Magnetic properties and magnetic fabrics of Pleistocene loess/palaeosol deposits along west-central Siberian transect and their palaeoclimatic implications

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Abstract: Rock-magnetic properties, in particular anisotropy of magnetic susceptibility (AMS) were investigated in detail for eight sections transecting southwestern and central parts of Siberia. The results obtained indicate that magnetic properties and magnetic fabrics of loess/palaeosol deposits in western and southwestern Siberia depend on superposition of two different mechanisms namely a pedogenic mechanism proposed for Chinese loess and a wind-vigour mechanism for Alaskan loess. The wind-vigour mechanism is predominant in loess deposits and this allows palaeowind directions during glacial periods to be determined. In palaeosols, the balance between both models strongly depends on the geographical position of the section and thus reflects the palaeoclimate. In western Siberia, palaeosols corresponding to OIS 3 have sedimentary magnetic fabric, while the magnetic fabric of palaeosols corresponding to OIS 5 is completely reworked by pedogenesis. Such differences indicate a warmer climate during OIS 5. In central Siberia, separated from the west by the Kuznetsk Ala-Tau mountain ridge, the magnetic properties and AMS of loess/palaeosol sequences agree with 'Alaskan' type of loess, suggesting a colder and windier climate during the Late Pleistocene. Therefore, the Siberian subaerial realm may be subdivided into two provinces based on the palaeoclimate conditions prevailing during the Late Pleistocene. These climatic provinces remain in the modern climate.

Anisotropy of magnetic susceptibility (AMS) and magnetic fabric of loess/palaeosol sequences have profitably been applied to solve a wide range of problems in Quaternary geology. Such problems deal for instance with determinations of the sediment source, distance and means of sediment transport, depositional conditions, prevailing palaeowind direction and degree and character of secondary reworking processes of primary aeolian deposits (Liu *et al.* 1988; Thistlewood & Sun 1991; Lagroix & Banerjee 2002).

Shape and degree of anisotropy as well as other magnetic properties of aeolian deposits strongly depend on the palaeogeographical features of sedimentation and subsequent reworking. Thus the magnetic fabric itself cannot be completely understood in isolation from other magnetic properties (such as different types of magnetic susceptibility and remanence) and other processes affecting the loess since its initial deposition. According to the relative variation of magnetic susceptibility (MS) magnitudes between loess and palaeosol, most deposits can be subdivided into two basic types (or models) (Heller & Evans 1995; Maher 1998). The first so-called 'Chinese' or 'pedogenic' type demonstrates 3–4 times higher magnetic susceptibility values in palaeosol than in loess horizons due to the enhancement of magnetic minerals (secondary pedogenic magnetite/maghemite formation) during warm and wet interglacial periods. The second 'Alaskan' or 'wind-vigour' type shows the opposite trend. Here, higher MS values are generally explained by the increased input of magnetic particles due to stronger winds during glacial periods. An additional criterion to distinguish these two types appears to be the frequency-dependence of magnetic susceptibility (FD). In 'Chinese' loess/palaeosol sections, the FD values in loess horizons are relatively low (1–3%, sometimes up to 5%) while in buried soils it increases up to 10–15% (Maher & Thompson 1991; Liu *et al.* 1994; Dearing *et al.* 1996) due to formation of ultra-fine grained biogenic and/or abiotic magnetic minerals during pedogenesis. In contrast, the FD-susceptibility does not exceed 2–3% at all in 'Alaskan' type loess and palaeosols, regardless of the lithology (Chlachula *et al.* 1998; Vlag *et al.* 1999; Matasova *et al.* 2001).

The two mechanisms (wind-vigour and pedogenesis) are also responsible for the diversity of magnetic fabrics of loess/palaeosol deposits. In order to reveal the differences, we compiled data from different authors (Liu *et al.* 1988; Thistlewood & Sun 1991; Reinders & Hambach 1995; Jordanova *et al.* 1996; Zhu *et al.* 1998; Lu *et al.* 1998; Zhu *et al.* 1999; Pan *et al.* 2001; Lagroix

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Table 1. *AMS characteristics of some loess/palaeosol deposits*

Region	Deposit	AMS degree %	AMS ellipsoid shape	K_{max} preferred orientation	K_{min} orientation	Reference
'Chinese'–type loess/palaeosol deposits						
Europe						
Belgium	loess	$2 < P' < 5$	oblate	yes	vertical	Hus 2003
	palaeosol	$P' < 2$	oblate	yes	vertical	Hus 2003
Ukraine	loess	$P' < 1.5$	oblate	yes	vertical	Hus 2003
	palaeosol	$P' < 1$	less oblate	no	vertical	Hus 2003
Germany	loess	$P < 3$	oblate	no	vertical	Reinders & Hambach 1995
Czechia	loess		oblate	no	vertical	Zhu *et al.* 2001
Bulgaria	loess	$P' < 2$	weakly oblate	no	vertical	Jordanova *et al.* 1996
	palaeosol	$P' < 1.5$	chaotic	no	chaotic	Jordanova *et al.* 1996
Asia						
China	loess	$h < 2$	oblate	yes	vertical or near vertical	Thistlewood *et al.* 1991; Guo *et al.* 2002
	loess	$P' < 3$	oblate	no	vertical	Zhu *et al.* 1999; Pan *et al.* 2001; Liu *et al.* 1988
China	palaeosol	$h < 1.5$	oblate	yes	vertical or near vertical	Thistlewood *et al.* 1991
	palaeosol	$P < 3$	oblate	no	vertical	Liu *et al.* 1988; Zhu *et al.* 1999
'Alaskan'–type loess/palaeosol deposits						
North America						
Alaska	loess	$3 < P' < 7$	oblate	yes	vertical	Lagroix & Banerjee 2002
	palaeosol	$3 < P' < 7$	oblate	yes	vertical	Lagroix & Banerjee 2002
Asia						
Central	loess	$2 < P' < 5$	oblate	yes	vertical	Hus 2003
Siberia	palaeosol	$2 < P' < 4.5$	oblate	yes	vertical	Hus 2003
Reworked loess/palaeosol deposits						
water lain redeposited						
China	loess	$3 < P < 6$	oblate	yes	near vertical	Liu *et al.*, 1988
reworked by slope process						
Alaska	loess	$P' > 3$	oblate	yes	inclined	Lagroix & Banerjee 2002
Alaska	palaeosol	$P' > 3$	oblate	yes	inclined	Lagroix & Banerjee 2002

$P = K_{max}/K_{min}$ (Nagata 1961), $h = (K_{max} - K_{min})/K_{int}$ (Rees 1966), for P′ see Jelinek 1981.

& Banerjee 2002; Guo *et al.* 2002; Hus 2003), which are represented in Table 1. Mostly both 'Chinese' and 'Alaskan' types of deposits are characterized by typical sedimentary fabrics with vertical or near vertical K_{min} orientation. In general, 'Chinese' type loess and palaeosols appear to be less anisotropic than the 'Alaskan' type ones. In Europe, the AMS degree decreases with the distance from the boundary of Pleistocene ice cover (see maps in Mangerud *et al.* 1999; Näslund *et al.* 2003) and magnetic fabrics become less expressed: oblateness is weaker and the predominant K_{max} orientation is lost. In Bulgarian palaeosols, the AMS axes are chaotically distributed due to pedogenic processes. The picture is more obscured on the Chinese Loess Plateau. The AMS degree is relatively low and a preferred K_{max} axis can present or absent both in loess and palaeosol. 'Alaskan' type of loess/palaeosol deposits in Alaska and Central Siberia demonstrate a well-defined oblateness and a distinct orientation of maximal AMS axes in both loess and palaeosol deposits.

The nature of the magnetic fabric of loess deposits is a widely debated topic. Some authors are of the opinion that AMS in loess/palaeosol deposits can reflect a primary magnetic fabric, being formed at the moment of deposition among and in association with other sedimentary material (Rolph *et al.* 1989; Lagroix & Banerjee 2002). Other authors explain the AMS fabric only in terms of secondary reworking processes, i.e. redeposition of loess material by water flow (alluvial, slope and proluvial environments), for example in Liu *et al.* (1988), Derbyshire *et al.* (1988). It is documented that in the case of a primary magnetic fabric in loess, the preferred orientation of the AMS maximum axes (i.e. magnetic lineation) may correspond to the predominant wind direction (Lagroix & Banerjee 2002), and hence to the general transport direction of the sedimentary material (Thistlewood & Sun 1991).

It has been concluded from numerous loess/palaeosol data sets (magnetic susceptibility, MS; natural remanent magnetization, NRM; saturated isothermal remanent magnetization, SIRM; anhysteretic remanent magnetization, ARM) worldwide, that magnetic proxy data from loess/palaeosol sequences reflect palaeoclimatic changes and hence can be used for the characterization of palaeoenvironmental conditions on regional and global scales (Kukla *et al.* 1988; Begét *et al.* 1990; Maher & Thompson 1992; Heller & Evans 1995).

The interrelation between the magnetic signature of loess/palaeosol sections and climatic fluctuations is supported by a strong correlation between magnetic susceptibility records and marine oxygen-isotope ($\delta^{18}O$) records. High $\delta^{18}O$ values during even-numbered oxygen isotope stages (OIS) (i.e. glacial periods) correlate with low MS values in 'Chinese' type and high values in 'Alaskan' type (Heller & Liu 1986; Begét *et al.* 1990).

The main purpose of this study is to investigate the behaviour of magnetic properties and magnetic fabrics of loess/palaeosol sequences across Siberia in order to make regional palaeoenvironmental reconstructions of the Middle and Late Pleistocene. The studied sections are spread along a sub-latitude transect from the southern part of West Siberia to the eastern part of central Siberia.

Study area

Siberia, due to its vast area and geographical position, remains a poorly investigated region of the northern hemisphere in terms of Quaternary geology. This territory is characterized by a highly diverse relief with vast plains in the western and north-central regions and broad highlands and high mountain ridges in the south and east. The cover of subaerial deposits with interbedded buried soils is widespread over the non-glacial zone of western, southwestern and central Siberia and is described hereafter as the Siberian subaerial realm (Volkov 1971). Stratigraphy, colour, carbonate content, grain-size distribution and other lithological parameters suggest a predominantly aeolian origin of the sediment sequences in the area. Subaerial deposits are genetically connected to specific landforms like crests, linear depressions, ridges, valley flats and steppe depressions. The subaerial cover in Siberia was formed under a dry and cold climate when valleys of second order rivers and both small and large lakes were dry. The accumulative relief is composed of loads transported from local sources. The global climatic changes during the Late Pleistocene with alternating dry or wet and cold or warm epochs are well recorded in Siberia, because the alternation of glacial and interglacial periods has resulted in sharp changes of the sedimentation environment. Hence, depositional and relief-forming processes have climatically dependent, cyclic characters.

The Near-Ob' crest plain is located in the southwestern forest-steppe part of the Siberian subaerial realm. It is composed of large linear landforms (crests) and their origin is still hotly debated. The linear crests, separated by depressions, are aligned in a WSW-ENE orientation coinciding with the predominant modern and palaeowind directions (Moskvitin 1940; Baranov & Blinova 1969) in the region. The height of some crests can exceed 150 m. The lower parts of the crests are comprised of alluvial and lake deposits, while the middle and top parts consist of loess and loess-like deposits with interbedded buried soils, partly reworked by bio-/cryoturbation and solifluction processes.

The most southwestern section studied – Belovo (52.6° N, 83.6° E) – is located on the central part of a crest cut by the Ob' river valley (Fig. 1). Further northward, the clear dissection of linear landforms is less pronounced. However, local river valleys retain an orientation parallel to the crests. Within this marginal part of the Near-Ob' crest plain we studied two sections: Lozhok (54.6° N, 83.3° E) and Mramorny (54.7° N, 83.4° E) (see Fig. 1). Both are located within the watersheds of second order rivers. Going northwards, we studied Toguchin section (55.2° N, 84.4° E) located on the foothills of the Salair mountain ridge, where lowlands are filled by loess and loess -like deposits (Fig. 1).

