Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 265 (2008) 498–514
EPSL
www.elsevier.com/locate/epsl

Magnetic indicator of global paleoclimate cycles in Siberian loess–paleosol sequences

Vadim A. Kravchinsky [a,*], Valentina S. Zykina [b], Vladimir S. Zykin [b]

[a] *Physics Department, University of Alberta, Edmonton, AB, Canada T6G 2J1*
[b] *Institute of Geology of the UIGGM, Siberian Branch of Russian Academy of Sciences, Novosibirsk, 630090, Russia*

Received 27 March 2007; received in revised form 5 October 2007; accepted 21 October 2007
Available online 26 October 2007
Editor: G.D. Price

Abstract

The loess–paleosol sequences of China, Siberia, Alaska and many other regions, along with lake sediments and glaciers, provide the only accurate paleoclimatic terrestrial records for intervals of thousands to hundreds of thousand years. The frequency dependence (FD) of magnetic susceptibility (MS) in such sequences has become the leading parameter for analyzing climatic change and Milankovitch (astronomical) periodicity in Siberian sequences; it is always higher in soil horizons than in loess. The enhanced FD parameter in soils is associated with ferromagnetic minerals, mostly magnetite, produced during pedogenesis. The MS and FD parameters of 670 samples from five sections in Siberia are reported here. Inter-section correlation is used to produce a combined FD time series for the studied sections. Chronological control is established by absolute dating and stratigraphic correlation. Spectral analysis of the FD time series reveals the presence of Milankovitch signals at ~100 kyr (eccentricity), ~40 kyr (obliquity) and ~23 kyr (precession) and demonstrates that Siberian loess–paleosol sequences are excellent continental recorders of long-term paleoclimatic changes. This suggests that the FD parameter can potentially be used more widely for evaluation of climate periodicity in loess/paleosol sequences in other parts of the world.

Keywords: loess; magnetic susceptibility; paleoclimate; Pleistocene; Siberia; paleosol

1. Introduction

Although it has been firmly demonstrated that changes in low field magnetic susceptibility (MS) of Chinese, Alaskan and other loess deposits are linked to paleoclimatic changes (Kukla et al., 1988; Begét et al., 1990; Evans and Heller, 2003), some studies show an apparent absence or complexity of this connection in Siberia (Kazansky et al., 1998; Virina et al., 2000; Matasova et al 2003; Feng and Khosbayar, 2004). Thus the magnetoclimatic model developed for Chinese loess, where MS is higher in soil than in loess, or the wind-vigor model, where MS is lower in soil than in loess (Evans and Heller, 2003), cannot be applied universally.

Chlachula et al. (1998) explained MS variations in one of the most representative loess/sol sequences of Central Siberia (Kurtak section) with the wind-vigor model in which stronger winds transport heavier magnetic particles during glacial periods. Soils were developed during warmer intervals when aeolian transport of dense magnetic

* Corresponding author: Tel.: +1 780 492 5591; fax: +1 780 492 0714.
E-mail address: vkrav@phys.ualberta.ca (V.A. Kravchinsky).

0012-821X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2007.10.031

particles from the parent sources did not play an important role; only fine ferromagnetic particles were formed during soil development. This led to a dilution of magnetic mineral concentration in soils and corresponds to low MS in soil intervals. Chlachula et al. (1998) correlated the MS pattern in soil horizons with oxygen isotope content in the interstadials to build a first chronological model of the section.

Recently Zander et al. (2003) obtained new dates for the section using thermoluminescence dating methods. On the basis of these new dates the chronostratigraphy for the Kurtak section was significantly modified (Frechen et al., 2005). In spite of the new chronology, the wind-vigor model still explains low MS for soil horizons in Kurtak very well.

Other sections of Western Siberia and Mongolia hundred kilometers from Kurtak, do not exhibit similar MS patterns (Kazansky et al., 1998; Matasova and Kazansky, 2004; Feng and Khosbayar, 2004). In these studies, soil intervals displayed enhanced or depleted MS for different paleosol intervals or no MS difference at all from loess. This makes interpretation of the MS profiles more complex and prevents interpretation of continuous magnetic measurements in the sections in terms of the kind of paleoclimatic periodicity observed in Chinese or Alaskan loess.

Grain size parameters could be another potential indicator of paleoclimatic variability, but such analysis is time-consuming, and the approach is not always universal, because of the fraction size variations for different locations. The purpose of our study was to reanalyze the detailed MS record of the Kurtak section using recent absolute dates, to verify if magnetic measurements could serve as a climatic proxy for different Siberian sections and to attempt a comparison of the Siberian loess/sol magnetic and global paleoclimatic records.

2. Geological setting

Loess–paleosol sequences are widespread over a vast territory of Siberia, from 50° to 60°N and 70° to 110°E (Fig. 1). Their overall thicknesses are a few tens of meters with an age range of more than 800kyr. The loess section varies in thickness from 100m in the Ob' hilly plain, through 40m in the Novosibirsk Ob' region and Kuznetsk basin, 15m in the Tobol–Irtysh region, to as thin as 5m in the Altai mountains. The sub aerial loess sequence has a well defined cyclic pattern produced by regular alternation of loess layers and soil complexes. Detailed correlation of over one hundred loess–soil sections with similar diagnostic features over a large territory has led to construction of

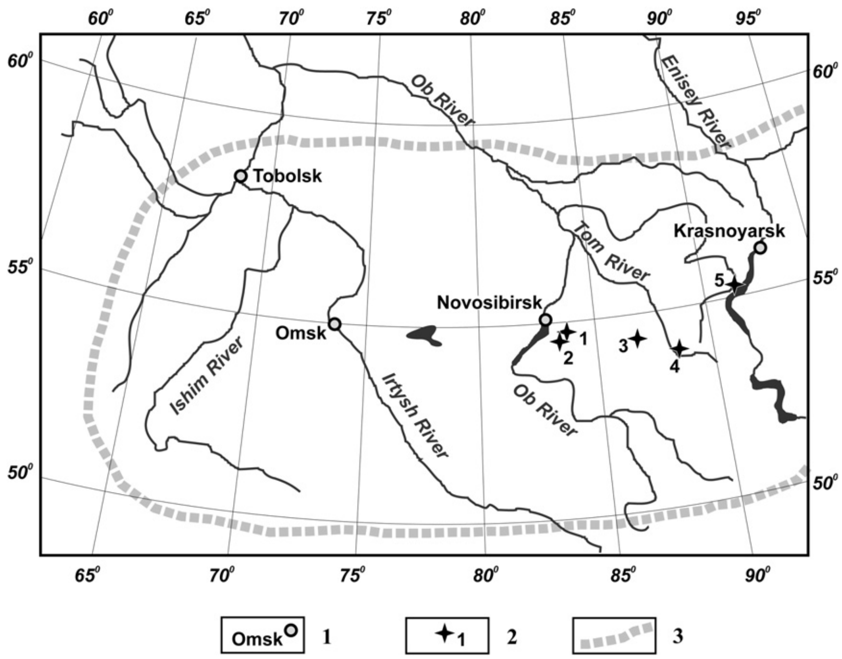


Fig. 1. Simplified map of Western–Central Siberia showing the study site locations. 1 – Mramorny (54°37'N, 83°25'E, altitude 155 m); 2 – Lozhok (54°27'N, 83°19'E, altitude 250 m); 3 – Bachat (54°12'N, 86°10'E, altitude 155 m); 4 – Novokuznetsk (53°43'N, 87°10'E, altitude 250 m); 5 – Kurtak (55°6'N, 91°24'E, altitude 155 m). Legend: 1 – major cities; 2 – studying sites location; 3 – border of the loess deposit distribution.

the complete loess–soil sequence of Siberia (Zykina, 1999; Zykin et al., 2000; Dobretsov et al., 2003). The sequences consist of relatively thick loesses and paleosols that underwent cryogenesis and gleization processes of different intensity (usually low or moderate). It was demonstrated that loess layers of Siberia correspond to relatively cold stages as evidenced by the oxygen isotope curve, Antarctic ice-core dust, and temperature curves and MS of the Chinese loess (Zykina and Zykin, 2003; Dobretsov et al., 2003). Paleosols have been formed during relatively warm interglacial stages and interstadials of the Quaternary.

The chronostratigraphy of the loess–paleosol sequences is based on correlation of the soil types, paleontology, radiocarbon and thermoluminescence dating methods (infrared optically stimulated luminescence (IRSL) and thermoluminescence (TL)) and has been published in numerous Russian and international journals (Zykina et al., 1981, 2000; Volkov and Zykina, 1991; Arkhipov et al., 1995, 1997; Zykina, 1999; Zykina and Zykin, 2003; Zander et al., 2003; Dobretsov et al., 2003; Frechen et al., 2005).

