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Late Pleistocene paleosols in the extra-glacial regions of Northwestern Eurasia: Pedogenesis, post-pedogenic transformation, paleoenvironmental inferences

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A B S T R A C T

Recent revision of the eastern boundary of the last glaciation of Eurasia opened new perspectives in the search of the paleopedological records in the north of Eastern Europe and Western Siberia. We studied paleosol-sedimentary sequences in the Upper Volga and Middle Ob basins as a regional paleoecological record for the Late Pleistocene thermochrons.

Two key sections Cheremoshnik and Belaya Gora containing MIS3 and MIS5 paleosol units and additional section Koskovo 2 with polycyclic MIS3 paleosol were investigated. Their timescale are based on C14 and U/Th datings as well as on stratigraphic and paleobotanical correlations. Macro-, meso- and micromorphological observations together with fossil insects and plant macrofossil were used as paleoenvironment proxy. MIS3 paleosols show abundant redoximorphic and cryogenic features that allow interpreting them as gleyic Cryosols. Sub-fossil insects and plant macrofossil reflect the cold climate conditions. Three incipient Ah horizons in Koskovo 2 pedocomplex point to multiple phases of pedogenesis, correlative to the MIS3 paleosol levels in different sections of the Eurasian loess belt and to the major interstadials of the Middle Pleniglacial of the NW Europe MIS5 paleosols are also characterized by gleyzation and peat accumulation, in this case we suppose geomorphological control on hydromorphic pedogenesis; however paleosol in Belaya Gora has clear signs of polygenesis including the phase of clay illuviation. Insect and plant remains from the lower paleosol level of the Belaya Gora section show the transition from cold (terminal phase of MIS6) to warm first, and then to a moderately cold climate (within MIS5). The obtained results contribute to understanding of soil and landscape zonality in the largest plains of Eurasia mostly during the warm phases of Late Pleistocene.

1. Introduction

Paleopedological archives provide one of the most important sources of information for reconstructing past environments due to the "soil memory", capable to generate records with high spatial resolution (Targulian and Goryachkin, 2004). In Eurasia loess-paleosol sequences, which form an almost continuous latitudinal belt are considered to be a proxy of the Quaternary climatic cycles, showing remarkable far distance transcontinental correlation of the sections (Haesaerts and Mestdagh, 2000; Bronger, 2003) and a good fit with the marine isotope curve (Bronger et al., 1998). Within these extensive loess-paleosol successions buried soils are supposed to be formed during the major warm periods (interglacials). The studies of some Late Pleistocene loessic sections produced

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much more detailed record for the last climatic cycle; there multiple paleosols (although underdeveloped) were related with the interstadials (Antoine et al., 2001; Terhorst et al., 2015). When precise instrumental dating was possible, accurate correlation of these incipient paleosols with the Greenland Interstadials was accomplished (Kadereit et al., 2013; Haesaerts et al., 2010).

However the availability of the well preserved and documented Quaternary paleopedological archives decrease sharply to the north of the Eurasian Loess Belt, when approaching to the margins of the Pleisocene ice sheets. Although few findings of the Pleistocene paleosols were reported even in Scandinavia (Olsen, 1998) where glacial erosion was most intensive, in general the data about such paleosols in the glaciated and the nearest periglacial region are rather few. The paleopedological research and prospection there was discouraged by the wide spread opinion that intensive geomorphic processes left little possibility for preservation of thin and fragile paleosol mantle. The paleoecological reconstructions in these regions rely mostly on the records extracted from the glacial, lacustrine, marine and other sediments.

Recent revision of the eastern boundary of the last glaciation of Eurasia reduced considerably the area, occupied by the ice sheet and subjected to glacial and periglacial erosion processes (Svendsen et al., 2004). This opened new perspectives in the search of the paleopedological records in the north of Eastern Europe and Western Siberia. Earlier we reported the results of our case studies in the Upper Volga (Rusakov and Sedov, 2012; Rusakov et al., 2007, 2015) and in the Middle Ob' (Sheinkman et al., 2016) basins. The studied profiles covered the whole last glacial-interglacial cycle, some of them reached the sediments of the MIS6 – Dnepr/Taz glacial. Recently we undertook the first attempt of inter-regional pedostratigraphic correlation, only for the units, corresponding to MIS3 – Bryansk/Karga interstadial (Sedov et al., 2016).

This paper presents our attempt of correlation and integral paleoecological interpretation of the paleosol-sedimentary sequences of both basins for the whole Late Pleistocene. It incorporates the results published earlier as well as new datasets for the recently discovered profiles. The paleopedological records were complemented with the geomorphological setting of the profiles which provide additional information about surface processes linked to paleoenvironments. In some of the studied sections insect remains and plant macrofossils were encountered in close relation to the paleosol levels. Combination of entomological data and study of plant macrofossils allows providing detailed paleoenvironmental reconstructions based on the presence of identified indicator species. We consider them to be a valuable complementary (although independent) proxy to the "paleosol memory", also characterized by a high spatial resolution. Integration of all these archives in a reconstruction of the environmental change since MIS5e and its comparison with the existing regional and global scenarios is the purpose of this paper.

2. Materials and methods

Chronological scale for the studied sections relies on the results of 2 instrumental methods: radiocarbon dating for 2 paleosol levels of Koskovo 2, upper paleosols of Cheremoshnik and Belaya Gora and 230Th/U dating for the lowest paleosols of the latter two sections.

Conventional radiocarbon dates were obtained in the Institute of Geography of RAS, Moscow (Russia). A $SrO_3Al_2O_3SiO_2$ catalyst was used for benzene synthesis. The fivefold standard was prepared in the Geological Institute of the Academy of Science (1981 GIN standard) by adding a calibrated amount of 14C-tracer benzene to C-dead benzene. The special practices used for dating old samples (close to the radiocarbon dating limit) are described in detail by Arslanov et al. (1993). All dates were calibrated following CalPal (2007).

230Th/U dating of organic-rich sediments was performed in the Köppen-Laboratory, St. Petersburg State University, Russia. In order to improve the reliability of the radioisotope dating we applied a modern version of isochronous approach which is based on agreement of isochronously-corrected ages obtained for a set of the same coeval samples analyzed with the use of two different analytical techniques: (1) acidic extraction of the sample – leachate alone technique (L/L-model) and (2) total sample dissolution technique (TSD-model) (Maksimov et al., 2006, 2012; Maksimov and Kuznetsov, 2010; Kuznetsov and Maksimov, 2012).

Five sub-samples for 230Th/U dating were selected from the humus horizon of the lower paleosol of the Cheremochnik key section. Their radiochemical analyses by both the L/L- and TSD-techniques were performed in accordance with the procedures proposed by Maksimov and Kuznetsov (2010), Kuznetsov and Maksimov (2012), and Börner et al. (2015). The 230Th/U ages of the soil layer were calculated with standard deviation error $\pm 1\sigma$ applying L/L- and TSD-analytical data in correspondence with isochronous approach (Geyh, 2001; Maksimov and Kuznetsov, 2010).

The mesomorphological study of undisturbed blocks from paleosol horizons was conducted in the Laboratory of the Chair of Soil Science and Ecology of Soils, Institute of Earth Sciences, Saint Petersburg State University using binocular MBS-10. Structurally undisturbed soil blocks were taken from selected horizons where evidence of MIS5–MIS3 pedogenesis was discovered. These blocks were impregnated with Crystal resin in a vacuum camera and, after solidification of the resin, used to prepare thin sections in the Thin Section Laboratory for Soils and Unconsolidated Sediments in the Institute of Geology, National University of Mexico (UNAM). Micromorphological observations were conducted under an Olympus BX51 petrographic microscope, and descriptions were based on the definitions and terminology of Bullock et al. (1985). We focused our observations on the characteristics of the groundmass, pores and pedofeatures which are indicative of the pedogenetic processes; also evidences of sedimentation were registered.

Samples for entomological and carpological analyses were sieved with the 0.2-milimeter soil sieves according to standard methods (Nikitin, 1969; Rasnytsyn, 2008; Elias, 2010). Identification of insect and plant fossils is based on the entomological collection and herbarium of the museum of Institute of Ecology of Plants and Animals Ural Branch of RAS.

3. Results

3.1. Characteristics of the study areas and geomorphological setting of the sites

The paleopedological, paleozoological and paleobotanical investigations were carried in two regions in which the key sections belonging to two types sequences were selected (Fig. 1). The first type contains by instrumental method reliably dated paleopedogenic levels of MIS3 and MIS5 in the north-center of the East European Plain (Upper Volga basin, Yaroslavl Oblast of Russia, the Cheremoshnik key section, 57°9′58.62″ N; 39°17′20.24″ E) and in the north-center of Western Siberia (Middle Ob' basin, Khanty-Mansi Autonomous Okrug of Russia, the Belaya Gora section). The second type sequences marked above represented by the key section Koskovo 2 (58°16′3.33″ N; 37°33′49.90″ E; Upper Volga basin, Yaroslavl Oblast of Russia). This section contains paleopedogenic detailed records with many individual soil profiles formed during MIS3.

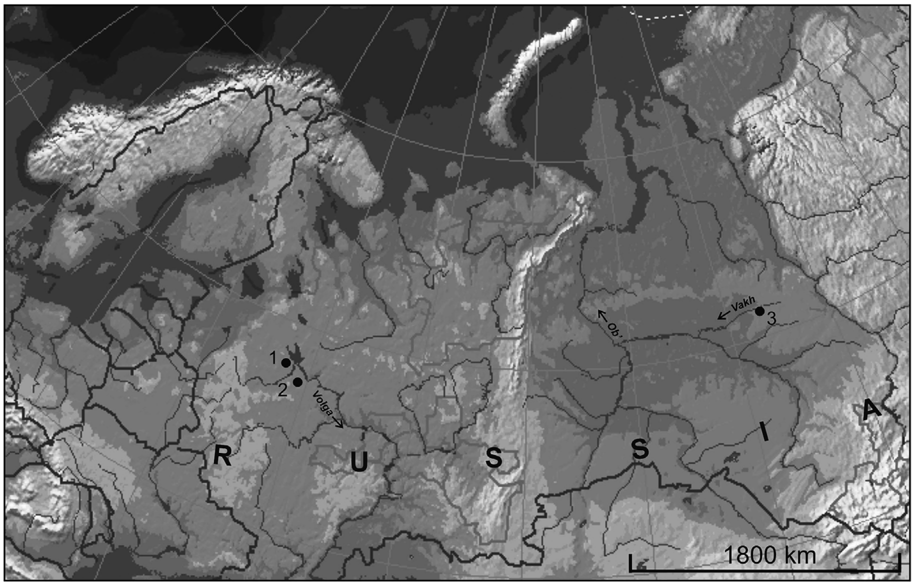

Fig. 1. Geographical location of the study sites.

We used the satellite images (GoogleEarth and YandexMaps) to identify and delimit the main forms of macro-relief in the areas of the studied sites. Different scales of some maps are caused by presence satellite data in open web resources (sources). Earlier research has shown that in the Valday glacial and periglacial zones in the north of Russian plain the periglacial relict geophorms (patterned ground, thermocarst) could be detected in the microrelief on the remote sensing images (Velichko et al., 1996). We applied similar approach to the small key areas near Cheremoshnik and Koskovo 2 sites, which are located on the same major landform as the studied profiles, using the images of the larger scale. The selected areas are free of forest and were recently cultivated, that permits observation and mapping of microrelief forms.

Present day climate is temperate humid, with mean annual temperature varying from +2.4° (the section Koskovo 2) to +3.4° (the section Cheremoshnik). The surface Retisols (WRB, 2014) are formed under South Taiga type of vegetation. Quaternary geological setting is defined by the effects of two last glaciations. The studied sections are located quite close to the Late Valday (Weichselian, MIS2) ice margins, according to recent reconstructions (Svendsen et al., 2004): the distance varies between 50 and 200 km. The ice sheet of penultimate Moscow (Saalian, MIS6) glaciation had larger extension; it completely covered the studied area. The glacial history defines the sedimentary sequences in which MIS3 paleosols are incorporated: they are overlain and sometimes underlain by glacio-lacustrine and solifluction deposits, probably with eolian component, whereas in the base of all sections the Moscow-Saalian till is found, on which the studied MIS5 Paleosols were studied.

In Cheremoshnik site this landsurface is limited to the east by the boundary with the younger lower terrace of the Nero Lake. A complex drainage network is developed within the upland area consisting of broad shallow combes and more resent (or rejuvenated) narrow, deeper, tortuous ravines; one of the latter is the Cheremoshnik Gully, in which the studied profile is exposed (Fig. 2). A larger scale satellite image reveals a multiphase structure of this gully which combines recent and ancient incision phases. The flat area to the south of the exposure shows a dense set of minor hollows of similar size which we interpret as a relict of the polygonal patterned ground (Fig. 2).

