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HOLOCENE ENVIRONMENTAL CHANGE IN SOUTH-EAST ALTAI EVIDENCED BY SOIL RECORD

ABSTRACT. The soils of Russian Altai highlands were used as a paleoenvironmental archive, as a source of dating material, and as a chronostratigraphic marker to describe Holocene environmental change in the studied area. Based on calibration intervals of 14C dates obtained for buried humus horizons (11 buried soils in 6 studied soil-sedimentary sequences) and some dates from pendants of contemporary soils, following stages of pedogenesis were recorded in studied soil-sedimentary systems and surface soils: 6.4 – 11.5 ky cal BP; about 4.9-5.3 cal BP; 2.5-3.8 cal BP; 0.6 – 1.2 cal BP. All studied surface soils in the basins nowadays develop in cold, ultra-continental water deficit conditions: Skeletic Kastanozems Cambic, Skeletic Cambisols Protocalcic, Skeletic Cambic Calcisol Yermic. The most extreme conditions of soil formation within Holocene were within the last 1-2 kyr. All buried soils were formed in better conditions, more balanced in water, with higher biological activity, mostly within steppe or forest-steppe landscapes. Cryogenic features had been insisting all over the Holocene till nowadays. Water demandant cryogenic features are met in buried soils up to the age of 1-2 ky cal BP. In the last millennia cryogenic processes are suppressed, water demandant features gave way to those which can be formed in contemporary water deficit conditions: simple fissures, frost sorting, and shattering. At lower levels (Kuraj basin) more or less arid cold steppe conditions insisted within the most part of Holocene. Initial stages of soil formation were often ground water affected, or at least shortly waterlogged. At the highest positions humid and relatively warm Early Holocene stage of forest pedogenesis is recorded for the beginning of Holocene, and a Late Holocene (last 3-4 kyr) cold humid phase, presumably under mountain tundra and/or alpinic. Microsedimentary intra-soil record in carbonate-humus pendants imprints fine fluctuations of soil water regime at initial stages of soil formation, controlled by local topography, and climatic changes in the second half of Holocene. General trends of environmental changes in the region recorded in soil and soil sedimentary systems are in well correspondence with other records of paleoenvironment.

KEY WORDS: paleoenvironmental records, soil-sedimentary sequences, paleosols, multilayered pendants, Altai, Holocene

CITATION: Maria A. Bronnikova, Yuliya V. Konopliankova, Anna R. Agatova, Roman K. Nepop, Marina P. Lebedeva (2018) Holocene Environmental Change In South-East Altai Evidenced By Soil Record. *Geography, Environment, Sustainability*, Vol.11, No 4, p. 100-111

DOI-10.24057/2071-9388-2018-11-4-100-111

INTRODUCTION

Paleoenvironmental changes in the Russian Altai in the end of the Late Pleistocene and Holocene have been studied using different proxy records and indicators, such as pollen, diatoms, and chironomids in lake sediments, landforms and lithostratigraphy of glacial, lacustrine, and fluvial deposits (Butvilovskij 1993; Rudoy and Baker 1993; Westover et al. 2006; Blyakharchuk et al. 2007; Ilyashuk and Ilyashuk 2007; Carling et al. 2011; Nazarov et al. 2012; Agatova et al. 2012, 2015 and many others). At the same time research on Holocene paleosol records of the region are few in number (Dergacheva et al. 2006; Dergacheva et al. 2007; Agatova et al. 2016; Bronnikova et al. 2017, 2018)

As far as the Altai is the ultracontinental mountain area with strongly differentiated climatic and landscape conditions, environmental changes here are not only time-, but also strongly space-dependent. Specific of soil body as a recording system is recording the information about surrounding local environment *in situ*, unlike sedimentary systems keeping generalized environmental information on the area of their sedimentation basins. Therefore soils, being environmental archive with high space-resolution (Targulian and Goryachkin 2008) (in comparison with sedimentary records which can have high time resolution at nearly always low space resolution) have certain preferences in paleoenvironmental reconstructions, especially in the areas with high spatial variability of environments.

