pleistocene–Holocene transition could be formed in permafrost-affected environment with relatively shallow permafrost table restricting vertical drainage. It is obvious that dry material is not frost-susceptible. If the water supply is small, no “wet” cryogenic processes such as segregation of ice, heaving, cryoturbation and solifluxion take place (Van Vliet-Lanöe, 1998; Van Vliet-Lanöe et al., 2004). Thus numerous features related to turbonation and solifluxion in the older buried soil prove a sufficient water supply of the soil: namely conditions at least seasonally close to field water capacity. Features related to redistribution of iron oxides also support seasonal over-moistening and reducing conditions. At the same time seasonal over-moistening hardly was continuous taking into account faint redoximorphic features and absence of noticeable impoverishment of subsurface horizons by iron compounds. Profile distribution pattern of carbonates supposes their possible seasonal lateral influx and impregnative accumulation followed by eluvo-illuviative redistribution in summer when the soil was well drained. There are also features evidencing high biological activity such as dark color of the 2A@ horizon, relatively high for 12,000 year old soil content of organic carbon, biogenic pores, and excrement.

Granular structure was described in the 2A@b horizon of the older soil of transitional period. Granular structure is very common for Cryosols and supposed to be originating from frost heave and/or from lateral displacement by solifluxion (Van Vliet-Lanöe, 1998, 2010; Van Vliet-Lanöe et al., 2004). Some authors attribute the formation of well rounded aggregates to gelification in water-saturated environments (Smith et al., 1991). The granular structure in studied soil most probably has dual genesis. It was created and supported both by zoogenic activities

### Table 2

Analytical characteristics of pedo-sedimentary sequences.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth, cm</th>
<th>pH</th>
<th>Corg., %</th>
<th>CaCO3, %</th>
<th>EC of water extract, mS/cm</th>
<th>Exchangeable bases, % Total exchange bases mEq/100 g</th>
<th>Fe2O3 d, %</th>
<th>Fe2O3 ox, %</th>
<th>Fe2O3 total, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0–15</td>
<td>6.7</td>
<td>6.62</td>
<td>0.07</td>
<td>0.288</td>
<td>64.5</td>
<td>3.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB@</td>
<td>15–24</td>
<td>7.7</td>
<td>4.66</td>
<td>0.14</td>
<td>0.326</td>
<td>74.9</td>
<td>2.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bk</td>
<td>24–40</td>
<td>8.5</td>
<td>4.02</td>
<td>0.48</td>
<td>0.436</td>
<td>77.6</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ab@</td>
<td>40–66</td>
<td>8.3</td>
<td>5.28</td>
<td>0.35</td>
<td>0.405</td>
<td>86.9</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ab@b</td>
<td>66–88</td>
<td>8.7</td>
<td>2.65</td>
<td>1.39</td>
<td>0.331</td>
<td>62.1</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ab@b+</td>
<td>88–112</td>
<td>9.0</td>
<td>1.19</td>
<td>16.46</td>
<td>0.587</td>
<td>46.5</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Section 233

| A       | 0–15      | 6.7 | 6.62     | 0.07     | 0.288                    | 64.5                                          | 3.03      |            |                |
| AB@     | 15–24     | 7.7 | 4.66     | 0.14     | 0.326                    | 74.9                                          | 2.74      |            |                |
| Bk      | 24–40     | 8.5 | 4.02     | 0.48     | 0.436                    | 77.6                                          | 0.31      |            |                |
| Ab@     | 40–66     | 8.3 | 5.28     | 0.35     | 0.405                    | 86.9                                          | 0.5        |            |                |
| Ab@b    | 66–88     | 8.7 | 2.65     | 1.39     | 0.331                    | 62.1                                          | 0.2        |            |                |
| Ab@b+   | 88–112    | 9.0 | 1.19     | 16.46    | 0.587                    | 46.5                                          | 0.7       |            |                |
(clearly detected by zoogenic pores with excrements) and by well-documented turbation and solifluxion.

Strongly stratified overbank sediments, which cover the older soil, contain continuous lamina rich in frost shattered charcoal particles (Fig. 5H). This lamina occurs in a number of sections. Possibly it records a prominent fire event which occurred at the Holocene transition.

