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Loess-palaeosol stratigraphy in the Yenisey basin, Southern Siberia

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Abstract: A high-resolution Late Quaternary Siberian palaeoclimatic record has been derived from the Kurtak Section 29 in the Northern Minusinsk Basin of the Southern Krasnoyarsk region. The 34 m-thick loess and palaeosol sequence provides evidence for strongly fluctuating palaeoclimates in northern continental Eurasia during the Late Quaternary with maximum amplitudes of climatic change between 130 and 10 ka BP. A succession of buried chernozemic, brunisolic and gleyed regosolic soils are consistently demarcated within bulk magnetic susceptibility depth functions, with increased values (≈ 250–650 x 10^{-2}S.I.) reflecting cold intervals and lower values (≈ 90–250 x 10^{-2}S.I.) indicative of warm and climatically moderate intervals. This specific magnetic susceptibility pattern (with the minima in the most weathered interglacial soils) is completely opposite to the Chinese loess susceptibility record, where the magnetic concentration level in palaeosols directly correlates with the degree of pedogenesis. A gradual magnetic mineral depletion during soil formation, coupled with a more intense wind activity during cold intervals leading to accumulation of greater quantities of larger ferrimagnetic grains, is assumed to account for the higher magnetic susceptibility capacity in loess. The magnetic susceptibility curve shows a globally diagnostic palaeoclimatic trend for the last two glacial-interglacial stages as recognised in deep-sea oxygen isotope records (OI Stages 7–1). The last interglacial (*sensu lato*) includes several relatively short warm as well as very cold intervals (correlated with the Oxygen Isotope Substages 5e–5a), with a gradual shift towards a strongly continental climate culminating around the peak of the last interglacial (ca. 125–110 ka BP).

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INTRODUCTION

Past climatic change, with a focus on the Quaternary Period (i.e. the time span of the last 2.5 Ma), has become an important multidisciplinary issue because of fundamental implications for the present global climatic development and prediction of future climatic change. Among the continental sediments used as climatically significant proxy data, loess has attracted most attention because of its high environmental sensitivity and long-term stratigraphic records. The accumulation of loess is correlated with cold and dry stages, when silt-sized particles were carried by wind from alluvial plains in ice-marginal areas and other periglacial deflation surfaces, and deposited in extraglacial areas as fine aeolian dust. During the following warm intervals, soils developed on the loessic substratum as a result of surface stability and increased temperature. Most data on loess come from several intensively-investigated areas in Central and Eastern Europe, Central Asia and China.

Siberia remains one of the least geologically known parts of the Northern Hemisphere, because of its vast territory and geographical isolation between the major Central Asian (Himalayan) mountain systems and the Arctic Ocean. Due to the pronounced atmospheric continentality, the south Siberian loess record provides an excellent source of high-resolution palaeoclimatic proxy data of regional, as well as global significance. It is also of major importance for establishment of a correlation framework with the European, Central Asian, and Chinese loess provinces. The Siberian data may significantly contribute to a better understanding of global climatic change and its controling mechanism during the Quaternary Period. The present study deals with loess deposits in the upper Yenisey River valley, investigated in 1993–1994, with a focus on the last interglacial-glacial cycle (130–10 ka BP), comprising the most complete record to date in northern Eurasia.

NATURAL SETTING AND GEOLOGY OF THE STUDY AREA

The study area is located in the Northern Minusinsk Basin in the southern part of the Krasnoyarsk Region between the Kuznetskiy Alatau on the west and the western foothills of the Eastern Sayan Mountains on the east (Fig. 1). In the northwest, the basin is connected by the Nazarovskaya Depression with the Western Siberian Lowland. The present climate is strongly continental with cold and dry winters with little snow cover, and warm to hot summers. Mean annual temperature is –0.5 °C (aver-

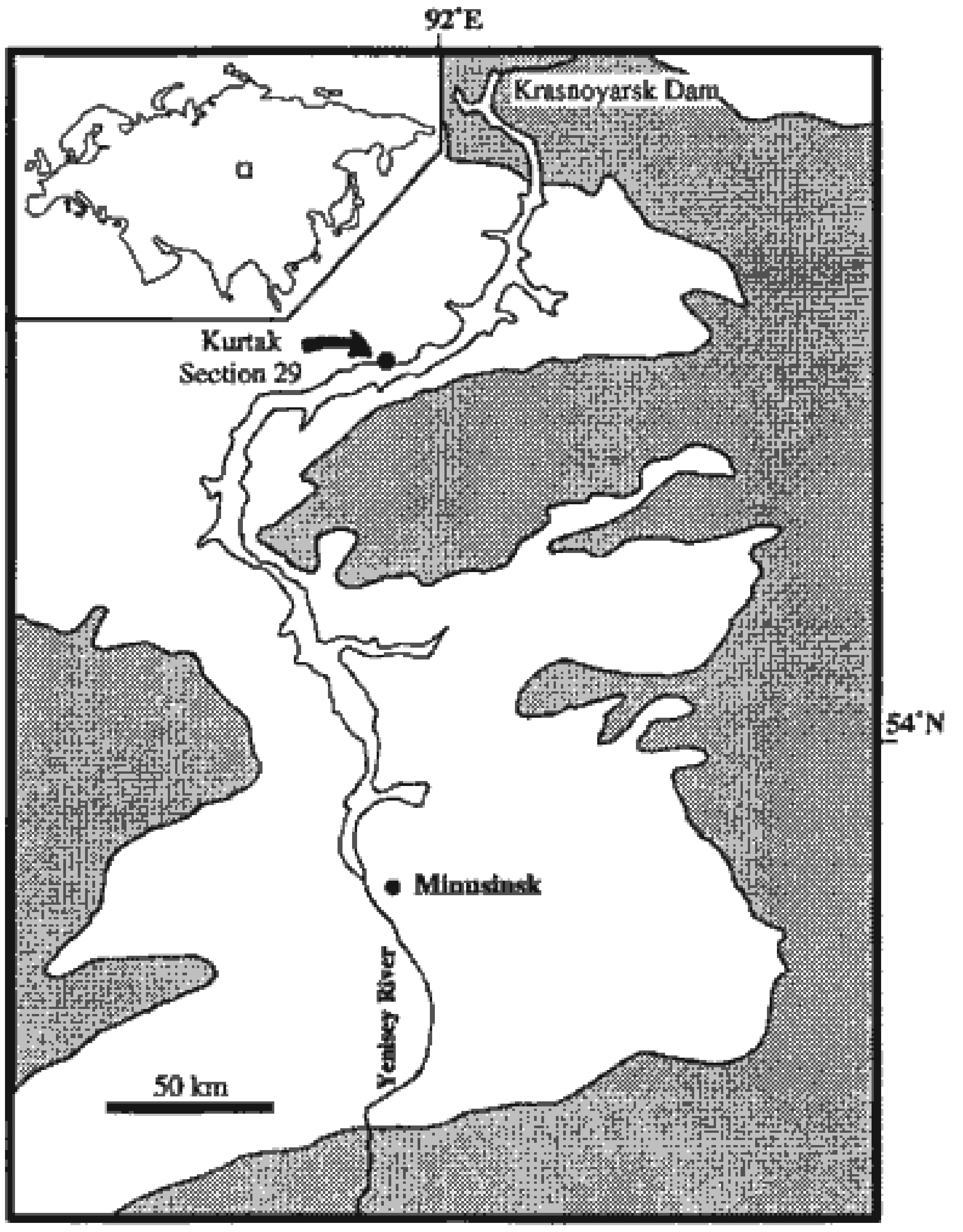


Fig. 1. Geographical location and topographic setting of the Minusinsk Basin with Kurtak site.

age January temperature –18.1 °C, July temperature + 17.6 °C); annual precipitation in the central steppe zone is 250–300 mm. The vegetation cover is characterised by grasslands in the interior basin; forest-steppe is established along the foothills, and mixed southern taiga prevails in the surrounding mountain.

KURTAK SITE (SECTION 29)

The principal study area is located near the Kurtak village in the upper Yenisey River valley at 91°30' W longitude and 55° N latitude in the steppe zone of the Northern Minusinsk Basin on the western side of the Krasnoyarsk reservoir. Because of the Krasnoyarsk dam construction in 1971, the Yenisey River, which is here about 7 km wide, flooded the valley to 65 m above its original floor to the present 247 m a.s.l. The adjacent slopes along the lake have been continuously modified by large-scale slumping and wave erosion undercutting unconsolidated loessic deposits, particularly along the western shore, causing a lateral slope retreat up to 10 m per year (a total of 0.5–4 km over the last 25 years). The lake erosion has exposed a nearly complete Late Quaternary geological record, with an abundant palaeolithic stone industry and a rich Middle-Upper Pleistocene fauna (DROZDOV et al. 1990, DEREVIANKO et al. 1992, DROZDOV et al. this volume).

The key section investigated (Kurtak 29) is situated in the central part of the Kurtak Site (the Berezhekovo