Besides paleoenvironmental meaning, soils can be used as a source of dating material, and as a chronostratigraphic marker, especially taking into account the deficit of appropriate dating material in sediments

of the studied area. Soil development in basins and valleys of the highland of Russian Altai (South-East Altai) has started after the drainage of dammed lakes existed there in the Late Pleistocene (Rudoy and Baker 1993; Butvilovsky 1993; Herget 2005 and many others). The oldest dates obtained from buried and surface polygenetic soils could be regarded as a low limit of subaerial phase and soil formation.

This paper is the first approach to generalization of authors' paleoenvironmental data both for polygenetic surface soils (survived at least ones an environmental change resulted in changing direction of soil formation), and a number of soil-sedimentary sequences studied in the area.

The main objective of the work is to describe soil record of Holocene environmental change in Russian Altai and to compare it with other known environmental records.

STUDY AREA AND OBJECTS OF RESEARCH

Objects of research (Fig. 1) are situated in the South-East Altai. This mountainous area is characterized by ultracontinental climate with high annual and diurnal amplitudes of temperature, permafrost-affected landscapes (permafrost table is 2-3 m in well-drained positions), low mean annual temperatures (about -6 °C) and low annual precipitation sum (less than 200 mm in the floor of the intermountain depressions, summer maximum), that support very specific cryoarid landscapes. Surfaces polygenetic soils containing multilayered coatings were studied on the example of landscape-altitude sequence in the South-Eastern Altai (Fig. 2): profile Bog-12, N 49°45.828' E 89°27.247' under a cryoxerophyte steppe with alpine elements (2400 m) in the Boguty river valley, profile Ak-8, N 50°16.282' E 89°35.722'

under a cryoxerophytic steppe (2200 m) in the lake Ak-Khol basin, and profile KA-1, N 50°03,944' E 88°29,061' under a deserted cryoxerophyte steppe (1900 m) in Chuya basin.

Buried paleosols of soil-sedimentary sequences was studied on the example of six objects (Fig. 3) in big river valleys and intermountain basins of Altai Mountains. Studied objects are as follows: Profile №1 in Kuraj basin, Borotal mouth, 1465 m a.s.l.; Profile №2 in Chuya river valley, between Kuraj and Chuya basins, Sukhoj brook mouth, 1635 m a.s.l. (50° 9'51.06"N, 88°11'19.32"E); Profile №3 in Chuya river valley, between Kuraj and Chuya basins, Kuektanar mouth, 1730 m a.s.l. (50° 9'36.00"N 88°17'46.50"E); Profile №4 in small tributary valley in Boguty river valley, 2472 m a.s.l. (49°45'44.96"N 89°26'14.31"E); Profile №5 in lake Ak-Khol basin, 2226 m a.s.l. (50°16'19.65"N 89°36'4.88"E); Profile №6 in Mogen-Buren River valley, 2083 m a.s.l. (50°14'25.00"N 89°41'59.20"E).

MATERIALS AND METHODS

Both surface polygenetic soils and buried paleosols of soil-sedimentary sequences located in the bottoms of big river valleys (Fig. 1, 3, sections 1-3) and within intermountain basins of Altai Mountains (Fig. 1, 3, sections 4-6, profiles KA-1, Ak-8, and Bog-12), between 1400 and 2500 a.s.l. were studied as markers of landscape stability and sources of paleoenvironmental information. Pedolithostratigraphy and soil morphology were studied at the field stage. Further micromorphological diagnostics of pedogenic processes was accomplished in thin sections, under a polarizing Nikon E200 Pol microscope. The radiocarbon dating of the samples from buried soils was performed by the scintillation method in the Institute of Geology and Mineralogy of the Siberian Branch of the Russian Academy of Sciences. The residual activity of carbon was measured on a Quantulus-1220 device. Dates obtained for buried soils are concerned as their minimal age.