From the layer of overbank sediments at the contact with the older buried soil statistically valid pollen data were obtained (layers above and below this contact were very poor in pollen grains). Arboreal pollen prevails here (67.1%). *Picea obovata* makes 32% of arboreal sum. There are variable herbs that occur in the spectrum: *Rosaceae, Caryophyllaceae, Ranunculaceae, Thalictrum sp., Rumex sp., Fabaceae, Lamiaceae, Primulaceae, Geranium sp., Viola, Compositae*, and *Cirsium*. Such a spectrum testifies on climatically warm and mild conditions in the basin during the layer’s accumulation which is in good correspondence with regional palynological data. Time border 11,000 cal yrs BP considered as a starting point of early Holocene afforestation: expansion of dark-coniferous forests in the South Siberian Mountains (Blyakharchuk et al., 2004, 2007). Thus afforestation of mountain surrounding of the basin took place, induced by general climatic amelioration, but basing on obtained soil data we could say that the landscapes within the basin stayed open.

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**Fig. 5.** Buried soils of the Pleistocene–Holocene transition (section 6): micromorphological features. A. ZBghb horizon: linear distribution of coarse grains, X. B. ZA@b horizon: involution of enriched in humus (darker) and enriched in clay material, ||. C. ZA@b horizon: 2nd order angular blocky structure, ||. D. ZA@b horizon: chamber with welded excrements, ||. E. ZA@b horizon: 1st order granular structure, ||. F. ZAnzb horizon: inclined subangular blocky structure, cross-stratified b-fabric, ||. G. ZAnzb horizon: inclined lenticular aggregates (a) and granular aggregated (b), 1/2 X. H. 2C horizon: internal fabric of a lamina with shattered charcoal particles, ||.
In spring time ice lenses melt and expandable clays swell. Shrinking cold climate with strong seasonality and available source of alkaline contradiction between cryogenic and vertic features. Arid or semi-arid ground (Vogt and Larqué, 1998, 2002). Contents of total magnesium some evidences of smectite neoformation in permanently frozen Campbell, 2004; Van Vliet-Lano decades. Cryosols are supposed to be related there with warming of the last.

Vertic features being normally attributed to subsurface horizons are blocky pedality, extreme hardness of peds, and cross-striated b-fabric. Of the younger buried soil such as high degree of inclined angular-titles stimulated development of Protovertic features in 2Anzb horizon. Lake could be more saline in more arid phases. Accumulation of smectites, chlorite, and clay minerals stimulated development of Protovertic features in 2Anzb horizon. Such conditions are for an instance realized in soils surrounding salt lakes (Furquim et al., 2010). Moreover there are soils with vertic properties were discovered in a neighboring Trans-Baikal region of the South Siberia (Kovda and Lebedeva, 2012).

Thus the short second phase of pedogenesis at the very beginning of the Holocene characterized by above-described set of features could be reasoned by warming which reduced intensity of cryogenesis and gave way to formation of vertic features, and/or by aridization restricted annual water supply and made soil less frost-susceptible. This phase of soil formation was preceded by a short ecological arid stress with extensive fires and an episode of intensive post-fire erosion–sedimentation. Most probably both warming and aridization took place. But the most important change seems to be in a distribution of annual precipitation sum and changes in hydrology of the area. At the background of general warming, seasonality of water supply was enhanced due to a rise of winter precipitations, a drop of summer precipitations and increased summer temperatures. These climatically induced changes stimulated the sharp changes in the character of pedogenesis from cold, cryogenic, permafrost-affecting, relatively balanced in water supply with seasonal over-permafrost water logging to warmer, arid with clear summer—autumn water deficit and possible spring water saturation.

Paleosols of the first two thirds of the Holocene have well developed profile which is generally similar on its genesis both to the older paleosols of the Pleistocene–Holocene transition and to the surface Calcic Mollic Glossic Turbic Cryosol. They differ from the older soils of Pleistocene–Holocene border mostly by much more developed profile where “Proto”–features had developed to its mature state. These paleosols differ from the surface non-solonetzic soils by strongly developed granular pedality not only in its top horizon, but also in subsurface horizons and by numerous variable calcitic pedofeatures. We regard both of these features as evidences of better water supply of this paleosol comparatively to the surface non-solonetzic soils.

Actually the relations between morphology of secondary calcite and conditions of its formation are not studied enough and to some extent contradictory (Durand et al., 2010; Kovda, 2008). Applying the actualistic approach we conclude that such a variety and abundance of secondary calcite in surface soils of the basin are found only in conditions of contemporary or recent additional (lateral) water supply: under a mountain slope and on soils of palsas islands. That means that soils that had been formed during the first two thirds of the Holocene, and had better water supply than contemporary soils in the same positions.