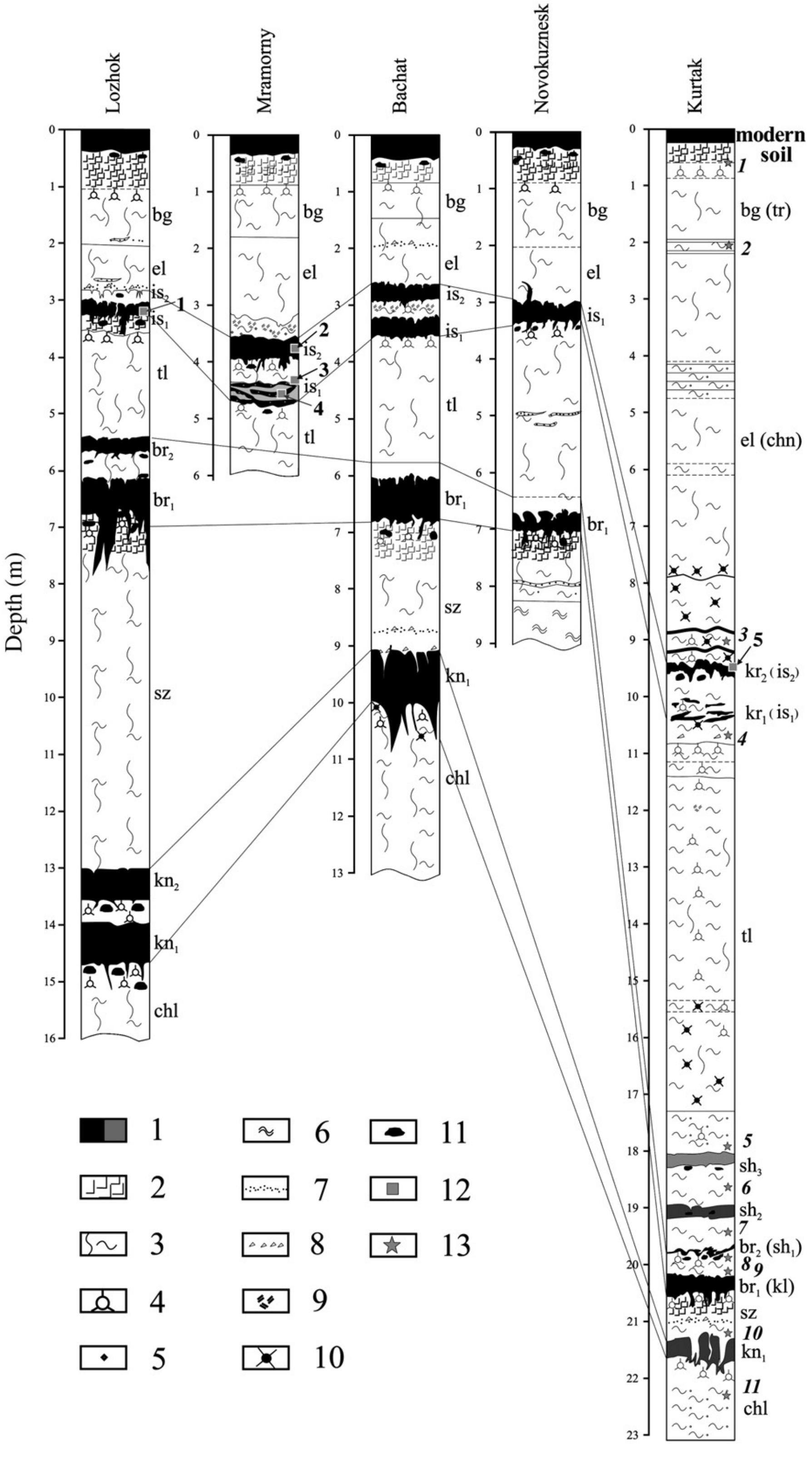
We re-sampled five Siberian (Fig. 1) loess–paleosol sections representing Middle–Late Pleistocene eolian sediments. Two sections are situated in West Siberia (Mramorniy and Lozhok), two in the Kuznetsk depression (Bachat and Novokuznetsk) and one in Central Siberia (Kurtak).

After all five sections were correlated on the basis of soil characteristics and absolute dating (Fig. 2), a composite section was constructed (Fig. 3). The Russian chronostratigraphic scheme considers the Pleistocene as lasting from 780 thousand years ago (Brunhes paleomagnetic chron) and the border between Middle and Upper Pleistocene at the base of oxygen isotope stage (OIS) 5 (Alexeev et al., 1997; Decisions…, 1999). Although the names of stratigraphic intervals vary in different parts of the world and there is a difference in ages of the intervals, the Russian stratigraphic scheme was recently correlated with North-West European scheme (Frechen et al., 2005). Following this correlation we included both N-W European and West and Central Siberian stratigraphic intervals in Fig. 3.

The fossil soils in the selected sections were correlated according to their specific diagnostic features. The morphology of the loess and soil and the microstructure, physical and chemical properties, type of humus and the optical properties of humic acids in the soil horizons have been studied in detail (Zykina et al., 1981, 1999, 2000; Volkov and Zykina, 1991; Arkhipov et al., 1995, 1997; Zander et al., 2003). All fossil soils were compared to their modern counterparts, to provide reliable evidence of the maturity of soil profiles, their duration and type of soil formation (Dobretsov et al., 2003; Frechen et al., 2005). Recent ^{14}C and TL dating enabled those authors to correlate loess layers and soil complexes to the stages of oceanic oxygen isotope stratigraphy (OIS). We considered the pedocomplexes to be marker horizons during construction of our chronological model. Following the stratigraphic scheme published by Frechen et al. (2005) the Koinikha soil complex formed in the latest Middle Pleistocene and is equated to OIS 7; the Berdsk soil complex evolved through OIS 5, and the overlying Iskitim pedocomplex correlates with OIS 3.

The sequence is described from the bottom to the top. The Middle Pleistocene uppermost soil was studied and sampled in Kurtak (Central Siberia) and can be correlated with Koinikha pedocomplex of western Siberia. The Koinikha pedocomplex has been described in Zykin et al. (2000) and has – like Kurtak – a soil profile with humus and illuvial-carbonate horizons with a thickness of ~0.4 m and ~0.35 m containing carbonate nodules and pseudomycelium. Our sampling section in Kurtak contains only one soil horizon, as does another site along the Ob' river; however in the Novosibirsk region the horizon is represented by two very close Chernozem soils. In the Kurtak section, it is represented by the lower dark-chestnut soil (Zander et al., 2003; Frechen et al., 2005). The structure of the soil profile, the microstructure of horizons, and the humate type of humus indicate the Chernozem type of the soils in West Siberia and their chestnut type in Central Siberia. Sub boreal soil-formation during the Koinikha interglacial occurred mostly in steppe and forest-steppe environment and produced thick clayey chernozem and chestnut soils in a moderately warm and wet climate. Compared to their modern counterparts, the Koinikha soils have thicker A horizons. More intense soil formation at the early stage is recorded in a more

Fig. 2. Chrono-stratigraphic correlation of the Upper and Middle Pleistocene loess and paleosoil sequences of the studied sections. Vertical scale is arbitrary. Loess: Bagan (bg); Eltsovka (el); Tulino (tl); Suzun (sz); Chulym (chl). Pedocomplex: Iskitim ($is_{1,2}$); Sukhoy Log (shl_{1-3}); Berdsk ($br_{1,2}$); Koinikha ($kh_{1,2}$). 1 – humus horizon; 2 – Bt horizon; 3 – loess loam; 4 – carbonates; 5 – coal; 6 – clay; 7 – sand; 8 – gravel; 9 – gleying; 10 – Fe–Mn nodules; 11 – krotovinas; 12 – C^{14} ages; 13 – TL and IRSL ages. C^{14} dating: 1 – >30 kyr, 2 – 26.3±0.7 kyr, 3 – 32.78±0.67 kyr, 4 – 33.1±1.6 kyr. Some TL and IRSL dating from Zander et al. (2003): ***1*** – 17.9±2.1 kyr (KUR1); ***2*** – 19.2±1.7 kyr (KUR3); ***3*** – 30.2±2.6 kyr (KUR13); ***4*** – 57.2±6.9 kyr (KUR15); ***5*** – 63±7.2 kyr (KUR38); ***6*** – 62.2±6.3 kyr (KUR23); ***7*** – 87.9±10.9 kyr (KUR22); ***8*** – 107±16 kyr (KUR36); ***9*** – 118±13 kyr (KUR21); ***10*** – 181±23 kyr (KUR19); ***11*** – >200 kyr (KUR18).



Lozhok
Mramorny
Bachat
Novokuznesk
Kurtak
Depth (m)
modern soil
bg
el
is2
is1
tl
br2
br1
sz
kn2
kn1
chl
bg (tr)
el (chn)
kr2 (is2)
kr1 (is1)
sh3
sh2
br2 (sh1)
br1 (kl)
1
2
3
4
5
6
7
8
9
10
11
12
13

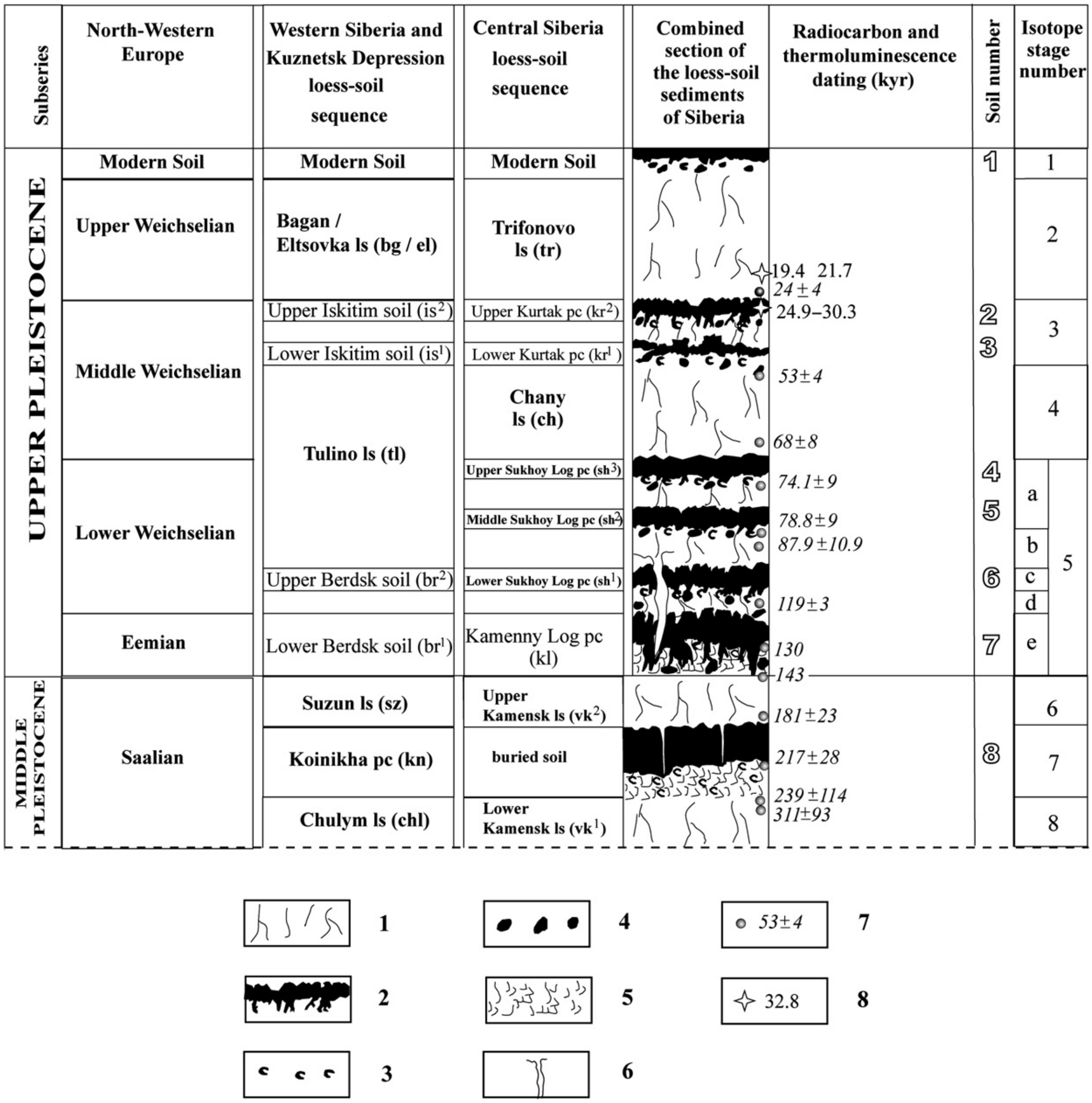


Fig. 3. Stratigraphy and correlation of Middle–Late Pleistocene loess–soil sequences in Western and Central Siberia. 1 – loess loam, 2 – humus horizon, 3 – carbonates, 4 – krotovinas, 5 – illuvial horizon, 6 – cryogenic wedges, 7 – IRSL and TL ages in kyr, 8 – radiocarbon ages in kyr. Abbreviations: ls – loess, pc – pedocomplex (buried soil).

mature and thicker profile of the lower soil. The soil can be easily recognized and correlated in different sections even when separated by hundreds of kilometers.