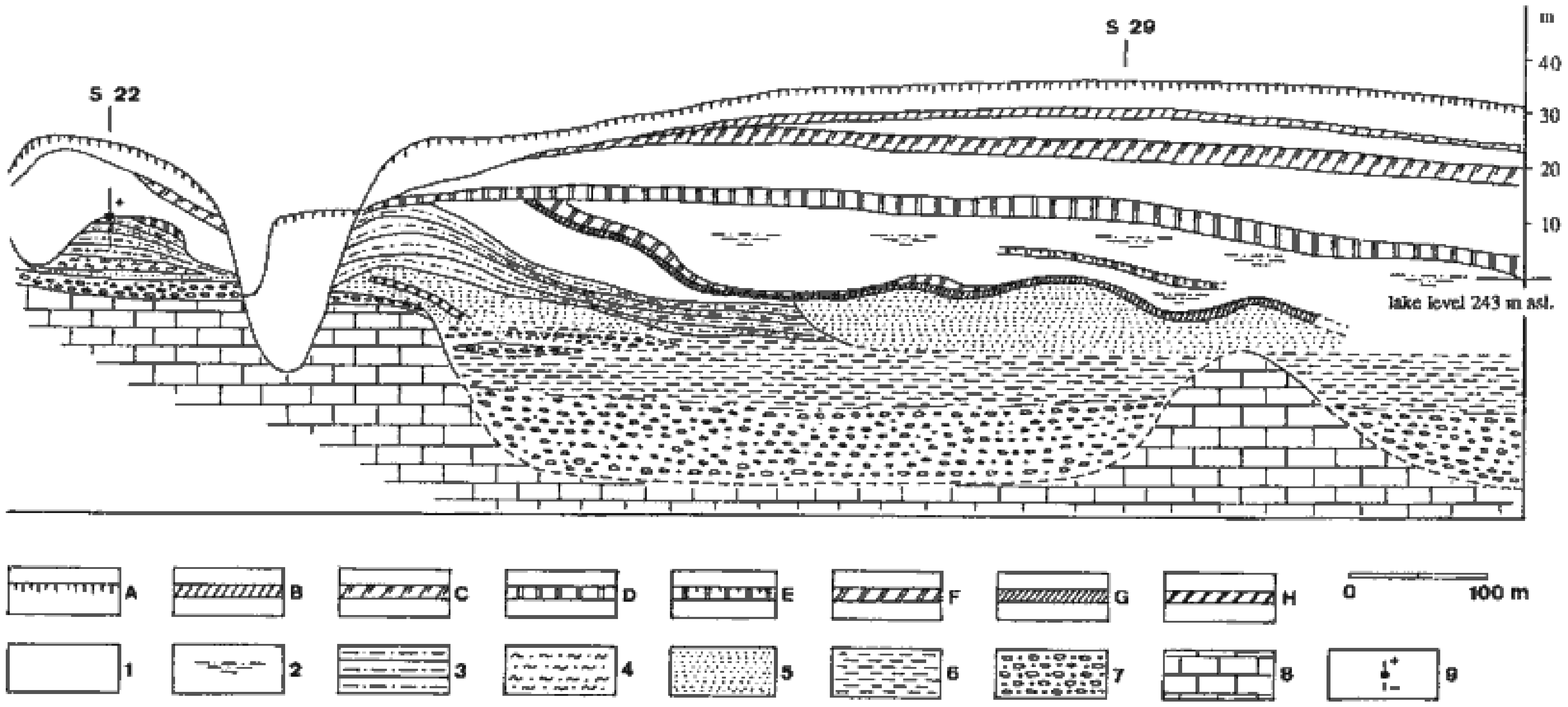


Fig. 2. Stratigraphic profile of the central part of the Berezhekovo Site with Kurtak Section 22 and Section 29.
Soils: A – recent (Holocene) Chernozem; B – Sartan (OIS 2) Pedocomplex; C – Kurtak (OIS 3) Pedocomplex; D – Last Interglacial (OIS 5) Pedocomplex; E – Penultimate Interglacial (OIS 7) Pedocomplex; F–H – Early Pleistocene soils.
Structural Geology: 1 – aeolian loess; 2 – colluviated loess; 3 – subaerial sands and silts (the Tazov/OIS 6 Glacial); 4 – periglacial alluvium (the Samarovo/OIS 8 Glacial); 5 – subaqueous sand (Early Pleistocene); 6 – subaqueous silt and clay (Early Pleistocene); 7 – sand and gravel of the Early Pleistocene 70/90–100 m terrace; 8 – sandstone bedrock (Carboniferous); 9 – palaeomagnetic M/B polarity boundary (modified according to V. P. CHEKHA 1993).

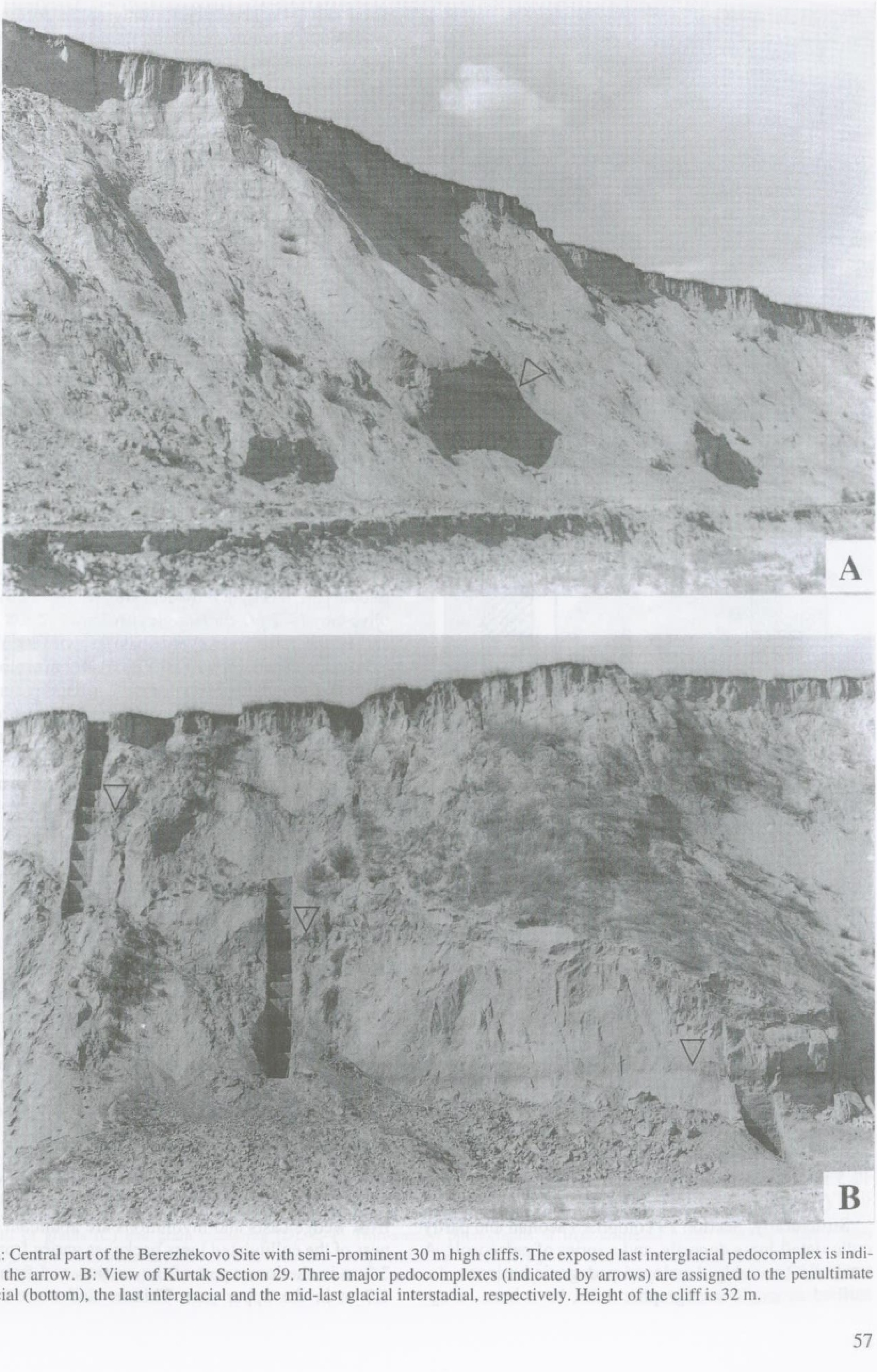


Fig. 3. A: Central part of the Berezhekovo Site with semi-prominent 30 m high cliffs. The exposed last interglacial pedocomplex is indicated by the arrow. B: View of Kurtak Section 29. Three major pedocomplexes (indicated by arrows) are assigned to the penultimate interglacial (bottom), the last interglacial and the mid-last glacial interstadial, respectively. Height of the cliff is 32 m.

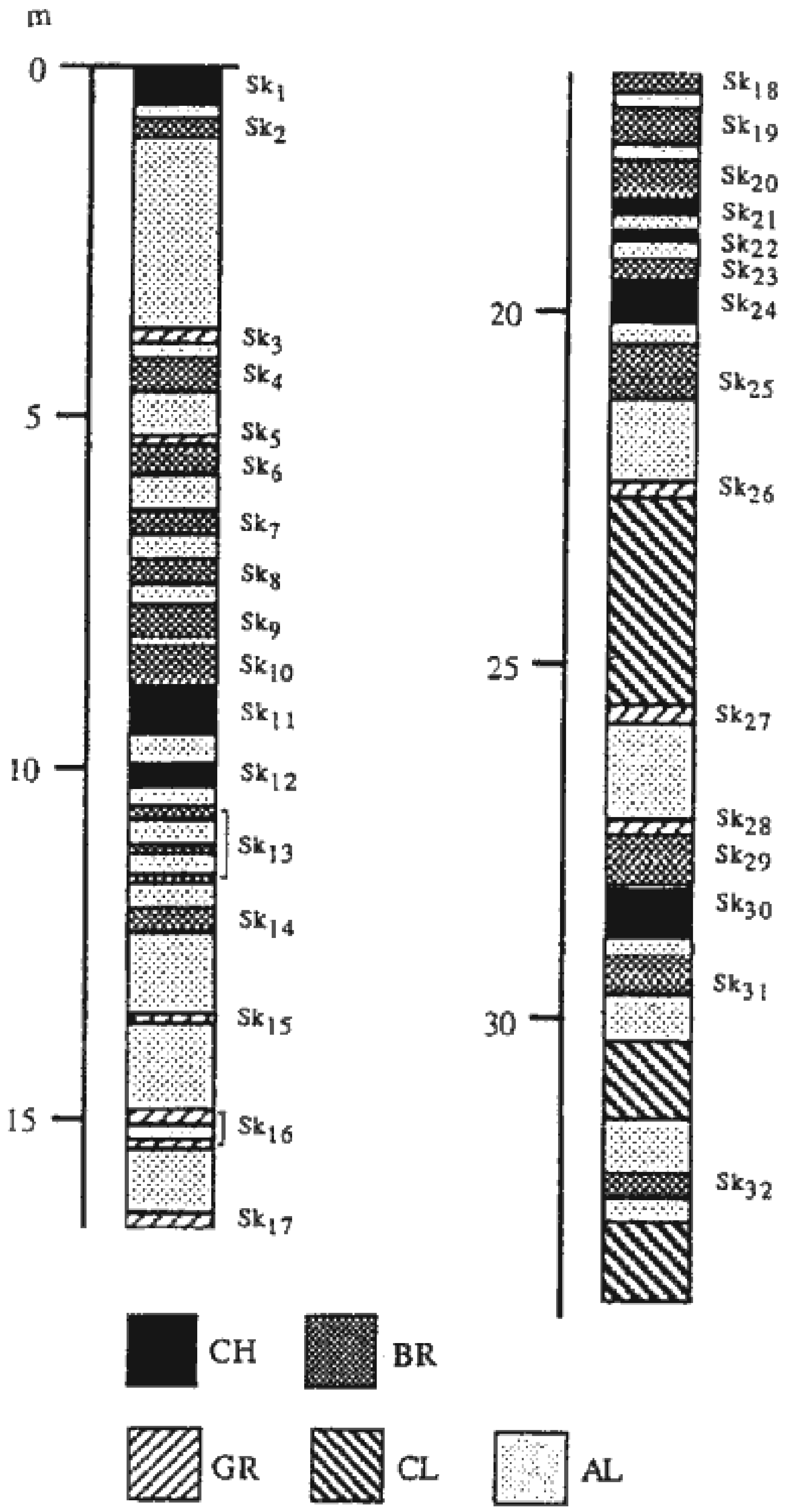


Fig. 4. Composite stratigraphic profile of Kurtak Section 29. CH – Chernozems; BR – brunisolic horizons (mostly colluviated); GR – gleyed regosolic horizons; CL – colluviated loess; AL – aeolian loess.

Sector), with the thickest loess deposits and the most complete series of buried palaeosols. A 20–35 m thick loess-cover mantles relics of two Early Pleistocene alluvial terraces (70–80 m and 90–100 m above the former river level) and the Carboniferous sandstone bedrock in the southern part of the site (Figs. 2, 3A). A 34 m high composite sequence is mapped in three adjacent and stratigraphically superimposed profiles I–III (16.0 m, 12.5 m and 6.6 m high) cut into a 70–90° steep slope wall (Fig. 3B).