The Kuznetsk depression is located east of the Salair mountain ridge and represents a slightly uplifted crested steppe and forest-steppe plain, which is surrounded by the Salair mountain ridge to the west and by the Kuznetsk Ala-Tau mountain ridge to the east and south. In the depression, we studied two sections: Bachat (54.5° N, 87.1° E) located within the river watershed in the central part of the depression and Novokuznetsk (53.8° N, 87.1° E) located on

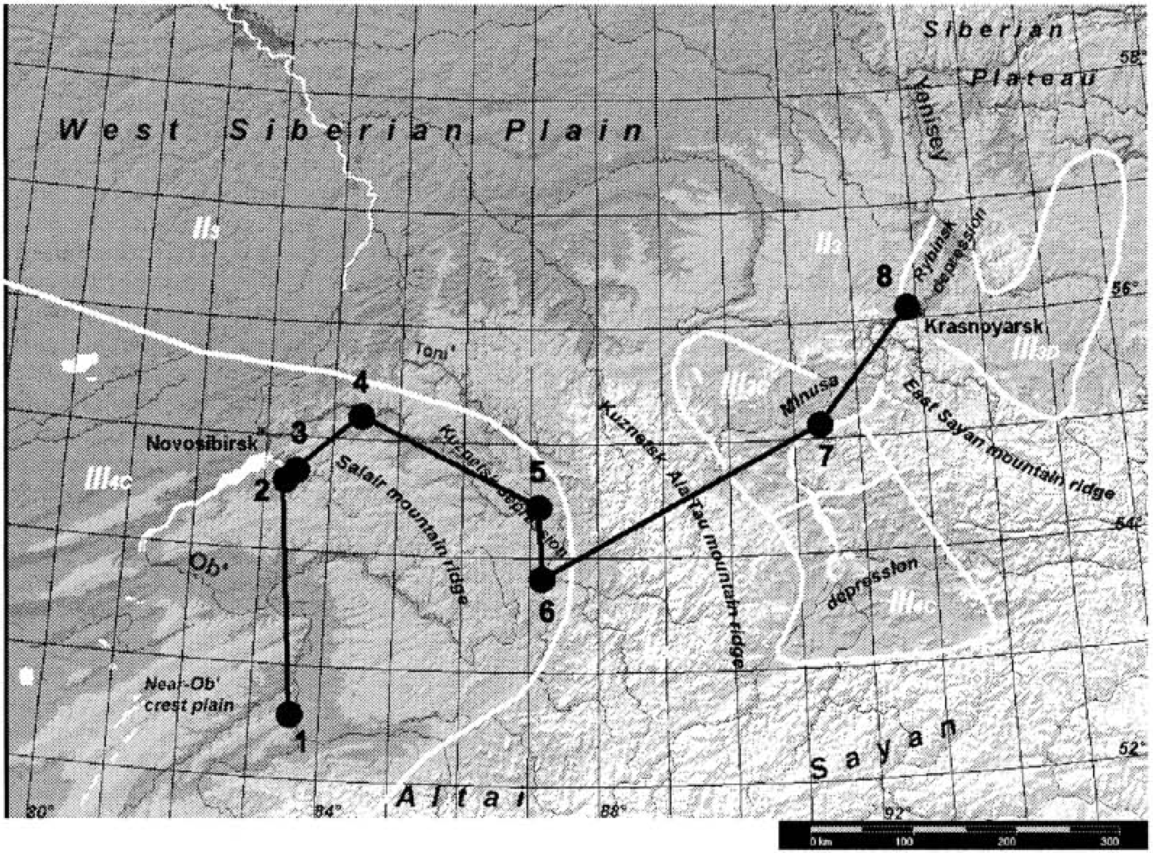

Fig. 1. Geographic map showing the location of the sections studied (black dots), the transect (black line) and the climatic sub-regions of the study area according to Davitaya & Pastukh (1960). The climatic division is given by white lines, zone names by white signs. Studied sections: 1 – Belovo, 2 – Lozhok, 3 – Mramorny, 4 – Toguchin, 5 – Bachat, 6 – Novokuznetsk, 7 – Kurtak, 8 – Tatyshev.

the right bank of the Tom' river in the southern part of the depression (Fig. 1).

The Minusa depression is located further NE, across the Kuznetsk Ala-Tau mountain ridge. It is completely surrounded by mountain chains. The studied Kurtak section (55.1° N, 91.4° E) is located in the northern part of the Minusa depression along the left bank of the Yenisey river (Fig. 1). More northward, downstream of the Yenisey river, there is the Rybinsk depression. The most northeasterly section studied, Tatyshev (56.1° N, 92.9° E) is located along the left bank of the Yenisey river within the Rybinsk depression (Fig. 1).

Present-day climate

According to the regional climate classification of the former USSR (Davitaya & Pastukh 1960) the southwestern sections (Belovo, Lozhok, Mramorny, Toguchin, Bachat and Novokuznetsk) belong to climatic zone III_{4C}, which is characterized by low humidity (evaporation/precipitation ratio 1.0–3.0), moderately cold (from −13 to −32 °C) winters and warm summers: ΣT° (the annual sum of the surface ground temperatures above +10 °C) exceeds 2200 °C and even 2400 °C (in Belovo). The Kurtak section belongs to zone III_{3C}, which is also characterized by low humidity and moderately cold winters. The summer here, however, is moderately warm with ΣT° less than 2200 °C. Tatyshev falls on the boundary between zones III_{3D} and II_3. The difference between III_{3C} and III_{3D} is the thickness of the snow cover (Table 2). Zone II_3 is characterized by normal humidity (evaporation/precipitation ratio 0.45–1.0), moderately cold winters and moderately warm summers. According to modern soil types, Dobrovolsky (1976) suggests that the locations of Belovo, Lozhok, Mramorny, Toguchin, Bachat and Novokuznetsk sections fall into a sharp continental climate region, while the locations of the Kurtak and Tatyshev sections fall into an extra-continental climate region.

Table 2. *Some present-day climatic characteristics in localities of studied sections*

Section	Modern soil type	Environment	*Winter temperature at surface [°C] DJF	*Summer temperature at surface [°C] JJA	Average T [°C] annual	Precipitation [mm/yr] annual	*Potential evaporation [W/m^3] annual	*Relative humidity at surface [%] annual	Snow cover [cm] annual	Distance to permafrost [km]	Number of days with $T > 20$ °C
Belovo	chernozem	steppe	−13.7	16.5	+2.0	220–320	111	88	25–30	375	35–40
Mramorny, Lozhok	leached chernozem	forest steppe	−14.9	16.7	−0.3	450–500	120	82	50	425	30
Toguchin	meadow chernozem	meadow steppe	−15.0	16.4	−0.4	450	113	80	>50	450	20–30
Bachat	leached chernozem	steppe	−14.9	15.3	+0.5	460–500	94	88	60	250	30
Novokuznetsk	grey forest soil (greyzem)	meadow steppe	−15.0	14.9	+0.4	500–550	92	90	90	225	20
Kurtak	grey forest soil (greyzem)	forest	−16.0	14.5	−1.3.	400	96	87	<50	75	10–20
Tatyshev	sod-podzolic soil	forest	−17.4	14.4	−1.3	400–500	104	86	>50	25	10–20

*From monthly long-term mean values (1968–1996)

Compiled from Baranov & Blinova (1969), Davitaya & Pastukh (1960), Gusthina (1979), Protsuk (1978), NOAA–CIRES Climate Diagnostics Centre internet database: *http://www.cdc.noaa.gov/index.html*).

Some features of the present-day climate for the sections studied are given in Table 2. The climatic divisions are shown in Figure 1.

Sampling and methodology

Oriented samples were collected from all eight sections. The thickness of the investigated sections varies from 7 to 24 m. All studied sections were cross-correlated using several stratigraphic methods: palaeopedology (morphological descriptions, micromorphological analysis, detailed study of organic matter) and biostratigraphy (small and large mammals) (Arkhipov *et al.* 1997; Zykina 1999; Foronova 1999). Stratigraphic correlations and corresponding age estimations are strongly supported by absolute dating, which is available for all studied sections except Toguchin and Novokuznetsk. Belovo has been dated by radiocarbon (C^{14}) (Zykina *et al.* 2000) and thermoluminescence (TL) methods (Arkhipov *et al.* 1997). Lozhok and Mramorny have been dated by C^{14} (Volkov & Zykina 1984). The *M. primingenius* bones in the Bachat section have been dated by C^{14} (Foronova 1999). Kurtak, being a famous archaeological site, has the most comprehensive dating with C^{14} (Svezhentsev *et al.* 1992) and TL methods (Zander *et al.* 2003), while Tatyshev has only a few radiocarbon dates (Yamskikh 1992) and TL dates (Frechen & Yamskikh 1999). Detailed geological descriptions of the studied sections and the correlation of loess/palaeosol horizons with marine oxygen-isotope stages (OIS) can be found in Volkov (1971), Zykina & Kim (1989), Yamskikh (1992); Arkhipov *et al.* (1997), Chlachula *et al.* (1997), Chlachula *et al.* (1998), Chlachula (1999); Zykina (1999), Zykina *et al.* (2000), Matasova *et al.* (2001); Matasova *et al.* (2002). The loess and palaeosol units have different local names assigned; however, the following designation is introduced for all sections: L1 to L5 (for loess units corresponding to glacial OIS 2, 4, 6, 8, 10, respectively) and PC1 to PC4 (for palaeosols (pedocomplex) corresponding to the interglacial OIS 3, 5, 7, 9, respectively). PC0 denotes the modern soil. Although our nomenclature is similar to that of Chinese loess/palaeosol sections, ours should not be correlated with the nomenclature of the Chinese Loess Plateau.

During our field studies, we observed the rudiments of another palaeosol, hereafter called L1PC, within loess L1 at Mramorny (Fig. 2). L1PC was not observed at all the other sections. Rock-magnetic data (Fig. 2), however, indicate its presence at Belovo, Toguchin, Bachat, Novokuznetsk and Tatyshev. L1PC is mostly known from other sections located to the northwest of the Siberian realm. According to Volkov & Zykina (1984), L1PC has an absolute date of 14 ± 2 ka.

Most samples were taken as oriented blocks 5 × 5 × 10 cm. The blocks were cut in four to six oriented standard samples (2 × 2 × 2) at the laboratory. The sampling intervals range between 3 and 5 cm. More than 2000 samples have been analysed in total. At some sections the loess was partly too loose and coarse grained (Kurtak section from 15.55 to 17.7 m and Tatyshev section from 12.5 to 12.9 m and from 14.2 to 15.5 m) to be sampled in blocks. A piston sampler and plastic boxes have been used in this case. As this sampling technique may induce a secondary magnetic fabric (Jordanova *et al.* 1996), the samples from the above mentioned intervals were not used for AMS studies.

Bulk magnetic low-field susceptibility was measured using a dual-frequency sensor (0.47 and 4.7 kHz) from Bartington Instruments. The frequency dependence of magnetic susceptibility (FD), determined as the difference between low- and high-frequency susceptibility ($K_{LF} - K_{HF}$) and expressed as a percentage of the low-frequency susceptibility, has been calculated. The anisotropy of magnetic susceptibility was measured on a Geofyzika KLY-3 Kappabridge. The three principal axes defining the AMS ellipsoid were determined from the 15-position orientation scheme suggested by Jelinek (1977). All anisotropy parameters (P' – corrected anisotropy degree; L – magnetic lineation; F – magnetic foliation; T – shape factor) were calculated according to Jelinek (1981) and Tarling & Hrouda (1993).

Various techniques were used to characterize the magnetic mineralogy of representative samples and magnetic extractions. The temperature dependence of magnetic susceptibility from room temperature to 700 °C was determined with the KLY-3 and CS-3 furnace in air.

The thermal demagnetization of SIRM, acquired in a 1.4 T direct current (d.c.) field, was also used to further the magnetic mineral characterization. The samples were heated from room temperature to 700 °C using a hand-made spinner magnetometer with a built-in shielded furnace (Burakov 1977). In order to assess mineralogical changes during the heating process, a second measurement run (SIRM acquisition and its thermal demagnetization) was conducted on the same sample. The NRM behaviour during stepwise AF demagnetization up to 100 mT and thermal demagnetization up to 700 °C was also analysed.

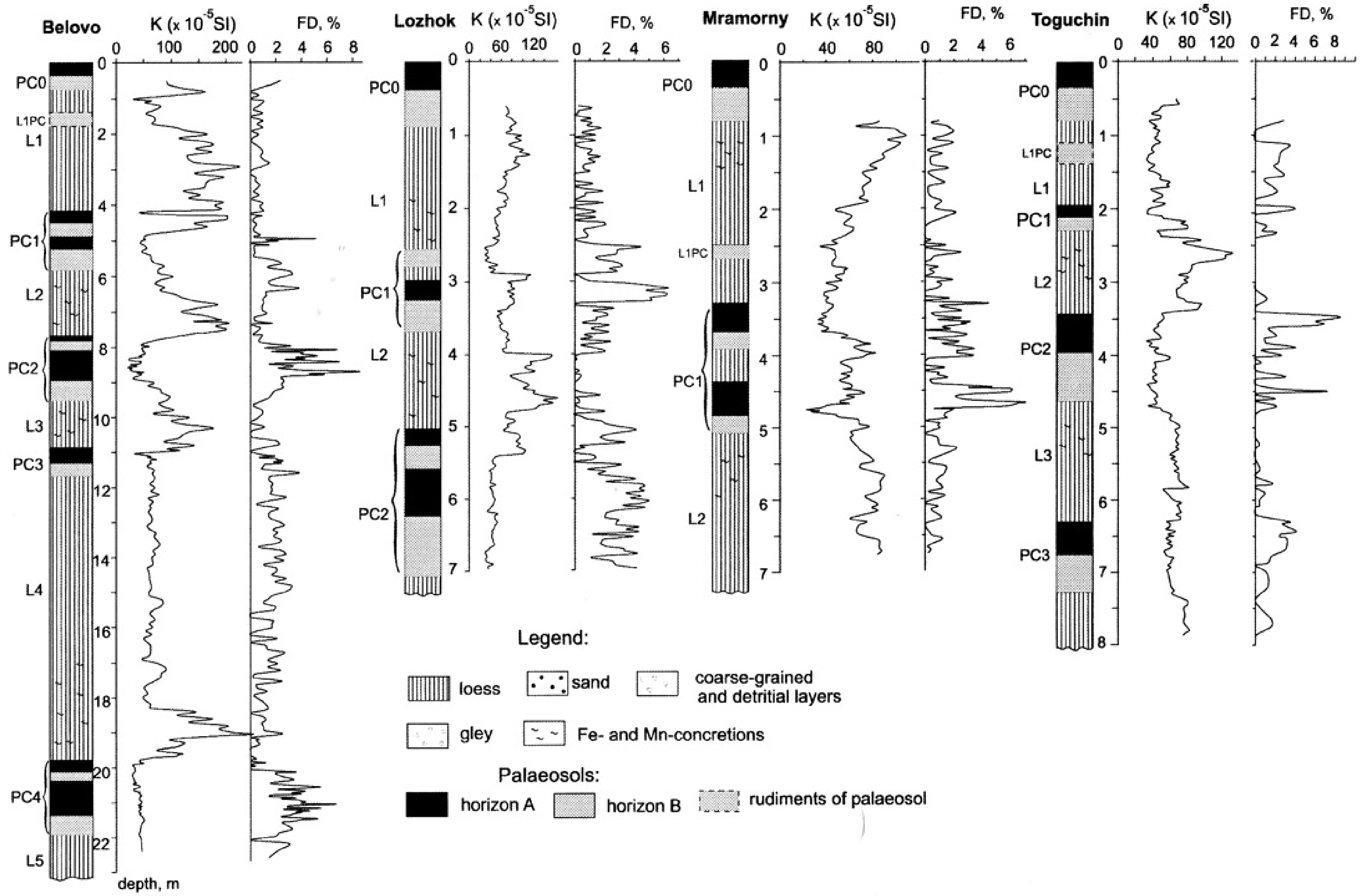

Fig. 2. Lithologies and variations of magnetic susceptibility (K) and frequency-dependent susceptibility (FD) for studied sections. Lithology subdivision for Belovo, Lozhok, Mramorny, Bachat, Novokuznetsk and Kurtak sections is given according to Zykina *et al.* (1981), Zykina *et al.* (2000), Matasova *et al.* (2001), Matasova *et al.* (2002) and Matasova *et al.* (2003). Lithology subdivision for Toguchin section is given according to field description by V. S. Zykina, for Tatyshev section – according to field description by D. Koz'min.