Several dates were obtained for carbonates and humus of layered pendants skinned

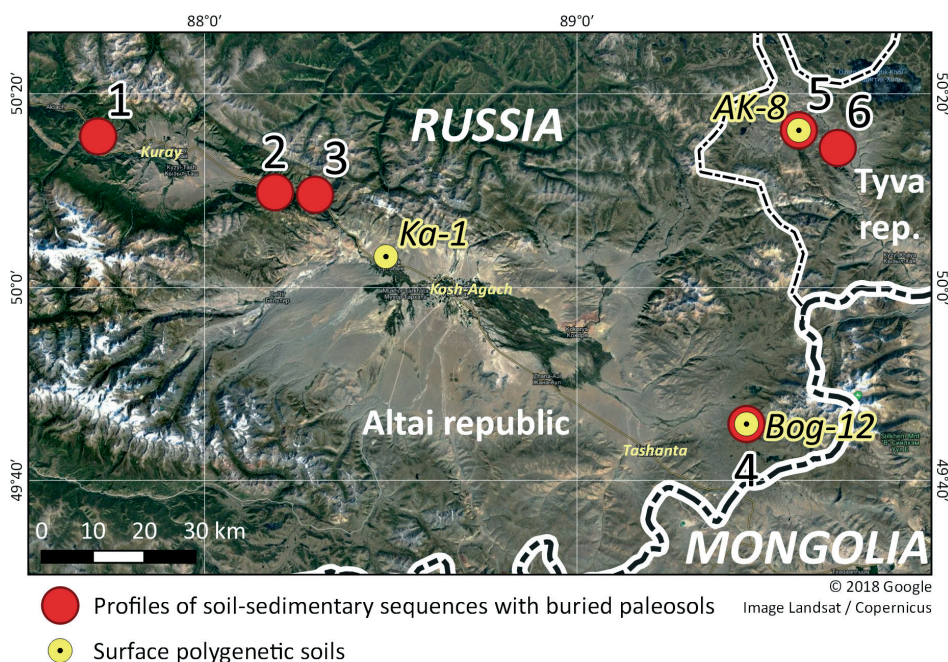


Fig. 1. Location of the studied objects.

Red points with numbers are positions of buried paleosols of soil-sedimentary sequences, yellow points are positions of studied surface polygenetic soils

Boguty valley

Skeletal Kastanozem

Cambic (2400 m), p. Bog12

Ak-Khol lake

Skeletal Cambisol

Protocalcic (2200 m), p. Ak-8

Chuya valley

Skeletal Cambic Calcisol

Yermic (1900 m), p. Ka-1

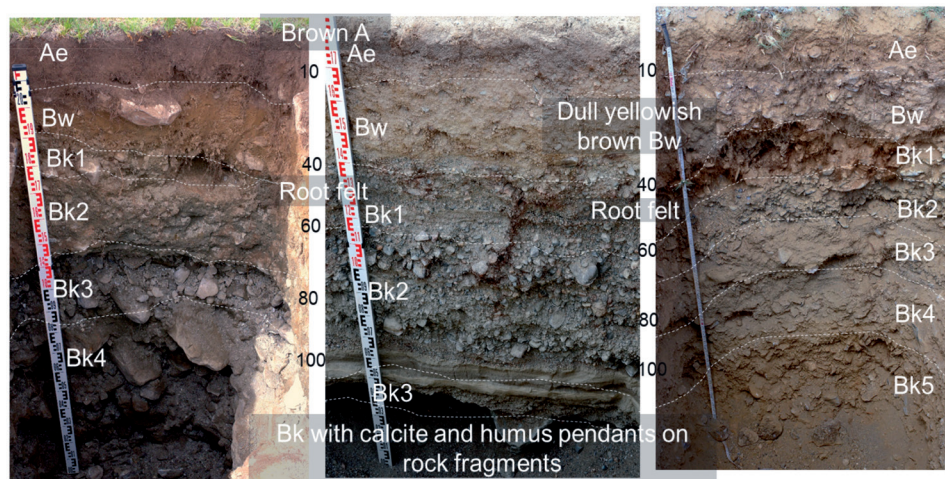


Fig. 2. Objects of research. Morphology of surface polygenetic soils

off coarse fragments within contemporary soils. Approaches for radiocarbon dating of carbonate coatings were earlier discussed in Pustovojtov (2003), Pustovojtov et al. (2007). The radiocarbon dating of pendants was performed at the Center of Isotope Research of the University of Georgia. The $^{14}\text{C}/^{13}\text{C}$ ratio in the graphite was measured using a 0.5 MeV tandem system - an accelerator-1.5SDH-1 Pelletron AMS mass spectrometer. All measurements were made relative to the OXI standard.