This soil complex is equated to OIS 7, which was confirmed by TL and IRSL dates from the Kurtak section (Zander et al., 2003; Frechen et al., 2005). Loess above the soil has strong features of denudation in Kurtak. Large grain sand and gravel detritus characterizes the erosional surface. Therefore the thickness of the soil horizon in Kurtak was shortened to ~0.75 m. Koinikha soil has a characteristic profile and was traced and described in other parts of Western Siberia where Suzun loess has a much larger thickness. For instance it is 6m in Lozhok section (the lower half of the loess interval was not excavated at the time of sampling), and 2m in the Bochat section that also has erosional surface (see Fig. 2). The large thickness of loess suggests an extended cold interval (OIS 6) between Koinikha pedocomplex and Lower Berdsk paleosol above.

The lower Berdsk pedocomplex overlies Suzun loess (Figs. 2 and 3) and the first TL dates constrain the age of the soil at 140±14 kyr and 130±10 kyr (Arkhipov et al., 1992, 1997); later successive dating of all Late Pleistocene horizons in the Kurtak section gave an age bracketed between 119±3 and 143kyr (Zander et al., 2003, Frechen et al., 2005), which correlates with OIS 5e. The lower Berdsk soil in all sections has a polygenetic structure and its well developed profile shows two phases of chernozem formation (Zykina et al., 1981; 2000; Volkov, Zykina, 1991; Arkhipov et al., 1995; Zykina and Zykin, 2003; Frechen et al., 2005). Chernozem soils with well defined illuvial horizons formed in automorphic conditions during the first half of the interglacial. Formation of the soil in a wet climate is inferred from a thick humus-accumulation horizon, illuviation cutans in microstructure, organic-clay ooids, and ferruginous and manganese haloes (Zykina et al., 2000; Arkhipov et al., 1995). The chernozem of that interval has a thicker profile and formed in a warmer and wetter climate than the modern variety. The morphotype of the soil is clearly recognizable and can be traced in all sections of western Siberia, the Kuznesk Depression and Central Siberia (Arkhipov et al., 1992, 1995; Zykina et al., 1981). On the basis of TL dating, the horizon corresponds to OIS 5e. The horizon was sampled in four sections (Kurtak, Bochat, Novokuznetsk, and Lozhok).

The Upper Berdsk soil in the Lozhok section and the Lower Sukhoy Log soil in the Kurtak section are immature chernozems. Their microstructure, humate type of organic matter in A horizons and the uniform distribution of basic oxides (R_2O_3) and silt particles along the soil profile indicate soil formation in steppe environments. No chernozem soils similar to their modern counterparts could develop during short formation periods in a strongly continental and dry climate. The absence of polygenetic soils is likewise due to the brevity of the soil formation cycle and stability of temperature and humidity throughout the interstadial.

The two upper soils of the Sukhoy Log pedocomplex are of chestnut type. The reddish color of the upper part of the profiles attests to soil formation in a dry steppe environment where high aridity reduces the productivity of ecosystems, speeds up mineralization of plant waste and, hence, decreases humus accumulation and increases the percentage of fulvic acids in humus. Fulvic and humic acids in humus are in roughly equal percentages or fulvic acids predominate ($C_{ha}/C_{fa} \leq 1$). The microstructure is typical for chestnut soils.

The TL dating in Kurtak places the Lower Sukhoy Log soil into the age interval between 87.9±10.9 kyr (above the soil) and 119±3 kyr (below the soil) (Zander et al., 2003). This time interval corresponds to OIS 5c (Fig. 3). The Upper Berdsk and Lower Sukhoy Log soils have the same morphotype (chernozem), structure, and thickness, and can be correlated throughout Siberia. They are preserved only in the Kurtak and Lozhok sections in the study area. Absence of this horizon in the Bochat and Novokuznetsk sections is most likely caused by deflation (wind erosion) recorded by sand-rich layers with fine debris, which occur above the Lower Berdsk soil. The layers indicate a depositional discontinuity. In general, the climate of all three warm Sukhoy Log intervals was cooler and drier than today's climate.

Other younger paleosol complexes are represented as one soil horizon in western Siberia and Kuznetsk Depression (Upper Berdsk soil) and three soils in the Kurtak section of Central Siberia (Lower Sukhoy Log soil) (Zykin et al., 2000) and consists of two soils in the Lozhok section, one lower soil in the Bachat and Novokuznetsk sections, four soils in the Kurtak section where it is determined as Kamenny Log and Sukhoy Log complexes. The absence of two or three soils from other sections is due to active deflation (wind erosion) that took place in Upper Pleistocene. All sections contain the lower soil of the complex which has the thickest profile and formed during the long last interglacial, called Kazantsevo in Siberia an Eemian in West Europe, in a very warm and wet climate. The three short warm intervals produced specific soils with thin poorly differentiated profiles (A and BC horizons).

The soil profile, thickness and stratigraphic position of the Middle and Upper Sukhoy Log chestnut soils are different from the Lower Sukhoy Log soil (Zykin et al., 2000). They have only been found in the Kurtak section and are not preserved in other sections of western Siberia. The preservation of the soil depends on depositional conditions, and poorly formed soils could be absent because of irregular behavior of regional scale eolian process during relatively weak and short warming. Absolute dating (Zander et al., 2003) indicates that both horizons correspond to OIS 5a (see Fig. 3).

The next younger unit of Siberian loess–paleosol stratigraphy consists of two soils – Lower and Upper Iskitim in western Siberia and Lower and Upper Kurtak in central Siberia. The two soils are separated by relatively thin loam (Fig. 3). The Iskitim (Kurtak) complex occurs everywhere as two soils and is easy to identify in all sections we studied due to its specific morphotypical features. It is preserved to different degrees in different sections depending on their geomorphology. Both soils are immature chernozems with humus (up to 30 cm) and poorly pronounced carbonate-illuvial (up to 35 cm) horizons. The two fossil soils show shorter and less differentiated profiles and shorter formation periods than the modern chernozem. The Iskitim soils show no profile differentiation according to the main components of bulk and grain size compositions, have high contents of Ca-bound humic acids in humus with their high optical density, and a chernozem-like microstructure. Soil formation was associated with moderate humus accumulation and carbonatization (Zykina et al., 1981; 2000; Zykina, 1999; Zykina and Zykin, 2003). The soils of the early pedogenic stage have more mature profiles and more clearly zoned A horizons and bear a signature of illuviation. Burrows and small mammal fossils in both soils belong to dwellers of open spaces of the steppe and forest-steppe zones.

The radiocarbon age of the Iskitim (Kurtak) pedocomplex is between 20 and 33 kyr (Zykin et al., 2003). The TL age just above the Upper Kurtak and below the Lower Kurtak soil is 24±4 kyr and 53±4 kyr respectively (Zander et al., 2003; Frechen et al., 2005). This corresponds to OIS 3. Although the preservation of the Iskitim pedocomplex depends on the geomorphological position of the section, the soils are well recognized and preserved in many loess–paleosol sections of Siberia. The Lower Iskitim soil is preserved at all sites. The Upper Iskitim soil is preserved only in the Kurtak, Bochat and Mramorny sections.

The modern soil of the combined section represents the Holocene warm interval. The soil was sampled in Kurtak and Lozhok. Modern soils in all sections are chernozem varieties formed during OIS 1 upon the Bagan-El'tsovka loess (OIS 2). The Bagan loess deposition occurred in a very dry climate (Volkov and Zykina, 1993).

For further convenience we named the paleosol horizons from the most recent (horizon 1) to the oldest one (horizon 8) in the composite Siberian section (Fig. 3). These numbers are used for marking the soil horizons in further figures. The Kurtak section is most representative and includes all soil horizons found in the other sections.

3. Methods

Overall, 670 oriented samples were taken in 5 and 8 cm^3 plastic non-magnetic boxes at 5−30 cm intervals from the 5 geological sections. The magnetic property measurements were made in the paleomagnetic laboratory of the Physics Department of the University of Alberta.

The natural remnant magnetization (NRM) of the samples was measured on a Molspin magnetometer. Samples were step-wise demagnetized in alternating fields (AF) up to 100 mT in 14 or 16 steps. The temperature dependence of magnetic susceptibility from room temperature to 700°C was measured with the Bartington Susceptibility/Temperature System in air. The isothermal remnant magnetization (IRM) was measured on six pilot samples from different soil and loess horizons to verify the nature of magnetic minerals.

Mass specific magnetic susceptibility was measured at two frequencies with a Bartington Instruments susceptibility meter at low-frequency (0.465 kHz) and high-frequency (4.65 kHz). The frequency dependency of magnetic susceptibility (FD) was calculated in percent. A number of special precautions have been taken during FD measurements to suppress the usually quite high noise level of the Bartington instrument. First of all every sample has been measured at least 3 times in different positions and the average has been taken as a value used in all further figures. All three measurements were fairly consistent and there were no unusually high errors. FD value was calculated from the average low- and high frequency MS value for every sample. FD data for Chinese loess is commonly greater than 5% (Evans and Heller, 2003). Chlachula et al. (1998) demonstrated that FD does not usually exceed 2% for the Kurtak site. In our study we measured the samples following Chlachula et al. (1998) recommendations with extra care during the evenings when the electromagnetic noise was lowest in the lab. The instrumental drift was also monitored and eliminated by taking 'air' readings before and after each sample measurement.