Thus, comparatively to contemporary surface soils, the soils formed in the first two thirds of the Holocene and buried about 4000–5000 cal yrs BP were formed in conditions of better, well seasonally-balanced water supply. There are evidences features related to a high biological activity, intensive “wet” cryogenic processes, additional (lateral) water supply and related seasonal short-term water logging. These soils buried by the last considerable sedimentation event over the fan never have any manifestation of solonization process, as opposed to contemporary soils, where Natric features are widespread together with signs of progressive salinization. There is no blocky or columnar structure, no high density, and no pedogenetic textural contrast in buried

### Table 3

Mineralogical composition of clay fraction (< 1 μm) in section 6.

<table>
<thead>
<tr>
<th>Horizons</th>
<th>Depth, cm</th>
<th>Composition of minerals: Mca — mica, Chl — chlorite, Kln — kaolinite, Sme — smectite, Vrm — vermiculite, Ild — interlayered, Qtz — quartz, Fsp — feldspars, Cal — calcite, Dol — dolomite</th>
<th>Groups of clay minerals, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anz#</td>
<td>0–17</td>
<td>Mca, Chl (Mg) or Chl-Vrm, Kln, Ild Chl-Sme, Qtz (tr*), Fsp (tr), Dol (tr)</td>
<td>Sme + Ild 60 8 32</td>
</tr>
<tr>
<td>2Ahkzn</td>
<td>17–35</td>
<td>Ild Chl-Sme, Chl (Mg), Mca, Kln, Qtz (tr), Fsp (tr), Cal (tr), Dol (tr)</td>
<td>Mca 21 37 145</td>
</tr>
<tr>
<td>2Blz</td>
<td>35–70</td>
<td>Sme, Chl (Mg) or Chl-Vrm, Mca, Kln, Qtz (tr), Fsp (tr), Cal (tr), Dol (tr)</td>
<td>Ktn 27 37 202</td>
</tr>
<tr>
<td>2Anzb</td>
<td>70–72</td>
<td>Sme, Chl (Mg) or Chl-Vrm, Mca, Kln, Qtz (tr), Fsp (tr)</td>
<td>Ktn 27 37 202</td>
</tr>
<tr>
<td>2Bkzb1</td>
<td>72–80</td>
<td>Sme, Chl (Mg), Mca, Kln, Qtz (tr), Dol (tr)</td>
<td>Sme 42 26 281</td>
</tr>
<tr>
<td>2Bkzb2</td>
<td>80–95</td>
<td>Sme, Chl (Mg), Mca, Kln, Qtz (tr), Fsp (tr), Dol (tr)</td>
<td>Sme 42 29 29</td>
</tr>
<tr>
<td>2Cn</td>
<td>95–102</td>
<td>Sme, Chl (Mg) or Chl-Vrm, Mca, Kln, Qtz (tr), Fsp (tr), Dol (tr)</td>
<td>Sme 48 27 102</td>
</tr>
<tr>
<td>2C</td>
<td>102–118</td>
<td>Sme, Chl (Mg) or Chl-Vrm, Mca, Kln, Qtz (tr), Fsp (tr)</td>
<td>Sme 45 23 102</td>
</tr>
<tr>
<td>2Ahlb</td>
<td>118–128</td>
<td>Sme, Chl (Mg), Mca, Kln, Qtz (tr), Fsp (tr), Dol (tr)</td>
<td>Sme 35 41 128</td>
</tr>
<tr>
<td>2Bkglb</td>
<td>128–145</td>
<td>Sme, Chl (Mg) or Chl-Vrm, Mca, Kln, Qtz (tr), Cal (tr)</td>
<td>Sme 37 39 145</td>
</tr>
<tr>
<td>2Bgb</td>
<td>145–184</td>
<td>Sme, Chl (Mg), Mca, Kln, Qtz (tr), Fsp (tr), Dol (tr)</td>
<td>Sme 33 40 184</td>
</tr>
<tr>
<td>3Bccb</td>
<td>184–200</td>
<td>Sme, Chl (Mg), Mca, Kln, Qtz (tr), Fsp (tr), Dol (tr)</td>
<td>Sme 43 32 200</td>
</tr>
</tbody>
</table>

* tr — traces.
soils. So that most probably alkalization, solonization and salinization are the processes related to Subboreal and Subatlantic time of increased continentality and aridization.

