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# The Loess-Paleosol Sequence at the Krasnogorskoye Section, the Low-Hill Zone of the Northeastern Altai Mountains

*The loess-paleosol sequence of the Krasnogorskoye section in the low-altitude area of the northeastern Altai Mountains can provide a yardstick for estimating the age of the Paleolithic sites, and reconstructing environmental and climatic changes. Its correlation with the similar sequence of the southern part of the West Siberian Plain is evaluated. Five pedocomplexes are studied in detail, evidencing the evolution of the Middle and Late Pleistocene soil formation from the Shadrikha interglacial to the Karga interstadial. Buried soils of the Shadrikha, Shipunovo, Koinikha, and Kazantsevo warm stages were formed under a climate that was warmer and more humid than today's. After the Kazantsevo interglacial, both the range and the frequency of climatic oscillations show marked changes. It is demonstrated that the warm stages of this interval differ from the earlier ones by lesser warming and shorter duration, by a cooler and more arid climate. Seven loess horizons dividing pedocomplexes are established. Nonmetric and metric analyses of quartz sand grains support the eolian origin of loess horizons under cryoarid conditions. The size of grains in the Late Pleistocene portion of the Krasnogorskoye section attests to the intensification of the loess processes. Higher magnetic susceptibility during the cool stages, and higher frequency-dependent susceptibility during the warm stages evidence marked climatic oscillations. After the Kazantsevo interglacial, the amplitude diminishes, and the pattern of paleoclimatic signal recorded by the magnetic properties of loess and paleosol in the section is close to the "Alaskan" type.*

Keywords: *Loess-paleosol sequence, Western Siberia, paleosols, Pleistocene, paleoclimate, stratigraphy.*

## Introduction

The discovery of chronologically diverse archaeological sites in the Altai Mountains makes the study of Quaternary deposits in that region highly relevant in the archaeological context. The most complete and widely distributed among these are loess deposits. Their analysis helps to evaluate the chronology of Paleolithic sites and to assess the environmental and climatic changes affecting Paleolithic society and its culture (Derevianko, Shunkov, Bolikhovskaya et al., 2005; Derevianko, Markin, Zykin et al., 2013; Zykin et al., 2005; Zykina, Zykin, 2012).

In the piedmont and low-hill areas of the northeastern Altai Mountains, loess-soil sediments have been studied along the Katun and Biya rivers, their tributaries, and on mountain slopes. On mountain slopes, the thickness of these formations varies from 6 to 16 m, while on terraces it reaches 26 m. Stratigraphic subdivision and paleogeographic reconstructions were based on the results of multidisciplinary studies, including paleopedology, sedimentology, geomorphology, and radiocarbon and paleomagnetic analyses. Krasnogorskoye section (Fig. 1) is the most representative among the examined loess-soil sections of the Altai Mountains. Five pedocomplexes and seven loess horizons underlying modern soil have been recorded there. A consistent correlation of Krasnogorskoye pedocomplexes and loesses with horizons of the reference loess sequence of Western and Central Siberia (Zykina, Zykin, 2012) in the respective morpho-typological indicators has allowed us to single out the Iskitim (MIS 3) and Berdsk (MIS 5c, e) pedocomplexes of the Upper Pleistocene, and Koinikha (MIS 7), Shipunovo (MIS 9), and Shadrikha (MIS 11) pedocomplexes as representing the Middle Pleistocene.

For the first time, the Krasnogorskoye section was correlated with that of Dolní Věstonice, Moravia, to address the issue of opposite models of magnetic susceptibility and to evaluate nonmagnetic pedological indicators in the loess and soil sequence (Babek, Chlachula, Grugar, 2011). Stratigraphic subdivision of the section was considered within the range of the Late (MIS 2 to MIS 5) and Middle (MIS 6) Pleistocene on the analogy with the Dolní Věstonice section. Our studies have provided important information on the structure of the section, allowing us to reconstruct the

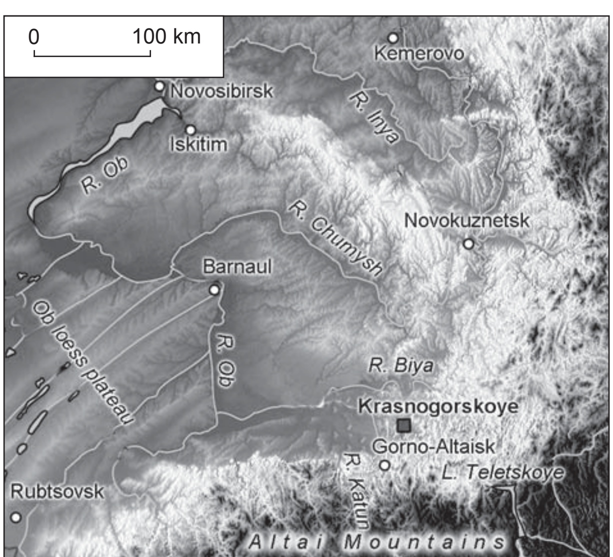


*Fig. 1*. Map showing the location of the Krasnogorskoye section in the low-hill zone of the Altai Mountains, in the south of Western Siberia.

formation of loesses and soils, to estimate the age of the Upper Pleistocene soil unit (MIS 3), and to assess the magnetic susceptibility of the deposits.

Genetic horizons of paleosols were indexed in accordance with the soil classification currently used in Russia (Egorov et al., 1977; Shishov et al., 2004). Subdivision of sediments was conducted following the International Chronostratigraphic Chart (ICC) for the Quaternary (implying division of the Pleistocene into Lower, Middle, and Upper stages), and placing its base at 2.588 Ma BP (Head, Gibbard, Salvador, 2008). The Lower/Middle Pleistocene boundary is put at 0.78 Ma BP.