4. Results and Discussion

The results of AF demagnetization enabled us to separate a stable normal polarity component usually starting from 5 to 20 mT. The demagnetization results demonstrate that all samples are from the Brunhes normal polarity chron. This is in agreement with the absolute dating.

Detailed petromagnetic analysis of Siberian loess and paleosol samples from the sections discussed in this study has been done before (Matasova and Kazansky, 2004; Chlachula et al., 1998; Matasova et al., 2001; Zhu et al., 2003). Those studies illustrated that the dominant magnetic mineral in loess and soil is magnetite (mostly multidomain). Maghemite and hematite are also present in relatively small amount in both soil and loess horizons. We conducted our own IRM measurements and measurements of the temperature-dependent MS on different soil and loess samples. Our measurements from every section reproduced earlier published results and are not discussed further in this paper.

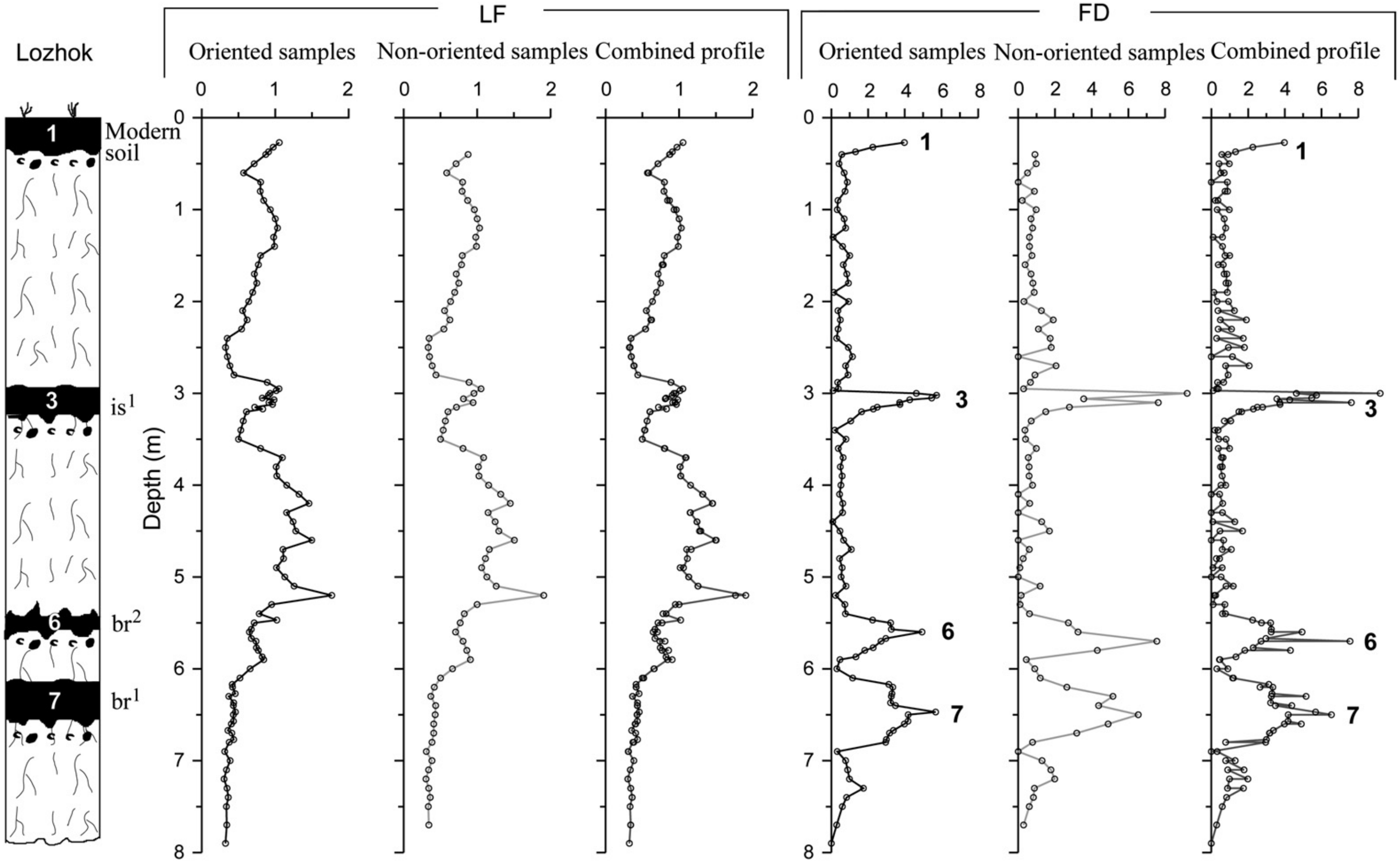


Fig. 4. Simplified profile of lithology and magnetic parameters for Lozhok section. LF – mass-specific low field magnetic susceptibility in (10^{-6} m^3 kg^{-1}), FD – the frequency dependence parameter (FD in % is determined as $FD=100*(\chi_{LF}-\chi_{HF})/\chi_{LF}$, where χ_{LF} (χ_{HF}) is low-frequency (high frequency) mass-specific magnetic susceptibility). Index near each soil means the soil horizon that corresponds to the stratigraphic column in Fig. 3. is^1 – Lower Iskitim soil; br^1 and br^2 – Lower and Upper Berdsk soils.

Fig. 4 demonstrates MS and FD measurement for two sets of samples, oriented and non-oriented, for the same section Lozhok. Non-oriented samples have been sampled in parallel profile that was made along the same wall ~10 cm away from the profile with the oriented samples. Some of non-oriented samples were sampled between oriented samples to fill in depth gaps and to make the sampling more continuous. The figure illustrates that oriented and non-oriented sample profiles have identical shape and magnitude of MS and FD. It is seen that soil horizons 1 and 3 have both high magnetic susceptibility and frequency dependence. In contrast soils 6 and 7 do not demonstrate any specific features on the MS plot but are very distinguished in the plot of FD parameter. Both data sets have been combined for further analysis in this paper.

In the next site, Novokuznetsk, two different cross-sections that were separated by ~120 m from each other (Fig. 5) on different slopes of the river terrace have been sampled. Soil 3 could be visually traced from one section to another in the field. Higher FD values for the soil 3 (4%) are distinguished from relatively lower values for loess above and below the soil (1%) although some noise is still present in both records. In contrast MS measurements for both sections do not demonstrate any correlation. Soil 7 has a high FD parameter (between 4 and 6%) but does not exhibit any MS variation between soil and loess. Loess below soil 7 has higher MS and the sandy layer of the fluvial origin at depth 7.8m has higher MS than does the loess.

We performed especially detailed sampling of the soil horizons on Kurtak site because it has recently been dated by thermoluminescence methods (Zander et al., 2003). The soil horizons were slightly thicker in our sampling sections than in Chlachula et al. (1998) and that enabled us to construct a profile with higher resolution. Our sampling took place about 150m from the sampling section published by Chlachula et al. (1998). Fig. 6 illustrates that in our study oriented and non-oriented sample profiles have identical features in MS and FD

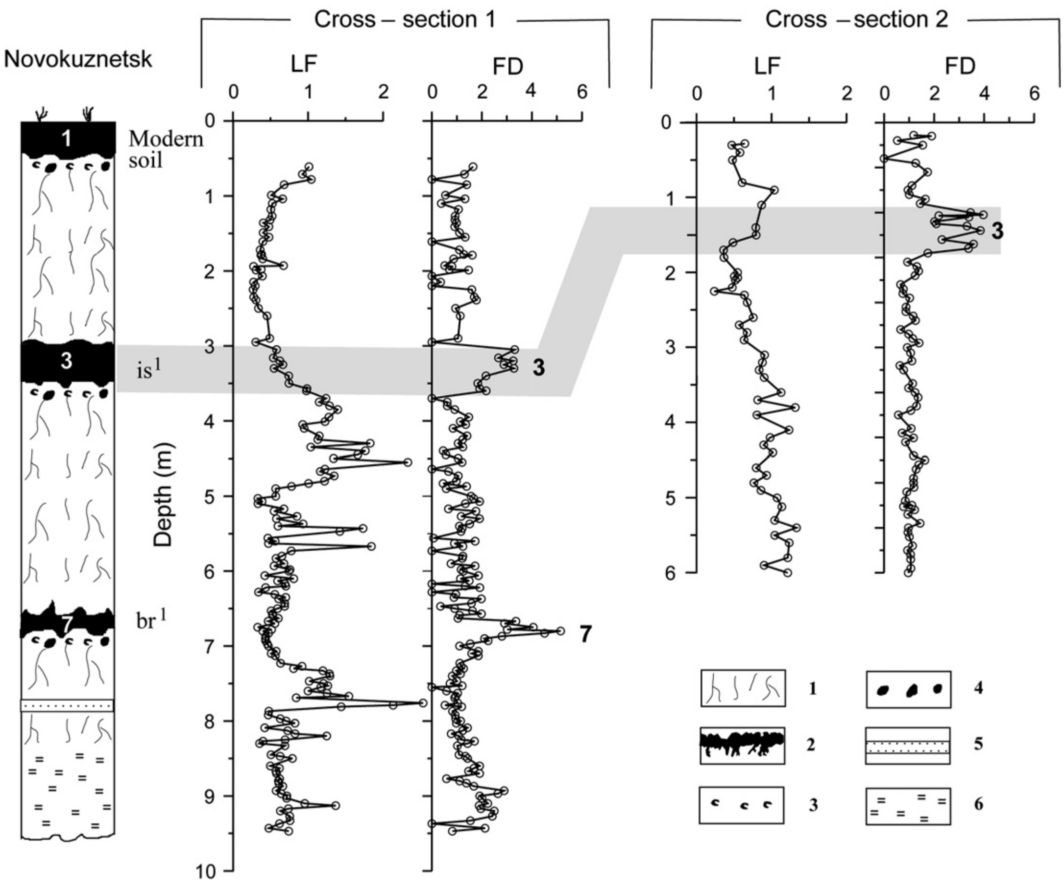


Fig. 5. Simplified profile of lithology and magnetic parameters for two cross-sections at the Novokuznetsk site. Same abbreviations as in Fig. 4. 1 – loess loam, 2 – humus horizon, 3 – krotovinas, 4 – illuvial horizon, 5 – sand, 6 – alluvium.