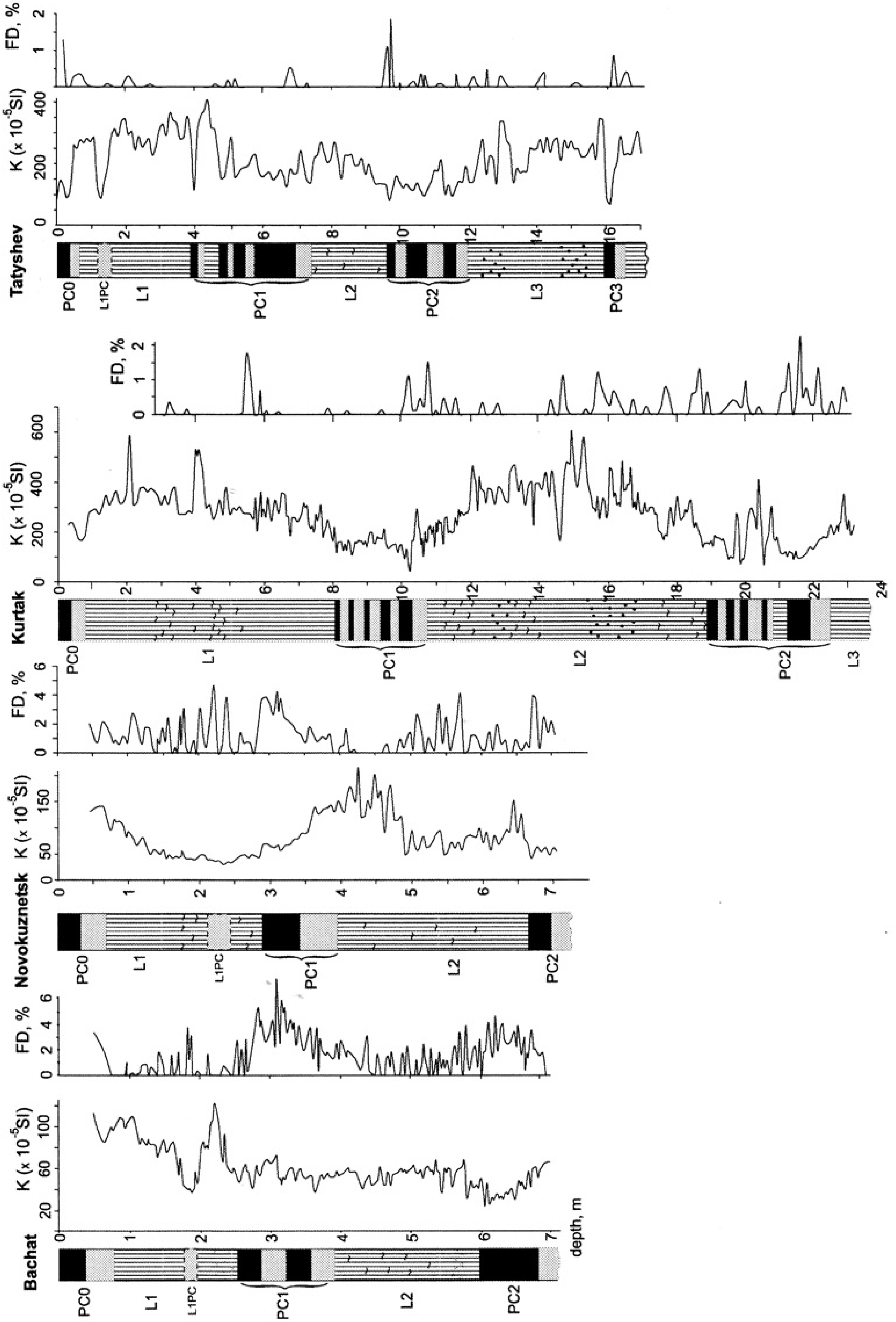
Tatyshev
PC0
L1PC
L1
PC1
L2
PC2
L3
PC3
K (x 10^{-5}SI)
FD, %
Kurtak
PC0
L1
PC1
L2
PC2
L3
K (x 10^{-5}SI)
FD, %
Novokuznetsk
PC0
L1
L1PC
PC1
L2
PC2
K (x 10^{-5}SI)
FD, %
Bachat
PC0
L1
L1PC
PC1
L2
PC2
K (x 10^{-5}SI)
FD, %
depth, m

Fig. 2. (*cont.*)

Table 3. *Mean magnetic susceptibilities and corresponding standard deviations for loess (L1 and L2) and palaeosol (PC1 and PC2) units of studies sections*

Section	Interval	N	K_{mean}	SD	Interval	N	K_{mean}	SD
	L1				PC1			
Belovo	1.8–4.13	137	159	29	4.2–5.3	34	51	9
Lozhok	0.8–2.3	102	74	14	3.0–3.5	30	73	11
Mramorny	0.8–2.0	42	84	12	3.2–3.7	41	40	4
Toguchin	1.4–2.0	33	53	13	1.9–2.1	10	29	5
Bachat	0.9–1.7	50	91	12	2.6–3.6	60	55	8
Novokuznetsk	0.8–2.1	86	62	24	2.9–3.4	32	71	11
Kurtak	1.0–7.8	282	303	73	8.0–10.2	176	152	31
Tatyshev	1.7–3.8	110	299	36	5.9–7.0	72	164	15
	L2				PC2			
Belovo	6.7–7.7	66	166	27	7.9–8.9	66	40	10
Lozhok	4.0–4.7	42	123	24	5.6–6.2	36	42	4
Mramorny	5.3–6.8	82	79	8	–	–	–	–
Toguchin	2.4–3.4	53	65	14	3.4–4.0	38	34	3
Bachat	4.0–5.8	98	54	7	6.0–6.8	46	41	10
Novokuznetsk	3.9–6.6	56	106	42	6.7–7.0	21	55	7
Kurtak	11.0–18.3	257	322	78	21.1–21.9	42	193	28
Tatyshev	7.5–8.7	80	222	30	9.8–10.8	58	125	17

Interval – the stratigraphic interval in metres within which susceptibility means are calculated; N – number of samples within the interval; K_{mean} – mean value of magnetic susceptibility in 10^{-5} SI units; SD – standard deviation in 10^{-5} SI units.

Each interval for susceptibility means calculation is chosen on the basis of the following principles: (1) Deposits within the interval must be the typical loess (palaeosol) with the pristine fabric, homogenous in colour and granulometry; (2) Sandy layers, gleyed layers and layers of coarse material are excluded; (3) Illuvial horizons of buried soils are excluded; (4) Intervals of expected rudiments of L1PC (according to rock-magnetic data) are excluded.

The S-ratio ($\mathrm{IRM}_{-0.3T}$: $\mathrm{SIRM}_{1.4T}$) has been used for a first-order characterization of the sample's coercivity of remanence (i.e. relative amounts of low-coercivity remanence to high-coercivity remanence) within different stratigraphic units.

The magnetic measurements were performed at three different laboratories – the Institute of Geology of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk), the Geophysical Institute of the Czech Academy of Sciences (Prague) and the Institute of Geology and Geophysics of the Chinese Academy of Sciences (Beijing).

Results

Magnetic susceptibility (K), frequency-dependent susceptibility (FD)

The variations of the volume magnetic susceptibility (K) and frequency-dependent susceptibility (FD) for all sections, as a function of depth, are plotted on Figure 2.

Near Ob' crest plain

The most characteristic picture is found in the section Belovo in the southwestern part of the plain where the loess units are characterized by higher values of K and palaeosols demonstrate low susceptibility values (Fig. 2). The differences in average K values for L1, L2 PC1 and PC2 units at Belovo are significant compared to their standard deviation (Table 3). Typical FD-susceptibility variations are observed. Increased FD values (up to 9%) correspond to palaeosol horizons while in loess units they do not exceed 3% (except in the upper part of L2 and in the upper part of L4).

A more complicated picture is found in the central part of the studied area. Loess and palaeosol horizons demonstrate both low and high K values (Fig. 2) in the northeastern part of the Near Ob' crest plain (sections Mramorny, Lozhok and Toguchin). The FD values, in contrast, indicate a more distinct regularity: enhanced FD values in palaeosols (up to 8%) and low values in loess (<3%).

Kuznetsk depression

The susceptibility behaviour at Bachat and Novokuznetsk is similar to Mramorny, Lozhok and Toguchin, except PC1, which has almost constant values over the whole depth range. Enhanced FD values up to 5% correspond to palaeosol horizons and L1PC rudiments in both sections, while loess units are characterized by FD values less than 3%, except the middle part of L2 loess in Novokuznetsk section (Fig. 2).

Central Siberia

The susceptibility variations at Kurtak and Tatyshev are similar to that in Belovo: loess units are characterized by higher values of K and palaeosols demonstrate low susceptibility values. The differences in K means of loess and palaeosol units in those sections are significant compared to the standard deviation (Table 3). The variations of the FD-susceptibility are much smaller (≤2%) in Kurtak and Tatyshev than in all other sections and do not depend on lithology (Fig. 2).

Magnetic susceptibility variations along the transect

Variations of K averages for different stratigraphic units of the Late Pleistocene (L1, L2,

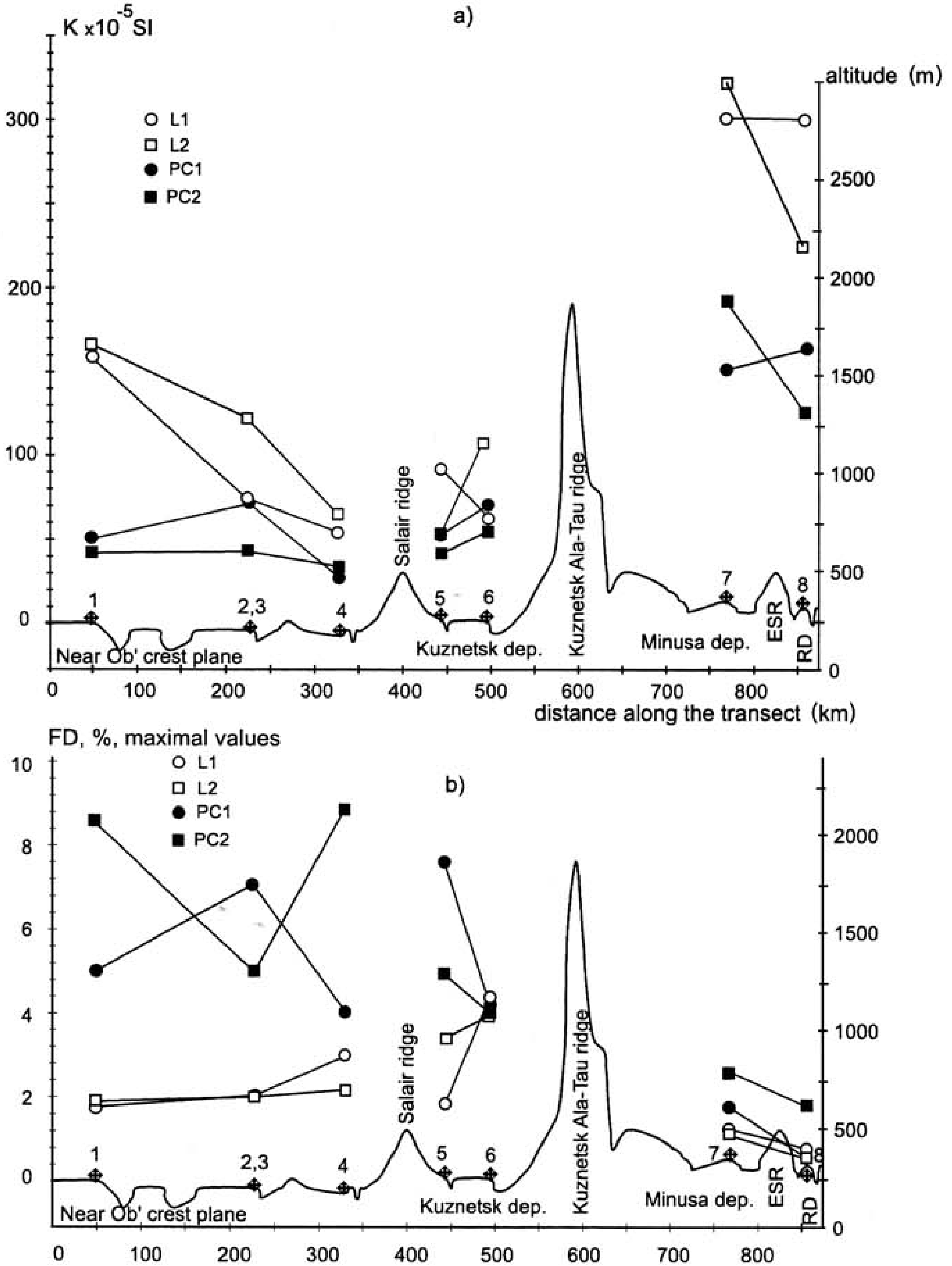

Fig. 3. Generalized relief profiles and changes in average values of magnetic susceptibility ma maximal FD values for L1, L2, PC1 and PC2 units along the transect. Numbers of sections correspond to Figure 1. Abbreviations: ESR – East Sayan mountain ridge, RD – Rybinsk depression.