## Geological structure of the section

The section is located in a former brickyard quarry, near the northern periphery of the Krasnogorskoye settlement, Krasnogorsky District of the Altai Territory. Five profiles located on the western wall of the quarry and descending successively the slope to the Barda River (Fig. 2) (52°18′36.8″ N; 086°11′28.4″ E; 300 m asl) were examined. We leveled the quarry's western wall, running perpendicularly to the river, described the profiles in detail, divided the section into stratigraphic units, and conducted paleopedological and lithological studies (Fig. 3). All the horizons of loesses and paleosols are deposited horizontally. The thickness of the section totals 24.5 m. The following Upper and Middle Pleistocene horizons (Fig. 3, 4) underlie modern chernozem soil:

1. The Bagan loess (**bg**) is loess-like loam 0.9 m thick, grayish-brown, dense, porous, with carbonate pseudomycelium. The second half of the horizon contains neoformations of iron as stripes and small spots. Rare manganese specks are visible.

2. The Eltsovka loess (**el**) is loess-like loam 1.5 m thick. Its upper portion is grayish-yellow; the coloration of the lower portion is variegated, owing to alternating grayish-light-brown and grayish-yellow-whitish streaks. The deposit is porous and dense. It contains loose carbonate concretions up to 2.0 cm in size, and numerous neoformations of iron as spots, stripes, and encrusted pores and root channels.

3. The Iskitim pedocomplex (**$is_1$–$is_2$**) is 1.9 m thick. It is composed of two paleosols separated by loess-like loam (0.3 m thick) representing the BCca horizon of the upper soil.

The profile of the upper soil contains the AUca and BCca horizons. The humus horizon (AUca) is 0.6 m thick. It is composed of loam that is dark gray with

*Fig. 2.* Lateral profile of the Krasnogorskoye section.

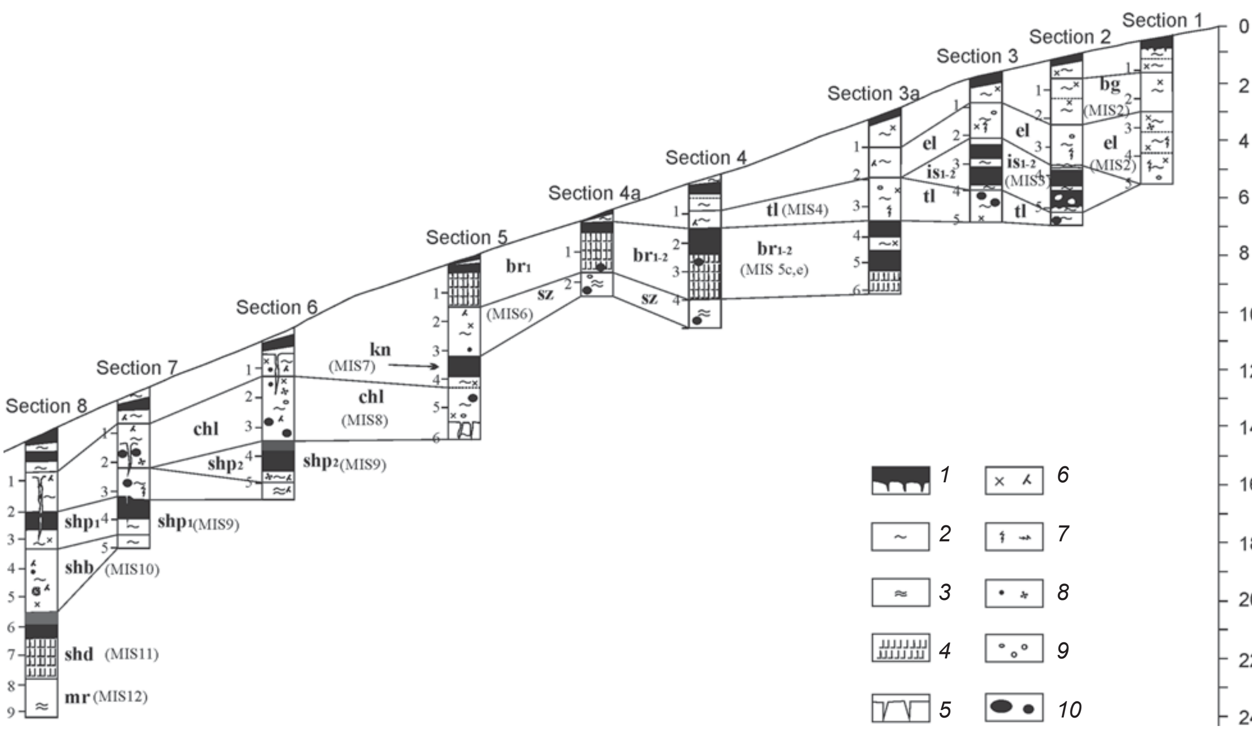


*Fig. 3*. Correlation between the horizons based on the Krasnogorskoye section.
*1* – humus horizon; *2* – loam; *3* – heavy loam; *4* – illuvial horizon; *5* – shrinkage cracks; *6* – carbonate neoformations; *7* – ferruginization; *8* – manganese specks; *9* – gleying; *10* – burrows.

a brown tint, containing a few grains of clayey sand, carbonates as pseudomycelium and encrusted root channels, as well as rare pieces of coal, and specks of manganese. The borders of the horizon are undulate; its coloration transits into the underlying horizon. The brownish-yellow, porous loam (BCca) separating horizons of humified soil is 0.3 m thick. It is dense, and contains carbonate pseudomycelium, and pores and root channels encrusted by carbonate. Small pieces of coal are few in number.