The radiocarbon age was calculated using the period of Libby half-life—5568 years. All dates were corrected for the natural isotope fractionation and calibrated in calendar years. Calibrated ages are reported as intervals with standard deviation of $\pm 2\sigma^{14}\text{C}$.

RESULTS AND DISCUSSION

Dating paleosols and carbonate pendants in surface soils

An absolute chronology for most of the sections presented in the paper have been discussed earlier in detail (Agatova et al. 2016; Bronnikova et al. 2017; Bronnikova et al. 2018). As based on calibration intervals of ^{14}C dates obtained for buried humus

horizons (11 buried soils in 6 studied soil-sedimentary sequences, Fig. 3) and some dates from pendants of contemporary soils, following stages of pedogenesis were recorded in studied soil-sedimentary systems and surface soils (Fig. 5): 6.4 – 11.5 ky cal BP (4 buried soils in objects №3, №4, carbonates of pendants); about 4.9–5.3 cal BP (1 buried soil in object №6); 2.5–3.8 cal BP (4 buried soils in objects №1, №2, №4, №5, humus of pendants); 0.6 – 1.2 cal BP (2 soils in objects №1, №2).

Polygenetic surface soils

All studied surface soils (Fig. 2) in the basins according to the Russian system are classified as cryoarid (Field Guide, 2008). Those are specific soils of cold, ultra-continental water deficit conditions under low productive cryoxerophytic short grass steppes and semideserts. At the same time in World Reference Base for Soil Resources studied profiles get into three different big groups: Skeletal Kastanozem Cambic (Bog-12, 2400 m a.s.l.), Skeletal Cambisol Protocalcic (Ak-8, 2200 m a.s.l.), and Skeletal Cambic Calcisol Yermic (Ka-1, 1900 m). The upper part of the soil profile (0–40 cm) in all studied surface soils is subdivided into brown A, rather high in organic carbon due to numerous fine plant residues, and



Fig. 3. Objects of research. Morphology and radiocarbon age of buried paleosols in soil-sedimentary sequences

dull yellowish brown Bw horizons. Both are characterized by granular microstructure, clayey-humus and silty coatings on mineral grains. The Bk horizons are very stony, characterized by a variety of multi-layered calcite and humus pendants rock fragments. Studied soils are polygenetic. Bk horizons contain evidences of a former consecutive change of illuvial and hydrogenic intra-soil migration and accumulation of carbonates as layers of multilayered calcite pendants in semiarid environments and illuviation of humus in humid conditions (humus layers of multilayered pendants). These stages

of soil evolution recorded in multilayered pendants were described basing on detailed morpho-analytical research in Bronnikova et al. (2017).

Despite location within permafrost-affected area and severe temperature regime, such highly water-demanding cryogenic features as wedges and tongues at horizon borders, material mixed by cryoturbation, disrupted soil horizons, involutions, organic intrusions, frost heave usually are very rare if any in both in polygenetic whole Holocene cryoarid sur-

face soils and in young contemporary soils at the top of soil sedimentary sequences. Though others related to frost action, such as silt cappings and other features related to frost sorting, frost-shattered aggregates and mineral grains, specific cryogenic structures: granular "ovoid", one and those related to ice lenses formation: lenticular, lens-like etc. occur but reveal rather modest development in surface soils.

Paleosols in soil-sedimentary sequences

All surface soils in studied soil sedimentary sequences have relatively thin (10-15 cm) brown humus horizon, rich in fine weakly humified plant detritus and poor in organic fine material (Fig. 4a). Topsoils of profiles 1-3 located within low river valleys (profiles 1-3) contain secondary pedogenic carbonates (Fig. 4b). Macromorphological cryoturbation features usually do not occur in surface soils of pedo-sedimentary sequences. All other cryogenic features are weakly manifested in surface soils comparatively to all buried ones.

All buried topsoils are mollic, dark coloured, have fine granular zoogenic structure (combined with cryogenic structural elements) (Fig. 4d-I, e-I), full of biogenic channels (Fig. 4e-II) and other signs of high biological activity.