Section Koskovo 2 is located in the southwest of the Mologo-Shecsna Lowland and on the adjacent terraced slopes of the Ovinishensk Upland. The upland terrace-like landsurface at Koskovo 2 site also has a complex network of ancient and recent erosional geoforms, similar to that of Cheremoshnik (Fig. 3). A key area documented at larger scale some 8 km to the east-northeast from the site showed some clusters of small hollows left behind by the patterned ground as well as several larger rounded closed depressions which we explain as a result of thermokarst subsidence (Fig. 3).

In the Western Siberia we studied the section Belaya Gora (61°27′ N; 82°28′ E), located on the left bank of the River Vakh, right tributary of Ob'. The Vakh Basin belongs to north-central part of the West-Siberian plate, which has a thick (2.7 km) sedimentary mantle accumulated since the Triassic. Quaternary deposits on top of the mantle have predominantly sandy texture. Traditional they have been attributed to glacial, fluvio-glacial and limno-glacial processes (Saks, 1953). However an alternative “non-glacial” hypothesis associates the Quaternary deposits of the northern part of the West-Siberian Plane with alluvial, lagoon and epi-continental marine environments (Popov, 1967; Lazukov, 1989). The climate within the study area is characterized by a mean annual temperature of −3.9 °C (Korkin and Kayl, 2014). It belongs to the northern sub-zone of the Middle Taiga (Ilyina et al., 1985). Stagnosols, Luvisols and Podzols are formed under forests whereas Histosols within the swamps.

The geomorphological setting of the Belaya Gora site in the Middle Ob' basin is quite different. It is characterized by a sequence of alluvial terraces of river Vakh of different elevation and age (Fig. 4). The most recent one is the low floodplain adjacent to the present day watercourse of the river. It should be stressed that the studied section corresponds to the highest and oldest terrace which is well known on the regional scale (Sheinkman et al., 2016). The profile was found in one of the very few locations where the river channel approaches and cuts the body of this high terrace.

3.2. Pedology, litho/pedostratigraphy and datings of paleosols sections

3.2.1. Cheremoshnik

In our recent publications (Rusakov et al., 2015; Sedov et al.,

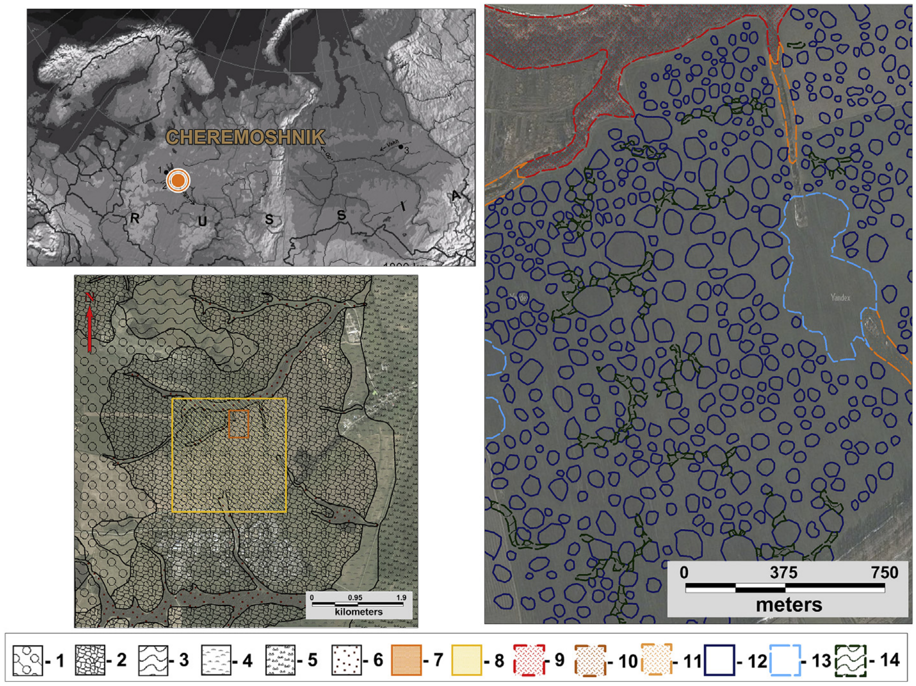

Fig. 2. Overview geomorphological map and detailed geomorphological interpretation map of the Cheremoshnik area. 1, 2, 3 – the upland flat terrace-like landsurface: 1 – with predominantly thermokarst lake depressions; 2 – with the relicts of polygonal patterned ground; 3 – areas with broad shallow combes – ancient fluvial beds; 4 – slope from the flat watershed to the lower lacustrine terrace; 5 – lower lacustrine terrace; 6 – development of recent (or rejuvenated) fluvial incision geoforms; 7 – location of the section; 8 – limits of the area where detailed geomorphological interpretation of the periglacial relict structures was made; 9,10,11 – phases of the gully incision; 12 – small hollows associated with the central parts of the polygons of the periglacial patterned ground; 13 – minor lake depressions of thermokarst origin; 14 – shallow channels connecting polygon hollows of the degraded patterned ground.

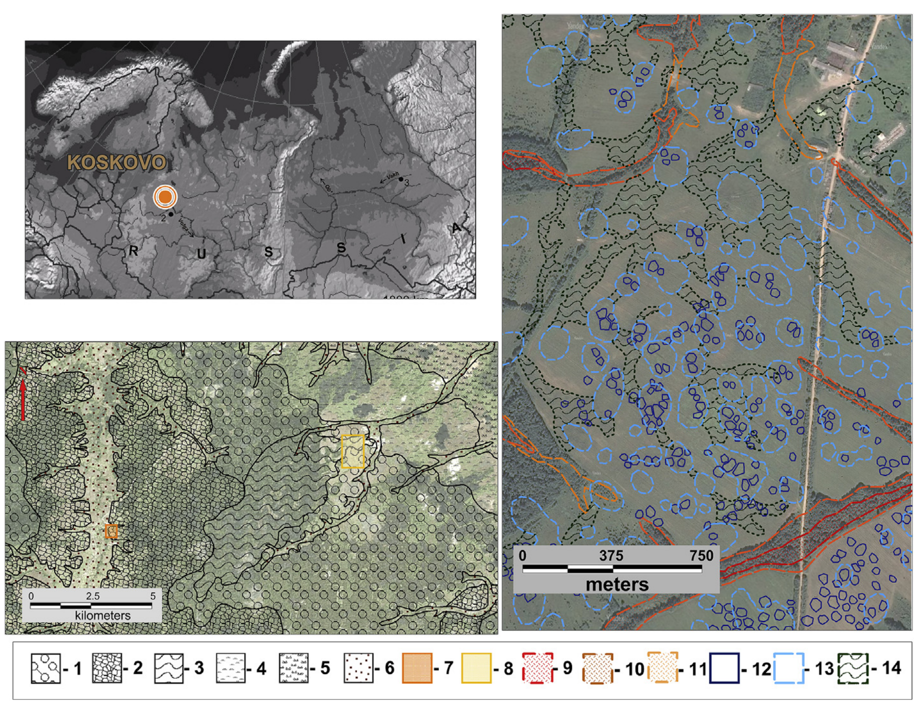

Fig. 3. Overview geomorphological map and detailed geomorphological interpretation map of the Koskovo 2 area (legend – same as in Fig. 2).

2016) we published Quaternary-geological, paleopedological and palynological results obtained from the key section Cheremoshnik (Fig. 5a) including also data on stratigraphy, numerical dating of paleosols/pedosediments, deposits, lithological compounds and some features of this key section. In this regard we are presenting briefly main data on this complexly organized heterochronous (MIS5–MIS1) of this soil-sedimentary stratum.

The base of the section was determined to be an Early Mikulino

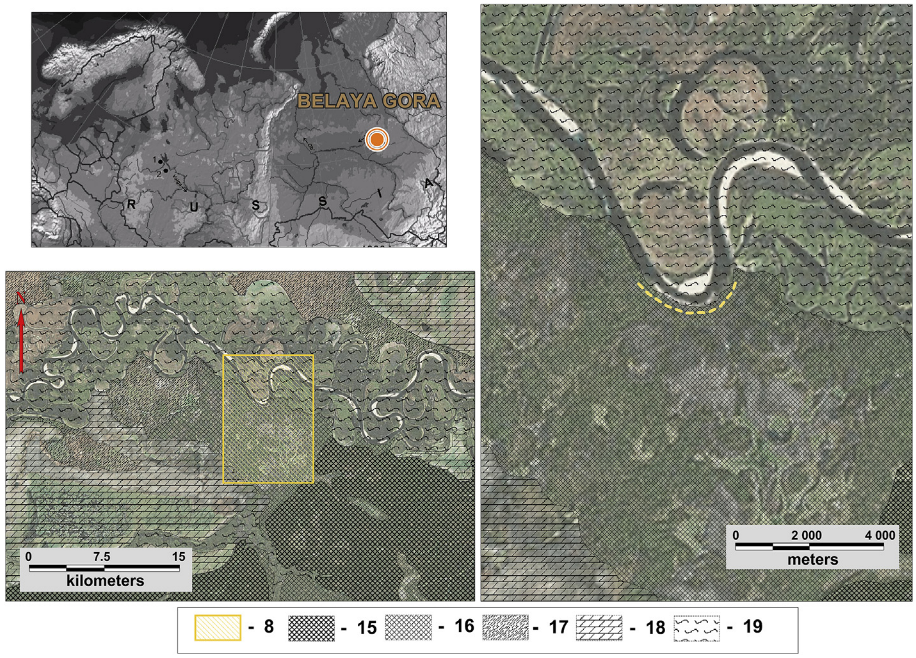

Fig. 4. Overview geomorphological map of the Belaya Gora area section. 8 – same as in Fig. 2; 15 – more drained areas, swampy sites are restricted to the erosional depressions; 16 – less drained part, swamps are spread on the main flat landsurface; 17 – middle alluvial terrace of the river Vakh; 18 – low alluvial terrace of the river Vakh (poorly drained, swampy); 19 – floodplain of the river Vakh.

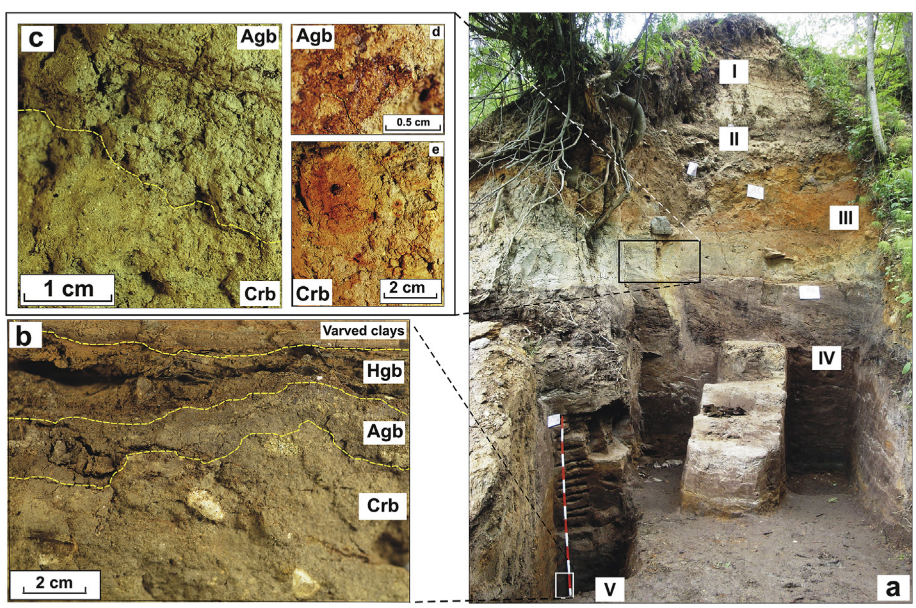

Fig. 5. The Cheremoshnik key section (Upper Volgs Basin). (a) General view of the exposure (2013). I–V – lithological layers: I – the Late Valdai (MIS2) loess-like (mantle) loam; II – detritus with clear features of a sequential gravelly stratum (MIS2); III – the Middle and Late Valdai (MIS3–VIS2) loams with rare inclusions of boulders; IV – the gyttia and peat deposits of the Mikulino age (MIS5); V – the pebbly loam of the Moscow (MIS6) till. (b) Mesomorphology of the Early Mikulino (MIS5e) Histic humus paleosol formed on Moscowian moraine deposits overlain by a preserved thin layer of varved clays. (c) Bryansk paleosol (MIS3) represented by Reductaquic Cryosol. The middle (second) level of pedogenesis. (d) The Agb horizon of the lower (first) level of the Bryansk paleosol. Visible presence of the ferruginous cutans on ped faces. (e) The gley horizon of the same paleosol. Diffusive and concentric Fe-new formations.