PC1, PC2) along the transect are plotted in Figure 3. It is evident that the magnetic susceptibility of loess/palaeosol deposits exhibits some trend: gradual decrease in K means of stratigraphic units downwind in a N-NE direction along the Near-Ob' crest plain up to Salair mountain ridge (sections Belovo, Mramorny, Lozhok and Toguchin). This tendency is more pronounced in loess than in palaeosols (Fig. 3). Behind the ridge, in Kuznetsk depression the K means increase slightly in almost all units. A sharp increase of K means (about 3 times) both in loess and palaeosols is observed behind Kuznetsk Ala-Tau mountain ridge in Central Siberia (Kurtak). Further northeastwards (Tatyshev), the K means decrease in the upper units (L1, PC1) and drop slightly or remain nearly constant in lower units (L2, PC2). It should be mentioned that palaeosol susceptibilities in central Siberia are relatively high. These values are comparable to loess susceptibilities from Belovo, only.

The FD value is about 2% in loess L1 and L2 and does not show much variation along the transect. The FD value of the palaeosols, in contrast, is variable. The highest values of about 9% are observed in the Near Ob' crest plane and intermediate values of about 5% in the Kuznetsk depression. Very low values (~2%) – comparable to loess – are found in the Minusa and Rubynsk depression, behind the Kuznetsk Ala-Tau mountain ridge.

Magnetic mineralogy

More than 500 samples of Siberian loess/palaeosol deposits were studied to analyse magnetic mineral composition. Some results have already been published in Zhu *et al.* (2000), Matasova *et al.* (2001), Zhu *et al.* (2003) and Matasova *et al.* (2003), so we shall give the common features with greater attention on unpublished data.

Near Ob' crest plain

At Belovo, the temperature dependence of magnetic susceptibility (TDS) for loess and palaeosol (Fig. 4a) are similar in appearance. The heating branch exhibits a small peak at about 300 °C and the distinct decrease of susceptibility near 580 °C (loess) and 620 °C (palaeosol). Some palaeosol samples display an additional susceptibility increase between 400 °C and 525 °C. The cooling and heating branches are equal between 575 and 700 °C. Below 575 °C, a considerable susceptibility increase is observed during cooling. The maximal susceptibility values on the cooling branch are observed at 500 °C for palaeosols and between 400 and 500 °C for loess samples. Further cooling causes a gradual decrease of magnetic susceptibility and the final susceptibilities are 2–4 times higher than initial ones. TDS curves for samples from Mramorny (Fig. 4b) and Lozhok (not shown) sections are not significantly different from those from Belovo section. The discrepancy in TDS behaviour between samples of the Belovo, Mramorny and Lozhok sections in general is in the position of the maximal susceptibility peak on the cooling branch.

The thermal SIRM demagnetization curves of loess and palaeosol samples from Belovo are quite similar in shape, but vary in the $SIRM_0$ intensity: loess values are 2 times higher than palaeosol values. There is significant decrease of SIRM between 180 and 350 °C, which is not pronounced during the second heating (see below). About 3–5% of the initial SIRM is retained above 580 °C. The complete demagnetization of SIRM is observed at 630 and 680 °C for loess and palaeosols, respectively. In order to assess mineralogical changes during the heating process, a second heating was performed. The sample was remagnetized and again thermally demagnetized (dashed in Fig. 4a). The initial SIRM values of the second heating curve are 30 to 40% lower than the initial values of the first heating. The second heating curve differs considerably from the first one and does not exhibit the significant SIRM decrease between 180 and 350 °C. Above 580 °C both curves are similar and the complete demagnetization of SIRM still remains at 630/680 °C.

The thermal demagnetization of NRM of samples from Belovo shows a strong intensity loss between 200 and 300 °C, which is more pronounced in loess than in palaeosols. However, the NRM decay is different. In loess, 75% of NRM is demagnetized by 250–300 °C, while in palaeosols 25% of NRM remains at 620 °C. The complete demagnetization of NRM is observed at 680 °C in both cases.

Alternating field (AF) demagnetization of NRM exhibits different behaviour in sections over the Near Ob' crest plain (Fig. 4a–c). In all cases, AF peak fields of 100 mT are not sufficient to demagnetize the NRM completely. Loess samples from Belovo have low NRM_0 intensities. The NRM decays rapidly with median destructive fields (MDF) between 10 and 20 mT. Ten per cent of the NRM remains at 100 mT. Palaeosol samples from the Belovo have MDFs of more than 65 mT (in individual soil samples more than 100 mT). About 40% of initial NRM remains at 100 mT. Loess samples from Mramorny (Fig. 4b) show a moderate NRM decay with MDFs about 30 mT and about 20% of residual NRM at 100 mT. NRM decay in palaeosol samples from

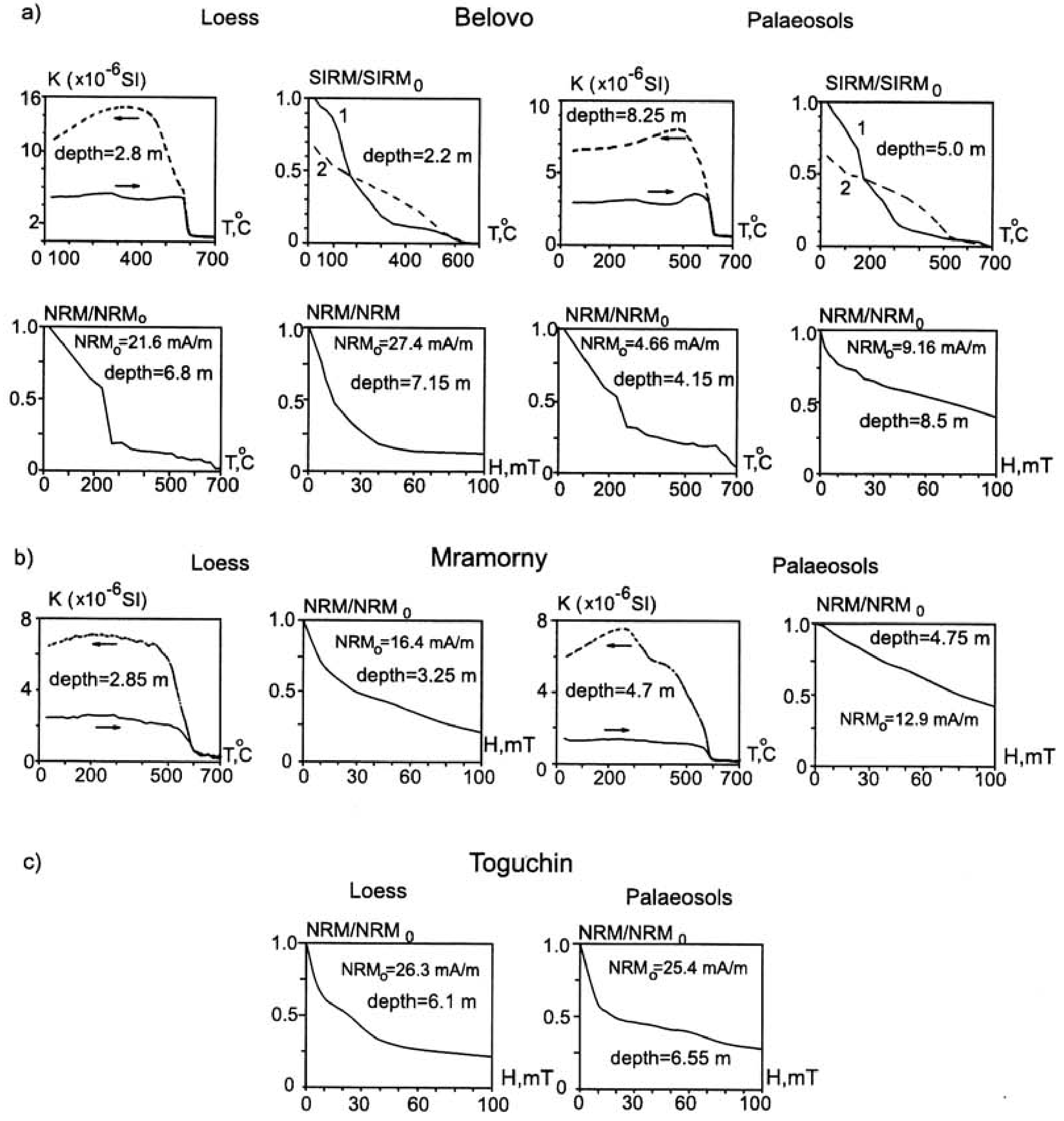

Fig. 4. Temperature dependence of magnetic low-field susceptibility (K), thermal demagnetization of SIRM, thermal and AF demagnetization of NRM of representative Siberian loess and palaeosol samples from the sections at: (a) Belovo, (b) Mramorny, (c) Toguchin, (d) Bachat, (f) Novokuznetsk, (g) Kurtak and (i) Tatyshev. XRD spectra are given of magnetic extracts from Bachat (e) and Kurtak (h). The solid (dashed) lines in K vs. T graphs represent heating (cooling) branch. Solid and dashed lines in SIRM-graphs represent first and second heating run, respectively.

the Mramorny section has a linear character with MDFs more than 70 mT. About 45% of initial NRM remains after 100 mT. Loess and palaeosol samples from Toguchin (Fig. 4c) have similar MDFs being 22 and 19 mT, respectively. The shape of the decay curves is similar and about 25% of the initial NRM remains at 100 mT.

Variations of S ratio versus depth for all sections studied within the crest plain are represented in Figure 5. In loess horizons from Belovo, the S ratio varies between 0.9 and 1.0 and falls slightly below 0.9 only for some samples from L1, L4 and L5. Sharp decreases of S ratio up to 0.74–0.85 are attributed to humus horizons of palaeosols PC1, PC2 and PC4. A similar behaviour is observed at Mramorny. At Toguchin, the S ratio scatters between 0.8 and 1 in L1, PC1 and L2. Below L2 the values are less scattered, being around 0.9. Distinct decreases down to 0.8 and 0.77 are observed in the