Surface soils of the delta-alluvial fan in its western part have nearly the whole Holocene age. These soils demonstrate obvious evidences of polygenesis. That means that a set of their characteristic morphological and analytical features is formed within more than one evolutionary stages coursed by successive environmental changes. As it was discussed earlier, diagnostic features of Calcic, Natric and Salic horizons are overlapped here within a single B horizon. Normally these features may occur within a single profile, but they are distributed in a depth from top to bottom of a profile as Natric, Calcic, then Salic horizons (features). Occurrence of these contradictory features within a single horizon of the surface soils could be considered as an evidence of their polygenesis. We suppose that secondary solonization (accumulation of exchangeable sodium and magnesium, alkalinization, risen mobility of clay and humus, consolidation, formation of massive columnar structure) followed by salinization (accumulation of readily soluble salts) of former Calcic horizon developed resulting from progressive aridization and a rise of continentality. Actually equilibrium within this triad of processes in the ultracontinental arid–subarid landscapes with close permafrost table seems to be very labile. In such landscapes these processes are especially sensitive to general fluctuations of water supply (as a cumulative result of atmospheric precipitation and its seasonal distribution, changes of base level of erosion, factors of atmospheric water redistribution: depth of permafrost table and its roof topography etc.).

Typical for Solonetz and diagenetically resistant features such as specific massive blocky or columnar structure, high density, sharp decrease of labile phase at risen illite in the composition of clay minerals, have not been found either in soils of Pleistocene–Holocene border or in soils

Fig. 6. Buried soils of the first two thirds of the Holocene (section 233): micromorphological features. A. Ab@ horizon: 1st order granular structure. B. Ab@ horizon: 2nd order blocky structure. C. A horizon: granular structure. D. Abkh@ horizon: chamber with excrements and micritic infilling. E. Abkh@ horizon: micritic coatings. F. Bk@ horizon: moderately developed weakly separated granular structure and crystallitic b-fabric and strong micritic impregnation. G. Bk horizon: crystallitic b-fabric and micritic nodule. H. Bk@ horizon: Fe nodules.
buried about 4000 years ago. This fact allows supposing that the time before 4000 BP was relatively more humid and more balanced in water supply (with the exception of the short period of sharp aridization imprinted in the younger paleosols of the Pleistocene–Holocene transition). Only the last 4000 years gave way to processes of solonization and salinization.

4.3. History of the Terekhol’ Lake and its islands

Together with soil-sedimentary sequences of the delta-alluvial fan, lacustrine sediments were studied in cores from the bottom of the Terekhol’ Lake and on palsas-islands, as well as soils developed on the islands of different height-age groups. A story of lacustrine sedimentation, appearance and following evolution of islands and their soils were reconstructed basing on litho-stratigraphic studies of dated sedimentary columns, supported by the data on bulk chemical composition. Complex group analysis of biological composition supplied with ecological analysis was applied for diagnostics of environmental changes in the lake and on islands. The method was developed by N.V. Korde (1960) for lacustrine sediments, and later supplemented and successfully approved for other water-related environments (Skyrninikova et al., 2011). These data were published in Bronnikova et al. (2010) and Panin et al. (2012). Here we only cite general conclusions and examine their correlation with above-stated paleopedological results.

The Terekhol’ Lake has thermokarst–alluvial-imposed origination. It appeared 11,000 cal yrs BP as a result of permafrost melting provoked by abundant river inundations. Five periods of enhanced river discharge and high lake water level were revealed: 11,000–10,500, 9500–9300, 7300–6200, 3800–3500 and 2700–2300 cal yrs BP. It was proved that the described fluctuations of water discharge and lake level in the Holocene have no relations to tectonic processes. Thus the fluctuations indicate climatic changes. The first half of the Holocene (before 6200 cal yrs BP) is characterized by unstable humidification and by sharp short-term changes of water influx into the lake. The highest water intervals were periods of risen river discharge. Steady aridization is characteristic of the second half of the Holocene. Reach-through winter freezing of the lake bottom resulted in formation of palsas islands during cryoarid epochs 6200–3800 and 2000 cal yrs BP — until now. These two generations of numerous palsas appeared to be stable enough until now. The 3800–2000 cal yrs BP period was somewhat more water abundant, mostly due to enhanced underground influx. The most severe and stable aridization is detected for the last 2000 years with relatively less arid XX century.