peat-dark humus paleosol which marked incipient subaerial pedogenesis on the Moscow (MIS6) moraine and was covered with a stratum of gyttja with a peat horizon (Histosol) which had formed 114–115 ka BP (Rusakov et al., 2015). The following paleosols were successfully identified within the series of weak stone gullied-channel sediments within the Valdai unit (from top to bottom): (1) pedosediment formed at the end of the Bölling interstadial (MIS2); (2) Trubchevskaya paleosol – Gleyic Turbic Cryosol (MIS2) and (3) Bryansk (MIS3) pedocomplex with three individual paleosol levels classified as Reductaquic Cryosols. This unit consists of a set of paleohorizons Agb and Crb (Fig. 7a). The radiocarbon ages of the paleohumus horizons and charcoal fragment from these paleosols vary between ~27,500 and 41,800 Cal BP (Sedov et al., 2016). The mesomorphological features of the middle levels are

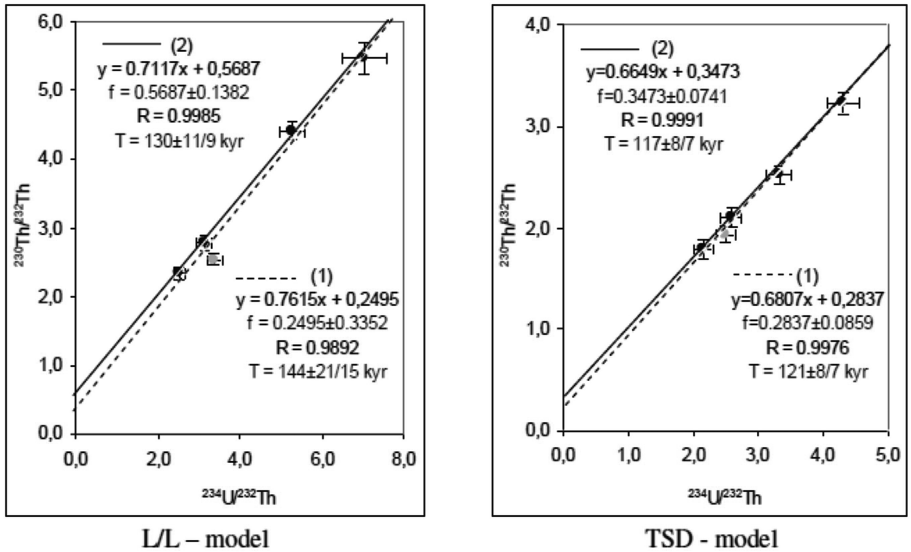

Fig. 6. Linear dependences (the isochronous lines), linear coefficients f and ^{230}Th/U dates obtained on L/L (left plot) and TSD (right plot) analytical data: (1) – for the five sub-samples from the horizon Agb at a depth 6.22–6.23 m; (2) – for the four out of five sub-samples from the horizon Agb at a depth of 6.22–6.23 m. In the latter case grey circle indicate data not included in age determination (sub-sample N° 2 – L/L-model, N°2t – TSD-model); f – the value of intersection the isochronous line on the Y-axis.

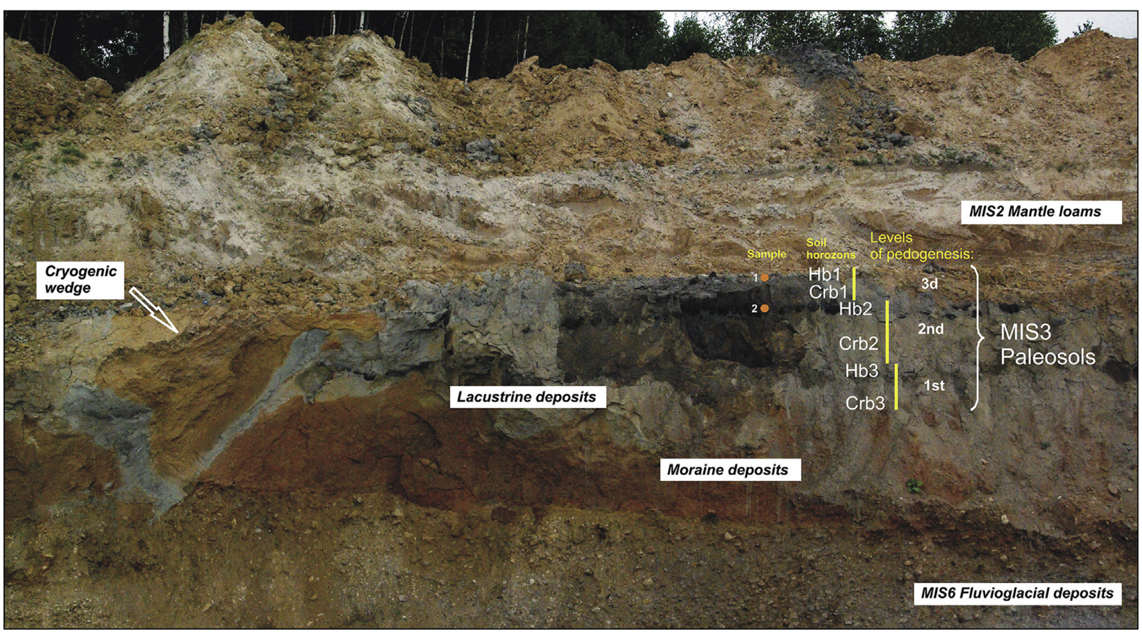

Fig. 7. General view of the section Koskovo 2 (Upper Volga Basin) with the position pedostratigraphic unit containing three levels of MIS3 paleosols and main stratigraphy strata marked and location of the huge cryogenic wedge. Place of sampling (the sample numbers 1 (top) and 2 (middle)) for entomological and carpological analysis are presented in the form of orange circles. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

represented on Fig. 5c–e. Paleohumus horizons of this pedocomplex are relatively thin (<5 cm), their color is grey with a bluish hue (5Y7/1; 5Y6/2, dry). There is in some cases a visible presence of the ferruginous cutans on ped faces of Agb horizon. The paleogley horizons (with a stratum of ~12 cm) are blue-grey. In the lower horizons of the Bryansk paleosol (Fig. 5e) is presence of diffusive and concentric Fe-tubular pedofeatures replacing ancient plant roots.

Below the Valdai unit (6.21–6.70 m) we observed the early Mikulino (MIS5e – according to the new U/Th date, presented below) paleosol formed on the Moscow (MIS6) moraine (Fig. 5b). This peat-dark (2.5Y3/3, dry) humus paleosol was formed on till deposits as it was overlain by a preserved 10-cm layer of varved clays (Fig. 5b). The unit of the profile of this paleosol does not exceed ~0.5 m, anyway it consists of a set of Hgb–Agbe–Cr1b paleohorizons. The unit of the histic and humus horizons is only ~2 cm. The Agb horizon is dark grey with a steel hue (10YR2/2; 10YR3/2, dry), loamy in texture and is characterized by a small blocky structure. There are inclusions of small ancient root fragments. The underlying gley horizons (6.23–6.50 m) are a bluish, light olive color with brownish/blackish spots on the ped faces. The Moscow (MIS6) moraine is represented brown-reddish clayey-sandy till layer with an olive hue with inclusions of gravel and boulders and characterized by a very high bulk density. The upper part of this till was visibly weathered.

A thin humus Agb horizon of the Early Mikulino Histic humus paleosol formed on Moscowian till deposits from 6.22 to 6.23 m depth of the Cheremoshnik key section was dated by 230Th/U method. The radioisotope data obtained using both L/L- and TSD-model is summarized in Table 1.

The analytical data obtained for the five duplicate sub-samples were taken into age calculation applying f linear coefficient (Maksimov and Kuznetsov, 2010) and yielded isochronously-corrected 230Th/U ages 144 ± 21/15 ka (L/L) and 121 ± 8/7 ka (TSD). The sub-sample №2 (2t) does not fully fit on the isochronous lines and therefore can be excluded from the age calculation (Fig. 6). In this case the isochronously-corrected 230Th/U ages 130 ± 11/9 ka (L/L) and 117 ± 8/7 ka (TSD) for a set of four out of five sub-samples are in a greater agreement and consistent with the proposed isochronous approach (Maksimov and Kuznetsov, 2010). These ages indicate that an early Mikulino peat-dark humus paleosol formation occurred probably at the beginning of the MIS5e interglacial.

3.2.2. Koskovo 2

The Koskovo 2 section is confined to the level of topography of 171 m a.s.l., where the surface drainage is unconfined. This section was found in a sand-gravel quarry (Fig. 7) providing a 50 m wide vertical cut. Cryogenic deformations represented by relatively wide and deep wedges spaced 5–6 m apart were observed from 2.5 m depth.

It is very important to notice that the MIS3 paleosols of the studied section are strongly fragmented and observed in exposures not as continuous levels, but as series of blocks of different sizes. One of this block represented on Fig. 7 where well preserved set of paleosols which characterized by a presence of three levels of pedogenesis. The MIS3 paleosols are developed on clay and loamy sediments of lacustrine origin deposited at the end of the Moscow glaciation or during the early Valdai glaciation (MIS4). The MIS3 paleosols are buried under ~2.5–3.0 m thick layers of loess-like sediments enriched in coarse silt, and known as mantle loams. The depositional environments are supposed to be glacio-lacustrine (dammed lakes existed within this territory during MIS2; Rusakov et al., 2008), although we do not exclude also eolian silt contribution.

The unit of MIS3 paleosols of the Koskovo 2 section consists of a set of paleohorizons (Hb1–Crb1–Hb2–Crb2–Hb3–Crb3) which belong to three well visible, adjacent profiles with a stratum of 0.3–0.6 m classified as Gleyic Turbic Cryosol. The dark brown grayish Hb horizons of paleosol profile are incorporated as clusters within the lower mineral texture is a result of buried relict cryogenic polygonal microrelief represented mainly by rounded block-polygons (Fig. 8a).

Some paleosol gley horizons clearly show humus as subvertical, greyish-brown colored zones, possibly as a result of cryoturbation-solifluction. A zonal coloration of the gley horizon with humus solutions and a sharp boundary between the colored and "clean" zones of the horizon Crb is clearly seen on horizontal section (Fig. 8b). This image also clearly shows a superimposed platy pedality, produced by ice lense development – a result of cryogenic processes. In the paleosol gley horizons of the middle and lower levels ocher zones, spots are preserved (Fig. 8c and e), which indicates that there are oxidation processes in the soils.

Below, for the first time, radiocarbon dates are given for the three pedogenic levels of the Koskovo 2 section (Table 2). As can be seen from the given data, the dating results are in the interval 34–55 cal yr BP, and the oldest dating (the first stage of pedogenesis) approaches the lower limit of the method.

3.2.3. Belaya Gora section

The base of the section Belaya Gora is formed by more than the 10 m thick stratum of pale sorted laminated fine sand (19.7–30.7 m) (Fig. 9a). In the upper part it becomes heterogeneous, with admixture of coarse sand and few gravels. Directly on top of this stratum a set of silty loam layers is deposited, in which the lower paleosol unit is developed (16.7–19.7 m) consisting of the following set of genetic horizons: Bg@ (16.7–16.85 m) – Ha (16.85–16.9 m) – ACr (16.9–17.7 m) – Cr (17.7–19.7 m). The mottled Bg@ horizon has loop-like pattern of the deformed brown mottles and stripes, generated by pedoturbation. Thin black Histic Ha horizon contains few relatively fresh wood fragments incorporated in highly decomposed organic matrix. Strongly gleyed blueish-grey ACrb (darker) and Crb are massive and structureless (Fig. 9b). The overlying thick sedimentary unit (4.55–16.7 m) is predominantly sandy with few clayey seams. Frequent inclusions of gravel and pebbles between 5 and 8 m are notorious. The rock fragments do not form concentrations and are immersed in the sorted laminated sandy material. Above these sediments the upper paleosol unit is located (3.55–4.55 m), developed in silty loams (Fig. 9a). It is presented by a Bg@ horizon which has pale grey color with few yellowish-brown mottles. Very well developed structure of angular or partly rounded granules and small blocks is produced by a dense net of fissures (Fig. 9d). A thin dark humus seam in the middle of horizon is deformed in a loop-like shape (Fig. 9c).