All buried profiles have numerous and variable features related to frost action. First of all these are glossic boundaries of humus horizons, disruptions of horizons, and involutions (Fig. 4c). There are turned vertically coarse grains (Fig. 4e-IV), results of frost shattering at all level: from big stones up to single mineral grains (Fig. 4f-II), frost sorting resulted in silt and loamy cappings on coarse fragments, linear and circular oriented silt and sand particles, and different types of cryogenic structures. Level of pedogenic accumulation of carbonates is very different: some of the profiles are free of carbonates (section 4, soils in time span 2,7-8,2 BP), or contain residual quantities of carbonates (lowermost soil in section 4, soil in section 5); others are rich in pedogenic carbonates in their Bk horizons (section 1-3, 6).

Buried topsoils and underlying horizons often demonstrate features related to mobility of fine amorphous organic matter (Fig. 4d-II, e-III) testifying on water availability, percolative water regime and intrasoil environment favourable for dispergation of amorphous organic material. In deep horizons of some buried soils redoximorphic features were described (Fig. 4 f-I). All paleosols in soil-sedimentary sequences within low river valleys reveals profiles with mollic horizons and accumulations of pedogenic carbonates which generally corresponds to water balanced steppe environment.

Some of the paleosols at the highest positions above sea level (above a contemporary timberline) demonstrate features related to humid or semi-humid conditions. Izotropic humus coatings were found in humus horizon of uppermost buried soil of section 4. This horizon was dated as 2.7 Cal. BP, but humus coating are obviously superimposed features for Ab horizon. Those were formed as a result of Al-Fe-humus migration from surface soil, later that 2.7 ky (Bronnikova et al. 2018).

The oldest of paleosols in the same section 4 has a texturally differentiated profile with coatings and infillings composed of oriented clay (Fig. 4h). Similar profiles are typical for soils of semi-humid climate under forest vegetation and good intra-soil drainage. Nowadays this site is located under meadow-steppe vegetation, above a contemporary timberline.

DISCUSSION

As can be seen from the above, all studied buried soils were formed at milder environmental conditions, and less (if any) water deficit comparatively to surface contemporary soils, in a more favourable environment for intra-soil biological activity. Two Following humid stages can be discriminated basing on soil data: 1. humid and relatively warm period about 8-11 ky ca BP of pedogenic textural differentiation, which is clearly imprinted only in one soil-sedimentary sequences located at the highest position (2400