Structurally, Section 29 comprises aeolian and partly colluviated-loess deposits, and a series of palaeosols. A total of 32 variably-developed pedogenic horizons, described as single stratigraphic units, have been recognised (Fig. 4). The lateral stratigraphic correlation is provided by a brunisolic (Bmkgj) horizon (Sk_{18}) for section profiles I and II at 16.5–17 m, and by a chernozemic (Ahy) horizon (Sk_{30}) for profiles II and III at 27.2 to 27.6 m below the present surface. Except for erosional surfaces on top of some palaeosol units, no stratigraphic hiatuses in the form of major disconformities have been identified.

Kurtak loess

General characteristics

Two principal loess/loessic facies are present at the site, as well as within the larger study area. The first (aeolian) loess facies is characterised by a massive, unstratified to weakly stratified light grey (2.5 Y 7/2 d/dry/), light brownish grey (2.5 Y 6/2 m/moist/) single-grain structure. Mottling expressed by varying amounts, size and distinctiveness of concentration and depletion of ferric oxides is present at several levels throughout the section as a result of water table fluctuations associated with initial soil formation processes (gleying). The aeolian loess in the upper part of the section is largely pale brown (10 YR 6/3 d) yellowish brown (10 YR 5/6 m); in the middle part, it is light brownish grey (2.5 Y 6/2 d) to light olive grey (5 Y 6/2 d)/dark greyish brown (2.5 Y 4/2 m); and in the lower part (very) pale brown (10 YR 7/3–6/3 d)/pale to dark brown (10 YR 6/3–4/3 m) colours predominate. Average pH values are 7.4. Fine-grained, matrix supported, 30–50 μm large angular to subangular quartz grains, and small voids within the silty material characterise the fabric of the sediment (Fig. 5 A–B). The aeolian loess forms 0.3–3.0 m thick packages intercalated by several, partly colluviated palaeosol horizons (soil sediment).

The second (niveo-aeolian/colluviated) loess facies is distinguished by a fine, irregular structure formed by interstratified, light brownish grey (2.5 Y 6/2 d) to light olive grey (5 Y 6/2 d)/dark greish brown (2.5 Y 4/2 m), pale brown (10 YR 6/3 d)/brown (10 YR 5/3–4/3 m), and brown (10 YR 5/3 d)/dark brown (10 YR 3/3 m), and undulating 0.2–1 cm thick silty to silty-loamy layers. The sediment is slightly sticky when wet and hard when dry, with average pH values of 7.6. Faint to distinct mottles are occasionally present, as well as white (10 YR 8/2 d) calcium carbonate concretions (1–2 mm diameter). Irregular, tapering laminae are either horizontally superimposed, or variably dip at 1–5° angles. Contrary to the first loess facies with smooth, gradual and diffuse contacts, the finely layered structure of the second facies is distinct and sharp. Minor (0.5–2 cm) frost wedge casts and involutions are abundant. Thickness of the colluviated loess packages varies from 1.5 to 3.2 m in the lower part of the section and from 0.2 to 1.0 m in the upper part. Thinner and more compact

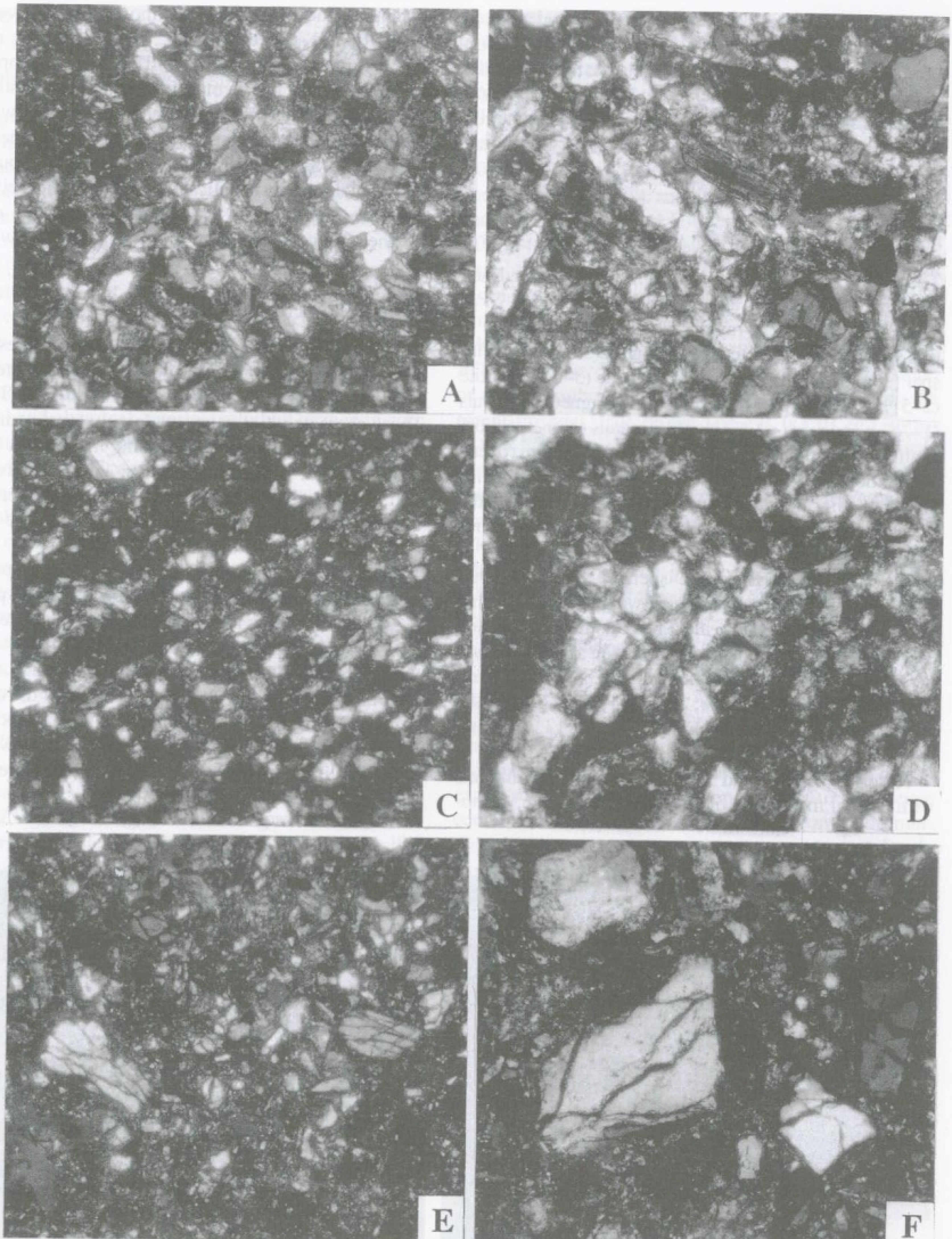


Fig. 5. A-B: Thin-section photographs of the typical loess deposited during the last glacial maximum (OIS 2) with fresh non-abraded and unweathered mineral grains, including less resistant forms as amphibole (indicated by the arrow). C–D: Thin-section photographs of the niveoaeolian loess facies from the lower part of the section between the last two interglacial pedocomplexes (OIS 6), with a partial rearrangement of grains (C) and grain clustering (D). E–F: Thin-section photographs of frost-shattered grains (mainly quartz) from frost-wedge cast in the A horizon of the chernozemic last interglacial (OIS 5e) soil. Fragmentation due to freezing of capillary water followed the origin decompression lines inherited from the eroded igneous and metamorphic bedrock. Horizontal frame width: (A, C, E = 1.2 mm; B, D, F = 0.64 mm).

Photos by R. A. Kemp.

brownish strata, however, may represent redeposited brown soils. Micromorphology of the loessic deposits is characterised by a more compact structure than in the first facies, with increased textural variability in the form of grain clustering and rearrangements. Horizontally-aligned structural patterns suggest secondary deformation during thaw cycles (Fig. 5 C–D).

Loess mineralogy

The overall loess (parent material) mineralogy (analysed in 10 major loess units and five soil horizons [Sk_9, Sk_{12}, Sk_{18}, Sk_{24}, Sk_{30}] by X-ray diffraction and determined in thin sections) is characterised by quartz (54–72 %), feldspar (10–23 %), calcite (4–7 %), chlorite (3–6 %), biotite (2–5 %), amphibole, muscovite and magnetic minerals (1–7 %), and rare (< 1 %) heavy minerals (garnet, zircon, apatite, tourmaline, sphene, rutile, augite, clinopyroxene and epidote). The changing brownish/greyish – greenish colour of the individual sedimentary bands within the loess deposits reflects variation of biotite and chlorite, respectively.

An EDX SEM (Energy Dispersive SEM) analysis based on calculation of elemental weight-percent distribution was applied to the most representative loess and palaeosol samples. Values of silica, iron and aluminium increase, and those of calcium decrease between the soil horizons (e.g., Sk_{24}, 42.1 %; 20.2 %; 12.1 %; 6.3 %), the colluviated loess (41.1 %; 17.6 %; 9.9 %; 13.0 %), and the aeolian loess (37.3 %; 17.0 %; 10.6 %; 16.8 %).

A series of iron and titanium compound minerals with typical magnetite, titanium-rich magnetite, titanomagnetite and ilmenite, as the most frequent, were detected by the subsequent ARL SEMQ electron microprobe mineralogical analysis. The highest proportion and the widest range of ferrimagnetic minerals was found in unweathered loess sediments (below Sk_2); lower amounts were observed in weakly developed soils (e.g., SK_9, Sk_{18}), and finally the lowest amounts in well-developed brunisolic and chernozemic soil horizons (e.g. Sk_{12}, Sk_{24}, Sk_{30}). The significance of this magnetic mineral distribution is discussed below.

Mineral grain morphology

SEM (100–1500x magnification) analyses of loess samples reveal (sub)angular shapes and unweathered surface morphology of most grains (30–50 μm) (Fig. 6). These characteristics suggest a largely local source and a short-distance transport of the silty material. A limited proportion of more mature, subangular/subrounded grains in some samples may reflect transport over longer distances and/or secondary deposition from the eroded Carboniferous sandstone bedrock.

Thermally induced fracturing along decompression fracture lines in silt grains has been observed particularly in aeolian loess found in the ice-wedge sediment fill in the last interglacial Chernozem (Fig. 5 E–F). Although other causes for disintegration of quartz grains may have been involved (e.g., unloading in the original geological formations), extreme cold and/or fluctuating climatic conditions with microscopic capillary water infiltrations into the incipient mineral grain fissures is believed to have been the principal agent.