Radiocarbon dating of humus from the dark deformed seam in the upper paleosol produces calibrated date 35,170 ± 350 yr cal BP (Beta-410187). Organic materials from the lower paleosol unit gave results outside the limits of radiocarbom method: more than 40 kyr

Table 1
Results of the radiochemical analyses of five sub-samples from the Agb horizon at a depth 6.22–6.23 m (the Cheremochnik key section) determined applying L/L-model and TSD-model after Maksimov and Kuznetsov (2010).

№	Ash %	^{238}U dpm/g	^{234}U dpm/g	^{230}Th dpm/g	^{232}Th dpm/g	$\frac{^{230}Th}{^{234}U}$	$\frac{^{234}Th}{^{238}U}$
L/L-model							
1	82,55	5,0217 ± 0,2027	5,5542 ± 0,2225	4,3201 ± 0,2333	0,7905 ± 0,0511	0,7778 ± 0,0523	1,1060 ± 0,0244
2	89,62	2,6278 ± 0,0628	2,8377 ± 0,0671	2,1214 ± 0,0857	0,8393 ± 0,0385	0,7476 ± 0,0350	1,0799 ± 0,0187
3	90,94	2,2035 ± 0,0681	2,4527 ± 0,0739	2,2673 ± 0,0875	0,9695 ± 0,0456	0,9244 ± 0,0452	1,1131 ± 0,0331
4	86,35	3,5114 ± 0,1341	3,8456 ± 0,1453	3,2154 ± 0,1123	0,7290 ± 0,0307	0,8361 ± 0,0430	1,0952 ± 0,0281
5	89,07	2,5536 ± 0,0556	2,7204 ± 0,0585	2,4186 ± 0,0928	0,8693 ± 0,0425	0,8891 ± 0,0391	1,0653 ± 0,0206
TSD-model							
1t	82,55	6,7110 ± 0,2917	7,0401 ± 0,3038	5,2725 ± 0,1616	1,6315 ± 0,0651	0,7489 ± 0,0396	1,0490 ± 0,0388
2t	89,62	3,9036 ± 0,1205	4,2765 ± 0,1290	3,3077 ± 0,1266	1,7121 ± 0,0783	0,7735 ± 0,0377	1,0955 ± 0,0338
3t	90,94	3,6664 ± 0,1588	3,8347 ± 0,1643	3,1668 ± 0,1426	1,7734 ± 0,0936	0,8258 ± 0,0513	1,0459 ± 0,0470
4t	86,35	4,7499 ± 0,1297	5,1764 ± 0,1396	3,9296 ± 0,1583	1,5563 ± 0,0718	0,7591 ± 0,0368	1,0898 ± 0,0226
5t	89,07	3,6127 ± 0,0732	3,8952 ± 0,0780	3,1533 ± 0,1560	1,5026 ± 0,0838	0,8095 ± 0,0432	1,0782 ± 0,0171

dpm/g – decay per minute per gram.

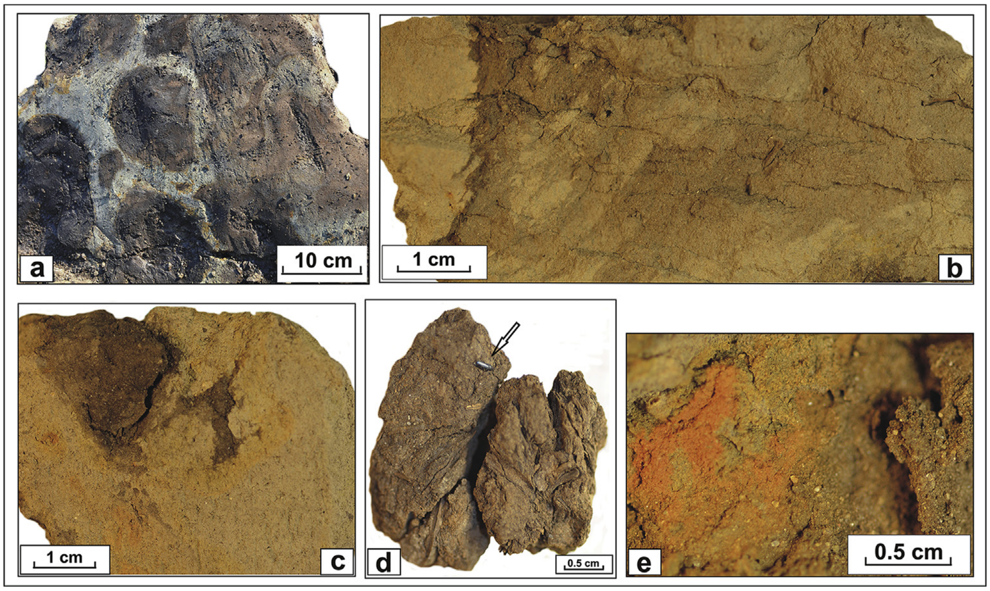

Fig. 8. Mesomorphology of the MIS3 Gleyic Turbic Cryosol of the section Koskovo 2 (Upper Volgs Basin). (a) The clearly expressed 2Hb (dark brown grayish) and 2Crb (glaucous bluish, the matrix) horizons of the middle (second) level of paleosol (3.2 m). The relict cryogenic polygonal microrelief represented mainly by rounded block-polygons. Horizontal section. (b) The lower 3Crb (first) level of the paleosol (3.1 m). Distinctly visible grayish-brown coloring parts intrapedal mass as result of crioturbation processes? Good visible overlapping of horizontal postshliere partibility of the horizon into separate blocks. (c) The 3Hb and 3Crb horizons of the lower (first) level of the paleosol (3.5 m). Slightly reddish-ochre diffuse spots restricted mainly near the Histic horizon. (d) The 2Hb horizon of the paleosol (3.2 m). Undisturbed slightly decomposed plant remains and well preserved elytra of the beetle (indicated by an arrow) are clearly visible. (e) The same horizon. Inclusions of bleached mineral grains in the mass of the horizon and ocher spots are visible. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Radiocarbon of the Koskovo 2 key section and corresponding calibrated ages.

Soil horizon	Depth, m	Levels of pedogenesis	Dated material	Laboratory code	^{14}C age (^{14}C yr BP ± 1Ʊ)	Calibrated age (cal yr BP)	MIS study
Hb1	2.8	3	Peat	IGAN-4918	30,140 ± 430	34,341 ± 340	3
Hb2	3.2	2	Peat	IGAN-4919	44,200 ± 1300	47,694 ± 1903	3
Hb3	3.5	1	Peat	IGAN-4999	49,520 ± 2200	55,326 ± 4512	3

(SOAN-7551, SOAN-7552) and more than 43.5 kyr, Beta 410188 (Sedov et al., 2016). The first estimate of 230Th/U age was obtained for the Belaya Gora peat profile. The preliminary data (~100 ky) suggest that the peat layer was deposited during the first half MIS5.

A stratigraphic diagram of the soil-sedimentary sequence (Fig. 10) shows the studied sections of the Upper Volga and Western Siberia basins, which allows correlating the levels of pedogenesis in the stage of MIS5 and MIS3.

3.3. Micromorphological observations in the paleosols

In Cheremoshnik, the A horizons of the three incipient paleosol members of the pedocomplex dated back to 27 ka BP have quite compact (Fig. 11a and b) groundmass. Rare pores are presented by discontinuous fissures with preferred horizontal orientation (Fig. 11b) and very few isolated chambers. Distribution of coarse particles in relation to fine material is non-uniform. In the sample from Agb2 horizon the area with microlamination was found: the layers enriched with sand grains alternated with those consisting of fine silt and clay components (Fig. 11a). We also observed ring-shaped concentrations of sand grains, most frequent in the Agb3 horizon (Fig. 11b) and sand clusters, forming loose infillings in the chambers better developed in Agb1 (Fig. 11c). Some larger rounded quartz sand grains are broken down by thin fractures which produce edges with the sharp angles (Fig. 11d). Organic materials are presented by faint dark organic pigment in some microareas and some sand-size charcoal particles, incorporated in the groundmass (Fig. 11e). Despite strong macroscopic gleyic features the ferruginous pedofeatures on microscopic scale are few. Only in Agb3 horizon we found an anorthic ferruginous nodule with angular fragmentary shape and signs of fracturing (Fig. 11f).

The upper paleosol level in Koskovo 2 showed a specific composition of the groundmass in the Hb1 horizon. It consists of a compact mixture of moderately decomposed plant tissue fragments of variable size and orientation and heterogeneous (sand-silt-clay) mineral material (Fig. 12a). The mineral Crb1 horizon is also very compact, with few discontinuous fissures and chambers. The sand grains demonstrate non-uniform distribution, commonly forming agglomerations of circular or irregular shape. We also observed circular concentric birefringence pattern of the oriented clay material (concentric b-fabric) in few microareas (Fig. 12b).

Two paleosol units of Belaya Gora show quite different micromorphological features. In the Bg@ horizon of the upper paleosol well developed structure of rounded blocky and lenticular aggregates is developed (Fig. 13a). Thin ferruginous hypocoatings developed at the aggregate edges comprise a specific notorious feature of this horizon. Thin humus-rich seam in the middle of the upper unit has very specific microscopic pattern: abundant fragments of partly decomposed plant tissues of different orientation are immersed in the silty-clayey groundmass (Fig. 13b). In the lower

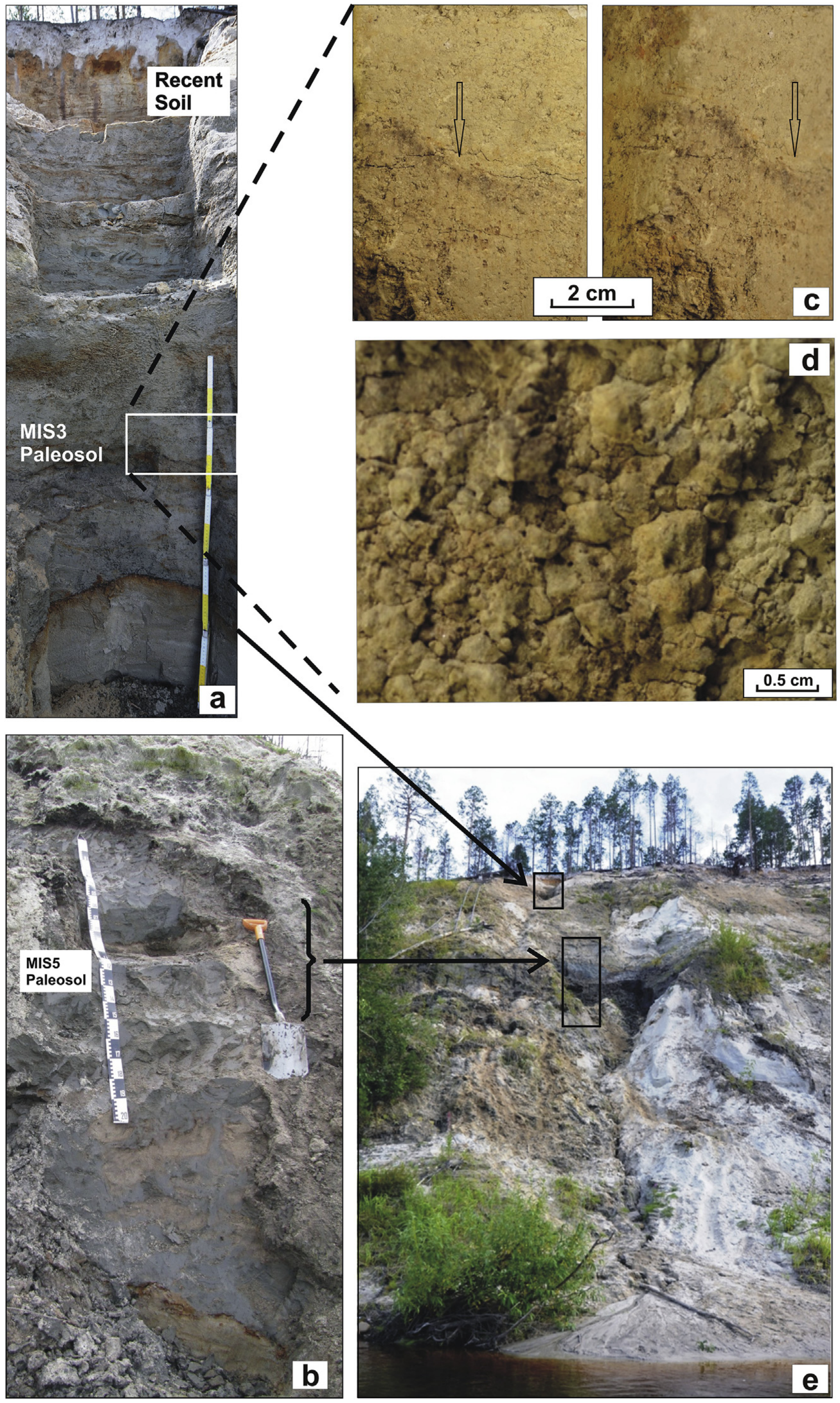

Fig. 9. Paleosol macro- and mesomorphology of the Belaya Gora section (Middle Ob' Basin). (a) The upper part of the section with the position of MIS3 paleosol marked. (b) The bottom part of the section with the position of MIS5 paleosol. (c) MIS3 paleosol profile: note deformed thin humus horizon. (d) The Crb horizon of the paleosol. Note well preserved a specific friable ooid and angular-fine cryogenic structure. Horizontal section. (e) General view of the section.

paleosol unit the Histic Ha horizon consists predominantly of brown partly decomposed organic debris. The fragments of plant tissues have parallel orientation and form quite compact structure (Fig. 13c). Few tissue fragments are found also in the underlying ACr horizon, being immersed in the silty-clayey groundmass. We were really surprised to detect in the lower Cr horizons some illuvial clay coatings with sharp interference colours. Majority of these pedofeatures were however deformed and partly incorporated in the groundmass (Fig. 13d).