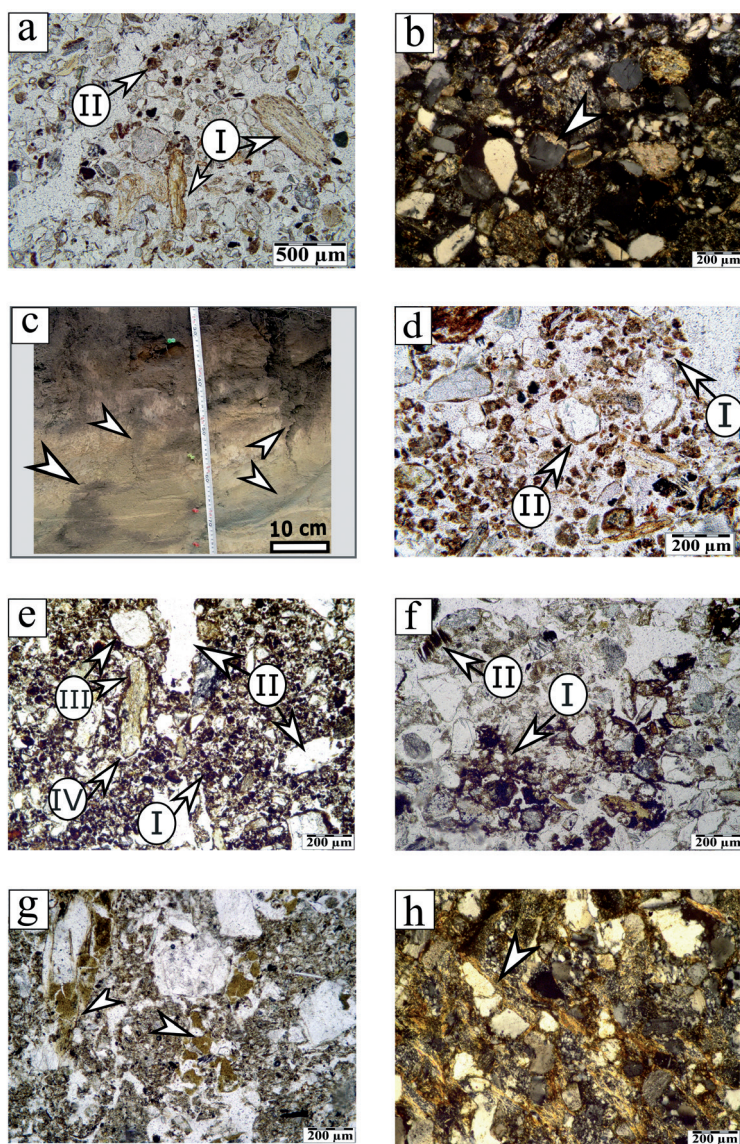


Fig. 4. Macro- and micromorphology of surface and buried soils:

- a) humus horizon of surface soil: poor in organic matter, non-humified fragments of plant tissues (I), nearly non-aggregated, few biogenic features (II) (profile 1); b) humus horizon of surface soil: pedogenic carbonates in coatings over sandy grains (profile 2); c) buried dark humus horizon: cryoturbation features at macro-scale (profile 3); d) buried dark humus horizon: rich in organic matter, fine granular biogenic microstructure (I), clay-humus coatings (II) resulted from alkaline intrasoil migration (secondary solonization) (profile 1); e) buried dark humus horizon: rich in humus, biogenic structure (I), biogenic channels (II), humus coatings (III) resulted from alkaline intrasoil migration (secondary solonization); vertically oriented grains (IV) - frost jacking (profile 3); f) BC horizon of buried soil: Redoximorphic features: diffuse Fe-Mn nodules (I), frost-shattered coarse biotite grain (II) (profile 2); g) buried dark humus horizon: isotropic humus coatings and infillings - spodic pedofeatures (profile 4, uppermost buried soil); h) buried Bt horizon: oriented illuvial clay (profile 4, lowermost buried soil)

a.s.l.); 2. two humid and cold sub-stages between 2.5 and 3.8 ky cal BP: 3.6-3.8 and earlier than 2.5-2.9 ky BP – Al-Fe-humus migration and accumulation of humus-Fe layers in multilayered pendants (Fig. 5, 6). The last stage is also most clearly recorded at the highest levels: 2200-2400 a.s.l.

Layered carbonate/humus pendants on rock fragment, being widely spread

pedofeatures in soils of cryo-xerophytic steppes occupying vast areas within intra-mountain basins and those slopes in a wide range of absolute heights, are regarded as a key indicator of Holocene environmental change for the region. Those pendants could be considered as intra-soil microsedimentary systems which layer by layer record soil forming conditions. Multilayered pendants were