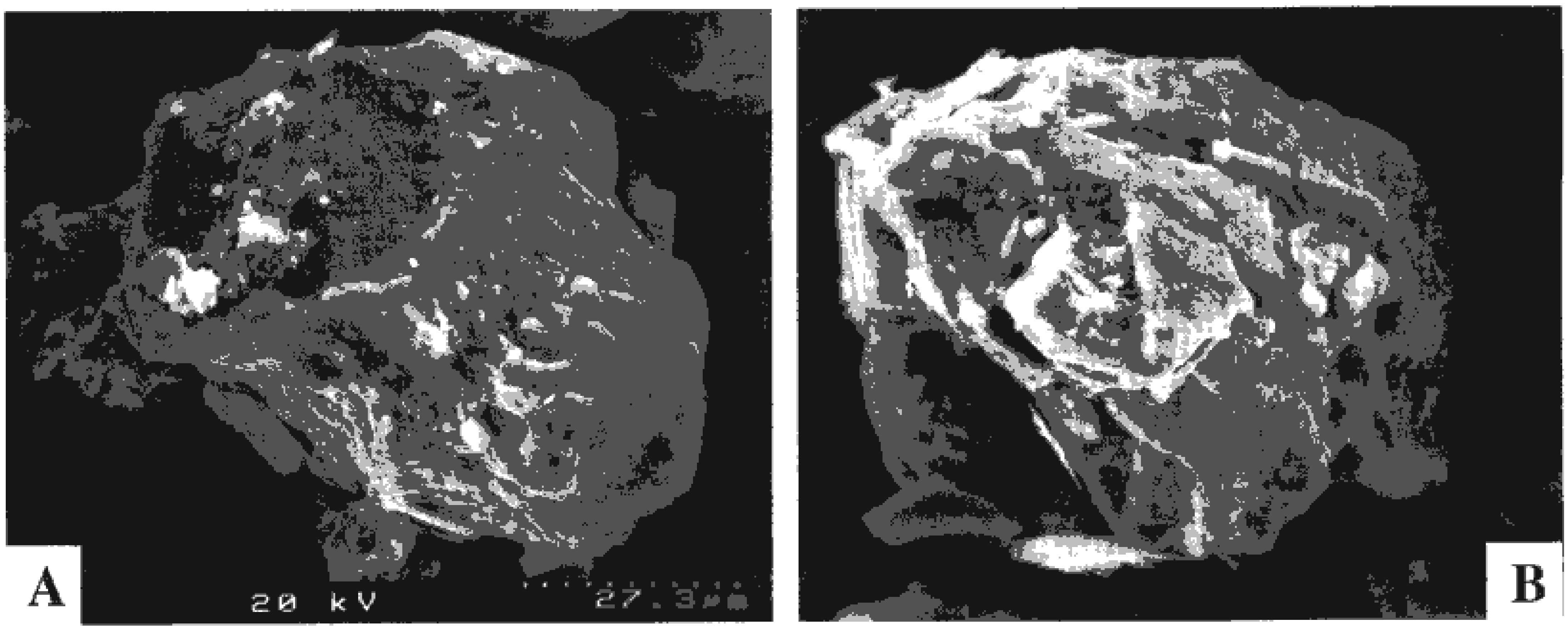


Fig. 6. SEM photographs of typical quartz (A) and magnetite (B) grains from the early last glacial loess. Presence of smaller subrounded quartz grains seen in the background (1) suggests a partly mixed origin in the loess, predominantly formed by local materials. The limited surface abrasion of most grains indicates short-distance transport of the silty sediment derived by glacial erosion of the igneous and metamorphic bedrock in the Kuznetskyi Alatau and the Eastern (Vostochnyi) Sayan Mountains, and redeposited by wind in the Yenisey River valley.

Palaeosol record

Objectives and methods of study

Palaeopedological studies at Kurtak were aimed to specify the nature and rate of pedogenic processes and to reconstruct environmental conditions prior to, during and after soil formation. The principal indicators of the past climatic change in A and B horizons are the amount of organic matter accumulation; the degree of clay illuviation (as expressed by clay coatings) and the intensity of brunification; $CaCO_3$ content and secondary carbonate precipitates (neoforms); signs of periglacial phenomena (solifluction, cryoturbation, frost disturbances), and magnetic susceptibility. Recognition and classification of fossil soils in the study section is based on a set of physical and chemical criteria, including change in colour structure, consistency, porosity, degree of mottling, and secondary calcium carbonate content, compared with the pedogenically unaltered parent material (loess). Field observations were supplemented by laboratory studies of thin sections.

In the Kurtak area, three groups of soils have been previously specified in terms of visibility and preservation. These are intact fossil soils; disturbed and partly redeposited soils by periglacial processes (solifluction, injections, involutions, cryoturbation, frost wedge casts); and poorly developed (incipient) soils (CHEKHA 1990). Pedostratigraphic correlation has been provided on the basis of soil morphology, substratum lithology, stratigraphic position of specific horizons, and their palynological and palaeontological content (DERGACHEVA et al. 1992, ZYKINA 1992). The most expressive units are well correlated laterally for a long distance between the sites (up to several kilometres), if exposed. Stratigraphical position, morphological characteristics, secondary periglacial deformations, and radiocarbon and palaeomagnetic (remanence) dating have been used to provide a chronostratigraphic control framework.

Palaeosol classification

Thirty-one buried palaeosol units displaying a various degree of pedogenic alteration have been identified below the present Holocene soil (Fig. 4). These include (in the level of soil orders) 7 Chernozems (including one on the present surface and one Cryosol), 17 Brunisols and 8 Regosols (The Canadian System of Soil Classification). The number of well-defined soils is, however, considerably less: most of the palaeosols are represented by weakly developed (initial) or colluviated soil horizons, mostly of the brunisolic and regosolic order.

Chernozems

Chernozemic palaeosols (classified as Orthic Dark Brown Chernozems) are the most distinctive pedogenic units (Sk_1, Sk_{11}, Sk_{12}, Sk_{21}, Sk_{22}, Sk_{24}, Sk_{30}), located at the depth 0 m, 9 m, 10 m, 18 m, 18.5 m, 19 m and 28 m below the present surface. They are distinguished by partly leached dark brown (10 YR 3/3 d)/dark greyish brown (10 YR 4/2 d) and very dark greyish brown (10 YR 3/1 m) Ah horizons with weakly developed, fine, granular structure and organic matter incorporation. The underlying mineral horizons (Bm) are dark brown (10 YR 4/3 d), very dark greyish brown (10 YR 3/2 m) silt loam, with a weak, medium subangular blocky structure and a few distinct, strong brown (7.5 4/6 m) mottles. Brown (10 YR 5/3 d) and dark brown (10 YR 3/3 m) colours and massive structure are characteristic of the BCca horizons, delimited where increased accumulation of calcium carbonate exceeds the original amount in the parent material. Pale brown (10 YR 6/3 d) and brown (10 YR 5/3–4/3 m) silty material with common, fine to medium, white (10 YR 8/2 d) calcium carbonate mottles within a massive porous and friable structure represents the Cca horizons above the unweathered carbonate-rich loess (Ck horizon). Microstructure of the chernozemic palaeosols is not clearly defined, likely because of insufficient development and/or compaction and secondary physical alteration by overburden compressing the original beds. In all soils krotovinas and some charcoal are present.

Brunisols

Brunisolic horizons are the most represented palaeosols in the section. They were classified by colour differences, soil structure grade, secondary calcium carbonate content, and frequency and degree of iron oxide mottling into two categories within the group of Eutric Brunisols. Orthic Eutric Brunisols, being the most common (Sk_2, Sk_4, Sk_{10}, Sk_{19}, Sk_{20}, Sk_{23}, Sk_{25}, Sk_{29}, Sk_{31}, Sk_{32}), are distinguished by pale brown (10 YR 6/3 d) or brown (10 YR 5/3 m) silt loam mineral horizons (Bmk) with a slightly sticky (w) and slightly hard (d) consistence, and weakly developed, medium subangular blocky structure. The upper part is usually colluviated or truncated; A horizons are not preserved. Transitional horizons (BCk), if developed, have lighter yellowish brown (10 YR 5/4 d), or dark yellowish brown (10 YR 4/4 m) colours, with some prominent or distinct yellowish red (5 YR 5/8 m) mottles, massive structure and secondary calcium carbonate concentrations. Ck horizons are light grey (2.5 Y 7/2 d) to white (2.5 Y 8/2 d), light brownish grey (2.5 Y 6/2 m) silt and massive. Gleyed Eutric Brunisols (Sk_6, Sk_7, Sk_8, Sk_9, Sk_{13}, Sk_{14}, Sk_{18}) are characterised by pale brown (10 YR 6/3 d)/ brown (10 YR 5/3 m) to light yellowish brown (10 YR 6/4 d)/ yellowish brown (10 YR 5/4 m) silt loam (Bmkgj) horizons with a very weak blocky to massive structure, slightly sticky (w)/slightly hard (d) consistence and common, and fine to medium, prominent, yellowish red (5 YR

5/8 m) mottles indicative of intensive gleying. This also affects, to a lesser extent, the underlying white (2.5 Y 8/2 d), light brownish grey (2.5 Y 6/2 m) silt horizons (Ckgj) with few, fine and medium, olive yellow (2.5 Y 6/8 m) mottles, and a massive structure.

The fabric of the incipient brunisolic mineral horizons is distinguished by an increase in clay and fewer voids compared to the parent material, and by large ferruginous mottles characteristic of initial oxidation-reduction processes, but without any apparent or only minor organic matter accumulation. More mature Brunisols show a further increase of illuviated organic matter, an advanced alteration of mineral horizons, as well as secondary accumulation of leached $CaCO_3$. Stratigraphically, Brunisols are located between Chernozems and Gleyed Regosols. In comparison with the well developed Chernozems, the brunisolic horizons are less disturbed by bio- and cryogenic processes, with fewer krotovinas and only minor frost wedge casts, suggesting limited biotic activity and less severe climatic fluctuations following their formation.

Regosols

Eight pedostratigraphic units (Sk_3, Sk_5, Sk_{15}, Sk_{16}, Sk_{17}, Sk_{26}, Sk_{27}, Sk_{28}) described as Gleyed Regosols are distinguished by weakly developed pedogenic (Ckg) horizons manifested by common, fine to medium, strong brown (7.5 YR 5/8 m) mottles, and faint to distincs, black (2.5 Y 2/0 m) mottles formed within a brownish grey (2.5 Y 6/2 d) dark greyish brown (2.5 4/2 m) silty, non-sticky (w) and soft (d) loessic material. The substratum is also partly mottled (Ckgj). Iron oxide precipitates are mainly distributed along vertical channel-like pores formed by grass rootlets. Except for incipient gleying features, there is no other major difference in micromorphology of Gleyed Regosols compared to the unweathered parent material (loess). Stratigraphically, Gleyed Regosols are located between aeolian or colluviated loess facies and (Gleyed) Brunisols.

D. Cryosol

Only one, laterally traceable Orthic Turbic Cryosol characterised by marked involutions and cryoturbations (Sk_{11}) has been recorded. It has a dark greyish brown (10 YR 4/2 d)/very dark greyish brown (10 YR 3/2 m) Ah(y) horizon and a very weak, fine, subangular blocky structure. Abundant charcoal is present. The light brownish grey (10 YR 6/2 d)/greyish brown (10 YR 5/2 m) mineral (Bmgy) horizon is formed in silty material with massive structure and common, medium to large, distinct, strong brown (7.5 YR 5/6 m) mottles. Both A and B horizons have been distorted by cryogenesis in the form of 10–50 cm x 2–15 cm lenses (Fig. 8). The soil is developed on a light grey (2.5 Y 7/2 d)/light brownish grey (2.5 Y 6/2 m) massive silty loessic substratum (Ck) with superimposed common, prominent, yellowish red (5 YR 5/8 m) to red (10 R 4/8 m) mottles and 1–3 cm large ferruginous concretions. Prior to the periglacial deformation, the original soil was of the Chernozem Order.