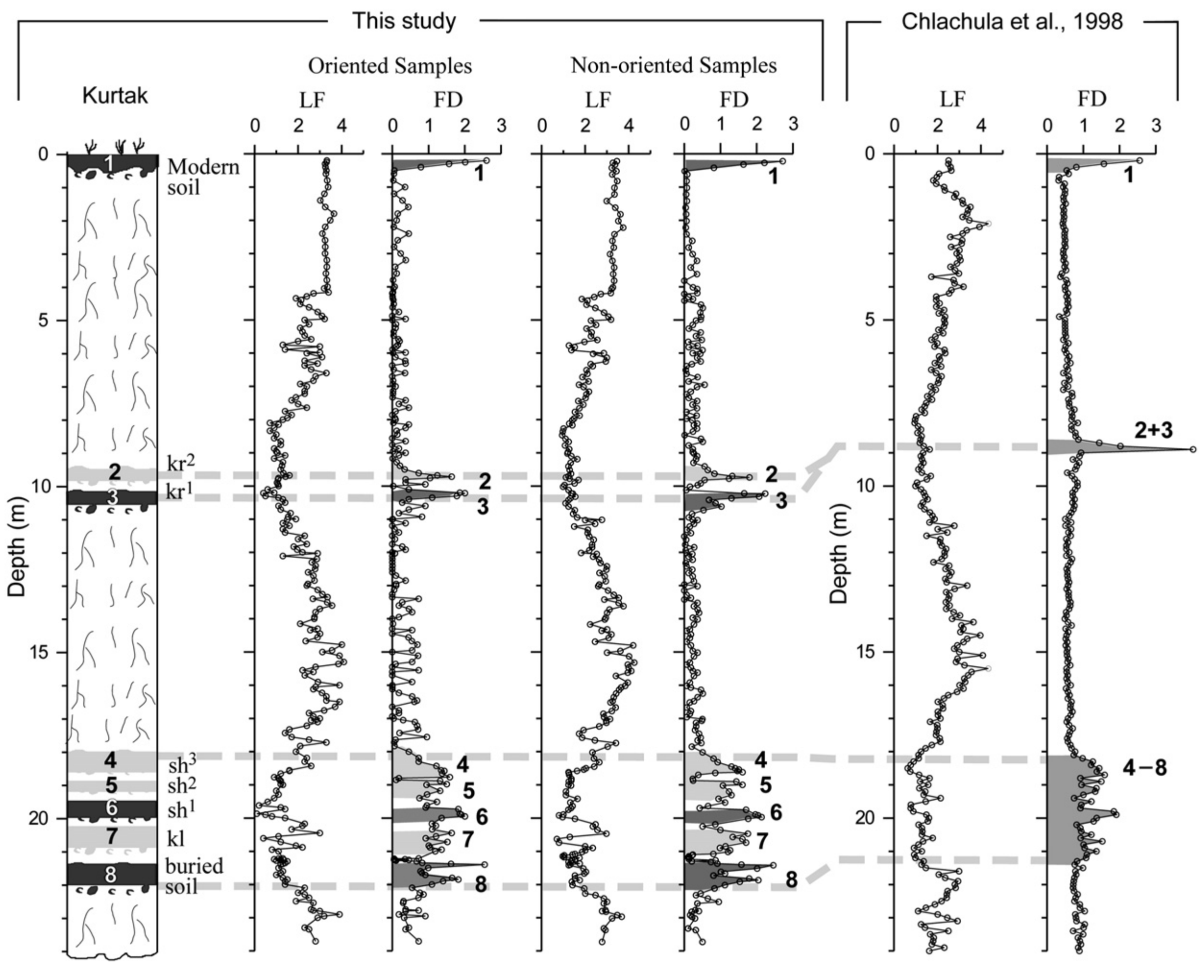


Fig. 6. Simplified profile of lithology and comparison of magnetic parameters for oriented and non-oriented sample profiles with magnetic parameters from Chlachula et al. (1998) at the Kurtak site. Same abbreviations as in Fig. 4. Index near each soil means the soil horizon that corresponds to the stratigraphic column in Fig. 3: kr^1 and kr^2 – Upper and Lower Kurtak soils; sh^1, sh^2, and sh^3 – Lower, Middle, and Upper Sukhoy Log soils, kl – Kammeny Log soil.

plots and are very similar to Fig. 1 in Chlachula et al. (1998). It is clear that MS is in general lower for the soil horizons and higher for loess; that supports the conclusion of Chlachula et al. (1998) about stronger winds in Kurtak area (Central Siberia) that transported dense magnetite from distant parent sources during colder periods. The minima of the MS values correlates with the soil intervals in both oriented and non-oriented sample cross-sections but do not show every soil horizon adequately. In particular soil 3 has low MS values but soil 2 is not visible in the MS profile. The FD variations, however, demonstrate visible correlation with every particular soil horizon. Both oriented and non-oriented sample profiles correlate perfectly between each other and there is general correspondence with FD profile of Chlachula et al. (1998).

Fig. 7 represents low-frequency MS measurements and calculated FD parameters for all sections together. For illustrative purpose we compared the measurements from other sections with the most complete Kurtak stratigraphic column using same numbering of the soil horizons as in Fig. 3. The comparison between sections was carried out on the basis of IRSL, TL and C^{14} ages and mammal faunas, and the correlation of the same soil types by stratigraphic position, composition, structure and color (Zykina et al., 1981; Arkhipov et al., 1995; Zykina and Zykin, 2003; Zykin et al., 2000, 2003; Zander et al., 2003).

Fig. 7 demonstrates that MS does not always correlate with the soil horizons. In many cases, MS does not vary in the soil horizons at all. The lack of correlation between soil intervals and MS values in

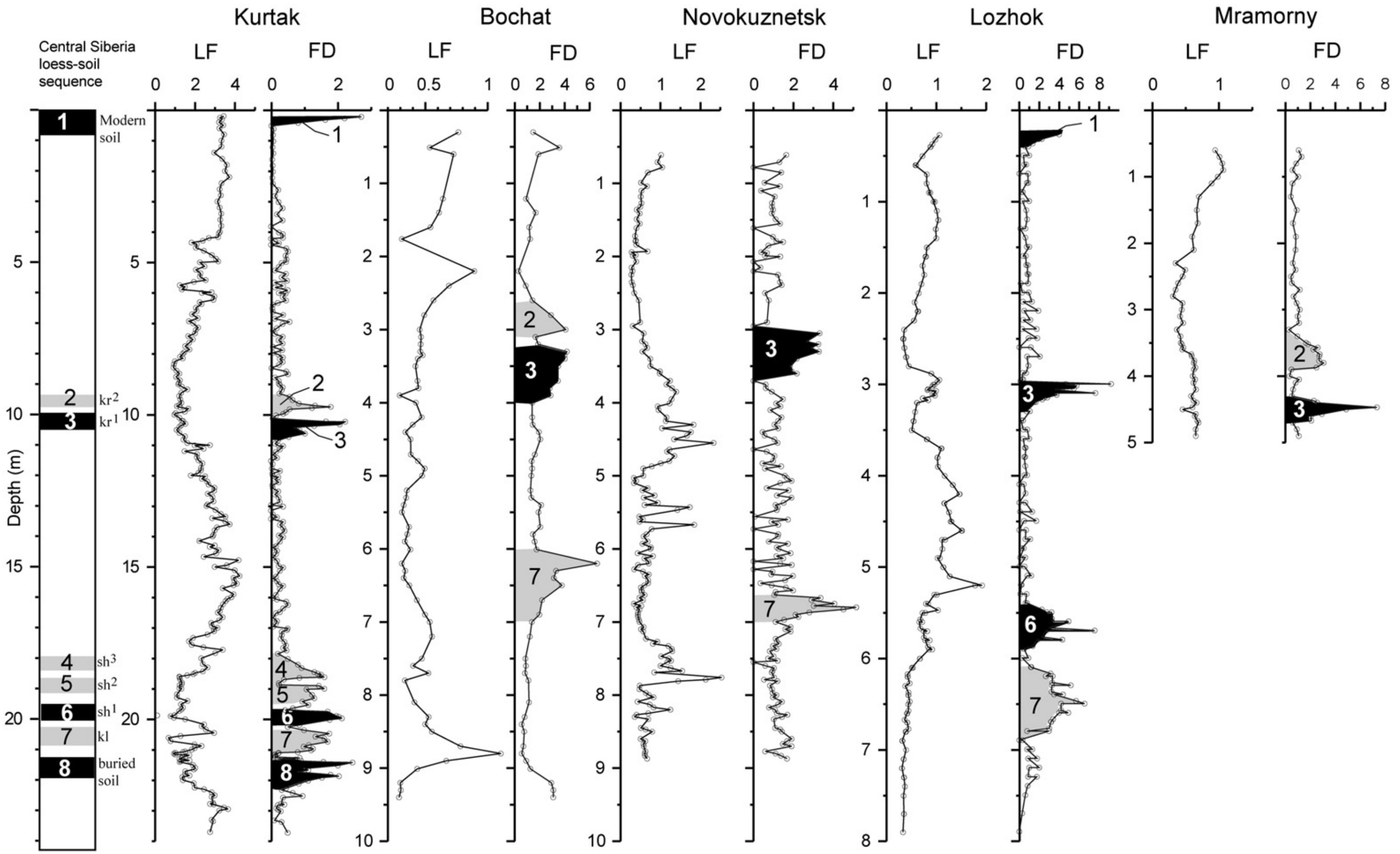


Fig. 7. Composite lithology in Central Siberian loess–paleosol sequence (Kurtak section) and magnetic parameters for all five studied sections. Numbers in the lithology column and on magnetic parameter profiles indicate Kurtak soils from the top. Indexes indicate Kurtak soils. LF – mass-specific low field magnetic susceptibility in (10^{-6} m^3kg^{-1}), FD – the frequency dependence parameter (FD in % is determined as $FD = 100*(\chi_{LF} - \chi_{HF})/\chi_{LF}$, where χ_{LF} (χ_{HF}) is low-frequency (high frequency) mass-specific magnetic susceptibility). Same index near each soil as in Fig. 6.