The lower soil consists of the AU and BCA horizons. The humus horizon (AU) is 0.5 m thick. It is composed of brownish-dark-gray, porous, dense, and noncarbonate loam, containing rare grains of clayey sand, small pieces of coal, and burrows up to 7 cm in diameter. Humified ovals and small wedges are visible along its lower margin. The BCA horizon belongs both to the lower soil and to the upper portion of Tulino loess. It consists of light brownish-yellow, porous, and dense loam 0.5 m thick. This horizon

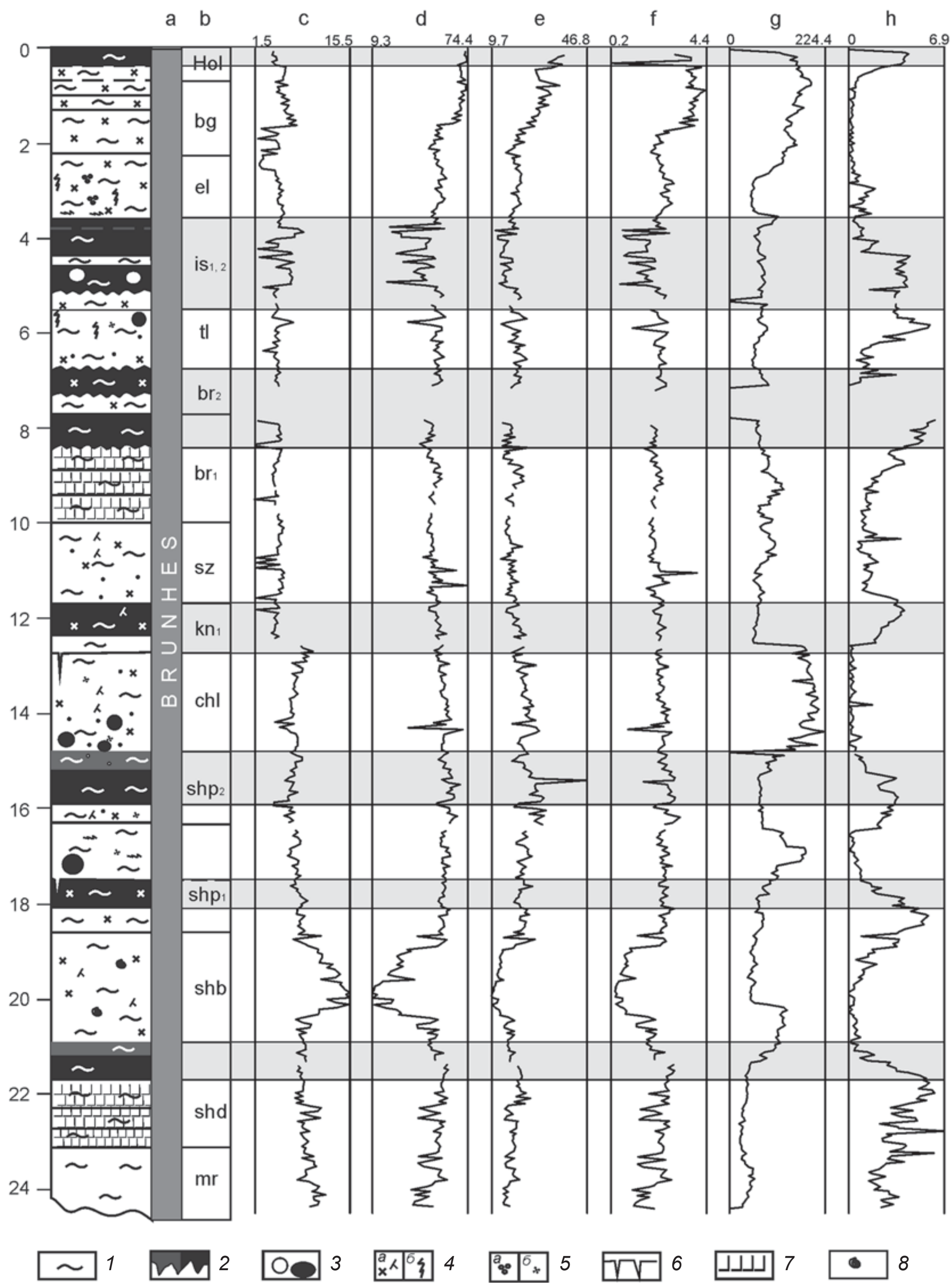


*Fig. 4*. Geological structure, grain size and petromagnetic characteristics of the combined Krasnogorskoye section.
a – paleomagnetic epoch; b – horizon index; c – clay fraction (< 2 μm), %; d – coarse silt fraction (16–63 μm); %; e – mean grain size, μm; f – U-ratio (=16–44 μm/5.5–16.0 μm); g – LF MS; h – FD MS.
*1* – loam; *2* – humus horizon; *3* – burrows; *4*: *a* – carbonate neoformations, *b* – ferruginization; *5*: *a*– gleying, *b* – manganese specks; *6* – shrinkage cracks; *7* – clay-illuvial and structural-metamorphic horizons; *8* – mollusk shells. Pedocomplexes: Hol – modern Holocene soil; is – Iskitim; br – Berdsk; kn – Koinikha; shp – Shipunovo; shd – Shadrikha. Loesses: bg – Bagan; el – Eltsovka; tl – Tulino; sz – Suzun; chl – Chulym; shb – Shibayevo; mr – Morozovo.

comprises root channels and carbonate neoformations represented by pseudomycelium and encrusted root channels. Burrows are numerous, and their diameter varies from 7 to 10 cm.

4. The Tulino loess (**tl**) is grayish-light-brown, slightly dense, loess-like loam whose thickness varies from 1.1 to 2.0 m. The deposit contains loose carbonate concretions up to 0.8 cm in size, and pseudomycelium. It abounds in hollow root channels, manganese specks, spots and strips of ferruginization, and burrows up to 7 cm in size. The lower boundary is uneven.