PALAEOCLIMATE RECONSTRUCTION

Palaeoclimatic interpretation is based on environmentally diagnostic characteristics of the loess facies and buried palaeosols (i.e. degree of soil weathering, thickness of mineral horizons) and periglacial features (such as cryoturbations, involutions, frost wedge casts). Additional evidence from the study area is provided by palaeomagnetic, palynological and palaeontological data (CHLACHULA 1995).

The massive structure, angularity of most silt grains, the increased proportion of the less stable minerals indicate the subaerial accumulation mechanism of the Kurtak loess. A niveoaeolian formation for the second loess facies is suggested by solifluction and other periglacial deformation phenomena (minor frost wedge casts and involutions). In the second loess facies, the specific laminated structure reflects cyclic (seasonal?) patterns of loess sedimentation. The craks in mineral grains from palaeosol ice-wedge casts, and minor involutins in sedimentary laminae further indicate very low/or fluctuating annual temperatures.

The palaeosol sequence in Kurtak Section 29 comprises a series of climatically diagnostic soils. Dark brown Chernozems are the most distinctive units with a fully-developed (Ah-Bm-BCca-Cca-Ck) profile; (Gleyed) Orthic Eutric Brunisols are characterised by mineral Bmk(gj) horizons; Gleyed Regosols are distinguished by mottled Ckg horizons. The gradual pedogenic alteration is evidenced in the palaeosol series, with an increasing weathering amplitude in the general sequence: loess-Gleyed Regosol-Gleyed Brunisol-Brunisol-Chernozem. The initial pedogenic alteration of parent material is expressed by incipient gleying in a cold, humid environment within a seasonally waterlogged setting. A progressive leaching of calcium carbonate from the original loessic substratum accompanied by organic matter accumulation in A horizons and brunification of B horizons reflects a gradual increase of summer temperatures and surface stability that contributed both to prolonged weathering processes and formation of brunisolic and, under more continental conditions, of chernozemic soils. Regosolic Gleysols indicate a very cold periglacial tundra; (Gleyed) Brunisols suggest a cold and relatively humid climate under (forest-) parklands; and Chernozems are typical of a continental (parkland-) steppe setting. Most of the brunisolic horizons (particularly the weakly developed ones) represent a transitional stage of pedogenesis between the initial regosolic/gleysolic horizons and chernozemic soils (in both directions) as a result of changing climatic conditions. They significantly differ in the degree of weathering from typical interglacial/warm interstadial brown forest soils.

In terms of palaeoclimatic evolution, three major climatic cycles can be recognised in the loess-palaeosol sequence, with a patterned succession of loess deposition followed by soil formation. The first (lower) cycle (C_1) is delimited by the brunisolic horizon Sk_{31} and the loess below the analogous horizon SK_{25}; the second cycle (C_2) by the brunisolic horizon Sk_{25} and the loess unit below the well-developed Brunisol/truncated Chernozem Sk_{12}; the third cycle (C_3) by Sk_{12} and the loess below the incipient brunisolic horizon Sk_2. The delimited trend of climatic fluctuations is consistently followed in the magnetostratigraphic profile by defined intervals throughout the climatic minima and maxima (Fig. 11). Onset of the fourth cycle (C_4) correlates with the brunisolic horizon Sk_2 below the present-day Chernozem Sk_1. All three defined cycles start with formation of Brunisol (Sk_{31}, Sk_{25}, Sk_{12}) distinguished by Bmk horizons with some krotovinas and moderately to well-developed BCca horizons. Separated by a thin cover of aeolian loess, the Brunisols are followed by chernozemic soils (Sk_{30}, $Sk_{24\text{-}22\text{-}21}$, Sk_{11}) with characteristic Ahy horizons. The first four dark brown Chernozems were severely disturbed by frost wedges (Figs. 9, 10); the fifth recorded Chernozem is cryoturbated and involuted, and subsequently transformed into a Cryosol (Fig. 8). The later development is uniform for all three cycles, continuing with formation of mature Brunisols, which occur either as a single unit (Sk_{29}, Sk_{23}), or in a series ($Sk_{20\text{–}19}$, $Sk_{10\text{–}9}$), succeeded by initial brunisolic horizons with a less-advanced degree of pedogenesis (Sk_{18}), some interbedded by thin, partly colluviated loess layers ($Sk_{8\text{–}6}$, Sk_4), and finally superimposed by Gleyed Regosols (Sk_{28}, Sk_{17}, Sk_5, Sk_3). The subsequent periods of loess accumulation mark the intervals of climatic minima. In the first cycle (C_1), most of the loess is colluviated, while it largely preserves its original massive aeolian structure in the later cycles (C_2, C_3). Transition between the cycles either shows a marked climatic amelioration with formation of a brunisolic horizon (C_1/C_2), or follows a gradual warming and a reverse Gleyed Regosol-Brunisol pedogenic trend (C_2/C_3).

A similar palaeoclimatic pattern is documented in the Late Pleistocene loess sections in western Siberia (Volkov - Zykina 1991), with loess deposition during dry and cold periods, reactivated soil formation processes during surface stabilisation under warmer conditions, and subsequent cryoturbation due to climatic cooling and increased humidity. This general trend corresponds to arctic tundra established during cold intervals, replaced by steppe-tundra/forest-tundra and later boreal forest during the warming intervals. Continental shrub steppe and forest steppe correlates with climatic optima (with dry, warm summers and cold winters). Increased humidity and less marked seasonality allowed recolonisation by (parkland) forest; further drop of temperature and precipitation decrease let to re-establishment of forest-tundra and steppe-tundra.

CHRONOLOGY OF THE LOESS-PALAEOSOL RECORD

The basis for the chronostratigraphic framework of the Kurtak loess-palaeosol record is provided by the radiocarbon chronology for the last 35 000 years (Orlova et al. 1990, Drozdov et al., this volume, Tab. 1), magnetostratigraphy and pedostratigraphy for the earlier periods. The existing radiocarbon dates from other Kurtak sections, laterally well-correlated with Section 29, allow a general temporal fixation of some major fossil soil and

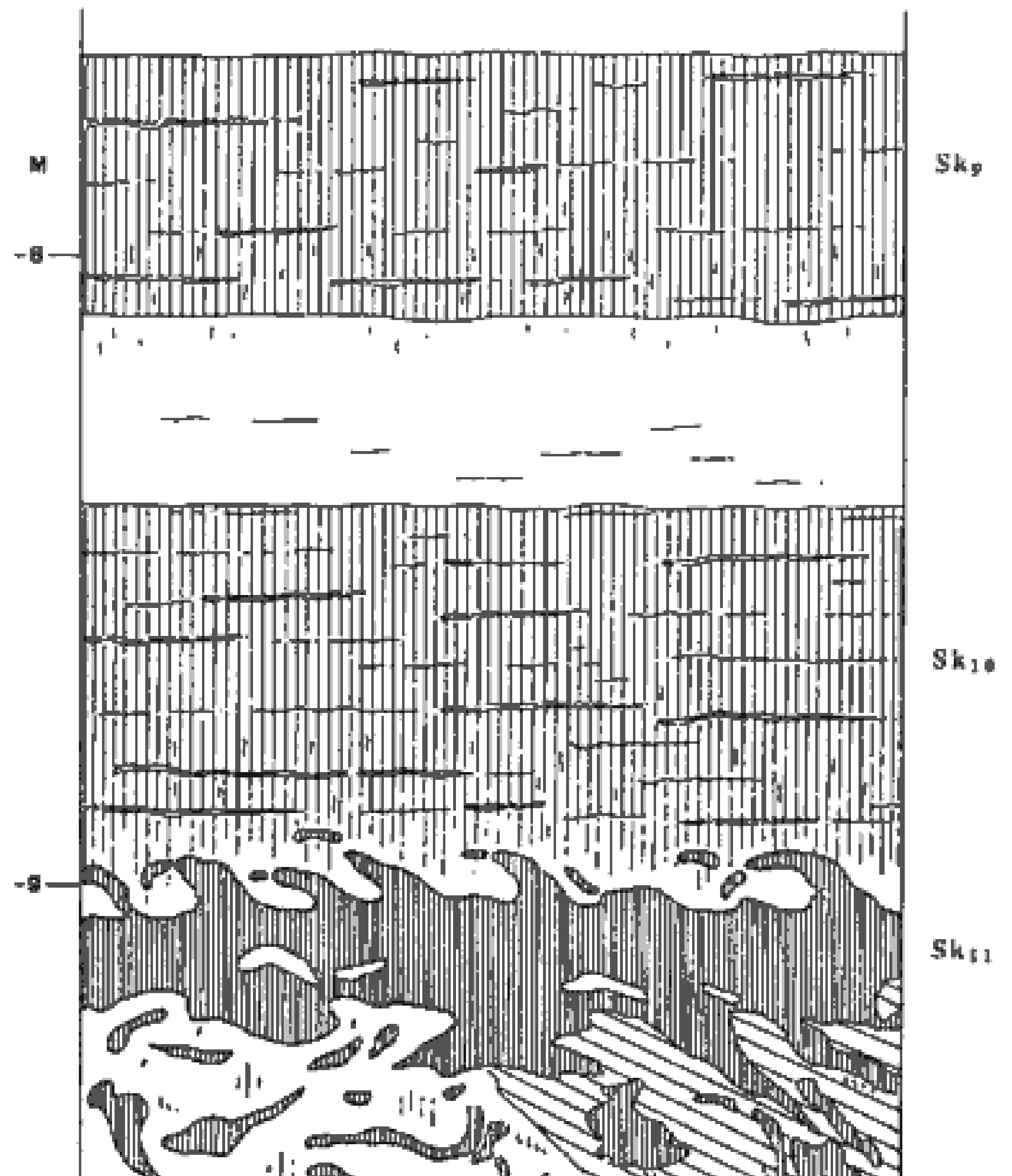


Fig. 7. Kurtak Section 29. The Karginsk (OIS 3) Pedocomplex (for legend see Fig. 8).