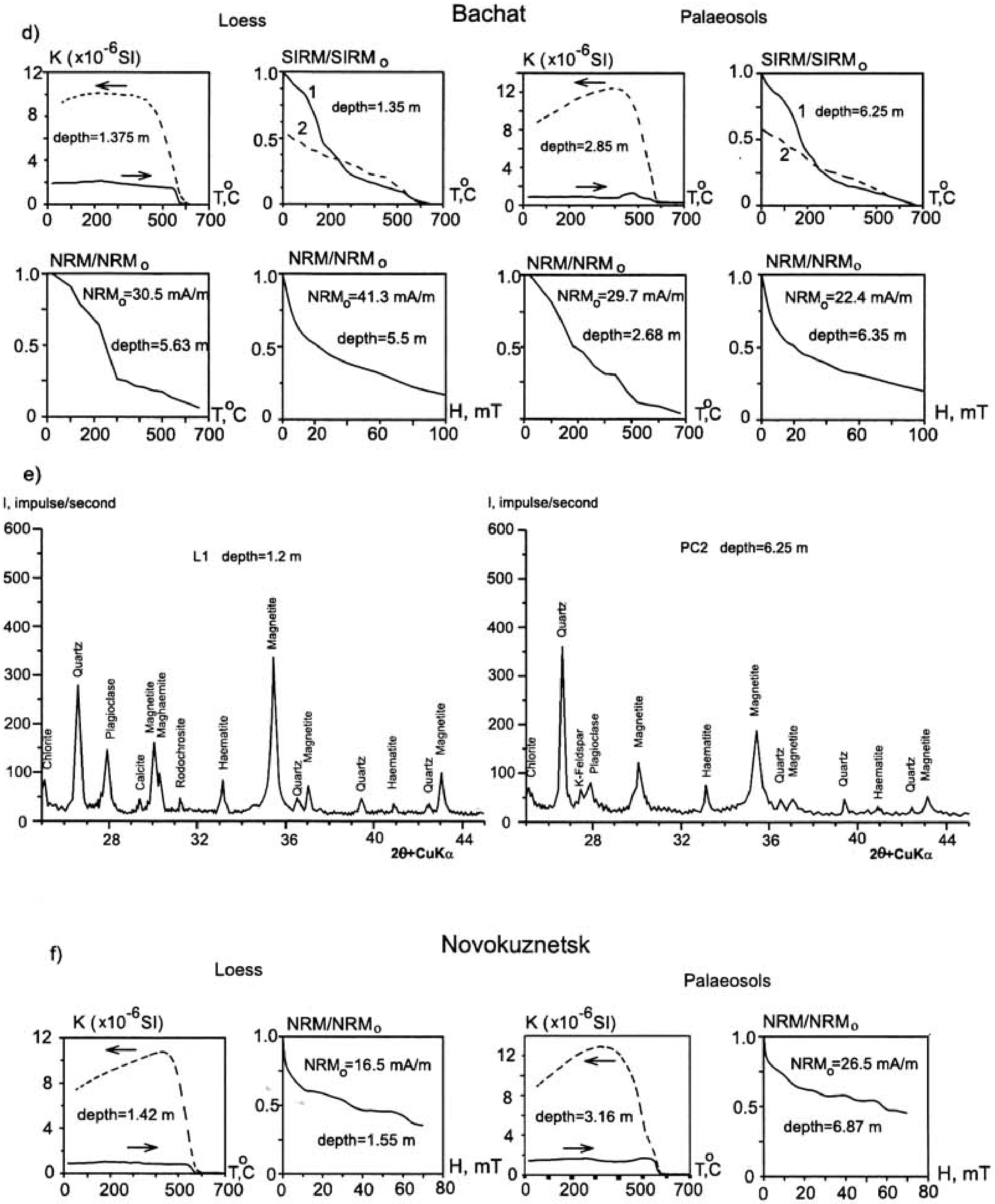

Fig. 4. (*cont.*)

humus horizons of PC2 and PC3, respectively. At Lozhok, the S ratio is about 0.95 over the entire section, except PC2 where it falls slightly below 0.9.

X-ray diffraction (XRD) analysis on the whole rock material from the Belovo section (not shown) indicates the presence of magnetite, maghemite and hematite for loess and for palaeosols.

Kuznetsk depression

The TDS behaviour of loess and palaeosol samples from Bachat (Fig. 4d) is quite similar to those from Belovo. The heating branch exhibits a small peak at about 300 °C and a distinct decrease of susceptibility near 580 °C. Palaeosol samples demonstrate an additional susceptibility increase between 400 °C and 525 °C. The cooling

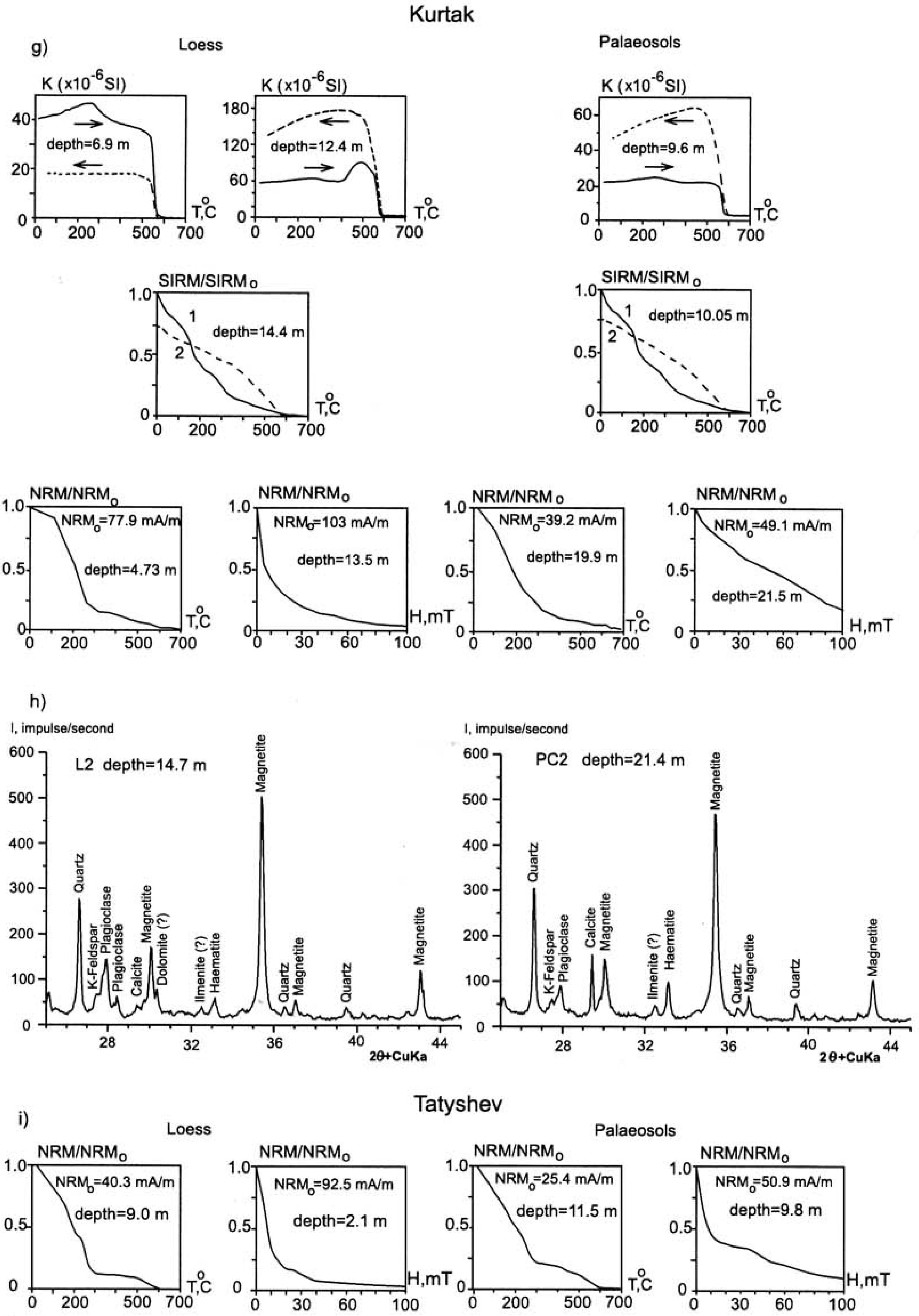
Kurtak
g)
Loess
Palaeosols
K (x10^{-6}SI)
depth=6.9 m
depth=12.4 m
depth=9.6 m
T,°C
SIRM/SIRM$_0$
1
2
depth=14.4 m
depth=10.05 m
NRM/NRM$_0$
NRM$_0$=77.9 mA/m
depth=4.73 m
NRM$_0$=103 mA/m
depth=13.5 m
NRM$_0$=39.2 mA/m
depth=19.9 m
NRM$_0$=49.1 mA/m
depth=21.5 m
H,mT
h)
I, impulse/second
L2 depth=14.7 m
PC2 depth=21.4 m
Quartz
K-Feldspar
Plagioclase
Plagioclase
Calcite
Magnetite
Dolomite (?)
Ilmenite (?)
Haematite
Magnetite
Quartz
Magnetite
Quartz
Magnetite
2θ+CuKa
Tatyshev
i)
Loess
Palaeosols
NRM$_0$=40.3 mA/m
depth=9.0 m
NRM$_0$=92.5 mA/m
depth=2.1 m
NRM$_0$=25.4 mA/m
depth=11.5 m
NRM$_0$=50.9 mA/m
depth=9.8 m

Fig. 4. (*cont.*)

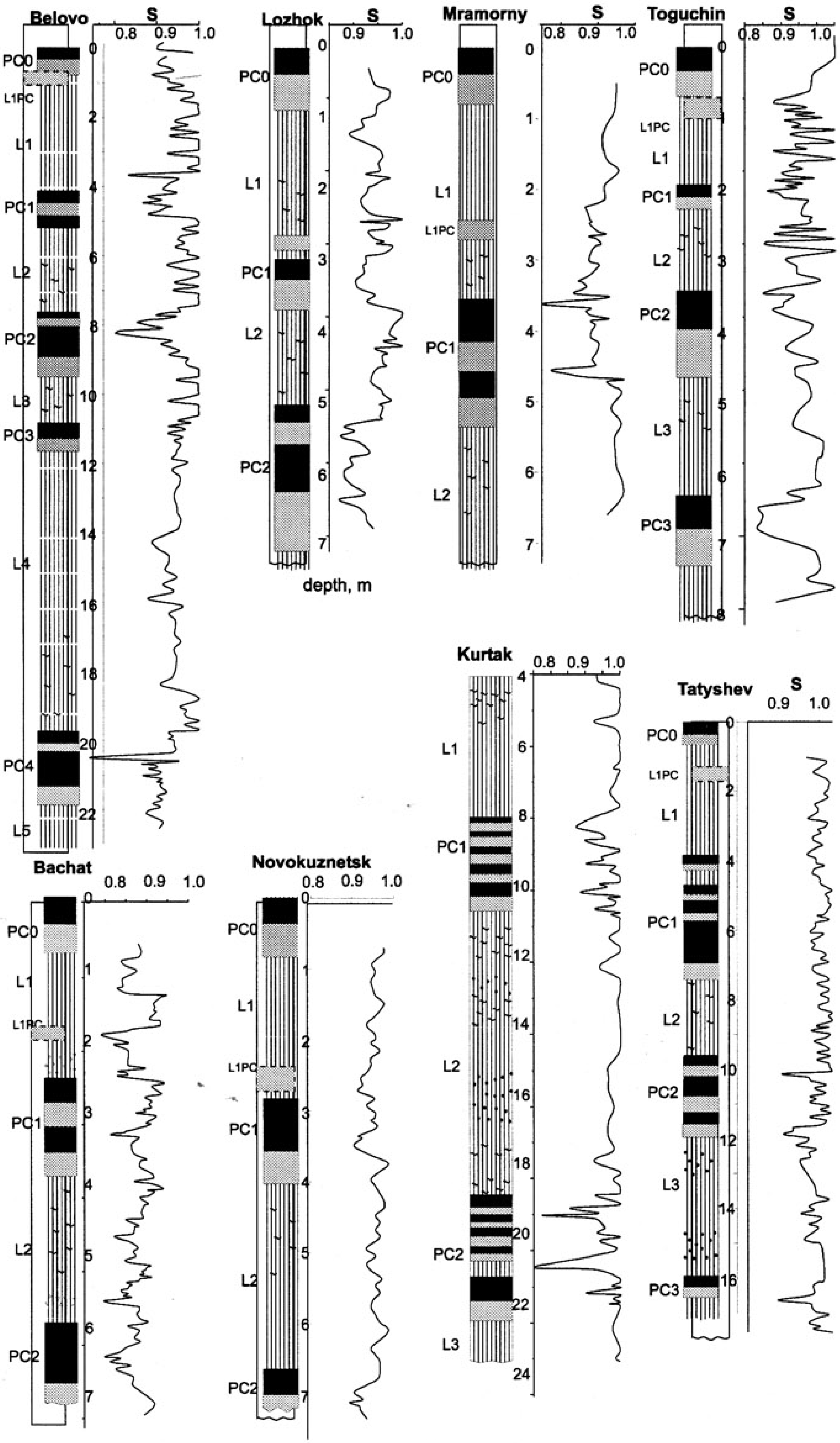

Fig. 5. Variations of the S-ratio versus depth of the studied sections.

branch follows the heating one between 600 and 700 °C and then increases dramatically. Maximal susceptibility values on the cooling branch are observed at 400–500 °C in palaeosol and between 200 and 500 °C for loess samples. The final susceptibilities are 5–10 times higher than initial ones. The highest ratios between initial and final susceptibility values correspond to palaeosol horizons. The TDS behaviour for samples from the Novokuznetsk section (Fig. 4f) is not significantly different from those from Bachat. The same peak at 300 °C and the peak above 450 °C (in palaeosols) are observed here. The final susceptibility values are 7–8 times higher than initial ones.

The thermal SIRM demagnetization curves for loess and palaeosol samples from Bachat are similar, but differ in their initial SIRM (lower in loess and high in palaeosol). Both loess and palaeosols are comparable in quality to the samples from Belovo (see above). However, the initial SIRM values at Bachat are 3–5 times lower than at Belovo. The SIRM of loess and palaeosols is demagnetized at 620/680 °C, respectively.

The NRM intensity decay during thermal demagnetization is different for loess and for palaeosol samples from Bachat. In loess, the NRM drops quickly. Less than 25% of the initial NRM remains at temperatures between 250 and 300 °C. The demagnetization curve of the palaeosol samples has a nearly linear character. Approximately 10 to 15% of the initial NRM remains above 580 °C. The demagnetization of the NRM is completed at 680 °C.

There is almost no difference in the AF demagnetization curve of the NRM between loess and palaeosols from Bachat. In both cases, the MDF is about 20–25 mT; 15% and 20% of the initial NRM remain at 100 mT in loess and palaeosol, respectively. Samples from the Novokuznetsk section are magnetically harder than in Bachat. The MDF of loess samples generally exceeds 30 mT and the residual NRM after 70 mT is about 35% of its initial value. The MDF of the palaeosols is about 50–55 mT and 45% of NRM still remains after 70 mT AF demagnetization.