5. The Berdsk pedocomplex (**$br_1$–$br_2$**) is composed of two soils separated by loess-like loam (0.4 m thick) representing the BCca horizon of the upper soil.

In the upper soil (**$br_2$**), the AUca and BCca horizons are clearly visible. The humus horizon (AUca) is 0.4 m thick. It consists of dark gray with a brownish tint, dense loam of low porosity. It contains hollow root channels and pseudomycelium. The underlying loam is 0.3 m thick, grayish-light-brown in color, dense, and low-porous. It comprises carbonate pseudomycelium, root channels, and small iron spots. This deposit forms BCca horizon.

The profile of the lower soil (**$br_1$)** is composed of humus (AU) and clayey-illuvial (BI) horizons. The AU horizon is 0.8 m thick. It contains brown-dark-gray, heavy, dense, low-porous, noncarbonate loam characterized by fine, nutty, grumous structure, and by manganese specks and ferrous pellets. The underlying clayey-illuvial (BI) horizon differs in color and structure. It is 1.6 m thick and comprises dense, heavy, low-porous, noncarbonate loam grayish-light-brown in color. The loam has a nutty-prismatic structure enlarging downward. Clayey films are visible on faces of structural elements. Burrows 7–10 cm in diameter can be encountered in the lower portion of the horizon.

6. The Suzun loess (**sz**) consists of light brown, dense, low-porous loam 1.7 m thick. The deposit has fissures running from its surface to the depth of 40 cm. They are filled with plate-like and tubular carbonate concretions. At the base of this deposit, roundish concretions (2 × 3 cm) are horizontally concentrated. Even lower, carbonate pseudomycelium, manganese pellets, and iron-encrusted root channels are present. The loess has a distinct lower boundary.

7. The Koinikha pedocomplex (**$kn_1$**) consists only of the lower soil of the pedocomplex, consisting of AUca and Bca horizons. The humus horizon (AUca) is 0.7 m thick. It consists of dark-gray-brown, dense, porous loam with root channels, carbonate pseudomycelium, and small white dots. Manganese specks, small (0.2 cm) manganese pellets, and iron-encrusted root channels are visible everywhere. The illuvial horizon (Bca) is 0.5 m thick. It is composed of grayish-light-brown, dense, porous loam containing carbonate pseudomycelium, carbonate-encrusted pores and root channels, small manganese pellets, and iron-encrusted pores. Clayey sand and burrows 5–7 cm in diameter occur there.

8. The Chulym loess (**chl**) is 1.45 m thick. It is composed of light yellowish-gray slightly greenish, dense, low-porous loam. Some of the root channels are encrusted by carbonates. Rare carbonate concretions (0.5–1.0 cm), pseudomycelium, and manganese pellets are present. The upper surface is undulate; in some places, it is oviform. The surface is broken by rare sinuous fissures 2 cm wide and up to 60 cm deep, which are filled with carbonate concretions. The deposit contains numerous burrows 5–7 cm in diameter. The lower boundary is distinct.

9. The Shipunovo pedocomplex (**$shp_1$–$shp_2$**) comprises two soils separated by loess-like loam belonging to the BCca horizon of the upper soil. The upper soil (**$shp_2$**) includes cumulative (AU), illuvial (Bmt), and BCca horizons. The humus horizon is 0.7 m thick. It is composed of brownish-gray, dense, low-porous, noncarbonate loam containing hollow root channels and numerous small (0.3 cm) and large (up to 0.6 cm) ferromanganese pellets. Dense carbonate concretions up to 2 cm in size occur in the upper portion of the horizon. The thickness of the Bmt horizon varies from 0.5 to 0.8 m. It consists of tawny-brown, dense, low-porous, noncarbonate loam characterized by a fine-grained, nutty structure and by the presence of clayey sand grains, carbonate concretions up to 1 cm in size, and ferromanganese pellets measuring up to 0.3 cm. The BCca horizon is 0.8–1.0 m thick. It comprises slightly greenish light gray, dense, porous loam containing manganese pellets, small ferrous spots, and thin root channels encrusted with carbonate. Isolated roundish carbonate concretions up to 3 cm in size are vertically oriented through the whole horizon. Burrows up to 7 cm in diameter are also present.

The profile of the lower soil (**$shp_1$**) comprises humus (AU) and illuvial (Bmt) horizons. The humus horizon is 0.7 m thick. It is composed of brownish-gray, heavy, dense, low-porous, noncarbonate loam, with hollow root channels, rare manganese pellets up to 0.3 cm in size, and grains of clayey sand. The thickness of the illuvial horizon varies from 0.5 to 0.8 m. This deposit is composed of tawny-brown, heavy, dense, noncarbonate loam with nutty and fine-prismatic structure and numerous grains of clayey sand. Manganese pellets (up to 0.2 cm) and roundish and flattened carbonate concretions (up to 2 cm) occur in this horizon.

10. The Shibayevo loess (**shb**) is formed by yellowish-gray with a green tint loam up to 2.3 m thick. The loam is dense and low-carbonate. Small manganese pellets occur everywhere. Spots of ferrous hydroxide, small carbonate concretions, and small shells of terrestrial mollusks are rarely encountered.

11. The Shadrikha pedocomplex (**shd**) consists of paleosol composed of humus (AU) and illuvial (Bmt) horizons. The humus horizon is formed of brownish-dark-gray, dense, low-porous, noncarbonate loam 0.8 m thick. The deposit contains many grains of clayey sand and a few manganese pellets. The illuvial horizon is 1.4 m thick. It consists of tawny-brown, dense, heavy, noncarbonate loam with a nutty structure enlarging downward, and clayey films visible on faces of structural elements. The deposit contains manganese pellets.