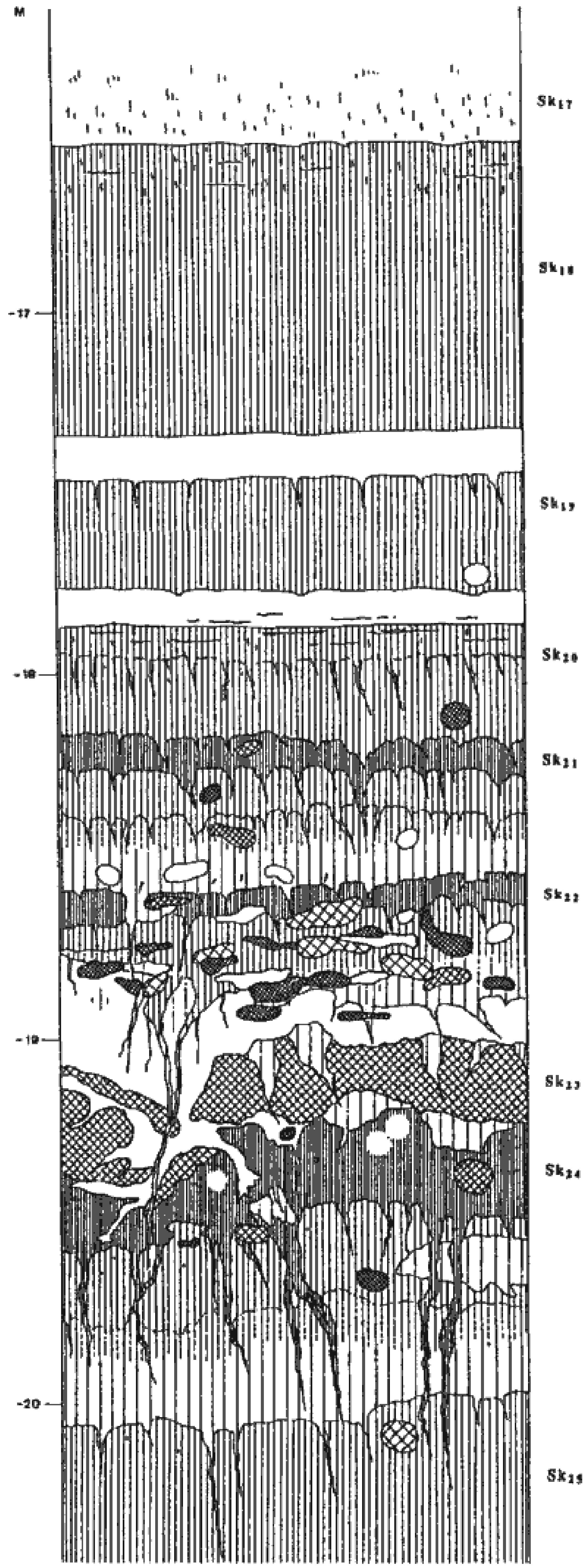
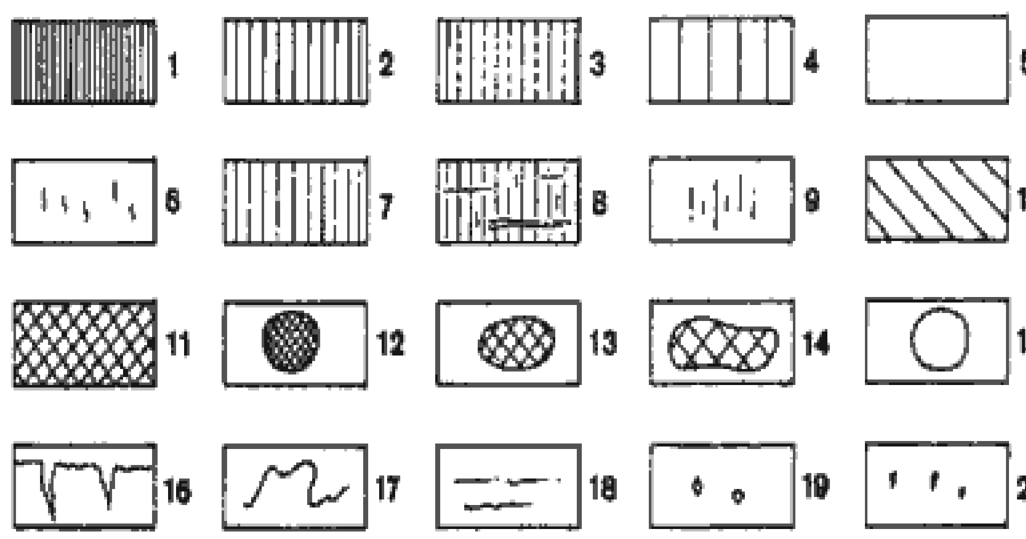


Fig. 8. Kurtak Section 29. The last interglacial pedocomplex (OIS 5; 130–74 ka).

loess horizons of the stratigraphic sequence. The Cryosol (Sk_{11}) within the complex of soils (Kurtak Pedocomplex – Fig. 8) is the most securely defined chronostratigraphic marker in the study area. It is radiocarbon dated on the basis of charcoal to 29 410 ± 310 yr. BP (SOAN-2806) at Berezhekovo Section 21 (horizon 3) and to 29 00 ± 400 yr. BP (GIN-6999) at the Kashtanka Site (horizon 11), and on the basis of wood from the southern part of the Berezhekovo Site to 30 400 yr B.P. (AECV-1938C). The lower soil (Sk_{12}) produced a date of > 30 000 yr B.P. (SOAN-2807) on charcoal, also from the nearby Section 21 (horizon 3). The single date of > 35 000 yr B.P. (SOAN–2805) on charcoal at the Kamennyy Log Site from a 5 m thick loess unit below the Kurtak Pedocomplex (Drozdov et al. 1990) supports the early last glacial (Zyriansk) age of the aeolian deposit incorporating several Gleyed Regosols (Sk_{15}–Sk_{17}).

The mid-Last Glacial (Karginsk) age of the Kurtak Pedocomplex in Section 29 is also secured by two palaeomagnetic high-amplitude anomalies at 6.8–7.2 m and 9.2–9.6 m below the present surface. The peak of the upper anomaly lies at the contact of the Ckgj horizon of a Gleyed Brunisol (Sk_7) and the Bmkgj horizon of the underlying Gleyed Brunisol (Sk_8). The lower recorded anomaly is within a loessic Ckg horizon below the involuted Cryosol (Sk_{11}). In respect of the existing ^{14}C dates on the Cryosol located between the two magnetic features, those correlate well with the later and earlier Lake Mungo/Laschamp-Olby Excursions at 26 ka BP and 31–35 ka BP, respectively (dates according to Lovlie 1989) (Fig. 10).

The underlying series of palaeosols with a progres-



1 – chernozemic Ah horizon; 2 – chernozemic/brunisolic Bm/Bmk horizon; 3 – chernozemic/brunisolic BCca horizon; 4 – chermozemic/brunisolic Cca horizon; 5 – loess (CK horizon); 6 – gleyed regosolic Ckg/Ckgj horizon; 7 – gleyed brunisolic (Bmkgj) horizon; 8 – partly colluviated brunisolic B horizon; 9 – fragmented chernozemic B horizon; 10 – undifferentiated infill of truncated surfaces; 11 – pedo-/bioturbated chernozemic-/brunisolic A/B horizon; 12–15 – krotovinas filled by matter of Ah horizons (12), Bm/Bmk horizons (13), BCca/Cca horizons (14) and by pure aeolian loess (15); 16 – frost wedge casts in Ahy and Bmky horizons; 17 – cryoturbations; 18 – minor solifluctions; 19 – small pebbles; 20 – charcoal.

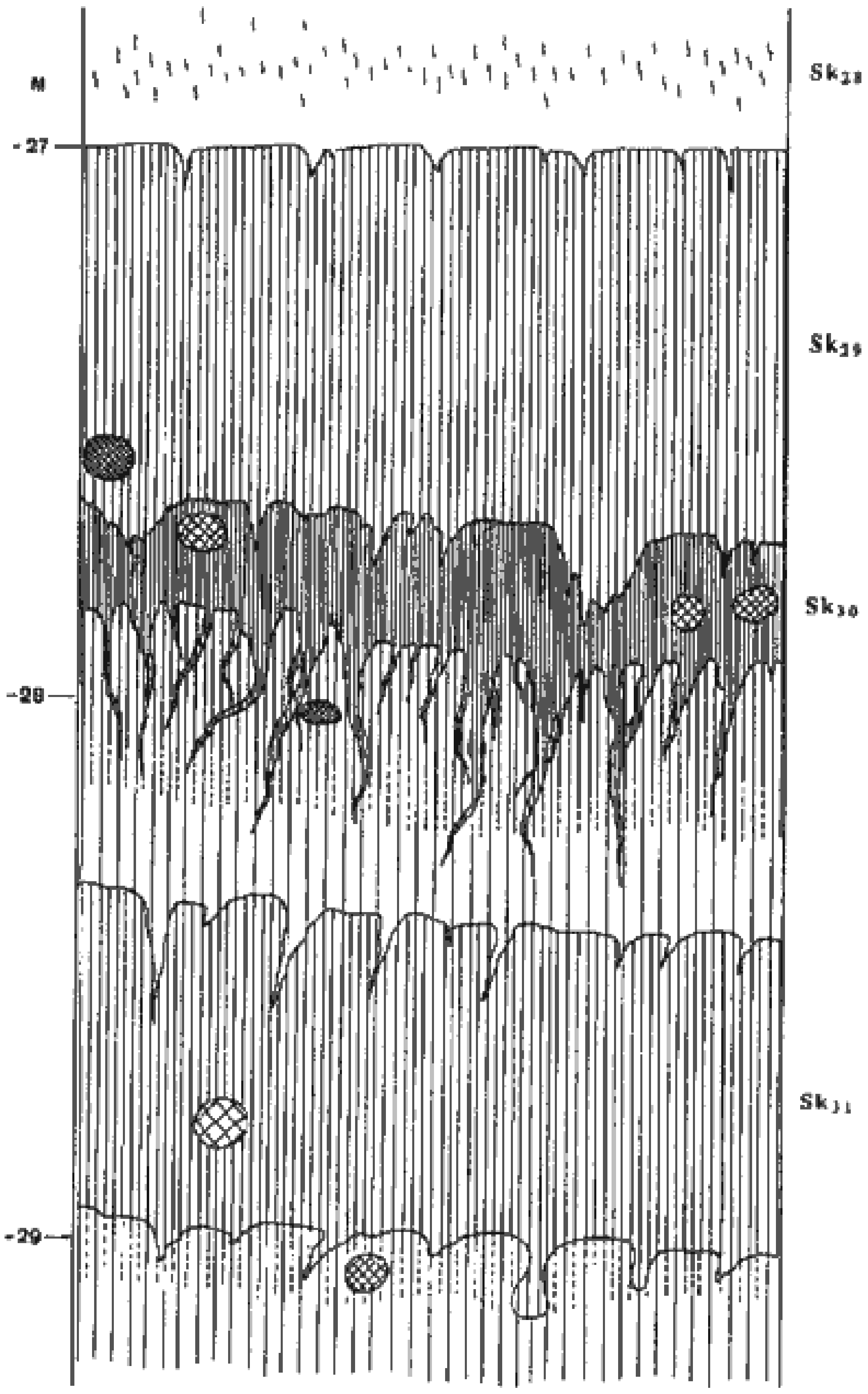


Fig. 9. Kurtak Section 29. The penultimate (late Mid-Pleistocene) interglacial pedocomplex (OIS 7) (for legend see Fig. 9).

sive pedogenic development down the stratigraphic profile, including three Brunisols (Sk_{18}–Sk_{20}) and two Chernozems (Sk_{21}–Sk_{22}), represents the Sukholozhskiy Pedocomplex (DROZDOV et al. 1990), assigned to the late last interglacial (OIS 5c–5a; 110–73 ka BP) on the basis of its stratigraphic position and the advanced degree of soil horizon weathering (Fig. 8). The pedocomplex is comparable with the Iskitim Pedocomplex in the southern Novosibirsk area (ARKHIPOV et al. 1992). A magnetic anomaly corresponding to the Blake excursion (117 to 111 ka BP; LOVLIE 1989) has been detected within the upper part of the underlying loess (OIS 5d) below the Chernozem Sk_{22} and previously reported from the nearby Berezhekovo Site 1 (DROZDOV et al. 1990). The lower and most developed Chernozem in the Kurtak Section 29 – the Kamenolozhskaya Soil – (Sk_{24}) is correlated with the last interglacial (Kazantsevo) climatic optimum (OIS 5e; 127–120 ka BP), and stratigraphically corresponds to the Berdsk Soil of Western Siberia (VOLKOV - ZYKINA 1982). This chronology is consistent with rodent taxa (*Myospalax myospalax laxmani*) and an early form of mammoth (*Mammuthus primigenius*), as well as typical Middle Palaeolithic (Mousterian) stone tools recorded on top and within the soil (DEREVIANKO et al. 1992), which is analogous to the present-day Chernozem. The underlying brunisolic horizon (Sk_{25}) likely represents a temporarily disrupted pedogenic development leading to formation of the above Chernozem (Sk_{24}).