4. Fossil insects and plant macrofossils from the paleosols

4.1. Koskovo 2

We looked at entomological and carpological material from two samples corresponding to the middle (sample 2) and top (sample 1) levels of pedogenesis (Fig. 7). Sample 2 has no traces of plant macrofossils. The results of the study of entomological material are presented in Table 3, Fig. 14.

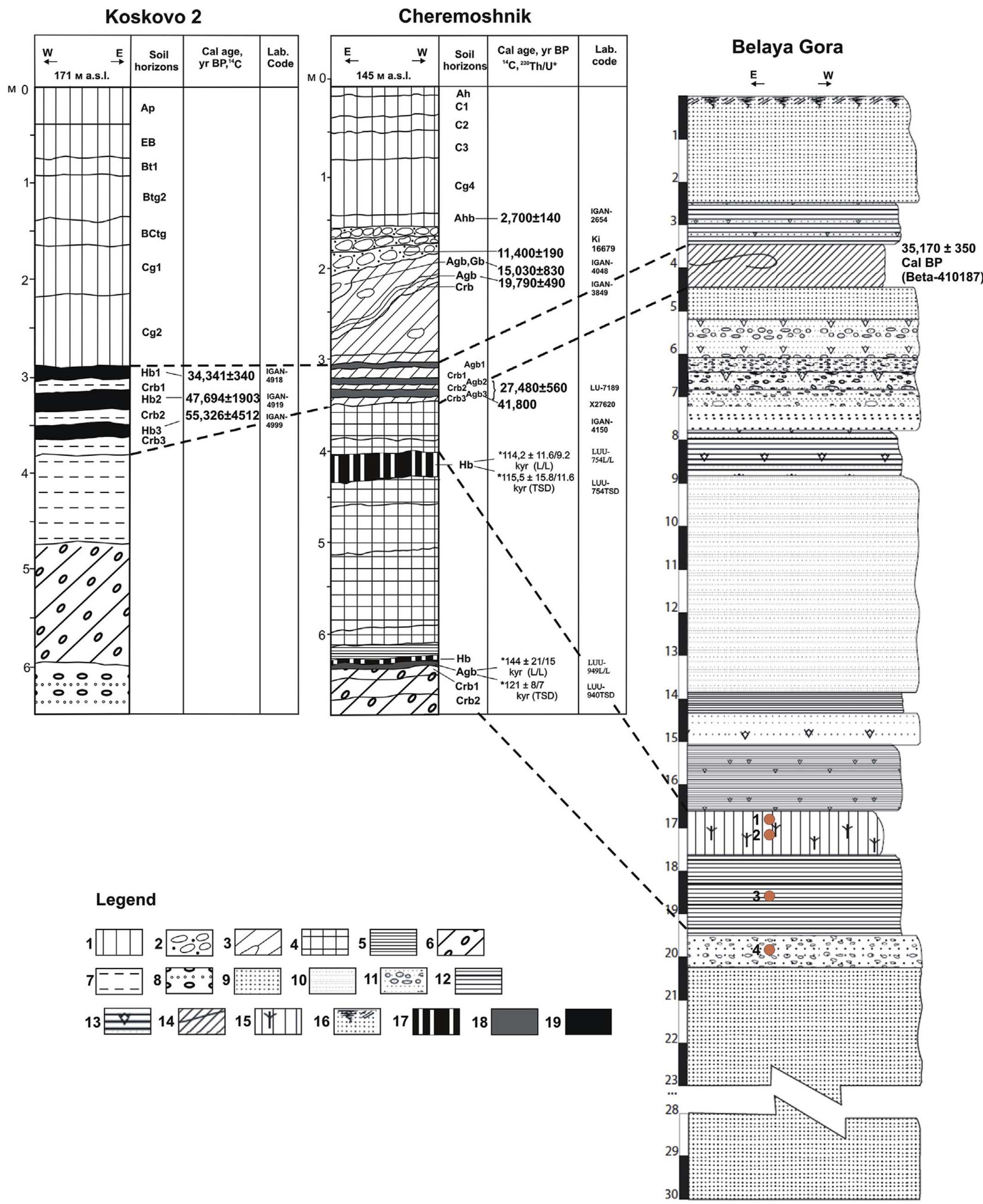

Fig. 10. Combined pedostratigraphic scheme of the Cheremoshnik, Koskovo 2 and Belaya Gora sections. 1 – loess-like (mantle) loams; 2 – gravelly stratum; 3 – layers with rare inclusions of boulders; 4 – gyttja layers; 5 – varved clay layer; 6 – till deposits; 7 – lacustrine layers; 8 – fluvioglacial layers; 9 – alluvial sand; 10 – fine laminated alluvial sand; 11 – gravel and pebble inclusions in the sand layers; 12 – loamy and clayey sediments; 13 – ferruginous pigmentation; 14 – upper paleosol unit (Bg@ horizon with thin humus seam); 15 – lower paleosol unit (Bg@ + Ha + ACr horizons); 16 – recent soil (Podzol); 17 – buried peat layer; 18 – Humic horizons of the paleosols; 19 – H horizons of the paleosols. Place of sampling (the sample numbers 1–4) for entomological and carpological analysis (the Belaya Gora section) are presented in the form of orange circles. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Sample 2 15 sub-fossil insect remains belonging to 6 individuals were collected. Among these we discovered species with mainly artic (*Pterostichus vermiculosus*, *Amara alpina*) and arctoboreal (*Pterostichus* cf. *pinguedineus*) distribution, which serves as an indisputable indicator of cold climate. The only species of polyzonal distribution is the hygrophilous water scavenger beetles *Hydrobius fuscipes*.

Sample 1 (upper layer). 78 fossils belonging to 33 individuals were collected. Arctic (*Pterostichus costatus*, *P. sublaevis*), arctoboreal (*Carabus truncaticollis*, *Diacheila polita*, *Elaphrus lapponicus*, etc.) and polyzonal (*Dyschiriodes globosus*, *Tryogenes nereis*, *Notaris aethiops*, etc.) species of beetles dominate; the discovered entocomplex reflects cold climatic conditions. Most of the beetles found in sample 1 inhabit wet, boggy biotopes. Hygrobionts and hygrophils also include representatives of groups whose modern latitudinal and zonal distribution is undefined, but the ecological belonging of which is clear. These include diving beetles (*Agabus* spp.), rove beetles (Omaliinae, *Olophrum* sp., *Stenus* sp., *Gymnusa* sp.). Mesophilic species are few: they include both arctic (*Pterostichus sublaevis*) and arctoboreal (*Carabus truncaticollis*,

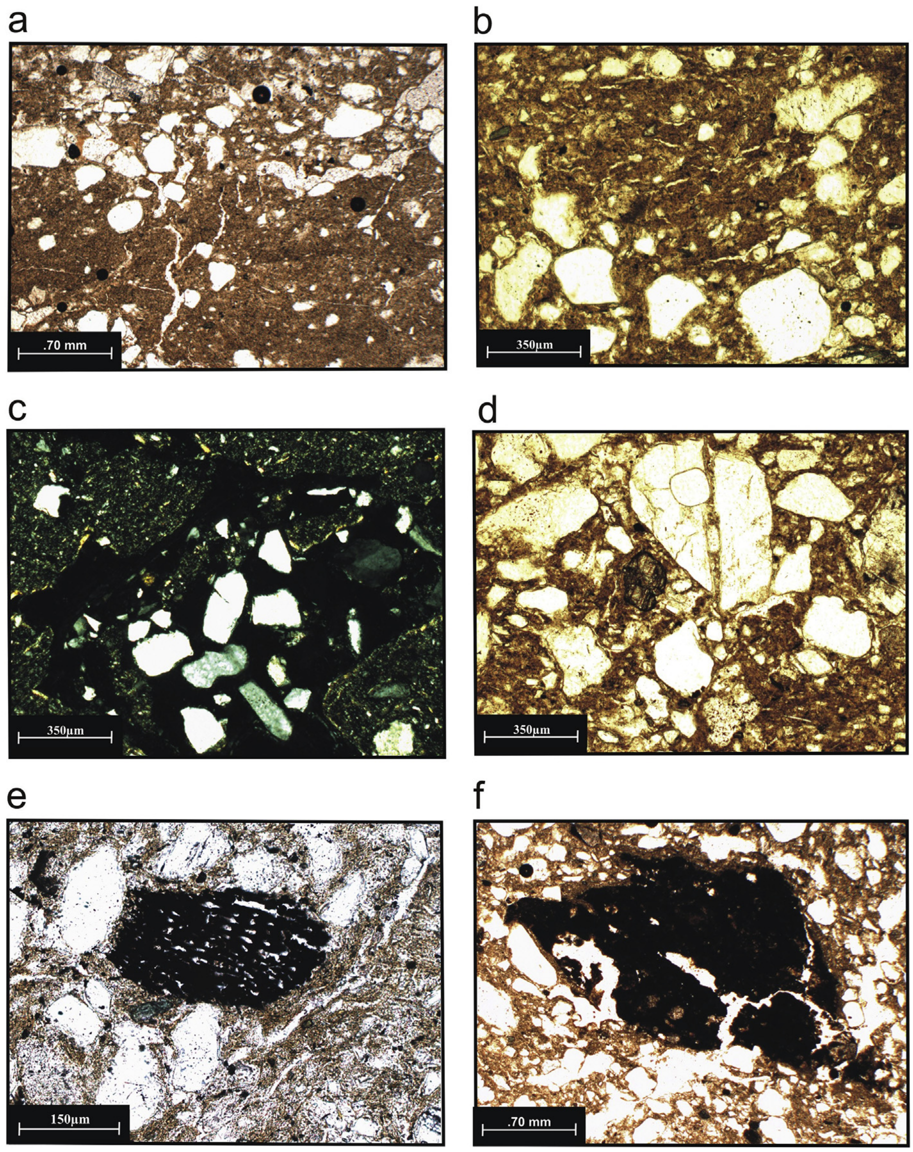

Fig. 11. Micromorphology of the MIS3 paleosol of the Cheremoshnik section. PPL – plain polarized light; N+ – crossed polarizers. a) Microlamination: alternation of the seams enriched in coarse particles (above) and fine material (below); note also compactness of groundmass with only few discontinuous fissures. Agb2 horizon, PPL; b) Circular pattern of sand grain distribution; note also thin discontinuous subhorizontal fissures in the clayey center of the circle. Agb3 horizon, PPL; c) Infilling of sand grains in a pore. Agb1 horizon, N+; d) Fracturing of a rounded quartz grain (upper center). Agb3 horizon, PPL; e) Charcoal incorporated in the groundmass. Agb3 horizon, PPL; f) Anorthic Fe-Mn nodule. Agb3 horizon, PPL.