The S ratios at Bachat are relatively low and generally less than 0.9 (Fig. 5). They vary between 0.85 and 0.95 regardless of the lithology of the section. Although lower S values (<0.83) are attributed to humus palaeosol horizons in the previously discussed sections, such low values are observed in a thin sandy layer in the middle part of L1 and in some levels of L2. In contrast, small variations between 0.9 and 1.0 are observed at Novokuznetsk. Nevertheless, here the lowest values (<0.93) are found in humus palaeosol horizons.

XRD analysis of the magnetic extraction from Bachat (Fig. 4e) indicates the presence of magnetite and hematite in palaeosols, while in loess horizons maghemite is also present, in addition to magnetite and hematite.

Central Siberia

The TDS curves for loess samples from the Kurtak section (Fig. 4g) are characterized by high values compared to the sections discussed above. However, the distinct decrease of susceptibility near 580 °C remains a common feature for all samples. Two types of TDS behaviour are found for loess units. The first type (sample from depth 6.9 m) shows a peak at about 300 °C on the heating curve while after heating to 700 °C the susceptibility decreases and is about half of its initial value at room temperature. The second type (sample from depth 12.4 m) exhibits a peak between 400 °C and 550 °C on the heating branch. While cooling down from 700 °C, the susceptibility increases greatly below 600 °C, reaching maximal values between 300 and 400 °C. Further cooling causes a gradual decrease and the final susceptibility at room temperature is 1.5–2.0 times higher than the initial values. The palaeosol samples from Kurtak have similar TDS characteristics to the other palaeosols described before.

As in Bachat, the thermal demagnetization of SIRM in Kurtak does not show any significant differences between loess and palaeosol. Both loess and palaeosol differ in their initial SIRM values only. The SIRM vanishes around 680 °C. After remagnetization the SIRM is about 25% lower. There is no difference in the SIRM between different loess.

The thermal demagnetization of NRM samples from the Kurtak section shows a considerable intensity loss between 180 and 300 °C, which is more pronounced in loess than in palaeosols. Above 580 °C, 1% of the NRM remains in the loess samples whereas in the palaeosol samples 5% remain. The NRM is completely demagnetized at 680 °C in both. Loess and palaeosols from Tatyshev (Fig. 4i) have a similar NRM intensity loss at 300 °C. At this temperature, the loess are demagnetized to 85% and the palaeosols to 75%. In the loess, the nearly complete NRM decay is observed at 600 °C. In the palaeosols, however, a small portion (<1%) of initial NRM is retained up to 700 °C, but such values are at the noise level of the instrument.

AF demagnetization of NRM of samples from Kurtak and Tatyshev may reflect the presence of low coercivity minerals. Loess samples demonstrate a rapid NRM decrease with MDFs less than 5 mT for Kurtak and 10 mT for Tatyshev. Between 5 and 10% of initial NRM remains at 100 mT. NRM decay in palaeosol samples from Kurtak has a nearly linear character with MDFs more than 60 mT. About 40% of initial NRM remains at 100 mT AF. In palaeosol samples from Tatyshev, 65% of the NRM decays below 10 mT (MDFs are less than 8 mT). Above 10 mT, the curve demonstrates a nearly linear character. About 15% of initial NRM remains at 100 mT.

Variations of S ratio versus depth for the sections Kurtak and Tatyshev (Fig. 5) show a decrease in palaeosol horizons. In general, the S ratio varies between 0.9 and 1.0 in loess horizons of both sections. However, the ratio is rather constant at Kurtak than at Tatyshev. All palaeosols (except PC1 in Tatyshev) demonstrate a distinct decrease of the S ratio below 0.9. The minimal S ratio values at Kurtak are 0.75 and at Tatyshev 0.85.

XRD analysis of the magnetic extraction from the Kurtak section (Fig. 4h) indicates the presence of magnetite and hematite in both loess and palaeosols. However the relative peak intensities may indicate a higher magnetite concentration compared to Bachat.

Anisotropy of magnetic susceptibility (AMS)

Near Ob' crest plain

The degree of anisotropy P′ for samples from the Belovo section (0.6) is relatively high compared to the other sections of the transect. P′ of individual loess samples can exceed 10%. In general, P′ falls within the range of 1.02–1.08 for loess horizons, while palaeosols predominantly have P′ values between 1.00 and 1.03, except for the middle part of PC2 palaeosol, where P′ exceeds 1.06. The depth variation of the AMS degree correlates with the magnetic susceptibility (Figs 2 & 6), in contrast to all other sections studied (see below). The AMS ellipsoid shape in loess horizons (L1 and L2) is predominantly oblate, more than 80% of samples have a shape factor of $T > 0.6$ (Fig. 6). The distribution of the principle susceptibility axes in loess demonstrates the typical sedimentary fabric, which is characterized by a minimum susceptibility axis in a nearly vertical direction and by a maximal axis quite close to the bedding plane. A slight magnetic lineation is also expressed. The maximal axes are well grouped in a SW-NE direction (Fig. 7). The mean directions of the minimal and maximal susceptibility axes, including their corresponding confidence limits, are given in Table 4. The magnetic fabric of palaeosol horizons at Belovo shows a different behaviour. Palaeosol unit PC1 has a similar magnetic fabric like the loess units, but the $K_{\max}$ axes cluster along the SSE–NNW direction. Palaeosol unit PC2 shows a rather random distribution of principal AMS axes. The shape factor (T) varies between −1.0 and 1.0 for both palaeosols.

The AMS degree in Lozhok (Fig. 6), Mramorny and Toguchin sections (latter two not shown) is lower than at Belovo and weakly correlates with susceptibility (Figs 2 & 6). P′ ranges between 1.01 and 1.06 in loess horizons, while palaeosols demonstrate P′ values between 1.00 and 1.03. Inclination variations of $K_{\max}$ and $K_{\min}$ show the same trend as in Belovo. The oblate shape of AMS ellipsoid is predominant in loess horizons, while palaeosol horizons demonstrate also nearly spherical and partly prolate shapes (Fig. 6). The maximal AMS axes are well grouped in loess horizons (Fig. 7). Unlike Belovo, the maximal AMS axes in L1 at Lozhok and Mramorny demonstrate a bimodal distribution: NW–SE and NNE–SSW (Fig. 7). At Toguchin, in contrast, a unimodal distribution is observed. Loess L2 exhibits a bimodal character only at Lozhok, with preferred $K_{\max}$ direction similar to L1. The preferred AMS $K_{\max}$ directions of L2 at Mramorny and Lozhok are similar to the corresponding mode in L1. Palaeosol unit PC1 demonstrates a SSW–NNE direction at Mramorny and Toguchin as the preferred orientation of $K_{\max}$, while at Lozhok no directional preference is seen (Fig. 7). Palaeosol unit PC2 has no preferred $K_{\max}$ orientation in all sections.

Kuznetsk depression

In contrast to the previously discussed sections, the AMS degree is not related to the susceptibility variations in both sections of Kuznetsk depression (Figs 2 & 6). Bachat demonstrates the lowest AMS degrees in the studied area. P′ ranges between 1.01 and 1.04 in loess horizons, while in palaeosols P′ does not exceed 1.02 (Fig. 6). The $K_{\min}$ inclinations are quite scattered throughout the sections; however, nearly vertical inclinations, correspond to loess layers and horizontal inclinations to palaeosol units. The shape factors vary between −1.0 and +1.0 in both loess and palaeosols, and the oblateness of the magnetic fabric is less pronounced in loess units. The palaeosols at Bachat show a random distribution of minimal and maximal AMS axes (Fig. 7).

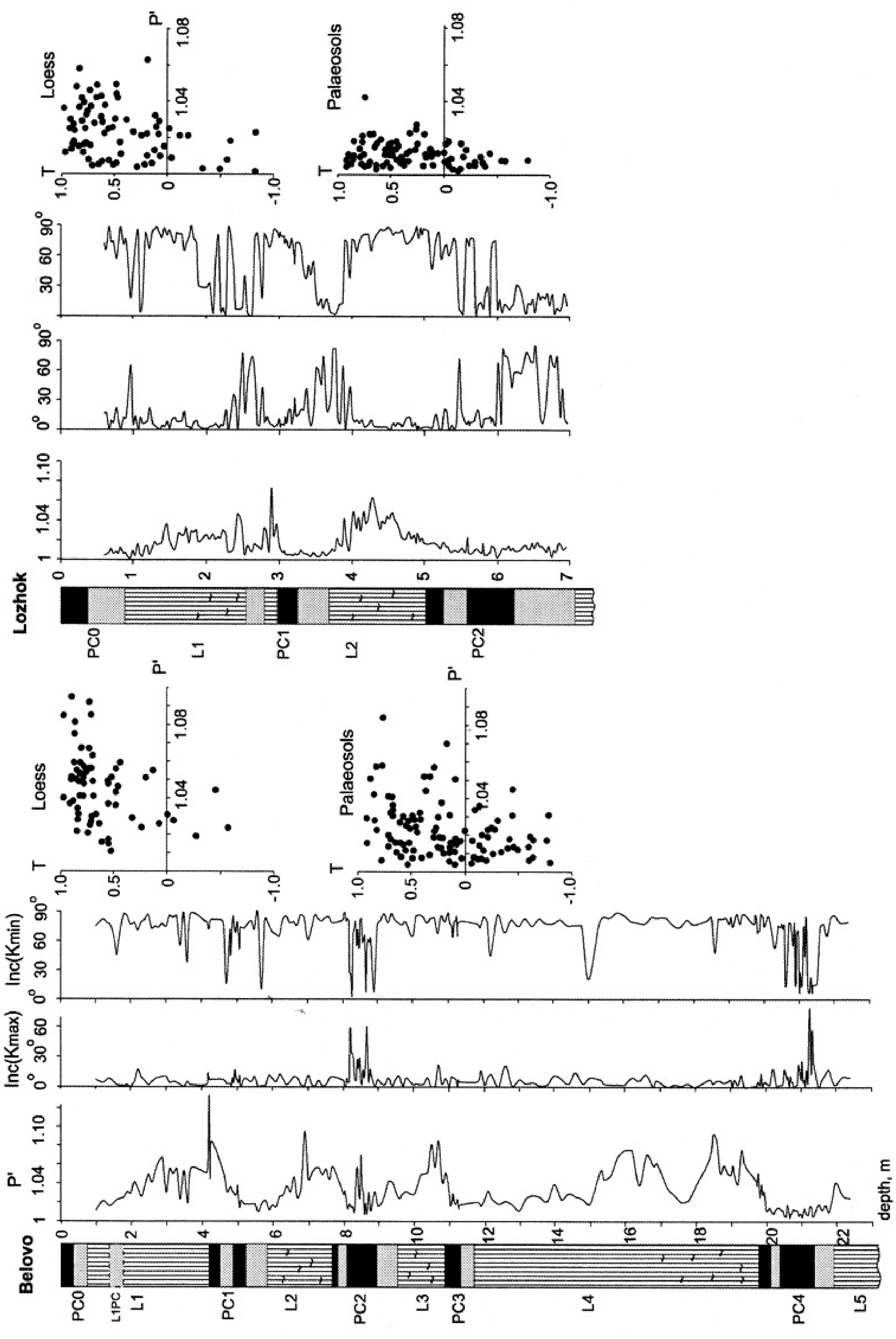

Fig. 6. Variations of AMS degree P′, inclinations of minimal and maximal AMS axes versus depth and plots of shape parameter T and AMS degree P′ of the studied sections.