The second well-developed dark brown Chernozem (Sk_{30}) between two brunisolic horizons (Sk_{31}, Sk_{29}) in the lower part of the Kurtak Section 29 (Fig. 9), and separated by a 3.5 m thick package of loess and a series of gleyed regosolic soil horizons (Sk_{26}–Sk_{28}) from the last interglacial pedocomplex (Sk_{18-25}), is believed to be of the penultimate (Tobol – OIS 7) interglacial or the following inter- Riss (Shirta) interglacial. The massive, largely colluviated loess deposits between the two interglacial soils is assigned to the penultimate glacial (OIS 6) period. The analogous loess deposits with a thoroughly cryogenically altered brunisolic (Bmky) horizon near the section base (Sk_{22}), are the earliest units of the stratigraphic profile. Because of the normal palaeomagnetic polarity within the Brunhes Chron, they are most likely to be late Middle Pleistocene in age (ca. < 300 ka BP).

In summary, the climatostratigraphically and palaeopedologically defined cycles are correlated with the last glacial and interglacial period (C_{3-2}), and (a later part of) the previous glacial/interglacial period (C_1) (Fig. 11).

MAGNETOSTRATIGRAPHY OF THE LOESS-PALAEOSOL RECORD

For the purpose of a relative chronostratigraphy, palaeomagnetic sampling was carried out providing a total of 340 samples (in 8 cm^3 plastic boxes) taken at 10 cm intervals from the 34 m section. In addition to magnetic remanence magnetic susceptibility was measured, as values of this parameter have been used elsewhere to indicate past climatic change (HELLER - LIU 1982, 1984; KUKLA 1987; KUKLA et al. 1988; KUKLA - AN 1989; DING et al. 1991; RUTTER et al. 1991; LIU et al. 1993; EVANS - HELLER 1994). A subsequent, high-resolution susceptibility sampling was made at 3 cm intervals within the last interglacial pedocomplex corresponding to a 6.5 m long stratigraphic profile. The samples were analysed using a Bartington magnetometer MS2 sensor calibrated by means of a series of pure chemical compounds in the Palaeomagnetic Laboratory of the Department of Physics, University of Alberta.

The analysis showed a marked and patterned fluctuation of susceptibility values through the stratigraphic record (Fig. 11). The relationship between the climatic change and magnetic susceptibility fluctuation is clearly evident, with the susceptibility maxima exactly corresponding to the inferred intervals of the most intensive

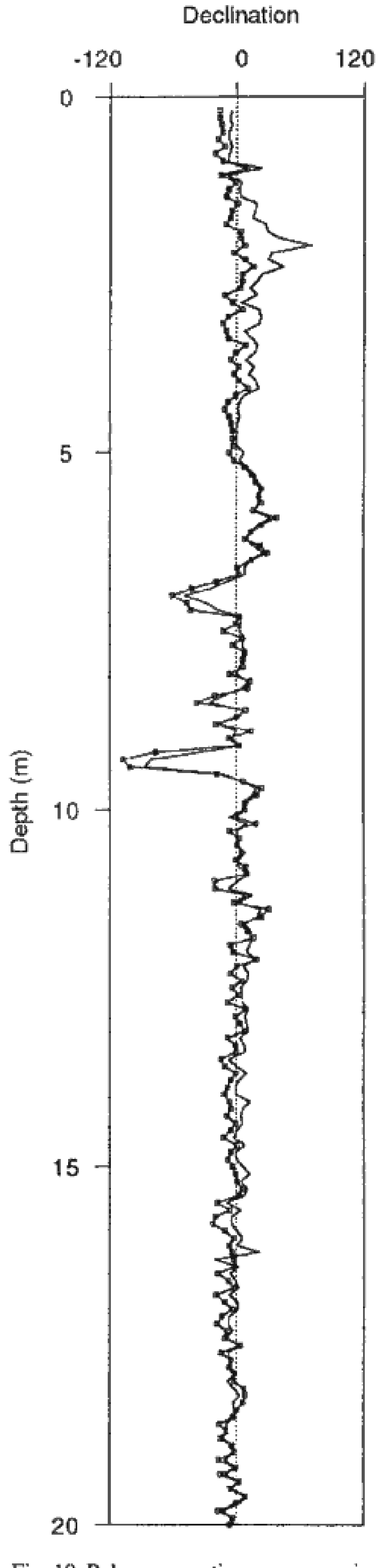


Fig. 10. Palaeomagnetic remanence signal in the upper part of the Kurtak Section 29 with two recorded anomalies. Their correlation with the later and earlier Lake Mungo/Laschamp-Olby excursions (26 ka and 31–35 ka BP) is supported by several radiocarbon dates ± 30 ka BP from a palaeosol horizon stratigraphically located between two mentioned palaeomagnetically significant peaks.

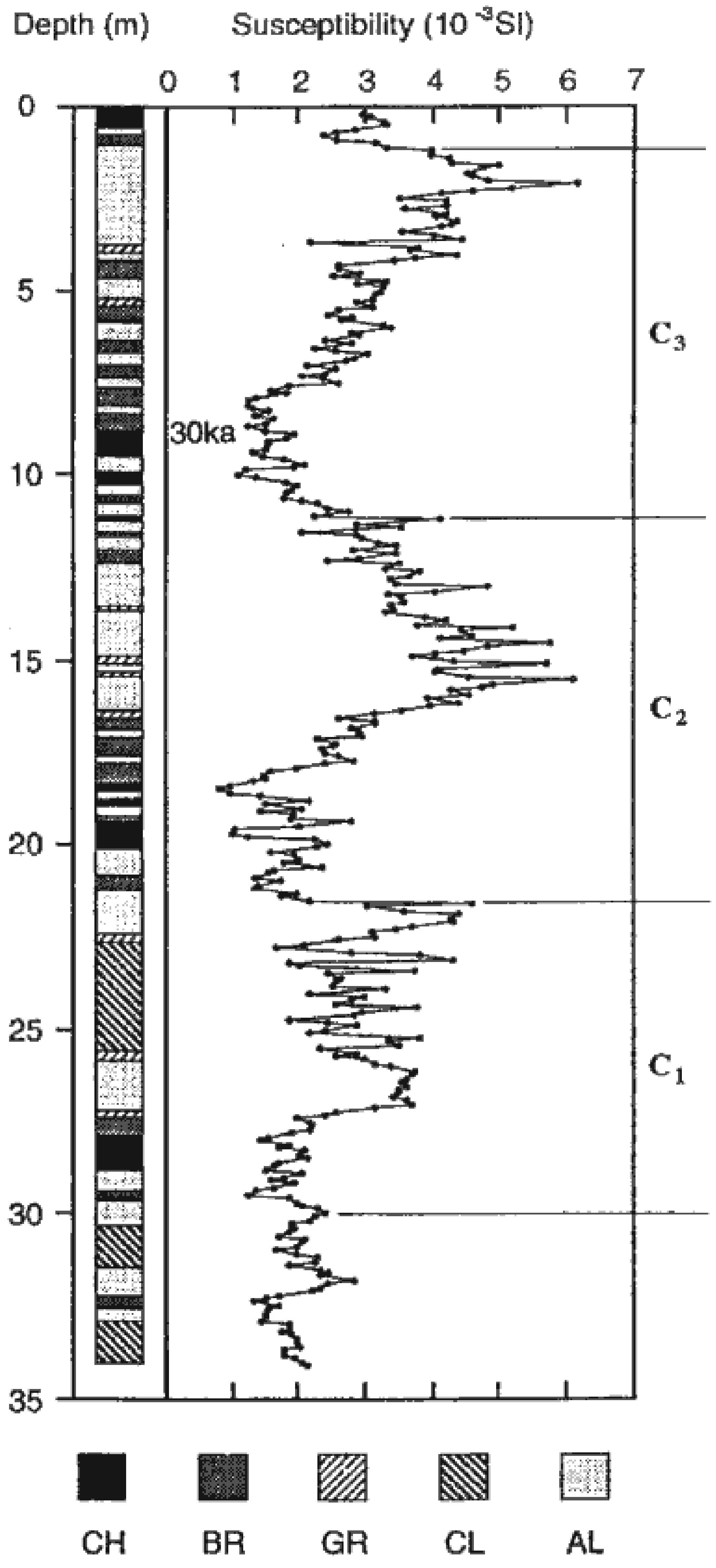


Fig. 11. Kurtak Section 29. Correlation of the loess-palaeosol record and the corresponding magnetic susceptibility curve.
CH – Chernozems, BR – Brunisols, GR – Gleyed Regosols, CL – colluviated loess, AL – aeolian loess, C_1–C_3 – palaeoclimatic cycles.

loess deposition, and the minima correlating with the most developed palaeosol horizons. The interglacial and interstadial Chernozems and well developed Brunisols are characterised by the lowest susceptibility values (90–150 x 10^{-5} S.I.). Increased susceptibility is found in weakly developed Brunisols /150–250 x 10^{-5} S.I.). Higher values were measured in the colluviated loess facies (160–410 x 10^{-5} S.I.). This supports the assumption of initial pedogenic activity following niveo-aeolian loess accumulation intervals. Further magnetic susceptibility increases are recorded in Gleyed Regosols (190–390 x 10^{-5} S.I.). Finally, the magnetic susceptibility peaks correlate with periods of aeolian loess deposition (350–580/650 x 10^{-5} S.I.). Even minor climatic oscillations are indicated by deviation of the magnetic susceptibility signal. For example, progressive mottling of aeolian loess corresponds to decreasing susceptibility values; periglacial deformation by frost action and cryoturbation of Ah and Bm chernozemic horizons are evidenced by sudden shifts towards higher values in the magnetic record.