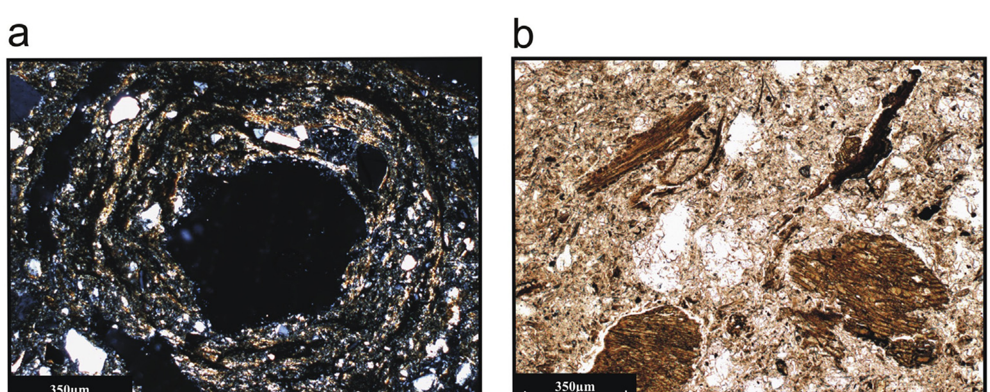

Fig. 12. Micromorphology of the upper level of the MIS3 paleosol unit of the Koskovo 2 section. PPL – plain polarized light; N+ – crossed polarizers. a) circular concentric pattern of clay orientation. N+; b) abundant plant tissue fragments, mixed with sandy-clay mineral material. PPL.

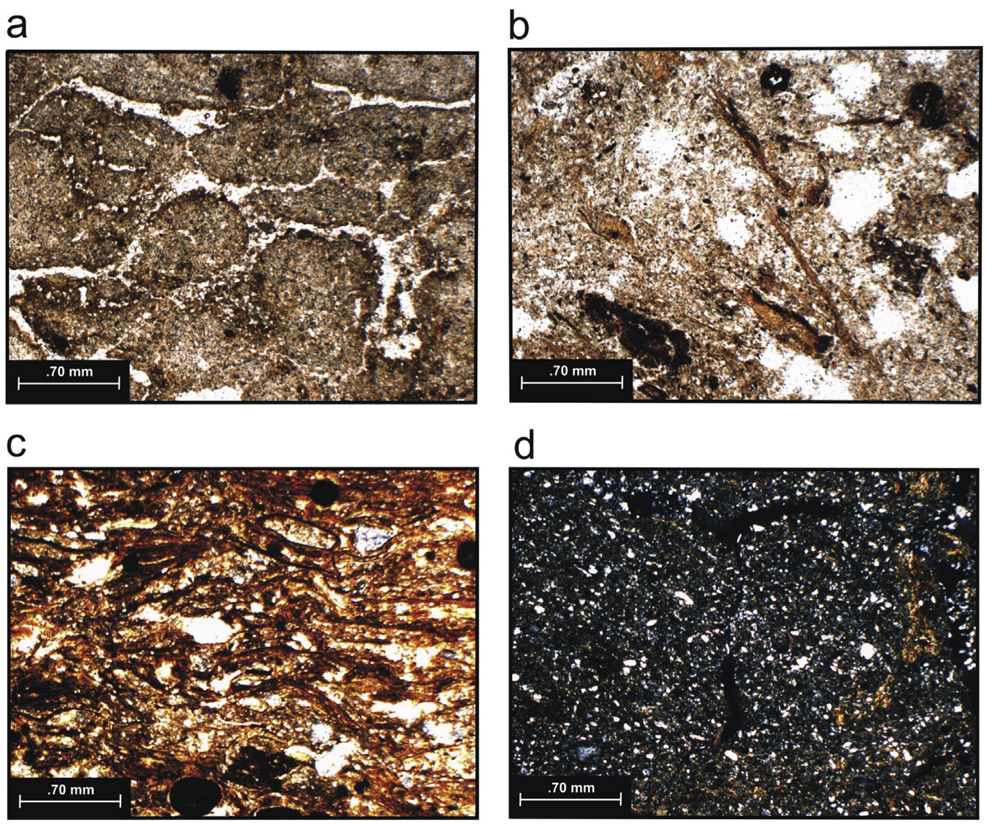

Fig. 13. Micromorphology of the paleosols of the Belaya Gora profile. a), b) Upper MIS3 paleosol unit; a) lenticular and rounded blocky aggregates, note dark ferruginous hypocoatings at the aggregate edges. PPL; b) Plant tissue fragments mixed with silty mineral material. PPL; c), d) Lower MIS5 paleosol unit; c) Parallel orientation of plant debris in the Ha horizon. PPL; d) Illuvial clay coating, deformed and partly incorporated in the groundmass. Cr horizon, N+.

Pterostichus cf. *pinguedineus*) species of beetles.

207 plant macrofossils belonging to 10 taxons (Table 4) were collected from sample 1 (top level). Woody species are represented by remains of the dwarf birch *Betula* sect. *Nanae/Fruticosa*, the condition of which does not allow for species identification (Fig. 15). The majority of grass species belongs to aquatic and bankside-aquatic vegetation. Hydrophytes are mainly related to small stagnant and weak-flowing water pools: deep swamp sites, small lakes, etc.: *Myriophyllum verticillatum*, *Potamogeton*, *Batrachium*, *Lemna trisulca*. Shallow water and bankside species are present: *Sparganium, Eleocharis palustris*. The sedge *Carex* dominates, remaining mosses are singular.

4.2. Belaya Gora section

Entomological and carpological material from the Belaya Gora section is taken from part of a 30.7-m precipice (Fig. 10); detailed results were published earlier (Zinovyev et al., 2016). We collected cryophylic complexes (Fig. 14) of insects and plant macrofossils from layers of the bottom part of the studied mass (Fig. 10). Thus, sample 4 (a depth of 19.7–20.45 m), Fig. 10 shows arctic tundral (*Pterostichus vermiculosus*, *Amara alpina*, *Tachinus arcticus*, *Micralymma* cf. *brevilingue*) and arctoboreal (*Pterostichus* cf. *pinguedineus*) species of beetles. The coleoptera complex represented by arctic and arctoboreal species (*Diacheila polita*, *Pterostichus* cf. *pinguedineus*, *P.* cf. *kokeili*, *P. costatus*, *P. vermiculosus*, *Bembidion* cf. *umiatense*, *Amara alpina*) is also described in sample 3 (a depth of 17.7–19.7 m, Fig. 10). Furthermore, here the dominating species (13% from the total number of individuals) is the arctic tundral rove beetle *T. arcticus*.

Arctoboreal poppies *Papaver* sect. *Scapiflora* (Rebristaya, 2013) became indicators of cold climatic conditions in the complex of plant microfossils from sample 4. Woody and water forms were not found. The complex of plant macrofossils characterizes grass communities with vegetation from high humidity habitats. Sample 3, shows relatively cryophilic swumpy tundra species *Betula nana*, *Ranunculus hyperboreus* and the water species *Potamogeton sibiricus*, characteristic of the flora of Yakutia and Taymyr (Flora of Siberia, 1988; Pospelova and Pospelov, 2007). Among grasses, the sedge *Carex*, buttercups *Ranunculus*, bloodroot *Potentilla* prevail. The presence of aquatic species (*Batrachium*, *Potamogeton*, *Myriophyllum verticillatum*) and species associated with disturbed soils (*Potentilla*, *Dianthus*), indicates erosion processes of the soil cover as a result of surface activity.

Two samples from the top part of the studied deposits include a species composition of insect and plant macrofossils complexes proved to be principally different. Thus, the entocomplex of sample 2 (a depth of 16.95–17.15 m) corresponds with horizon ACr (16.9–17.7 m) shows mainly polyzonal (*Eubrychius velutus*, *Pterostichus nigrita*, etc.) and boreal (*Trechus rivularis*, *T. secalis*, *Pterostichus diligens*, *P. strenuus*) species of beetles. The occurrence of *T. secalis* fragments might be indicative of warmer, in comparison to modern, climate because this species is distributed to the south of the location of Belaya Gora today. The discovery of the rifely beetle of the genus *Dryops* (fam. Dryopidae) in sample 2 implies river genesis of the formation of the studied layer. In sample 1 (a depth of 16.70–16.95 m, Fig. 15) of the location in question, together with arctoboreal, boreal (*Pterostichus oblongopunctatus*, *P. diligens*, *Trechus rivularis*, etc.) and polyzonal species, arctic species of beetles (*Pterostichus sublaevis*) are singular.

Table 3
List of insects found in two samples of Koskovo 2 site.

Taxon	sample 2 (middle level of pedogenesis)	sample 1 (upper level of pedogenesis)
Fam. Carabidae		
Carabus truncaticollis		1
Elaphrus lapponicus		1
Diacheila polita		2
Dyschiriodes globosus		1
Bembidion (Asioperyphus) sp.		1
Pterostichus sublaevis		2
Pterostichus vermiculosus	1	
Pterostichus costatus		1
Pterostichus (Petrophilus) sp.		3
Pterostichus (Cryobius) cf. *pinguedineus*	1	2
Pterostichus sp.		2
Amara alpina	3	
Amara cf. *torrida*		2
Fam. Dytiscidae		
Agabus sp.*1*		1
Agabus sp.*2*		1
Fam. Hydrophilidae		
Hydrobius fuscipes	1	
Fam. Staphylinidae		
Olophrum sp.		1
Omaliinae indet.		4
Stenus sp.		1
?Gymnusa sp.		1
Staphylinidae indet.		1
Fam. Chrysomelidae		
Chaetocnema sp.		1
Fam. Curculionidae		
Tryogenes nereis		1
Notaris aethiops		1
Isochnus sp.		1
Insecta indet.		1
Total amount of fragments	6	33

In the complex of plant macrofossils from sample 2 woody vegetation is represented by the spruce *Picea obovata*, the larch *Larix sibirica*, the birch *Betula* sect. *Albae* and the raspberry *Rubus idaeus*. Species of bankside thickets and woodland edges (*Naumburgia*, *Thalictrum* cf. *minus*, *Urtica dioica*, etc.) are abundant. Among grasses remnants of swamp plants dominate – *Carex*, *Comarum palustre*, *Calla palustris*. Near-aquatic and aquatic species are singular (*Sparganium*, *Hippuris vulgaris*, *Potamogeton*). The composition of the paleoflora of sample 2 does not show any indicative species of warmer or colder climate in comparison with modern climate. The complex of plant macrofossils from sample 1 (Fig. 15) together with boreal plant species contained relatively cryophilic swamp-tundra species: *Ranunculus hyperboreus*, *Selaginella selaginoides* and *R.* cf. *pygmaeus*. Species of forest swamps (*Calla palustris* and *Typha*) are present, aquatic species are singular (*Batrachium*).

5. Discussion

5.1. Pedostratigraphy of Upper Volga and Middle Ob in the context of the late Pleistocene continental and global records

Geomorphological position of all studied profiles corresponds to the elevated oldest landsurfaces where the most complete records of the Pleistocene landscape development are expected.

The 230Th/U ages $130 \pm 11/9$ ka (L/L) and $117 \pm 8/7$ ka (TSD) obtained for thin soil horizon Agb from 6.22 to 6.23 m depth testify that the time of peat-dark humus paleosol formation can be correlated with MIS5e. These dates are consistent with the 230Th/U dating $114 \pm 12/9$ ka (L/L) and $115 \pm 16/12$ ka (TSD) of overlying buried peat layer from the 4.3–4.0 m depth of the key section Cheremoshnik (Rusakov et al., 2015). The 230Th/U age of peat-dark humus paleosol from 6.22 to 6.23 m depth corresponds to local pollen assemblage zone LPAZ2 correlated with zone M1 by Grichuk (1982, 1989), while the 230Th/U age of peat layer from the 4.3–4.0 m depth correspond to local pollen assemblage zone LPAZ5 correlated with zone M4 (Rusakov et al., 2015). All of these data indicate that the time of paleosol and overlying peat formation is related with the MIS 5e, i.e. Mikulino (Eeamian) Interglacial. Similar combined pollen and 230Th/U dating results were obtained for a number of peat profiles from the Russian Plain (the Mikulino Site, Smolensk Province, Russia; the Fili Site, Moscow, Russia; the Murava Site, Belarus), which had been formed during the first half of MIS5 (Mikulino, Eemian Interglacial) (Kuznetsov and Maksimov, 2003, 2012; Maksimov et al., 2006; Maksimov and Kuznetsov, 2010). The first preliminary 230Th/U age (~100 ky) and the results of pollen analysis obtained for the Belaya Gora peat profile also correspond to this time.