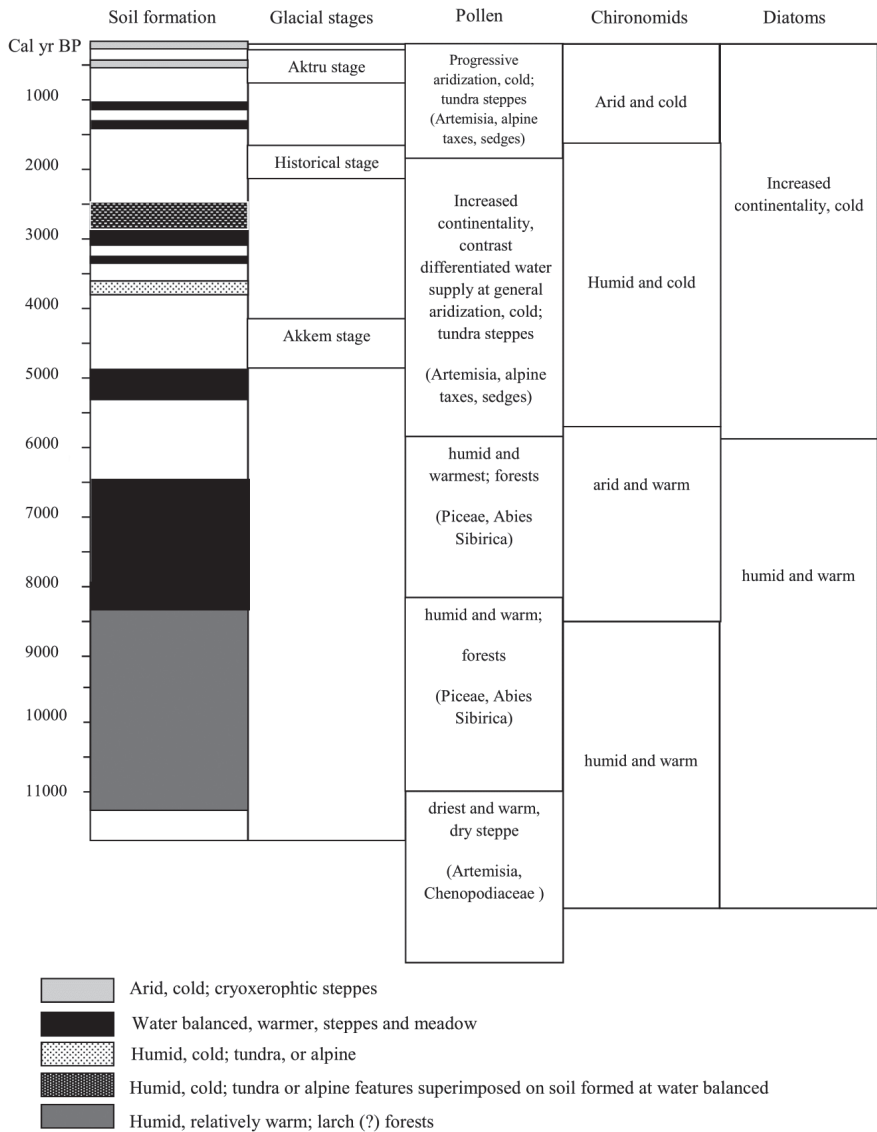


Fig. 5. Correlation of soil record and other paleoenvironmental archives.

Compiled basing on own data (soils), and published data: Ilyashuk and Ilyashuk 2006 (Chironomids); Westover et al. 2006 (Diatom); Blaycharchuk et al. 2007 (Pollen); Agatova et al. 2012 (Glacial stages)

studied in three soil profiles at different absolute heights, have the same set of layers differing in composition and morphology (morphotypes), and similar sequences of morphotypes in all studied soils. These sequences have recorded following generalized phases of soil evolution: 1) semiarid, groundwater-affected (successive phases of high standing, and seasonally fluctuating waters); 2) semiarid, not influenced by ground waters; 3) well drained humid; 4) resumption of semiarid conditions (Fig. 6). The first phase is related to initial soil formation after dammed lakes drainage. Following changes in pedogenesis were due to progressive drop of water level in residual lake/river basins; others are explained by fluctuations of climatic humidity. For now, the only humid phase was dated by ^{14}C of humus (about 4 ky cal BP), and general minimal age of pendants (about 8 ky cal BP) was estimated for one of the studied soils. Multilayered pendants have great future potential as a paleoenvironmental indicator and dating tool. Further studies those features in surface soils of different locations will yield new data on the chronology of subaerial phase started after ice melting or drainage of dammed lakes in the mountain basins, as well as on time frames of climatically conditioned changes of soils and landscapes.

As a generalization of obtained data on

surface soils and soil sedimentary sequence following conclusions could be resumed. The initial soil formation could start at different ages in basins with different a.s.l.; low limit of the initial soil formation could be estimated as 11-8 kyr cal BP. Soil, and soil-sedimentary systems have recorded general trends of on-spot soil formation, including the initial stages. These trends testify that the most extreme conditions of soil formation within Holocene were within the last 1-2 kyr.