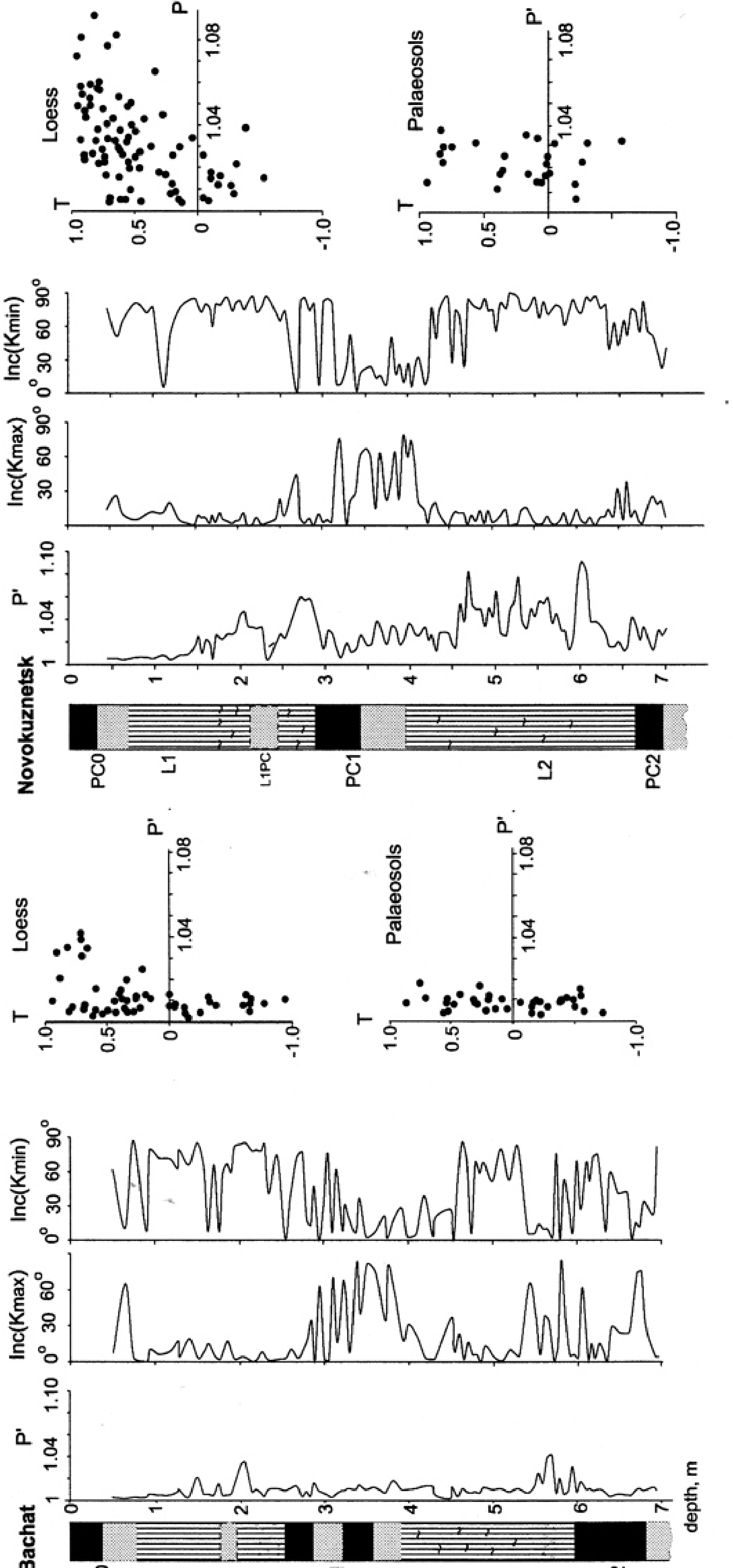
Novokuznetsk
PC0
L1
L1PC
PC1
L2
PC2
P'
1
1.04
1.10
0
1
2
3
4
5
6
7
Inc(Kmax)
30 60 90°
Inc(Kmin)
0° 30 60 90°
Loess
Palaeosols
T
1.0
0.5
0
-1.0
1.04
1.08
Bachat
PC0
L1
L1PC
PC1
L2
PC2
P'
1
1.04
1.10
Inc(Kmax)
0° 30 60°
Inc(Kmin)
0° 30 60 90°
depth, m
Loess
Palaeosols
T
1.0
0.5
0
-1.0
1.04
1.08

Fig. 6. (*cont.*)

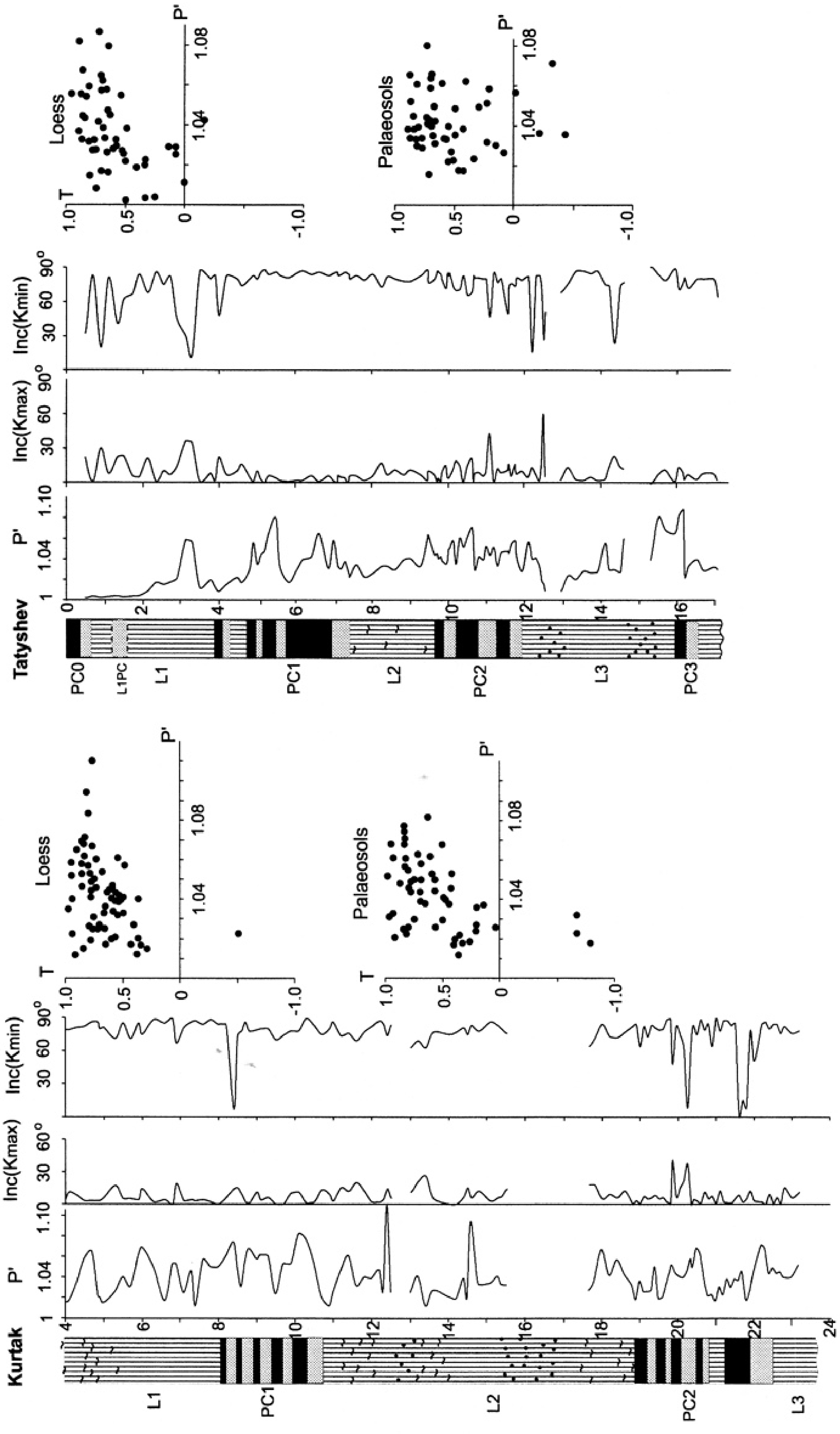
Tatyshev
PC0
L1PC
L1
PC1
L2
PC2
L3
PC3
0
2
4
6
8
10
12
14
16
P'
1
1.04
1.10
Inc(Kmax)
30
60
90°
Inc(Kmin)
30
60
90°
Loess
Palaeosols
T
1.0
0.5
0
-1.0
P'
1.04
1.08
Kurtak
L1
PC1
L2
PC2
L3
4
6
8
10
12
14
16
18
20
22
24
P'
1
1.04
1.10
Inc(Kmax)
30
60°
Inc(Kmin)
30
60
90°
Loess
Palaeosols
T
1.0
0.5
0
-1.0
P'
1.04
1.08

Fig. 6. *(cont.)*

Table 4. *AMS data for loess (L1 and L2) and palaeosol (PC1 and PC2) units of studied sections*

Horizon	N	D_{max}(°)	I_{max}(°)	α_{95} (°)	D_{min}(°)	I_{min}(°)	α_{95} (°)
Belovo section							
L1	22	242	6	29	58	86	4
PC1	22	168	2	8	80	85	6
L2	18	235	5	21	8	83	12
PC2	no preferred orientation						
Lozhok section							
L1	18	13	3	9	81	82	6
L1*	22	302	6	9	100	84	5
PC1	no preferred orientation						
L2	14	24	3	12	94	85	4
L2*	15	263	2	20	116	87	5
PC2	no preferred orientation						
Mramorny section							
L1	19	223	5	11	52	88	6
L1*	8	300	2	15	39	86	6
PC1	29	11	2	11	148	88	3
L2	25	296	1	12	12	80	4
Toguchin section							
L1	11	56	1	21	274	89	9
PC1	6	26	1	24	165	82	9
L2	6	17	5	29	58	87	26
PC2	no preferred orientation						
Bachat section							
L1	20	235	6	22	358	85	7
PC1	no preferred orientation						
L2	17	232	5	20	27	85	15
PC2	no preferred orientation						
Novokuznetsk section							
L1	20	285	2	10	111	84	4
L1*	19	185	1	3	80	85	5
PC1	no preferred orientation						
L2	24	91	2	12	246	85	4
L2*	12	181	1	15	155	88	4
PC2	no preferred orientation						
Kurtak section							
L1	24	270	5	15	88	87	3
PC1	11	272	7	21	76	86	6
PC1*	11	182	3	23	52	85	5
L2	32	237	5	9	66	84	5
PC2	25	7	1	13	348	88	5
PC2*	17	98	2	22	304	86	5
Tatyshev section							
L1	10	213	3	38	131	88	12
PC1	28	239	4	10	114	88	3
L2	27	232	6	11	29	84	4
PC2	17	224	13	15	60	83	5

N – number of samples; D and I – mean declination and inclination of the AMS axes, respectively; α_{95} – semi-angle of cone of confidence (P = 0.05); min and min indexes denote maximal and minimal axes. In case of two differently oriented assemblages of AMS direction in one unit, the second direction is given in the row just below, with the unit name marked by *.

The loess/palaeosol deposits at Novokuznetsk are characterized by enhanced AMS degrees compared to those from Bachat. Especially in L2, P′ exceeds 1.09, but ranges between 1.01 and 1.04 in palaeosol units (Fig. 6). The scatter of Kmin and Kmax inclinations are much less than at Bachat and follow a similar trend as in sections of the Near Ob' crest plain. The shape of the AMS ellipsoid is essentially oblate for loess units. However, values between −0.5 and 0 are also observed. The AMS ellipsoids in palaeosols have rather neutral shapes, only a few samples demonstrate oblateness with *T* values close to 1. Palaeosols PC1 and PC2 in

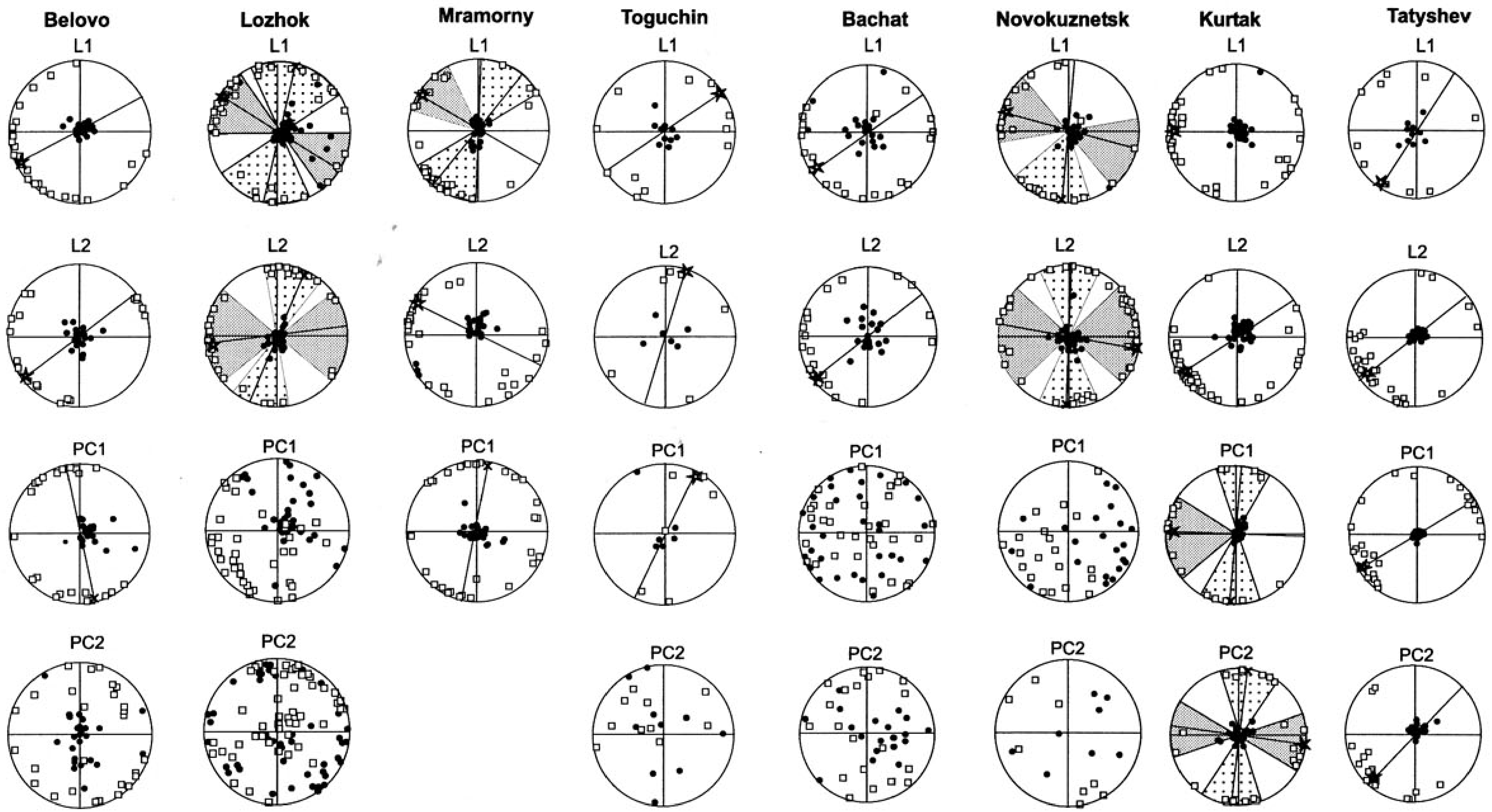

Fig. 7. Stereoplots of K_{max} (squares) and K_{min} (dots) principal AMS axes for loess (L1, L2) units and palaeosols (PC1 and PC2) for all studied sections. In sections Lozhok Mramorny, Novoreznetsk and Kurtak two different directions were found (marked by different colours). Mean directions are shown by stars and crosses and given in Table 4 with corresponding confidence limits.

both sections have no preferred K_{max} orientations. The maximal susceptibility axes in L1 and L2 at Bachat are grouped in SE–NW direction. The means are not statistically different from those of Belovo and Toguchin (Fig. 7). The loess units at Novokuznetsk have a bimodal distribution of preferred K_{max} axes (Fig. 7) W–E and S–N, being similar to Lozhok.