12. The Morozovo loess (**mr**) is light brown, heavy, dense, noncarbonate loam containing manganese pellets. Its visible thickness is 1.5 m.

## Stratigraphy of the loess-paleosol sequence

The 24.5-meter thick subaeral deposits at Krasnogorskoye (Fig. 3, 4), which consist of loess-like loams and soils, were correlated with those of Western and Central Siberia, using morphological indicators of soils, lithological features of loess horizons, and radiocarbon analysis (Zykina, Volkov, Dergacheva, 1981; Zykina, Zykin, 2012; Frechen et al., 2005). Since the stratigraphic horizons of the mentioned loess-paleosol sequence correspond distinctly to marine oxygen isotope stages and other global climate records, it can be used as a reliable reference scale for regional and global correlations (Dobretsov, Zykin, Zykina, 2003; Zykina, Zykin, 2003, 2008). In the Krasnogorskoye section, seven loess horizons are recognizable (from bottom to top): Morozovo (MIS 12), Shibayevo (MIS 10), Chulym (MIS 8), Suzun (MIS 6), Tulino (MIS 4), Bagan and Eltsovka (MIS 2). The section represents five pedocomplexes: Shadrikha (MIS 11), Shipunovo (MIS 9), Koinikha (MIS 7), Berdsk (MIS 5c, e), and Iskitim (MIS 3). Morphotypically, the Shadrikha, Berdsk, and Iskitim pedocomplexes are most representative. These pedocomplexes are traced over large areas. The loess-paleosol section near Krasnogorskoye, then, was formed during the Middle and Late Pleistocene.

## Fossil pedocomplexes

In the environs of Krasnogorskoye, the modern soil consists of leached chernozem formed in the forest-steppe zone. Two chernozems of the Iskitim pedocomplex have weakly differentiated, thin profiles, containing characteristic carbonate neoformations (pseudomycelium) and burrows. The soils are similar in organic matter content; humic acids predominate over fulvic acids. The $C_{ha}/C_{fa}$ ratio in the humus horizon of the upper soil equals 1.07; in the lower soil it is 1.05. Differences in grain size and bulk compositions across the soil profiles are insignificant. Therefore, in spite of the weak differentiation and small thickness of the soils, the presence of characteristic carbonate neoformations and burrows goes to prove that the Iskitim soils were formed as chernozem in forest-steppe environments. The weak differentiation of the Iskitim soils, as compared to modern soils, can probably be explained by the short period of their formation, and by growing aridization of the climate in the Late Pleistocene. The radiocarbon date of 23,065 ± 420 BP (SOAN 9484) (cal BP 27,955 ± 445), generated on a sample of the humus horizon of the upper soil in the Krasnogorskoye section, supports the correlation of the pedocomplex with MIS 3. According to the radiocarbon and thermoluminescence dates, the formation of the Iskitim pedocomplex took place during the interval from 53 ± 4 to 24 ± 4 ka BP (Zykina, Volkov, Dergacheva, 1981; Zander et al., 2003; Frechen et al., 2005), corresponding to MIS 3 (Bassinot et al., 1994).

The Berdsk pedocomplex consists of two chernozems. The upper soil is characterized by an underdeveloped thin profile, whose period of formation was shorter than that of the lower soil. The organic carbon content in the humus horizon amounts to 0.67 % of the soil weight, and decreases to 0.40 % in the illuvial horizon. Humic acids and fraction associated with calcium predominate in the organic matter content. The $C_{ha}/C_{fa}$ ratio in the humus horizon equals 1.1; in the carbonate-illuvial horizon it amounts to 0.6. Differences between the soil horizons in texture and bulk composition are insignificant. An accumulation of silicate calcium, associated with soil formation processes, can be observed in the illuvial horizon. Humus accumulation and carbonate formation operate as dominant soil forming processes. The principal pedogenetic soil properties point to growing aridization in the Late Pleistocene. The soil was formed in a forest-steppe environment during a short, warm Early Zyryanka interstadial, which, according to thermoluminescence dates (Zykina, Zykin, 2012; Zander et al., 2003; Frechen et al., 2005), corresponds to the MIS 5c substage (Bassinot et al., 1994).

The lower soil of the Berdsk pedocomplex displays well-developed profile subdivisible into humus and illuvial horizons. The soil contains burrows. Structurally, this is a chernozem clayey-illuvial profile developed during a long period of time, in the forest-steppe zone, under conditions of warm and humid climate in the Kazantsevo interglacial, correlating with the MIS 5e substage (Ibid.). The organic carbon content in the humus horizon reaches 0.65 %; in the illuvial horizon it amounts to 0.23 %. The qualitative composition of the humus is characterized by a prevalence of humic acids. The $C_{ha}/C_{fa}$ ratio is 1.2 in the humus horizon, and 0.5 in the illuvial horizon. Insignificant traces of eluvial-illuvial differentiation in terms of sesquioxide and grain size composition are observable in the soil profile. According to micromorphological data, the migration of the silt fraction can be clearly traced. The soil profile is leached free of carbonates. The significant thickness of the Kazantsevo soil, and its claying and well-developed profile, bring it closer to Middle Pleistocene soils, and move further from overlying Upper Pleistocene soils. According to dates obtained from the Kurtak section in Central Siberia, the chronological interval corresponding to the formation of this soil lies within 143–119 ka BP (Frechen et al., 2005; Zander et al., 2003).