All buried soils were formed in better conditions, more balanced in water, rather active biologically, mostly within steppe or forest-steppe landscapes. Meanwhile, cryogenic features had been insisting all over the Holocene till nowadays, so that the region still was permafrost affected, and climatically rather severe (with long, cold winters). Those cryogenic features demanding satisfactory water supply, are met in buried soils up to the age of 1-2 ky cal BP, in the last millennia ones gave way to cryogenic features which may occur even at limited water availability, such as simple fissures, frost sorting, frost weathering and frost shattering forming shear surfaces (Van Vliet-Lanoë 2018; Konishchev and Rogov 2017).

At lower levels (Kuraj basin) more or less arid cold steppe conditions insisted

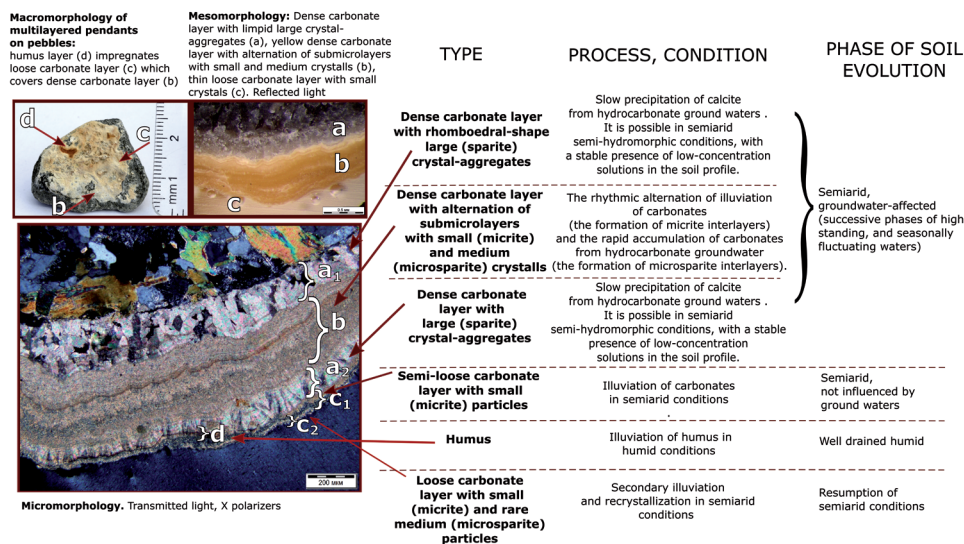


Fig. 6. Phases of soil evolution as based on morphotype sequences in pendants

within the most part of Holocene (means fluctuations of climate possibly were not that sharp in the low valleys). Initial stages of soil formation were often ground water affected, or at least shortly waterlogged. At the highest positions humid and relatively warm Early Holocene stage of forest pedogenesis is recorded for the beginning of Holocene, and a Late Holocene (last 3-4 kyr) cold humid phase, presumably under mountain tundra and/or alpine. Microsedimentary intra-soil record in carbonate-humus pendants imprints fine fluctuations of soil water regime at initial stages of soil formation, controlled by local topography, and climatic changes in the second half of Holocene. General trends of environmental changes in the region recorded in soil and soil sedimentary systems are in well correspondence with other records of paleoenvironment (Fig. 5). At the same time soil record much better reflects local specific of environmental change, differences in chronology between localities. Discrepancies between different types of records are due to different level of generalization of the collected materials, different sensitivity, reflectability, response

time and other specific characteristics of recording systems (soils, sediments, glaciers etc.), and single indicators (pendants, pollen, diatoms etc.). Careful analysis of all these record- and indicator-dependant discrepancies in order to combine better different paleoenvironmental records in a single, not contradictory, so to say, purified picture, promise to be fruitful.

ACKNOWLEDGEMENTS

We dedicate this paper to our big friend and field driver Gennadij Amyrovich Bodelukov who gone away early but will always leave in our hearts. He contributed his rare skills, goodwill and energy to the field part of this research.

This study in its theoretical foundation and part of analytics was supported by state assignment project 0148-2016-0002, it also was partly funded by RFBR (field studies in different years were financially supported by grants 16-05-01035, and 17-04-01526; micromorphological studies – 17-04-01526, analytic studies – 17-04-01526, and 18-05-00998). ■

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Received on July 4th, 2018

Accepted on November 15th, 2018

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