Siberian loess–paleosol sequences can be explained by different processes that took place during the soil formation. Maher (1998) reviewed a variety of processes that may lead to the enhancement or depletion of the magnetic signal in soils. Enhancement is common in well-aerated surface soils (like in China), while gleying, acidification and podzolisation cause MS to decrease by destroying original magnetic minerals and/or by limiting the formation of secondary ferrimagnetics. Magnetic minerals in soils may originate from the parent sediment (loess in our case) and be produced during processes of the soil formation. Newly produced magnetite can be biogenic or inorganic by genesis and have very small particle size (single domain or pseudo single domain magnetite). It is possible to distinguish between primary and secondary ferrimagnetics by measuring FD parameter, which increases sharply as the particle size drops below ~30 nm (Mullins, 1977; Maher, 1998).

One of the most common complexities obscuring correspondence between paleosols and magnetic susceptibility is gleization. Gleization is a soil-forming process, caused by poor drainage conditions, which results in the reduction of iron, and other elements and in gray coloration, and mottling. Gleization is primary dependent on local topography and occurs in the flat areas or in the depressions even if they are small. It was found that gleying decreases the susceptibility values about two times in the North American Great Plains (Rousseau and Kukla, 1994). For one reported section in the Ukraine the decrease was about three times (Nawrocki et al., 1996).

Gleization can occur with different intensity in different geological conditions, which is important reason for the variation in susceptibility. Feng and Khosbayar (2004) reported MS values for soil intervals in two North Mongolian sections of ~20 kyr age. Lower MS indicated the gleyed layers in one section and had no specific correspondence with soils in another section situated ~270 km away. MS demonstrated a negative correlation of the susceptibility with higher silt percentage and organic matter content in soils. de Jong et al. (2005) demonstrated that in general MS of the coarser fractions was larger than MS of the clay fractions for both Gleysolic and Chernozemic soils. Feng and Khosbayar (2004) proposed that reducing conditions of studied soil development contributed to the alteration of magnetic minerals from strongly magnetic forms to weakly magnetic forms and was an indicator of redox cycles in North Mongolian soils.

Grimley et al. (2004) reported high degree reductive dissolution of detrital magnetite and maghemite (aided by microorganisms) in the modern hydric soils (soils that are sufficiently wet in the upper part to develop anaerobic conditions) of the Midwestern USA that led to the lower MS values. They have also found that the newly formed ultra fine ferrimagnetics, however, gave always higher FD values (5–10%) for such soils. Maher (1998) speculated that soils with near neutral pH (5.6–7.8) are the most prone to ultra fine ferrimagnetic formation.

A number of processes could enhance or deplete the MS signal at different Siberian sites and at different times. Matasova and Kazansky (2004) attempted to explain these differences with variable strength of the wind and parent material composition rather than with effect of gleization. The FD parameter is however always enhanced in the paleosol horizons relative to the loess horizons at all studied sites. This indicates that the larger number of ultra fine superparamagnetic ferromagnetic minerals is a result of in-situ bacteria production and chemical processes occurring in the soil (Evans and Heller, 2003) and is not a function of stronger wind or type of the transported material. Probably the low value of FD in Siberian loess–soil sequences (2–6%) compared to China (5–10%) is a result of local relatively wet conditions that led to partial destruction of the magnetic minerals including ultra fine particles. That could cause reduction of MS and FD signals.

So-called 'stagnic properties' of gleyic soil come from water stagnation at shallow depth, resulting in seasonal water saturation of the surface soil (van Breemen, 2002). While iron oxides, including superparamagnetic particles, dissolve in reduction conditions caused by gleization, living bacteria are still producing new tiny magnetite particles keeping FD number relatively high (enough to be measurable with the Bartington) (Grimley et al., 2004). Stanjek et al. (1994) also described biogenic greigite (iron sulphide) in the soil that has superparamagnetic properties and therefore may be an additional factor for the FD signal in soil.

Distinction between superparamagnetic magnetite and greigite in the soil requires special studies that might be a subject for future work. However relatively high FD in all studied paleosols confirms continued production of superparamagnetic particles, most likely of biogenic origin, during the soil formation (interglacial interval) even when MS signal caused by terrigenic magnetite is notably reduced.

We marked every FD parameter peak with a number that corresponds to the eight soils of the Kurtak section. (Zykin et al., 2003) demonstrated that the soil horizons are indicators of relatively warm and wet climate. Thus we can apply the FD parameter as a climatic proxy for

Siberian sections where the MS record does not reflect paleoclimatic changes conspicuously.

Chlachula et al. (1998) compared Kurtak's record with North Pacific eolian dust flux and reported a visible paleoclimate proxy link between continental and oceanic record. Following this approach we attempted to carry out the frequency analysis of the FD record in order to identify Milankovitch periodicities and thus to establish quantitative link between Siberian loess record and global climate records.

Although Kurtak is the most representative section, the rate of the eolian material accumulation varies significantly along the section. Using the stratigraphic and age model built by Frechen et al. (2005) one can see that the accumulation of the loess was one order faster during the last ~100 kyr (from 20 to 30 cm/kyr for upper ~20 m). The sedimentation rate for the older time interval (between ~100 and ~300 kyr) is 1–2 cm/kyr (lower 5 m of the Kurtak section). The difference can be explained by partial eolian denudation of the sediments to some extent. Another reason could be a change of the general and local wind direction and its strength and the source of eolian material. Paleorelief also could play important role in the rate of loess accumulation (better preservation of loess in little depressions than on heights). Frechen et al. (2005) demonstrated that dramatic changes took place before Kamenny Log soil formation (see their Fig. 3). As a result during conversion of depth to age we have higher resolution for the upper part of the section than for the lower one. We assigned different ages to different depths based on Zander et al. (2003) and Frechen et al. (2005) absolute dating and then interpolated ages linearly between these tie points.

In order to proceed further with the frequency analysis we also correlated and then stacked all five FD records from the studied sections into a combined record. We converted depths into time for every section individually, applying all available age data discussed above (Zykin et al., 2000; Zander et al., 2003). Tuning to any reference curve was not applied. Sedimentation rates are quite variable for the sections and, first of all, we correlated top and bottom of every soil layer between sections. After that we "stretched" the loess horizons between soils in terms of time. If we had any information on denudation process and interruption in the sedimentation process we applied a time break in the record. For example we have two Berdsk soils in Lozhok section and only one in Bachat as a result of eolian denudation. We had to cut out the time interval that corresponds to the second Berdsk soil accumulation period. All sections were compared to the Kurtak section that has many dated horizons.

Then the sections were combined by putting their FD data on a common age scale by linear interpolation between the correlation points and averaging the two values whenever their ages were identical. The resulting curve was smoothed by the least squares method and then resampled at 0.5kyr equal intervals.

Next the stacked FD record for loess–paleosol sections was compared to other global and regional paleoclimatic records (Fig. 8). The most complete paleoclimatic records in the North Asian region are MS (Kravchinsky et al., 2007) and biogenic silica (Prokopenko et al., 2001; Colman et al., 1999) records from Lake Baikal. The Baikal records are at about the same latitude as our sections (~52°N).

As was shown in earlier Lake Baikal studies, MS has a strong inverse correlation with biogenic silica variations (King et al., 1993; Peck et al., 1994). Diatomaceous organisms that produce biogenic silica are more productive during warmer climatic conditions, and the concentration of biogenic silica is thus higher in interglacial intervals than in the intervening colder glacial intervals. Because silica is diamagnetic, the observed susceptibility values are lower during relatively warm intervals when more biosilica is produced. That leads to the inverse correlation between the biosilica content and the MS of the lake sediments. Visible correlation of major features between the FD parameter and Baikal climatic records is illustrated in Fig. 8.

The FD parameter profile and correlates well with the oceanic oxygen isotope record from MD900963 (Bassinot et al., 1994) (Fig. 8). Soil 1 corresponds to the interglacial stage 1, soils 2 and 3 to stage 3, soils 4 to 7 to stage 5, and two peaks of the soil 8 to stage 7.

The FD parameter record was further compared to the Southern Baikal latitude (52°N) insolation curve calculated from Lascar's solution (Laskar, 1990). The insolation curve was used to calculate the insolation signal frequency and to compare it with the Siberian loess frequency. The comparison of MD900963 and solar radiation curves shows the well-known shift of the curves at about 10kyr (Fig. 8).

For comparison of global and continental records, we performed spectral analysis on the FD parameter, MS and biogenic silica from Lake Baikal, oxygen isotope data from MD900963, and solar radiation (Fig. 9). Power spectra were calculated by the Blackman–Tukey method (Blackman and Tukey, 1958) with a Bartlett window. The entire procedure follows that described by Paillard et al. (1996) and uses their software.

Fig. 9 illustrates the power spectrum for the entire 280 kyr dataset (oceanic oxygen isotope, insolation, MS