The Koinikha pedocomplex consists of the lower soil, which demonstrates features of chernozem and brunizem. The morphotype of the profile, carbonate neoformations, burrows, and microstructure of the humus horizon (highly aggregated soil mass, coagulated and feebly oriented humus-clay plasma) suggest that the soil was formed by chernozem type under the conditions of a warm and humid climate. Relics of brunizem soil formation are demonstrated by a distinct brown coloration of the profile, presence of manganese specks and small pellets, light soil compaction, and enrichment with iron and aluminum hydroxides. According to P. Duchaufour (1965), brunizems are typical of regions with a less pronounced continental climate as compared to the chernozem zone. This soil type is described as transitional between chernozem and burozem (brown soil). Soil humus is humate-fulvatic in its qualitative composition; the $C_{ha}/C_{fa}$ ratio in the humus horizon equals 0.85. Mineral mass is stable; redistribution of the silt faction and sesquioxides across the profile is not observed. In the Kurtak section, the soil of this type is dated within the range of 236–181 ka BP (Zander et al., 2003).

The Shipunovo pedocomplex is composed of two buried soils with brown coloration of their profiles. The profiles are differentiated by their types of brunizem. They are noncarbonated, but contain manganese and ferromanganese specks testifying to hydromorphism; burrows are present. The composition of the humus is humate-fulvatic; the $C_{ha}/C_{fa}$ ratio equals 0.9. The soils are weakly differentiated in terms of bulk composition. The main soil forming processes include lessivage and agrillization, most apparent in the lower soil. The microstructure of both soils demonstrates movement of the silt fraction and ferrous hydroxides down the profiles. Judging by the types of the soils, soil formation took place under warmer and more humid climate conditions as compared to the modern ones. The structure of the pedocomplex and degree of maturity of its soil profiles correspond to MIS 9 (Zykina, Zykin, 2012).

The Shadrikha pedocomplex consists of brunizem with a profile differentiated into humus and illuvial horizons. Burrows occur in the horizons. This pedocomplex is close to chernozem in its properties. However, in distinction from chernozem, its profile is leached and lacks a carbonate horizon; reaction is subacid; a horizon of illuvial clay accumulation is available; clay forms at the expense of primary minerals. The presence of ferromanganese concretions in the profile suggests gleying processes. The humus can be characterized as humic and fulvic by its composition; the $C_{ha}/C_{fa}$ ratio equals 0.8. The bulk composition of the soil shows that differentiation of the profile by its content of aluminum, silicon, and iron is weak; $SiO_2/R_2O_3$ ratios change insignificantly across the profile. In terms of microstructure, the illuvial horizon contains ferrous-clay cutans, formed along pores and faces of structural elements. According to the obtained data, the main processes responsible for the formation of brunizem were humus accumulation, agrillization, and lessivage. The availability of a deposit of mature soil suggests that the soil was formed over a long period of time in a climate rather humid and warmer than at present, during the Shadrikha warm interglacial, corresponding to MIS 11 (Bassinot et al., 1994). Brown forest soils of the early stage of the Shadrikha interglacial in Western Siberia may serve as an analog for this soil (Zykina, Zykin, 2012).

## Grain size composition of loess-like loams

The grain size analysis assesses the proportion of dimensional fractions in the section and reveals their dynamics. One of the principal challenges of this analysis is to gain a greater understanding of the environment in which the deposits were accumulated.

Grain size composition was determined with the aid of Laser Particle Sizer Fritsch Analysette 22 MicroTec, with the measuring range of 0–1000 μm. The analysis was conducted in the Laboratory for the Cenozoic Geology, Paleoclimatology, and Mineralogical Indicators for Climate, in the Sobolev Institute of Geology and Mineralogy SB RAS. Samples were taken successively from the shielding surface down to the base of the section, with 5 cm spacing. Clay (< 2 μm; Fig. 4, c) and coarse silt (16–63 μm; see Fig. 4, d) fractions, and mean grain size (Fig. 4, e) were selected as the most representative indicators reflecting the formation of the deposits. In addition, the U-ratio (the ratio of 16–44 and 5.5–16.0 μm fractions) was calculated (Fig. 4, f). This parameter disregards fine-grained clay particles accumulated mostly by secondary processes, and coarse particles probably deposited by saltation (Vandenberghe, 1985; Nugteren et al., 2004). Thus, the U-ratio reflects the course of sedimentation, without secondary processes, and provides evidence of wind flow strength.

Grain size analysis of the Middle and Upper Pleistocene deposits revealed a predominance of coarse silt fraction (Fig. 4), typical of loess sediments. As compared to Upper Pleistocene loess-soil deposits of the Ob loess plateau (Sizikova et al., 2015), contemporaneous horizons of the Krasnogorskoye section contain a somewhat greater quantity of coarse silt. In general, a trend towards a decrease in quantity of clay fraction from MIS 12 to MIS 2 is clearly observed across the profile: the content of clay is 1.5 to 2 times greater in the Middle Pleistocene horizons than in Upper Pleistocene ones. However, an increase in the quantity of coarse-silt fraction and, consequently, in grain size is evident in the Upper Pleistocene horizons. In this case, it can be explained by the presence of numerous ferromanganese neoformations, rather than by strength of wind flow. The scatter of grain size values mirrors the fluctuations of wind velocity at each stage of loess accumulation. In the Upper Pleistocene portion of the section, a trend towards an increase in mean grain size can be observed (Fig. 4, e). Values of the U-ratio also become greater (see Fig. 4, f), especially in Eltsovka and Bagan loesses. Therefore, our earlier conclusion about the greater intensity of loess accumulation in the Late Pleistocene is supported with regard to the Barnaul (Sizikova et al., 2015) and Novosibirsk (Sizikova, Zykina, 2015) parts of the Ob region and to the plain adjoining the Altai.

## Morphoscopy of quartz sand grains

The morphoscopy and morphometry of quartz sand grains make it possible to determine the processes prevailing during sedimentation, and to describe the paleogeographic conditions accompanying them. Well-rounded grains with a coefficient of roundness of 50–70 % are typical of eolian sediments (Velichko, Timireva, 1995).