Basing on these dates we correlate the profiles of Cheremoshnik and Koskovo 2 (Fig. 10) and conclude that the paleosol levels of both major warm stages (thermochrons) of Late Pleistocene: Mikulino/Kazantsevo interglacial (MIS5e) and Bryansk/Karga interstadial MIS3 (Simakova, 2006) are present in these sections. Thus, further correlation with the stratigraphic schemes of the neighbouring loess regions of the Eastern Europe and Western Siberia (to the south of the studied territories) is possible. The lower paleosols correspond to Mezin pedocomplex of the loess-paleosol stratigraphy of European Russia (Velichko et al., 2006) and with the Berdsk Pedocomplex in the Western Siberia (Zykina and Zykin, 2008).

More complex correlation should be developed for the paleosol levels corresponding to MIS3. Whereas Belaya Gora profile has only one paleosol level corresponding to MIS3, the profiles in the Upper Volga region: Cheremoshnik and Koskovo 2 – have three incipient

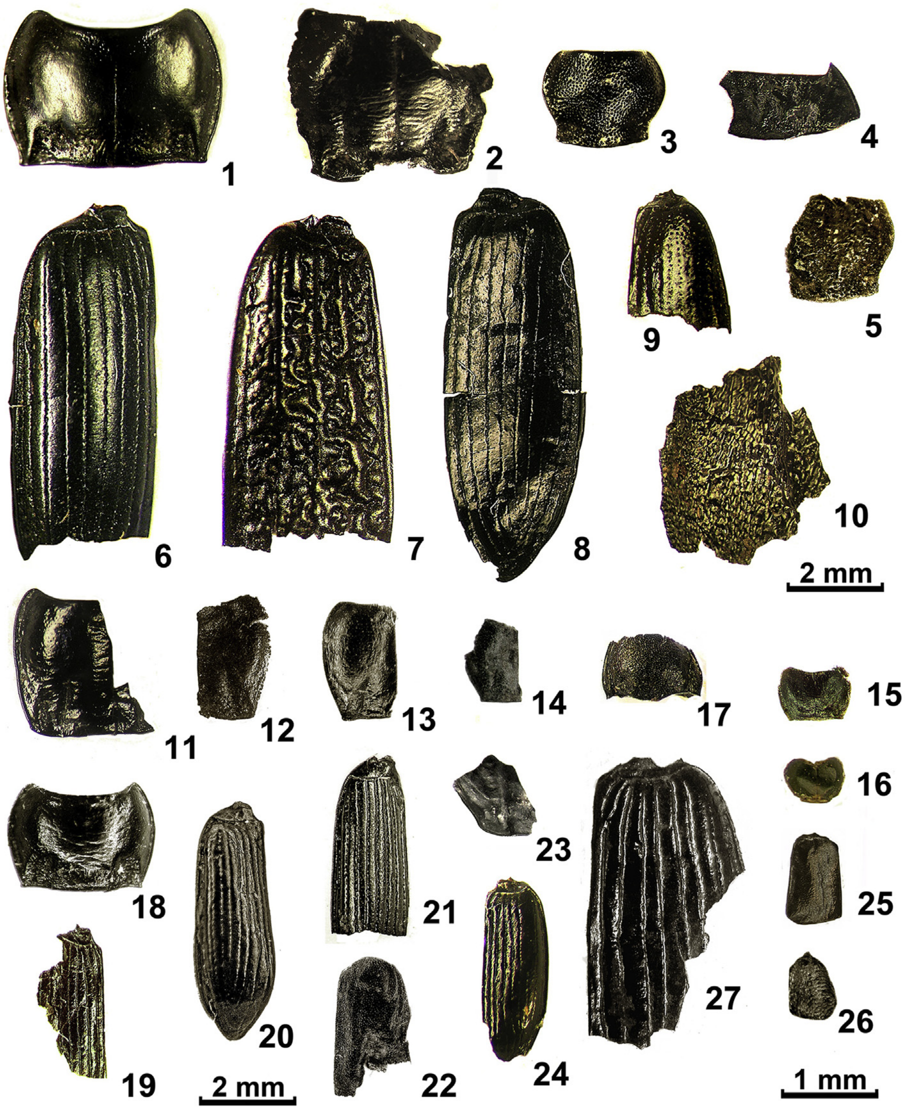

Fig. 14. Fragments of beetles, found in the Koskovo 2 (1–10) and Belaya Gora sites (11–27). 1 – *Amara alpina*, sample 2, pronotum; 2 – *Pterostichus sublaevis*, sample 1, pronotum; 3 – *Diacheila polita*, sample 1, pronotum; 4 – *Agabus* sp., sample 1, right part of pronotum; 5 – *Elaphrus lapponicus*, sample 1, pronotum; 6 – *Amara alpina*, sample 2, left elytra; 7 – *Pterostichus vermiculosus*, sample 2, left elytra; 8 – *Stereocerus haematopus*, sample 2, left elytra; 9 – *Diacheila polita*, sample 1, right elytra; 10 – *Carabus* cf. *truncaticollis*, sample 1, fragment of elytra. 11 – *Pterostichus costatus*, sample 3, pronotum; 12 – *Pterostichus* cf. *oblongopunctatus*, sample 1, right part of pronotum; 13 – Pterostichus cf. pinguedineus, sample 3, left part of pronotum; 14 – *Pterostichus diligens*, sample 2, left part of pronotum; 15 – *Trechus rivularis*, sample 1, pronotum; 16 – *Trechus secalis*, sample 2, pronotum; 17 – *Dryops* sp., sample 1, pronotum; 18 – *Amara alpina*, sample 4, pronotum; 19 – *Agonum* cf. *fuliginosum* sample 1, left elytra; 20 – *Pterostichus* cf. *pinguedineus*, sample 3, left elytra; 21 – *Pterostichus* cf. *pinguedineus*, sample 4, left elytra; 23 – *Dryops* sp., sample 1, left elytra; 23 – *Pterostichus sublaevis*, sample 1, fragment of pronotum; 25 – *Tachinus arcticus*, sample 4, left elytra; 26 – *Micralymma* cf. brevilingu, sample 4, left elytra; 27 – *Pterostichus costatus*, sample 3, right elytra.

Table 4
Taxa list of plant macrofossils found in two samples of Koskovo 2 site.

Taxon	Number of fossils
Betula sect. Nanae/Fruticosa	29
Sparganium sp.	4
Eleocharis palustris (L.) Roem. & Schult.	44
Carex sp.sp.	73
Potamogeton sp.sp.	13
Lemna trisulca L.	1
Batrachium sp.sp.	28
Myriophyllum verticillatum L.	3
Rumex acetosella L.	1
Potentilla sp.	2
unidentifiable	9

paleosols for this interval. However the direct correlation of these 3 paleosols between 2 studied profiles is not supported by the obtained radiocarbon dates: the ages of the lower MIS3 soils of Cheremoshnik are younger than that of the lower paleosol levels of Koskovo 2 (Table 2).

When we first described these paleosols in the Upper Volga region we associated them with Bryansk soil unit of the European Russian loess sequences (Rusakov et al., 2007). Also a single paleosol level corresponding to Karga Interstadial was identified in the Middle Ob basin (Sheinkman et al., 2016). Later however we detected multiple events of paleopedogenesis corresponding to MIS3 in some profiles of the Upper Volga (Rusakov and Sedov, 2012; Sedov et al., 2016).

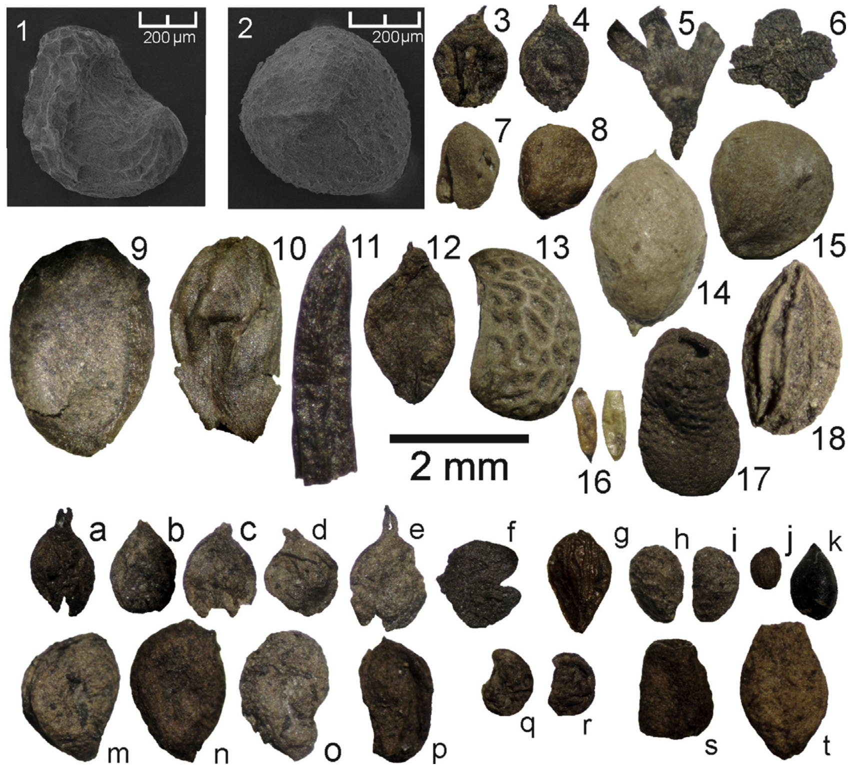

Fig. 15. Plant macrofossils from the sites Belaya Gora (1–18) and Koskovo 2 (a–t). 1– *Papaver* sect. Scapiflora, seed; 2 – *Selaginella selaginoides,* megaspore; *Betula nana*: 3,4 – nutlets, 5 – scale, 6 – leaf fragment; 7 – *Ranunculus* cf. *pygmaeus,* nutlet; 8 – *Ranunculus hyperboreus,* nutlet; 9 – *Larix sibirica,* seed; *Picea obovata*: 10 – seed, 11 – needle; 12 – *Betula* sect. Albae, nutlet; 13 – *Rubus idaeus,* seed; 14 – *Potamogeton sibiricus,* endocarp; 15 – *Ranunculus monophyllus,* nutlet; 16 – *Typha* sp., tegmens; 17 – *Calla palustris,* seed; 18 – *Thalictrum* cf. *minus,* nutlet. *Betula* sect. Nanae/Fruticosa: a–e – nutlets, f – leaf fragment; g – *Eleocharis palustris,* fruit; h, i – *Batrachium* sp., nutlets; j – *Lemna trisulca,* seed; k – *Rumex acetosella,* nutlet; m–p – *Potamogeton* sp., endocarps; q, r – *Potentilla* sp., nutlets; s –*Myriophyllum verticillatum,* mericarp; t – *Sparganium* sp., endocarp.

Certain similarities however could be found between the studied sections and some detailed loess-paleosol stratigraphies of Eurasia which also demonstrate multiple levels of MIS3 pedogenesis. Koskovo 2 section has three levels of MIS3 paleosols with quite broad time span of the radiocarbon dates. The age of the upper paleosol fits to the range of Bryansk soil of the European Russia loess sequences. However the lower levels with the dates older than 40 ka BP are clearly more ancient then Bryansk soil interval. Similar distribution of ages was earlier established in the MIS3 pedocomplex of Cheremoshnik: upper humus horizons produced the date 27.5 cal ka BP – which fits to the range of Bryansk soil – whereas the lower humus horizon was older that 41 cal ka BP (Sedov et al., 2016). In the loess sections of the East European plain paleosols corresponding to the early MIS3 have been encountered called Alexandrovka soil (Sycheva and Sedov, 2012). In the loess-paleosol sequences in the south of Western Siberia within the MIS3 Iskitim pedokomplex Zykina and Zykin (2003) discriminate the Early Karginian and late Karginian paleosol levels. In the European loess belt recent studies also point to 2 major MIS3 paleosol units in a number of sections, especially well expressed in the profiles of Rhine valley: in Nussloch these are Lohner Boden (late MIS3) and Gräselberger Boden (early MIS3) (Antoine et al., 2001), in Schwalbenberg - Sinzig soils (late MIS3) and Upper Remagen soils (early MIS3) (Schirmer, 2012). These two major paleosol units within MIS3/ Middle Pleniglacial are supposed to correspond to the NW European interstadials Denekamp (ca 35.5–32.5 ka) and Hengelo (ca 43.5–41.5 ka) well established on the basis of paleobotanical proxies (Kolstrup and Wijmstra, 1977). The resolution of the studied paleosol archives still does not permit their correlation with more detailed global climate records, e.g. with Greenland interstadials.