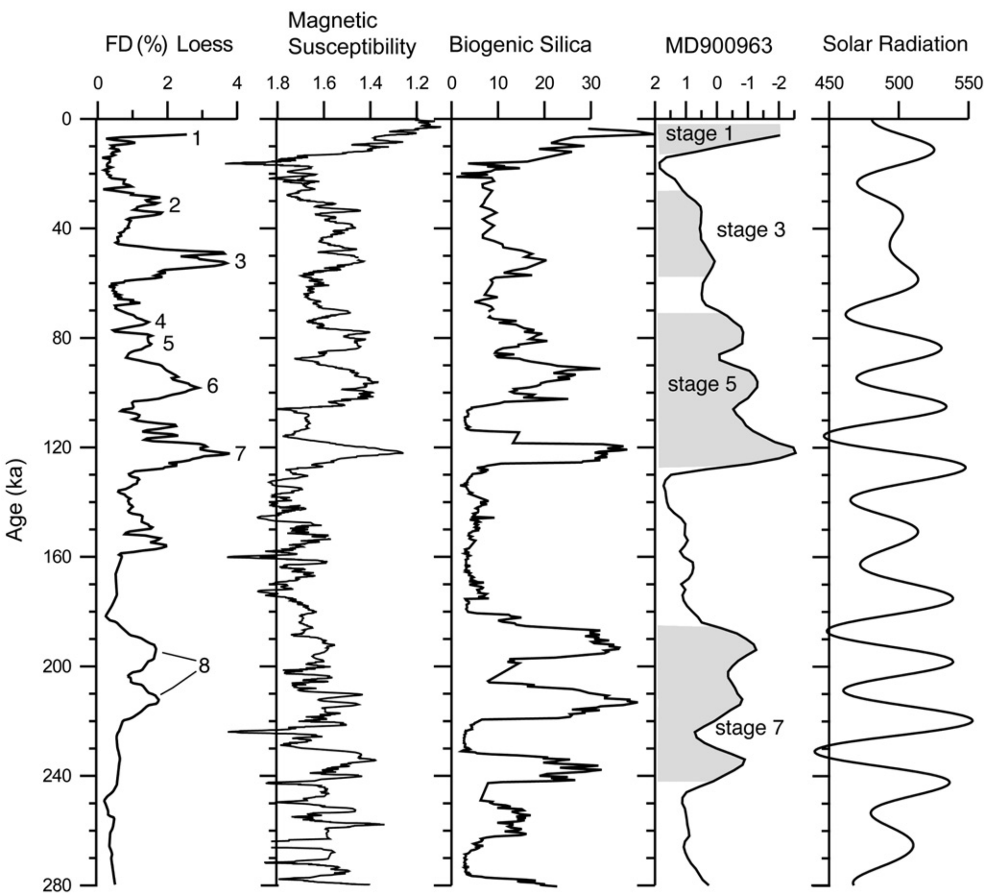


Fig. 8. Correlation between FD parameter for Siberian loess (non-oriented sample profile is shown for simplicity), whole-core combined magnetic susceptibility profile for Baikal cores BDP-93-1 and BDP-93-2 in 10^{-5} SI unites (Kravchinsky et al., 2007), biogenic silica profile from BDP-96-2 (Prokopenko et al., 2001) is completed by BDP-93-2 core for the last 60 kyr in wt.% (Colman et al., 1999), δO^{18} oxygen isotope curve from MD900963 (Bassinot et al., 1994), and Solar Radiation curve for 52°N calculated from Lascar's solution (Laskar, 1990). Logarithm of the magnetic susceptibility is plotted. Note reversal scales for magnetic susceptibility and oxygen isotope curve.

and biogenic silica from Lake Baikal, and FD parameter for the combined section). MS and FD frequency graphs had a visible linear trend and were detrended to highlight acquired periodicities. The Milankovitch peak at ~100 kyr (eccentricity) is clearly visible for the oxygen isotope records and can be identified for all Siberian records (the biogenic silica and MS in the Baikal record and Siberian loess FD parameter record). Two peaks, ~40 kyr (obliquity) and ~23 (precession) can be seen in all records. The 40 kyr peak is slightly shifted for the Siberian loess combined FD record and for the biogenic silica record in Baikal to the frequency ~0.028 cycles/kyr (or ~35 kyr period) although it is not shifted in MS Baikal record. All Baikal records contain one additional 29 kyr non-Milankovitch period for longer than 300 kyr datasets (Kravchinsky et al., 2007). Although we cannot clearly observe 29 kyr period in our 280 kyr records, the overlapping of 40 and 29 kyr periods could probably influence the shifting of the 40 kyr period.

It is well known that the oceanic and solar radiation time series do not exhibit a similar progression in the spectral domain for the last ~ million years. The ~100 kyr peak amplitude dominates the oxygen isotope curve, and the ~23 kyr peak dominates the solar radiation record (Hinnov, 2000). The 100 kyr eccentricity peak is not recognizable in the insolation curve during the last 280 kyr.

Lake Baikal and Siberian loess sequences are centered in the region of north-central Eurasia where energy balance modeling (Short et al., 1991) has suggested that the seasonally dominated precession signal should have its greatest impact on glacial–interglacial temperature changes for the last 800 kyr. We therefore expected that precession forcing at the 23 kyr band would be much larger than at the 40 kyr obliquity and 100 kyr eccentricity bands. Indeed, the precession

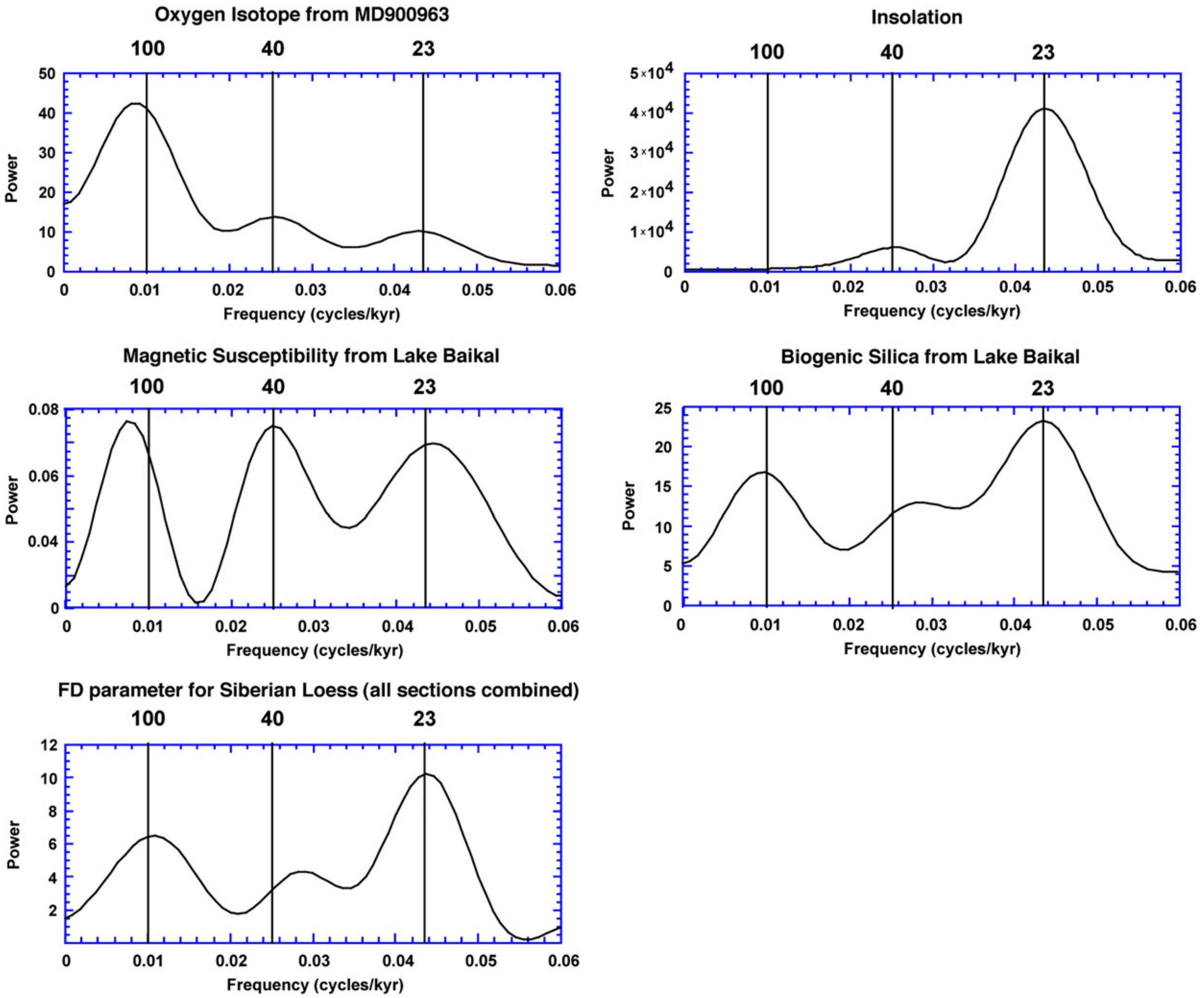


Fig. 9. Spectral analysis of the 280 kyr δO[18] oxygen isotope curve from MD900963 (data from Bassinot et al., 1994), insolation curve for 52°N (data from Laskar's solution (Laskar, 1990), stacked magnetic susceptibility record from Lake Baikal (data from Kravchinsky et al., 2007), BDP-93-2 biogenic silica record (data from Prokopenko et al., 2001; Colman et al., 1999), FD parameter for Siberian loess stacked record for all five sections. The analysis was performed using a 1-kyr step, signal band-width of 0.018, and 420 lags. The confidence interval at the 90% level is given by relation $0.55 < \Delta P/P < 2.54$ for all graphs. Vertical lines indicate the orbital (Milankovitch) periodicities (in kyr).

signal appears to have relatively high power amplitude in the spectral evolution of climate in the lake Baikal record (both MS and biosilica records) during the last 280 kyr period. Nevertheless 100 kyr period has high power amplitude in both Baikal and loess records. This supports the notion that the predicted summer temperature model (Short et al., 1991) and the insolation power spectra calculated from Laskar's solution with strong eccentricity peak play an important but not dominant role in the continental climate evolution. Probably we have the case of mixture of both types of spectra with high amplitude eccentricity (oceanic record) and high amplitude precession (insolation) in Siberian continental records for the last 280 kyr.

5. Conclusion

Our results, therefore, support the idea that climate over north-central Asia, which is one of the most continental areas of the world, responded to the global climatic changes, even though the studied localities are situated thousands of kilometers from the best paleoclimatic records: the Atlantic Ocean, the Chinese Loess Plateau and Lake Baikal. This response corresponds to the power spectra amplitudes for the continental interior and global data sets. The obliquity with ~100 kyr period still has strong influence at our datasets like in the oceanic record, at the same time the precession is much more pronounced. The FD high-resolution profiles of the loess–paleosol sections can be used as one more quantitative proxy to study the periodicity of climatic variability encoded in the geologic record.

Acknowledgements

The study was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Russian Foundation for Basic Research (Projects #07-05-01109). The paper benefited from the helpful comments and suggestions of F. Lagroix, N. Rutter, M. Lema and E. Nyland. We thank T. Lippiatt, R. Hansen and M. Cannon for their help in the laboratory.

References

Alexeev, M.N., Borisov, B.A., Velichko, A.A., Gladenkov, Yu.B., Lavrushin, Yu.A., Shik, S.M., 1997. The Quaternary stratigraphic scale. Stratigr. Geol. Correl. 5, 105–108 (In Russian).

Arkhipov, S.A., Gnibidenko, Z.N., Zykina, V.S., Krukover, A.A., Shelkoplyas, W.N., 1992. Geological structure and general strategy of chronological study of Kurtak archaeological region. In: Arkhipov, S.A. (Ed.), Palaeoecology and Settlement of Early Man in Northern Asia and America. Siberian Branch of Russian Acad. Sci., Krasnoyarsk, pp. 10–14 (In Russian).

Arkhipov, S.A., Volkova, V.S., Zykina, V.S., Bakhareva, V.A., Gus'kov, S.A., Levchuk, L.K., 1995. Natural and climatic changes in West Siberia during the first third of the next century. Russ. Geol. Geophys. 36, 48–68 (In Russian).