Quartz grains of the medium sand fraction (0.25–0.5 mm) were examined under Altami CM0870-T binocular microscope, according to the methodology elaborated in the Institute of Geography RAS, Moscow (Ibid.). Second electron images (SEI) of grains were obtained using a JEOL JSM-6510LV scanning electron microscope in the Center for Multielement and Isotope Analyses in the Sobolev Institute of Geology and Mineralogy SB RAS. The roundness of grains was determined by comparison with the template by L.B. Rukhin (1969) and by the five-class characterization of A.B. Khabakov (1946). Then, coefficients of roundness and degree of dullness (Velichko, Timireva, 1995) were calculated for each sample. The dullness of grains was visually inspected and classified from glossy to matte. This method had previously been used for studying loess deposits in the south of Western Siberia: in the Novosibirsk (Sizikova, Zykina, 2015) and Barnaul (Sizikova et al., 2015) parts of the Ob basin. On the plain bordering the Altai, this method was applied for the first time.

In this article, we present data on the morphoscopy of sand grains from loess horizons only, since most quartz grains from paleosols were badly damaged by chemical weathering; so their surfaces mostly display traces of silica dissolution, etching along microcavities, and dissolution of the grain surface.

Loess horizons of the Krasnogorskoye section are similar in terms of shape, degree of roundness, and the main elements of surface. All the horizons are dominated by grains of the III and IV classes of roundness, with matte or semi-matte surfaces. Grains of the II class are less numerous; grains of the I class are rare. The coefficients of roundness calculated for each horizon of the section are between 60 % and 70 %; the degree of dullness varies from 68.5 % to 80 %. Lower values are typical of the Upper Pleistocene loesses

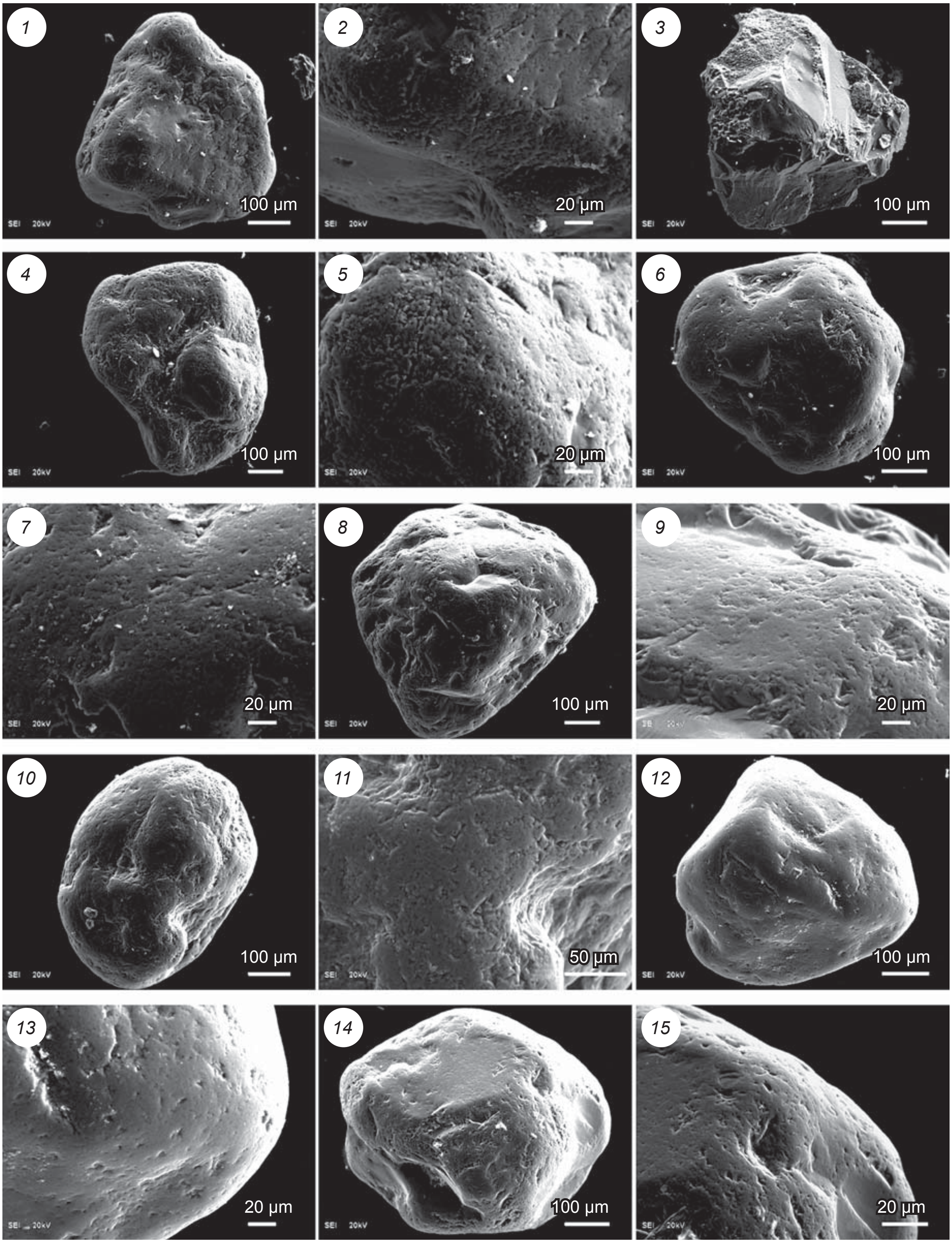


*Fig. 5*. Morphoscopy of quartz sand grains from loess horizons of the Krasnogorskoye section.
*1*, *2*, *3* – Bagan; *4*, *5* – Eltsovka; *6*, *7* – Tulino; *8*, *9* – Suzun; *10*, *11* – Chulym; *12*, *13* – Shibayevo; *14*, *15* – Morozovo.