The susceptibility curve from Kurtak Section 29 provides definite evidence of climate-dependent magnetic variations correlated with deposition of loess and formation of palaeosols. The observed magnetic pattern, however, is completely opposite to that from the Loess Plateau of China where the susceptibility peaks are located in palaeosols and the magnetic signal is about 3–4 times higher than in loess (HELLER - LIU 1982). The pattern in China is explained in terms of an in situ formation of ultrafine magnetic minerals in the process of parent material weathering (ZHOU et al. 1990, MAHER - THOMPSON 1991) and a haematite enrichment of the pre-existing magnetite under humid and warm climate (HELLER - LIU 1982). Magnetic susceptibility of the Kurtak loess, how-

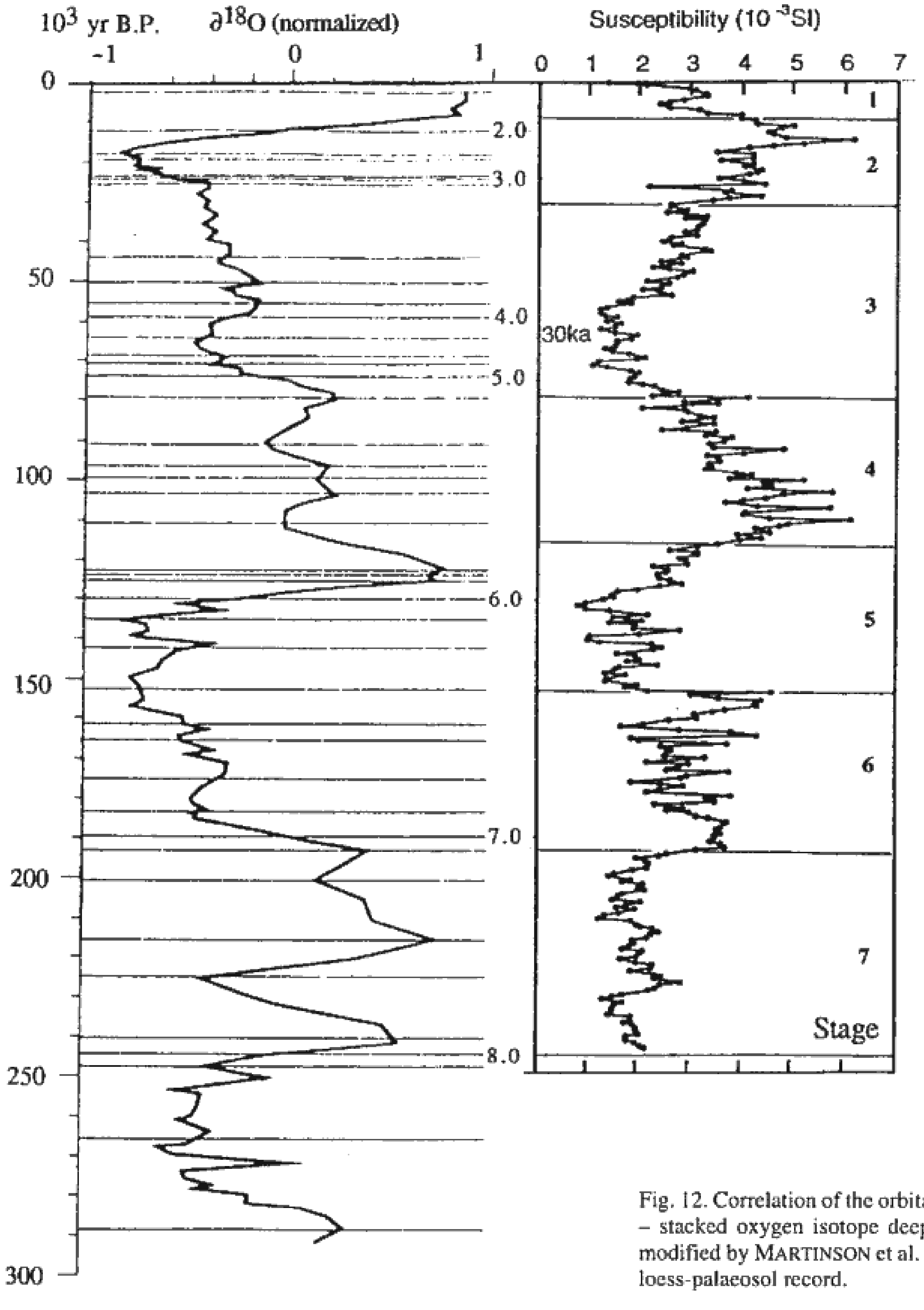


Fig. 12. Correlation of the orbitally based chronostratigraphically – stacked oxygen isotope deep-sea record (PISIAS et al. 1984, modified by MARTINSON et al. 1987) with the Kurtak Section 29 loess-palaeosol record.

ever, is 5–25x higher than some of the Chinese loess with average values of 20–70 x 10^{-5} S.I. (AN et al. 1991: Fig. 1; LIU et al. 1991: Fig. 12). An analogous magnetic susceptibility pattern has also been reported from the loess in Alaska (BEGÉT - HAWKINS 1989) and the French maar lakes (THOUVENY et al. 1994).

The element SEM and the ARL SEMQ electron microprobe mineralogical analyses suggest that differences in the quantitative and qualitative distribution of ferrimagnetic minerals in the study section account for the recorded pattern of susceptibility variation. A partial depletion of less stable ferrimagnetic elements from the original minerals due to weathering processes of the loessic substratum by alteration into less susceptible iron minerals under periodic oxidation and reduction conditions may explain the decreased magnetic signal in palaeosols. The total magnetic susceptibility capacity of the southern Siberian loess and palaeosol records may thus *a priori* depend upon the quantity and quality of primary magnetic minerals within the unaltered parent material inherited from original geological sources. Increased wind activity during cold intervals deriving larger mineral (including ferrimagnetic) grains is likely another major factor. Nevertheless, even though the warmer intervals are characterised by lower magnetic susceptibilities, the observed frequency dependance of magnetic susceptibility indicates that a new magnetic mineral is produced as a result of pedogenesis during interglacial and interstadial times (CHLACHULA et al. 1998).

Overall, the magnetic susceptibility record in the Kurtak Section 29 perfectly monitors the past climate change in the area for the last two glacial-interglacial cycles, with an increasing, high-resolution temperature deviation amplitude during the Late Pleistocene cycle (130–10 ka BP).

In terms of a general palaeoclimatic evolution, both the loess-palaeosol sequence and the magnetic susceptibility curve indicate a changing, but patterned climatic pathway during the upper Late Quaternary. Some consistent regularities with the deep-sea oxygen isotope records are apparent, with $\delta^{18}O$ inversely correlating with the S.I. magnetic susceptibility values (Fig. 12). The chronostratigraphic framework for the oxygen isotope stage subdivision of the Kurtak Section 29 magnetic susceptibility record is provided above.

From a climatostratigraphic viewpoint, a significant drop in temperature ended a prolonged period of relative environmental stability manifested by the Chernozem (Sk_{30}) in the lower part of the section, presumably corresponding to the Oxygen Isotope Stage 7 and assigned to substage 7a (Fig. 12). The following cold period (OIS 6) experienced significant short-term climatic fluctuations, contributing to intensive loess colluviation between two cold and arid intervals with aeolian loess sedimentation. A new long-term landscape stabilisation with intensified soil formation disrupted by intervals of loess deposition and periglacial surface deformation is correlated with Stage 5. Dramatic climatic amelioration after the termination of the first climatic cycle (Fig. 11) is consistently recorded in the deep-sea oxygen isotope curve (Termination II, i.e., the base of Stage 5, ca. 130/127 ka BP (Fig. 12). The magnetic susceptibility peaks, corresponding to a series of palaeosols with decreasing degree of pedogenesis, are correlated with the Oxygen Isotope Substages 5e, 5c, 5a of the last interglacial (*sensu lato*). Reactivated loess sedimentation relates to progressive cooling during the early stage of the last glacial (OIS 4), culminating in several cold and hyperarid stadials evidenced by the first magnetic susceptibility maxima. The following interval of susceptibility decrease and appearance of (gleyed) brunisolic horizons corresponds to the mid-Last Glacial interstadials (OIS 3). The mid-Last Glacial (Karginsk) climatic optimum (associated with a well-developed Brunisol or a truncated Chernozem) was likely as warm, but more humid than the present (Holocene) interglacial. Gradual cooling leading to formation of Gleyed Brunisols and Gleyed Regosols indicates that the transition towards the last glacial stage (OIS 2) was less dramatic than during the previous glacial interval (OIS 4). A marked drop of annual temperatures associated with intensive loess deposition during the last glacial maximum is indicated by the second magnetic susceptibility peak. A progressive postglacial warming towards present conditions defines the final climatic stage (OIS 1).

SUMMARY AND CONCLUSIONS

The loess-palaeosol stratigraphic sequence from the Kurtak area provides evidence of complex and highly fluctuating climatic changes in the Upper Yenisey basin and southern Siberia in general. Although temporarily limited to more recent stages of the Quaternary Period, the Kurtak section comprises a unique, and continuous high-resolution record for the last glacial-interglacial cycle, and most, if not all of the previous late Middle Pleistocene cycle. Magnetic susceptibility has proven to be a very sensitive, high-resolution indicator of climate change in the region.

Mineralogical composition of the loess and fresh surface morphology of the fine silt fraction indicate a predominantly local provenance of the loess deposits. The larger, angular to subangular minerals, including the less resistant forms, presumably originate from igneous and metamorphic rocks eroded in the Sayan Mountains. After being transported by ablation dicharge and periodically accumulated within the alluvial plain of the Yenisey River during cold and dry climatic intervals, the fine silty detritus became redeposited by wind onto the eastern slopes of the Kuznetskiy Alatau Mountains.

Some loess deposits were subsequently colluviated under more humid conditions with (seasonal?) input of the aeolian dust onto a thin, subsequently melted snow layer. Such a niveo-aeolian loess formation process, implying a higher amount of winter precipitation and moderately cold climate, would account for most of the subaerial deposits in the earlier stages of sedimentation.

Initial pedogenesis in the form of gleying occurred during intervals of decreased loess deposition within an arctic tundra-steppe setting with periodically saturated ground. Gradual increase of annual temperatures and improved surface drainage led to formation of gleyed regosolic and gleyed brunisolic horizons, and eventually well-developed brunisolic soils corresponding to establishement of periglacial steppe-tundra, forest-tundra and boreal forest, respectively. Increase of summer temperatures caused a shift towards a semiarid, strongly continental climate that led to expansion of grasslands and a retreat of forest into higher, more humid mountain locations.

The high resolution loess-palaeosol sequence from the Kurtak area shows a marked onset of the last interglacial as evidenced by the thick basal Chernozem (Sk_{22}) followed by a series of gradually less developed chernozemic and brunisolic soil horizons. An analogous stratigraphical record has been documented at Iskitim and other sites on the Priobie Loess Plateau, suggesting broadly comparable palaeoclimatic (OIS 5) conditions over a larger area of southern Siberia (ZYKINA et al.; this volume).

Deep ice wedge casts in all buried Chernozems attest to relatively short and very cold episodes during the interglacial periods. Within the last interglacial, the coldest time interval is correlated with substage 5d and evidenced by up to 1.5 m deep frost wedge casts dissecting the substage 5e Chernozem. Periglacial activity during the last glacial interstadials was limited to reduced frost-wedge formation processes and some solifluction, both indicative of a less continental and more humid climate. Following the last interglacial, the climate in the Minusinsk Basin as well as other areas of southern Siberia became more pronounced with cold and dry stadials during the last glacial stages interspersed with moderate mid-last glacial interstadials. The climate during the late Middle Pleistocene seems to have been less continental, with milder and/or less arid conditions during glacial stages.

Because of its location in the geographical centre of Asia, and a geomorphological isolation with largely reduced atmospheric effects of the world's oceans and related air-mass circulation flows, the loess-palaeosol sequence from the Northern Minusinsk Basin provides one of the most complete Late Quaternary palaeoclimatic continental records in northern Asia.

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