Arkhipov, S.A., Zykina, V.S., Krukover, A.A., Gnibidenko, Z.N., Shelkoplyas, V.N., 1997. Stratigraphy and palaeomagnetism of glacial and loess–soil deposits on the West Siberian Plain. Russ. Geol. Geophys. 38 (6), 1065–1085 (In Russian).

Bassinot, F.C., Labeyrie, L.D., Vincent, E., Quidelleur, X., Shackelton, N.J., Lancelot, Y., 1994. The astronomical theory of climate and the age of the Brunhes–Matuyama magnetic reversal. Earth Planet. Sci. Lett. 126, 91–108.

Begét, J.E., Stone, D.B., Hawkins, D.B., 1990. Paleoclimatic forcing of magnetic susceptibility variations in Alaskan loess during the late Quaternary. Geology 18, 40–43.

Evans, M.E., Heller, F., 2003. Environmental Magnetism: Principles and Applications of Enviromagnetics, Elsevier Science, Academic Press.

Blackman, R.B., Tukey, J.W., 1958. The Measurement of Power Spectra from the Point of View of Communication Engineering. Dover, New York.

Chlachula, J., Evans, M.E., Rutter, N.W., 1998. A magnetic investigation of a Late Quaternary loess/palaeosol record in Siberia. Geophys. J. Int. 132, 128–132.

Colman, S.M., Peck, J.A., Hatton, J., Karabanov, E.B., King, J.W., 1999. Biogenic silica records from the BDP93 drill site and adjacent areas of the Selenga Delta, Lake Baikal, Siberia. J. Paleolimnol. 21, 9–17.

Decisions of the Interdepartmental Stratigraphic Working Group Meeting on Quaternary period of West-Siberian plain, 1999. United Institute of Geology and Geophysics. Siberian Branch of Russian Acad. Sci., Novosibirsk.

de Jong, E., Heck, R.J., Ponomarenko, E.V., 2005. Magnetic susceptibility of soil separates of Gleysolic and Chernozemic soils. Can. J. Soil Sci. 85, 233–244.

Dobretsov, N.L., Zykin, V.S., Zykina, V.S., 2003. Structure of the loess–soil sequence of West Siberian Pleistocene and its correlation with Baikal and global climate records. Dokl. (Reports) Russ. Acad. 391 (6), 821–824 (In Russian).

Feng, Z.D., Khosbayar, P., 2004. Paleosubarctic Eolian environments along the southern margin of the North American Icesheet and the southern margin of Siberia during the Last Glacial Maximum. Palaeogeogr. Palaeoclimatol. Palaeoecol. 212, 265–275.

Frechen, M., Zander, A., Zykina, V., Boenigk, W., 2005. The loess record from the section at Kurtak in Middle Siberia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 228, 228–244.

Grimley, D.A., Arruda, N.K., Bramstedt, M.W., 2004. Using magnetic susceptibility to facilitate more rapid, reproducible and precise delineation of hydric soils in the midwestern USA. Catena 58, 183–213.

Hinnov, L.A., 2000. New perspectives on orbitally forced stratigraphy. Annu. Rev. Earth Planet. Sci. 28, 419–475.

Kazansky, A.Yu., Kravchinsky, V.A., Zykina, V.S., Matasova, G.G., Metelkin, D.V., 1998. The applicability of magnetic methods for revealing of climatic signal in loess–soil sequences of Siberia. In: Derevyanko, A.P. (Ed.), Problems of climatic and environmental reconstructions in Holocene and Pleistocene in Siberia. Publ. House of Russian Academy of Science, Siberian Branch, OIGGM, pp. 191–202 (In Russian).

King, J.W., Peck, J.A., Gangemi, P., Kravchinsky, V.A., 1993. Paleomagnetic and rock-magnetic studies of Lake Baikal. Russ. Geol. Geophys. 34, 174–192 (In Russian).

Kravchinsky, V.A., Evans, M.E., Peck, J.A., Sakai, H., Krainov, M.A., King, J.W., Kuzmin, M.I., 2007. A 640 kyr geomagnetic and paleoclimatic record from Lake Baikal sediments. Geophys. J. Int. 101, 101–116.

Kukla, G.F., Heller, F., Ming, L.X., Chung, X.T., Sheng, L.T., Sheng, A.Z., 1988. Pleistocene climates in China dated by magnetic susceptibility. Geology 16, 811–814.

Laskar, J., 1990. The chaotic motion of the solar system: a numerical estimate of the size of the chaotic zones. Icarus 88, 266–291.

Matasova, G.G., Kazansky, A.Y., Zykina, V.S., 2003. Superposition of Alaskan and Chinese models of paleoclimate records in magnetic properties of Upper and Middle Neopleistocene deposits in southern West Siberia. Russ. Geol. Geophys. 44, 638–651.

Matasova, G.G., Kazansky, A.Yu., 2004. Magnetic properties and magnetic fabrics of Pleistocene loess/palaeosol deposits along west-central Siberian transect and their palaeoclimatic implications. In: Martin-Hernandez, F., Luneburg, C.M., Aubourg, C., Jackson, M. (Eds.), Magnetic Fabric: Methods and Applications. Geological Society, London, pp. 145–173. Special Publications, 238.

Matasova, G., Petrovsky, E., Jordanova, N., Zykina, V., Kapicka, A., 2001. Magnetic study of Late Pleistocene loess/palaeosol sections from Siberia: palaeoenvironmental implications. Geophys. J. Int. 147, 367–380.

Nawrocki, J., Wojcik, A., Bogucki, A., 1996. The magnetic susceptibility record in the Polish and western Ukranian loess–paleosol sequences conditioned by paleoclimate. Boreas 25, 161–169.

Maher, B.A., 1998. Magnetic properties of modern soils and Quaternary loessic paleosols: paleoclimatic implications. Paleogeogr. Paleoclimatol. Paleoecol. 137, 25–54.

Mullins, C.E., 1977. Magnetic susceptibility of soil and its significance in soil science – a review. J. Soil Sci. 28, 223–246.

Peck, J.A., King, J.W., Colman, S.M., Kravchinsky, V.A., 1994. A rock-magnetic record from Lake Baikal, Siberia: evidence for Late Quaternary climate change. Earth Planet. Sci. Lett. 122, 221–238.

Paillard, D., Labeyrie, L., Yiou, P., 1996. Macintosh program performs time-series analysis. Eos Trans. AGU, 77, 379.

Prokopenko, A.A., Karabanov, E.B., Williams, D.F., Kuzmin, M.I., Shackleton, N.J., Crowhurst, S.J., Peck, J.A., Gvozdkov, A.N., King, J.W., 2001. Bogenic silica record of the Lake Baikal response to climatic forcing during the Brunhes. Quat. Res. 55, 123–132.

Rousseau, D.D., Kukla, G., 1994. Late Pleistocene climate record in the Eustis loess section, Nebraska, based on land snail assemblages and magnetic susceptibility. Quat. Res. 42, 176–187.

Short, D.A., Mengel, J.G., Crowley, T.J., Hyde, W.T., North, G.R., 1991. Filtering of Milankovitch cycles by Earth's geography. Quat. Res. 35, 157–173.

van Breemen, N., 2002. Soil Formation. Second Edition. Secaucus. Kluwer Academic Publishers, NJ, USA, p. 415.

Stanjek, H., Fassbinder, J.W.E., Vali, H., Wägele, H., Graf, W., 1994. Evidence of biogenic greigite (ferrimagnetic Fe_3S_4) in soil. Eur. J. Soil Sci. 45 (2), 97–103.

Virina, E.I., Faustov, S.S., Heller, F., 2000. Magnetism of loess–palaeosol formations in relation to soil-forming and sedimentary processes. Phys. Chem. Earth (A) 25 (5), 475–478.

Volkov, I.A., Zykina, V.S., 1991. Cyclicity of subaerial deposits of Western Siberia and climatic history in the Pleistocene. In: Zakharov, V.A. (Ed.), Climatic Evolution, Biota and Habitation Environments of Man in the Late Cenozoic of Siberia. Institute of Geology, Geophysics and Mineralogy SB AN USSR, Novosibirsk, pp. 40–51 (In Russian).

Volkov, I.A., Zykina, V.S., 1993. Southern West Siberian plain: reconstruction of environments from studies of subaerial deposits, in Evolution of landscapes and climates of the Northern Eurasia. In: Velichko, A.A. (Ed.), Late Pleistocene-Holocene history of landscapes and climate in Northern Eurasia. Elements of prediction, issue I. Nauka, Moscow, pp. 32–36 (In Russian).

Zander, A., Frechen, M., Zykina, V., Boenigk, W., 2003. Luminescence chronology of the Upper Pleistocene loess record at Kurtak in Middle Siberia. Quat. Sci. Rev. 22, 999–1010.

Zhu, R.X., Matasova, G., Kazansky, A., Zykina, V., Sun, J.M., 2003. Rock magnetic record of the last glacial–interglacial cycle from the Kurtak section, southern Siberia. Geophys. J. Int. 152, 335–343.

Zykin, V.S., Zykina, V.S., Orlova, L.A., 2000. Quaternary warming stages in Southern West Siberia: environment and climate. Russ. Geol. Geophys. 41, 295–312.

Zykin, V., Zykina, V.S., Orlova, L.A., 2003. Reconstruction of environmental and climatic changes during the Late Pleistocene in Southern West Siberia using deposits from the Lake Aksor basin. Archeol. Ethnol. Anthropol. Eurasia 4 (16), 2–16.

Zykina, V.S., 1999. Pedogenesis and climate change history during Pleistocene in Western Siberia. Anthropozoikum 23, 49–54 (In Russian).

Zykina, V.S., Volkov, I.A., Dergacheva, M.I., 1981. The Upper Quaternary Deposits and Fossil Soils of Novosibirsk PreObje. Russian Academy of Sciences, Moscow. (In Russian).

Zykina, V.S., Volkov, I.A., Semenov, V.V., 2000. Neopleistocene climate history in West Siberia: evidence from the Belovo reference section. In: Derevyanko, A.P. (Ed.), Reconstruction of Holocene and Pleistocene climates and environments of Siberia. Institute of Archaeology and Ethnography SB RAS, Issue 2, Novosibirsk, pp. 229–249 (In Russian).

Zykina, V.S., Zykin, V.S., 2003. Pleistocene warming stages in Southern West Siberia: soils, environment, and climate evolution. Quarter. Int. 106–107, 233–243.