(Bagan, Eltsovka, and Tulino). Micropits forming a specific surface are the main element of microrelief (Fig. 5, *1*, *2*, *4–15*). Such a pitted surface may be caused by the collision of grains in air flow (Velichko, Timireva, 2002). Micropits formed in cavities (Fig. 5, *2*, *5*, *10*, *13*) are indicative of a long stay of the grains in air-flow. In addition to micropits, large saucer-shaped and groove-shaped "pits" are visible. Some grains, especially in the Upper Pleistocene loesses, display a conchoidal fracture (Fig. 5, *3*), which can be explained by frost-induced weathering (Ibid.). Some grains, mostly from Middle Pleistocene loesses, demonstrate features of chemical processes, such as dissolution of grain surface or etching of cavities (Fig. 5, *10*, *11*), although these are far less pronounced than on grains from paleosol horizons.

## Magnetic properties of the sediments

The Krasnogorskoye section is homogenous in terms of magnetostratigraphy. The magnetic cleaning of specimens has divided natural magnetization into viscous and detrital components. The viscous component is unstable, and can be removed by heating to 200 °C. The detrital component carries primary magnetization; the magnetization vectors retain their direction when heated to 600 °C. The statistical analysis of residual magnetization vectors for the viscous and primary components suggests that both had formed under the same positive polarization (Fig. 4, a), matching the modern condition.

Petromagnetic characteristics, such as magnetic susceptibility ($\chi$) and frequency dependent magnetic susceptibility (*FD*), depend largely both on regional and global climatic parameters. In the paleosol horizons of Krasnogorskoye, *FD* values are higher than those in loesses, where they approximate zero (see Fig. 4, g). On the contrary, magnetic susceptibility in loesses is greater than in paleosols (see Fig. 4, h).

Significant increase of *FD* values in soils suggests that intense formation of fine superparamagnetic and single-domain magnetic materials resulted from pedogenesis, which took place during warm and humid periods. However, at that time, $\chi$ values were lower than in cold periods. This can probably be attributed to high wind activity in cold and dry periods, resulting in the transport of large masses of weathered detritus.

The oscillations of magnetic susceptibility in the section correspond to "Alaskan" model (Westgate, Stemper, Pewe, 1990); however, high *FD* values (reaching 7 %) do not fit this model completely. This finding evidently indicates a greater climatic fluctuation range as compared to those of the northern ("Alaskan") and southern ("Chinese") (Liu et al., 1993) regions. This is especially true for sediments corresponding to MIS 7 – MIS 12.

## Conclusions

Stratigraphic, paleopedological, lithological, and paleomagnetic data, combined with the results of radiocarbon analysis obtained for the Krasnogorskoye section, made it possible to determine the chronological intervals during which the loess-paleosol sequence had been formed in the Middle and Late Pleistocene. Morozovo loess at the base of the section correlates to MIS 12 (Zykina, Zykin, 2008, 2012). The structure of the Pleistocene pedocomplexes of the Altai Mountains is similar to that of the pedocomplexes in the southern part of the West Siberian Plain. It clearly reflects odd warm stages of continuous global sequences. The reconstruction of a sufficiently complete loess-paleosol sequence in the low-altitude zone of the Altai Mountains at Krasnogorskoye (including five pedocomplexes and seven loess horizons), and the finding that pedogenesis in the Middle Pleistocene followed the brunizem type, have enabled us to reveal a distinct tendency of soil formation during the interglacial stages from the Middle to the Late Pleistocene: the climate became more and more arid. The Brunizem type of soil formation of the Shadrikha and Shipunovo warm stages, the brunizem-chernozem type of the Koinikha stage, and the chernozem type of Kazantsevo stage taking place under a climate that was warmer and more humid than today's, were all changed by a chernozem forest-steppe type of soil formation under the colder and more arid climate of the Early Zyryanka and Karga interstadials. The predominant tendency was the aridization of climate. The amplitude and frequency of climate oscillations changed significantly after the Kazantsevo interglacial. This caused lesser warming, and a shorter duration of warm stages. The climate became cooler and more arid, as mirrored by a simpler structure of soil profiles and their decreased thickness. During the warm interglacial stages of the Middle Pleistocene, the climate in the low and medium-high mountain regions of the Altai Mountains was more humid than in the adjoining West Siberian Plain.

The grain size analysis of the Krasnogorskoye samples indicates a trend of increase in loess accumulation during the Late Pleistocene. The high coefficients of roundness and the degree of dullness, as well as numerous micropits on grain surfaces in all loess horizons, point to the eolian origin of loess horizons under cryoarid conditions. We also found traces of frost-induced weathering, and chemical processes on grains.

Paleomagnetic analysis has demonstrated that all the sediments in the section were formed during the Brunhes normal epoch. Petromagnetic data generally support the above inferences. Higher magnetic susceptibility during the cold stages, and higher frequency-dependent susceptibility during the warm stages, evidence marked climatic oscillations. After the Kazantsevo interglacial, the amplitude diminishes, and the pattern of paleoclimatic signal recorded by the magnetic properties of loess and paleosol in the section is close to the "Alaskan" type.

The structure and composition of the loess-paleosol sequence in the Krasnogorskoye section testify to a varying intensity of atmospheric circulation during the cold glacials, warm interstadials, and interglacials of the Pleistocene. Cold stages were characterized by climate aridization, and a greater intensity of circulation of the atmosphere, which became saturated with dust, causing the growth of loess horizons during sedimentation. These processes led to the expansion of cold deserts, and to the formation of large deflation surfaces and closed deflation hollows varying in size (Zykin, Zykina, Orlova, 2003). During warm stages of the Middle and Late Pleistocene, soil horizons were formed in the Krasnogorskoye section.

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