5. Conclusions

Thus the conducted studies of alluvial soil-sedimentary sequences, lacustrine sedimentary sequences, and surface soils of the Terekhol’ Basin allowed one to establish following evolutionary stages for different components of the geosystem and environmental conditions corresponding to these stages. Maximal intensity of fluvial processes in the basin took place in the very Late Pleistocene; this stage was terminated at the Pleistocene–Holocene border by two successive paleosols (12,200–11,000 cal yrs BP). First of them was formed in a meadow-steppe (or tundra-steppe?) permafrost affected landscape with a considerable water supply and short seasonal over-permafrost water stagnation. The second one was formed during a short phase of relative warming and/or sharp aridization, in conditions of suppressed biological activity and seasonally contrast water regime. The thermokarst–alluvial-imposed Terekhol’ Lake appeared in the basin about 11,000 cal yrs BP, and then it extended its water area due to permafrost melting, particularly because of seasonal river floods. Phase between 11,000 and 4000 cal yrs BP was generally unstable concerning moistening, but at the same time well balanced towards precipitation/evaporation ratio and annual distribution of atmospheric precipitation. There were no seasonal floods due to well balanced water regime. Progressive aridization started about 6200 cal yrs BP. Most arid phases occurred 6.2–3.8 and 2.0–0 cal yrs BP. In these phases newly formed permafrost elevated numerous palsas-islands due to reach-through freezing of the lake and lacustrine sediments. The phase 3800–2000 cal yrs BP was some more abundant in water. The last 2000 years are characterized by the most severe and steady aridization. The lake level dropped and its flowage decreased considerably. In soil mantle this last aridization is imprinted in a wide distribution of Natic features and in progressive salinization.

We can conclude that general trends of climatic changes recorded in fluvial soil-sedimentary sequences and in lacustrine sediments of the basin are the same: unstable humidification of the first half of the Holocene, the warmest and most humid interval in the middle of Holocene, increasing aridization in its second half and especially in the last 2000 years. Similar general trends were described earlier basing on studies of different sedimentary and paleosol records in Tyva, Altaj, Trans-Baikal region, Mongolia (Vipper et al., 1976; Rudaya et al., 2009; Dergacheva et al., 2006; Blyakharchuk et al., 2004, 2007, 2008; Schwanghart et al., 2009; Vorob’eva, 2010).

In spite of revealed similar general regularities, lacustrine record differs from paleosol one in some important details. The most contradictory is the Pleistocene–Holocene transition and particularly Pre-Boreal period. There are a lot of discrepancies among researches in the understanding of this epoch. This is explained most probably by drastic, fast, and oscillatory climatic changes at that time. Lacustrine record of the Terekhol’ Basin testifies on a short but intensive rise of water influx. Actually that was the time of the establishing and first expansion of the lake. This event was related to melting of the permafrost due to both early Holocene climatic warming and enhanced seasonal inundations. At the same period soils recorded warming and increased seasonality of the water supply. The established lake most probably wasiguate in small part to the regulation of local hydrology and changes in soil water regimes. We suppose that the appearance of vertic features in soils is related to generally improved drainage of the area after the lake establishment more than to climatic aridization.

As it was mentioned earlier (Sedov et al., 2009), the lacustrine record has higher resolution on the time scale. This conclusion is valid even in the case of Terekhol’ Lake which is characterized by extremely low rates of sedimentation. Particularly there is no detailed paleosol record for a long-term and environmentally labile epoch of the Boreal, the Atlantic and the beginning of the Subboreal. The only one buried soil corresponds to this long period. It contains generalized palimpsest record. It is hardly possible to reconstruct and date it step-by-step.

At the same time paleosol data provide more space-specific and definite picture of landscape conditions. That is especially important for very complicated and variable permafrost-affected landscapes of ultracontinental mountain regions. Thus, Late Pleistocene–Holocene environmental evolution in the Terekhol’ Basin appeared to be generally low-contrast as based on paleosol data. In spite of fluctuations of river discharge and lake water level which seem to be considerable, studied area stays all the time in the frame of more or less continental permafrost sub-arid to arid conditions with landscapes varying from meadow-steppe (probably tundra-steppe in the very beginning) to dry steppe.

Acknowledgments

This work became possible due to long-term collaboration with archaeologists and first of all with Dr. I.A. Arzhantseva. We’d like to express our special thanks to the Non-commercial Organization Cultural Foundation “Por-Bazhyn” for financial support and great help in organization of fieldworks. Funding for field and laboratory research in 2009–2011 was provided by the Russian Foundation for Basic Research (projects 09-04-01742-a, 09-05-00351a, 09-04-10511-k). We are very grateful to our friendly and highly professional field team: E.D. Sheremetksaja, Dr. A.E. Ivanova, LG. Shorkunov, S.S.