5.2. Pedogenesis of the paleosols and its paleoenvironmental implications

Pedogenetic properties of the lower MIS5 paleosols point to the following dominants soil forming processes: accumulation of poorly decomposed plant debris as peat and strong gleyzation of the mineral material. In particular, in Cheremoshnik the MIS5 paleosol has a Histic horizon – well preserved layer of peat. A Histic horizon is also present in the MIS5 paleosol of Belaya Gora however it is quite thin. Below it lies gleyic organo-mineral ACr horizon, underlain by strongly gleyed Cr horizon. These processes correspond to hydromorphic pedogenesis which takes place in swampy environment under water-saturated conditions. The comparison of the studied profiles with the other Eurasian terrestrial late Pleistocene records demonstrates certain discrepancies. On one hand, correlative reliably dated peat from Eemian/Mikulino/Kazantsevo thermochron is known from a number of sites on similar latitude or even to the north of the studied regions: Northern Germany (e.g. Börner et al., 2015), north of European Russia (Maksimov and Kuznetsov, 2010), north of Western Siberia (Astakhov et al., 2005).

However in the loess-paleosol sequences to the south of our research areas the MIS5e paleosols are represented the “automorphous” profiles, corresponding to the classic zonal sequence: Luvisols and Retisols (Albeluvisols) in Europe from Atlantic coast to Central European Russia (Haesaerts and Mestdagh, 2000); Chernozems in the south of Europe – Danubian Basin (Bronger, 1976;

Marković et al., 2009) and the south of Western Siberia (Zykina and Zykin, 2003). These paleosols have their direct analogues in the Holocene soil mantle and frequently are similar to the local (or nearby) recent surface soils (Sedov et al., 2013), although in the Central and Eastern Europe Eemian forest Luvisols are sometimes found in the areas, where Holocene soils are steppe Chernozems (Morozova et al., 1998).

According to the pollen diagrams from the Mikulino peat in Cheremoshnik (Rusakov et al., 2015) and numerous other pollen data, forest vegetation prevailed in Northern European Russia and even in the north of Western Siberia (lower Ob basin) during MIS5e. This arise expectations to find the automorphous paleosols of forest type in these regions. However although Podzolic soils corresponding to Eemian and covered by Wiechselian glacial deposits were found as far to the north as Finland (Pitkäranta, 2009), these findings are still very few. What are the factors of formation and preservation of the hydromorphic MIS5 paleosols in Cheremoshnik and Belaya Gora sections? In Cheremoshnik we suppose that the Histosol was formed in a wetland which occupied a permanently moist depression. Geomorphological analysis demonstrated that the ravine of Cheremoshnik is multiphase and inherits an earlier erosional form. It is highly probable that a ravine/small valley existed here throughout the Late Pleistocene, being the site of hydromorphic soil development during geomorphologically stable warmer periods and increased erosion and colluviation processes were activated due to climate deterioration or recently due to human impact.

The setting of Belaya Gora is quite different. Here the gleyic MIS5 paleosol is developed on an elevated well drained alluvial terrace and underlain by permeable sand deposits. Why hydromorphic pedogenesis took place in such unfavourable position? We speculate that waterlogging above icy permofrost is responsible for it. This hypothesis was applied earlier to explain pedogenesis of the gleyic paleosols of MIS3 (Sedov et al., 2016) and MIS3/MIS2 transition (Terhorst et al., 2015). From the first glance this mechanism seems to be not valid for the interglacial paleosol formed under warm climate without permafrost. We should consider however the possibility of polygenesis of the lower paleosol unit of Belaya Gora. The micromorphological observations demonstrated presence of clay illuvial pedofeatures in the strongly gleyed horizon (Fig. 13d). It means that this soil passed the stage of good internal drainage and Luvisol type of pedogenesis, before gleyzation took place. This allows us to suppose the following succession of the soil formation phases: 1) clay illuviation and development of luvic features corresponding to temperate forest ecosystem during the warmest MIS5e and 2) development of permafrost and cryo-hydromorphic pedogenesis during the late substages of MIS5 (beginning of the interstadial). In fact many Mikulino/Eemian paleosols in loess areas are pedocoplexes or polygenetic soils with evidences of early Wurmian cold continental or cryomorphic pedogenesis superimposed on the interglacial temperate forest paleosol (Velichko et al., 2006; Sycheva and Sedov, 2012).

MIS3 pedogenesis in all studied sections agrees with our model of hydromorphic soil development conditioned by permafrost. This led us to the conclusion of existence of a vast zone of tundra gley soils in the center-north of Eastern Europe and Western Siberia, in the region currently occupied by taiga ecosystems (Sedov et al., 2016). The difference of Siberian (Belaya Gora) paleosol consists in very well developed cryogenic structure. This could be explained by more continental paleoclimate in Siberia, with stronger seasonal contrasts of temperature and moisture that promoted aggregation of soil mineral horizons.

5.3. Paleoecological interpretation of the fossil plant and insect complexes and its comparison with the paleosol proxies

Combination of entomological data and study of plant macrofossils allows providing detailed paleoenvironmental reconstructions. Identified indicator species became a valuable source of information for landscape evolution and paleoclimatic reconstructions.

5.3.1. Koskovo 2

The entomological material is indicative of a cold climate and corresponds to open tundra landscapes both for the middle (sample 2) and top (sample 1) levels. Based on this, we can only suppose that conditions were more humid during the formation of the layers corresponding to sample 1.

Based on the species composition, the studied complex of beetles of Koskovo 2 is closest to the faunas of the locations Peelo (the Netherlands), Bełchatów (Poland), where the same beetle taxons (*Pterostichus vermiculosus*, *P.* (*Cryobius*) spp., *Elaphrus lapponicus*) reflecting cold climatic conditions and landscape distribution of the modern tundra and forest-tundra type are found (Nazarov, 1984; Kasse et al., 1998). Cold-resistant species of ground beetles *Diacheila polita*, *D. arctica*, *Elaphrus lapponicus*, *Amara alpina*, rove beetles (*Holoboreaphilus henningianus* Sahlb., *H. nordenskioeldi*, etc.) were also found on the territory of England and France, but in general the species composition of the entocomplexes is closer to the population of boreal landscapes of the northern part of Fennoscandia (Bos et al., 2004; Brown et al., 2007; Ponel, 1995). At the same time, the composition of both of the Koskovo 2 site's samples' entocomplexes lack components presented in synchronous faunas of Western and Eastern Siberia, such as weevils *Otiorhynchus karkaralensis*, *O. kazakhstanicus* (Zinovyev, 2011; Legalov et al., 2016), abundant in the faunas of western Siberia to the south of 58° N, species of the genus *Stephanocleonus*, *Coniocleonus*, as well as pill beetle *Morychus viridis* (Sher et al., 2005; Kuzmina, 2015), common in corresponding eastern Siberian complexes. Thus, the entocomplexes of the location Koskovo 2 are closer to central European ones in their species composition, rather than to western and eastern Siberian faunas of coleoptera.

The Koskovo 2 complex of plant macrofossils consists of local species of wide distribution. Cryophilic species, with the exception of dwarf birches, are not present. Currently certain species of dwarf birches (*Betula nana* and *B. humilis*) can be found at research sites in forest swamps (Flora of East Europe, 2004). The lack of tree fossils (considering the presence only of dwarf birches) and typical swamp species, a depleted taxonomical compound of the paleocomplex allow us to assume a tundra-like local vegetative community. The studied sequences were formed in the vicinity of a shallow pool of water, at the banks of which ernika grew. The obtained data agree with the results of the studied palynological spectrums of the final stage of MIS3 at the Russian Plain, based on which moderately cold climatic conditions were determined. During this time, various periglacial vegetation with no modern analogues was distributed throughout the territory of the Russian Plain (Borisova, 1995; Simakova, 2006). Periglacial forest-tundrasteppe with areas of forest vegetation, meadow steppe formations, tundra groups and halophilic groups of a steppe type was located in the central regions of the Russian Plain between 54° and 59° N during the Bryansk Interstadial (33–24 ka) (Simakova, 2006).

5.3.2. Belaya Gora

The species composition of insects and plant macrofossils presented in samples 3 and 4 of the location Belaya Gora (Fig. 10) is analogous to the conditions of modern tundras: species related to the forest zone and forest litter were not found. Based on an analysis of modern ecological requirements for the discovered indicative species, we can say that the climatic conditions were quite close, likely matching modern typical (sample 4) and shrub (sample 3) tundras of Western Siberia.

Complexes of insects and plant macrofossils from samples 1 and 2 of the location Belaya Gora are principally different, which implies the existence of forest communities. Furthermore, the discovery of thermophilic carabus Trechus secalis in sample 2 of the specified location allows us to suppose a warmer, in comparison to modern, climate. According to entomological and carpological data, the deposits in sample 1 of the profile in question formed in cool climatic conditions and landscape distribution analogous to modern north taiga forests.

The data collected at the location Belaya Gora most strongly correlate with the dynamics of the entocomplex within the site Karymkarsky sor at the boundary of MIS6-MIS5 (Zinovyev, 2012). Thus, in the layer of peat dated 131 ± 31 kyr BP (Arkhipov and Volkova, 1994) we discovered complexes of beetles allowing for the reconstruction of rather warm climate with the inclusion of thermophilic carabus *Trechus secalis* (Zinovyev, 2012), while the underlying layer shows arctic and arctoboreal species of beetles, which implies a colder, in comparison with modern, climate. The results obtained for sample 2 of the site Belaya Gora correspond to the existing understanding of the nature of the entocomplexes of the beginning of MIS5 in Western and Eastern Europe (Ponel, 1995; Coope, 1986; Nazarov, 1984). Thus, the substage MIS5e is related to the discovery of thermophilic species of beetles in Western and Eastern European deposits (Walkling and Coope, 1996; Coope, 2010; Ponel, 1995; Nazarov, 1984, 1986), for example, the northward expansion of mediterranean species of beetles shown for the territory of modern England (Coope, 2010).

Plant macrofossil assemblages described for the MIS5e optimum in central regions of the Western Siberia and East-European Plain also comprise a significant portion of thermophilic species (Martynov and Nikitin, 1964; Nikitin, 1970; Novenko et al., 2011). The assemblages recovered from Belaya Gora section contain no thermophiles. Based on the species composition, the “warmer” complex of sample 2 is comparable to the paleoforms obtained from the lower part of the peat layer of the location Kiryas (60°57′ N) dated to the MIS5c substage (Laukhin et al., 2007). Consequently, the lower part of the studied mass can be related to the MIS5d substage, to which periglacial landscapes corresponded.

Thus, the pedocomplex of the central part of the profile Belaya Gora consists of the paleosol members formed in principally different landscape conditions. The top layers of the complex reflect relatively warm conditions of warm substages of MIS5, whereas the lower layers, evidence rather cold tundra environment at the end of MIS6 or beginning of MIS5. The paleoecological interpretation of the entomological and paleobotanical materials is in good correspondence with the pedogenetic interpretation of the paleosols. In Belaya Gora the “forest type” complex of insect and plant species in the thin Histic horizon agrees with the Luvic features in the mineral horizon below, which we associate with pedogenesis under boreal forest vegetation. The paleontological and paleobotanical data from Koskovo 2 which point to tundra ecosystems agree with the findings of gleyed cryogenic paleosols also typical for tundra. All three levels are interpreted as gleyic cryoturbated soils developed on icy permafrost – the kind of pedogenesis expected in the cold tundra landscapes. Presence of aquatic plant residues could be explaines with supposed (by geomorphological data) existence of water bodies of different size close to the site: larger ones in the erosional depressions or smaller, associated with thermocarst and patterned ground tiny lakes and ponds.

In general the whole set of obtained geomorphological, paleopedological and paleontological results conforms with the hypothesis of an extensive cold tundra zone with cryogenic gleyic soils in the most part of north-easter Europe and north of Western Siberia (with possible extension more to the east) during the end of MIS3 (Sedov et al., 2016).

6. Conclusion

1) There are well preserved paleosols in the Late Pleistocene sedimentary sequences of Eastern Europe and West Siberia to the north of the loess belt, close to the area of the last glaciation; these paleosols correspond to the warmer periods MIS3 and MIS5 that is confirmed by C14 and U/Th dates.
2) The pedogenetic as well as plant and insect macrofossil proxies from the MIS5 paleosols are indicative of temperate forest ecosystems similar to the present ones.
3) The MIS3 paleosols present the features of cryogenic processes as well as gleyzation, conditioned by permafrost; in agreement with this, the macrofossil record points to the cold tundra ecosystems which existed during Middle Valdai/Karginian interstadial in the region of present day taiga forests.

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