Central Siberia

In the Minusa depression just behind the Kuznetsk Ala-Tau ridge, the AMS degree increases in comparison with the Kuznetsk depression. P′ ranges between 1.02 and 1.10 and between 1.00 and 1.08 for loess at Kurtak and Tatyshev, respectively. Palaeosols demonstrate P′ values between 1.01 and 1.08 in both sections. The stratigraphic distribution of K_{max} and K_{min} inclinations at Kurtak and Tatyshev is generally similar to Belovo. Steep K_{max} inclinations, however, are quite rare (Fig. 6). Both loess and palaeosol horizons demonstrate a predominant oblate magnetic fabric with mean T values >0.5.

The K_{max} axes are mainly distributed along an E–W orientation in loess L1 at Kurtak; L2 shows a NE–SW orientation. Both loess layers at Tatyshev show NE–SW orientation of the AMS maximum axes. The K_{max} axes of the palaeosols units PC1 and PC2 at Tatyshev have the same orientation as the loess. At Kurtak, in contrast, a bimodal distribution is observed. The two observed predominant directions (E–W and S–N) correspond to different parts of the palaeosol units. All mean K_{max} directions of humus horizons coincide with those of the overlying loess units, while the means of K_{max} directions of illuvial horizons are in good agreement with those of the underlying loess. A similar observation has been made by Matasova *et al.* (2001).

Discussion

Magnetic mineralogy

Magnetite appears to be the predominant magnetic mineral of Siberian loess/palaeosol deposits. It has clearly been identified by the temperature dependence of magnetic low-field susceptibility. Most of the loess and palaeosol samples demonstrate a considerable decrease around 580 °C (Fig. 4d, f, g, i). Magnetite has also been identified by X-ray diffraction (Fig. 4e, h). Due to its high magnetization (Dunlop & Özdemir 1997), magnetite is believed to cause higher susceptibilities in loess layers, especially at Kurtak and Tatyshev (Fig. 2). Highest NRM values were also observed at Kurtak and Tatyshev (Fig. 4g, i). The low FD-values in loess layers may indicate the absence of superparamagnetic grains, and the susceptibility of the loess is mainly caused by multidomain grains. Equidimensional single domain grains of magnetite, which are also responsible for high susceptibilities (Dunlop & Özdemir 1997), are not expected to occur in loess. In palaeosols, however, superparamagnetic grains are present.

Concerning the temperature behaviour, the susceptibility drops down above 580 °C in some samples (Belovo, Mramorny, Fig. 4a, b). The curves show a small bulge around 250–350 °C and thermal demagnetization of SIRM demonstrates a considerable loss of intensity at the same temperature range. The second heating run of the SIRM does not show such a feature. This behaviour indicates the presence of maghemite in the samples, which converts to hematite during heating (Dunlop & Özdemir 1997). The presence of maghemite in samples from Belovo and Kurtak is also supported by (1) the reversible character of partial TDS heating/cooling paths below 300 °C (Zhu *et al.* 2003; Matasova *et al.* 2003) before maghemite-hematite conversion, and their irreversible character after the conversion above 400 °C (Zhu *et al.* 2003; Matasova *et al.* 2003), and (2) the fact that TDS behaviour of magnetic extracts indicates the same susceptibility peak at 350 °C on the heating branch and a slight decrease in total susceptibility after cooling (Matasova *et al.* 2003). Maghemite may be present as oxidation cover of magnetite grains in loess horizons and magnetite probably can be completely oxidized to maghemite in palaeosol units as the result of pedogenesis. Matasova *et al.* (2001) and Zhu *et al.* (2003) observed a suppression of the Verwey transition in samples from Kurtak and Bachat, being a indicator for weathering of magnetite grains (Dunlop & Özdemir 1997).

Alternating field demagnetization of NRM indicates the presence of high coercivity remanence-carrying minerals. Loess/palaeosol samples from the Near Ob' crest plain and the Kuznetsk depression still retain 10–50% of the NRM at 100 mT (Fig. 4a–d, f). Palaeosols from Kurtak and Tatyshev retain 25% and 10%, respectively (Fig. 4g, i). The S ratio represents the proportion of low-coercivity minerals to high-coercivity minerals. Figure 5 shows that lower values (about 0.8) are related to palaeosol units, whereas loess layers have rather constant values around 1. Due to the field applied of 1.4 T, lower S ratios may be related to hematite. Thermal demagnetization of NRM and SIRM (Belovo, Fig. 4a) also suggests the presence of hematite above the superparamagnetic grain-size limit. Hematite is clearly identified by XRD spectra (Fig. 4e, h). The enhanced occurrence of hematite in soils may be indicative of a rather dry climate (Maher 1986, 1998). The relative peak intensities of hematite are much smaller than for magnetite, suggesting a lower percentage of hematite being present. Evidence for remanence-carrying goethite has not been found. It may occur as superparamagnetic particles. As hematite is formed in competition with goethite (Schwertmann 1988), it may have existed at the time when the soil was formed but dehydrated later.

As discussed, loess/palaeosol deposits of the Siberian aeolian realm contain three different magnetic minerals and have a similar qualitative magnetic composition. Susceptibility, FD- value and S ratio profiles, however, are different and show variations in dependence of the geographical position of the sections. Hence, the magnetic properties of the sediments are determined by relative concentration differences.

It is very important that similar composition of magnetic minerals (magnetite, hematite and maghemite) and also found in the other loess/palaeosol provinces such as Chinese loess plateau and Alaska (Florindo *et al.* 1999; Guo *et al.* 2002; Heller & Evans 1995; Lagroix & Banerjee 2002). NRM decay curves during thermal demagnetization of Chinese palaeosols (Heller & Evans 1995; Pan *et al.* 2001; Guo *et al.* 2002) are very similar to Siberian palaeosols. Chinese palaeosols during AF demagnetization show MDF < 10 mT, while for Siberian palaeosols MDF can exceed 50 and even 80 mT, indicating the greater concentration of high coercivity minerals (probably, hematite). This higher hematite concentration is supported by the difference in Hcr values of Chinese and Siberian deposits. The first are characterized by Hcr values from 20 to 50 mT (Florindo *et al.* 1999; Pan *et al.* 2001; Guo *et al.* 2002) and the second by Hcr of 60–80 mT (Zhu *et al.* 2003). It may appear that the enhanced hematite concentration in Siberian loess and palaeosols in comparison with Chinese ones is responsible for their higher magnetic anisotropy. However this is probably not the case, because loess/palaeosol deposits in Alaska are characterized by Hcr values 40–55 mT (Lagroix & Banerjee 2002) within the range of Chinese Hcr, while the AMS degree for loess/palaeosol deposits in Alaska more closely resembles the AMS degree of Siberian deposits.

The difference in magnetic anisotropy of Chinese loess/palaeosol deposits on the one hand and Siberian and Alaskan deposits on the other results not from a difference in magnetic composition or the proportion of hematite concentration but is most likely determined by different climatic and environmental conditions in those regions.

Palaeoclimatic reconstruction

The magnetic signature of loess/palaeosol units in the Siberian subaerial realm is controlled by the superposition of two mechanisms: the wind-vigour mechanism and the pedogenic mechanism. Both depend strongly on local and regional climate.

Near Ob' crest plain

The most distinct picture showing this superposition is observed in the southwestern part of the Near Ob' crest plain. Both mechanisms are most pronounced at Belovo. During glacials, the wind strength is strongest and the wind-vigour mechanism causes higher susceptibility values with a preferred orientation of magnetic grains. During interglacials and interstadials, high temperatures and moderate humidity force pedogenesis, and much less material is deposited due to lower wind strengths. Pedogenesis may not be strong enough to form larger quantities of single domain magnetite/maghemite particles, because palaeosols susceptibilities are not enhanced, compared to those of loess. Pedogenesis causes enhanced FD values (Figs 2 & 3) and lower S ratios (Fig. 5) and, along with weathering, cryo- and bioturbation processes cause a destruction of magnetic fabric in palaeosols (Fig. 7). The superposition of both processes is seen in a direct correlation between magnetic susceptibility and degree of anisotropy (Figs 2 & 6).

Towards the north and NE, the superposition of the two mechanisms still holds true but is less pronounced resulting in an obscured picture due to slight differentiation in magnetic properties between loess and palaeosols. This process is governed by an equilibrium between humidity, temperature conditions and distance from the detrital source. Wind strengths are weaker and the correlation between AMS degree and preferred orientation of magnetic minerals is less pronounced (Fig. 7). The decrease of magnetic susceptibility and slight increase of FD values in loess horizons (Figs 2 & 3) observed towards the Salair mountain ridge may be caused by a relative increase in humidity of the palaeoclimate, as is observed in the modern climate (Table 2). The susceptibility remains nearly constant between different palaeosol units, while FD values and S ratios demonstrate large scattering.

However, the FD values are still higher, and the S ratio is lower than in loess horizons (Fig. 2). This means that pedogenesis in palaeosols from the Near Ob' crest plain is controlled mainly by precipitation and less by the temperature, similar to China (Maher & Thompson 1995).

Kuznetsk depression

The slight increase of magnetic susceptibility in palaeosol units in the Kuznetsk depression (sections Bachat and Novokuznetsk) results most probably from a little stronger pedogenesis. It may result from higher relative humidity and snow cover, moderate temperatures and lower evaporation (at Novokuznetsk) as indicated by modern climatic conditions (Table 2). The FD values of loess horizons are also slightly increased, suggesting that climatic conditions favour pedogenic activity. However, the magnetic susceptibility and the S ratio both demonstrate irregular variations. The AMS degree is low and not related to the susceptibility. The magnetic fabric of the palaeosol unit PC1 and PC2 is completely random, which also favours the argument that stronger pedogenesis has taken place. The AMS degree in palaeosol units shows an inverse correlation with pedogenic intensity determined from FD values (Jordanova & Jordanova 1999). Increased FD values correspond to lower preservation of the initial parent loess deposit and the magnetic fabric is distorted or lost by pedogenic reworking. The annual temperature in the Kuznetsk depression is much lower relative to Belovo, while humidity is higher (Table 2). Apparently, increased humidity influences the strength of pedogenic activity rather than temperature.

Minusa and Rybinsk depression

Further northeastward, behind the Kuznetsk Ala-Tau mountain ridge, the difference between loess and palaeosol is clearly expressed in the magnetic properties. Most likely, the palaeoclimate was rather dry and cold with strongest wind intensity due to the closer position to the Siberian High. Thus, much more loess was deposited and the sections are thicker (Kurtak vs. Belovo). Deposits from Kurtak and Tatyshev sections evidently correspond to the pure 'Alaskan' model without significant pedogenesis. However, lower S ratios in palaeosol units at Kurtak may indicate the formation of pedogenic hematite (see below).

The S ratios indicate that high coercivity minerals, namely hematite, occur mainly in palaeosol units. This occurrence seems to be also dependent upon the climatic conditions, for example S ratios PC1 vs. PC2 units for all sections (Fig. 5). Hematite forms via dehydration and structural rearrangements from poorly crystalline ferrihydrite in competition with goethite (Schwertmann 1988). This reaction favours hematite in low humidity and nearly neutral pH values. Such conditions are met in the present day soils of the Siberian realm (especially in the southwestern part), which are mostly chernozems (Table 2).

We argue that pedogenic hematite formation in dry climates with low humidity is an important factor. Novokuznetsk has the highest relative humidity (90%), highest precipitation and lowest evaporation. Therefore, it demonstrates the smallest variation of the S ratio (Fig. 5).

It seems that temperature and humidity are affecting the neoformation of pedogenic magnetite/maghemite rather than the formation of pedogenic hematite. On the Chinese loess plateau, remanence carried by hematite seems to be of detrital origin, whereas pedogenic hematite is superparamagnetic (Spassov *et al.* 2003). We propose the same situation for Siberian loess/palaeosols units, where hematite probably is of both detrital and pedogenic origin for southwestern sections and mainly of pedogenic origin in palaeosol units from central Siberia.

Thus, pedogenic enhancement of magnetic minerals seems be a non-negligible factor in loess/palaeosol sections of the Siberian subaerial realm.

Palaeowind direction

The unaltered loess has retained its primary magnetic fabric with orientation of magnetic grains (W–E or SW–NE) according to the predominant palaeowind direction. High AMS degree, preferred orientation of AMS axes and essentially oblate magnetic fabric testify that these loess layers have undergone compaction only, without any secondary reworking. The palaeowind intensity probably is pronounced in the AMS degree. Palaeowind directions for L1 loess units are more or less uniform (from WSW–NNE to W–E, Table 4, Fig. 7) and close to the modern wind direction all over the studied area (Fig. 7). At Lozhok and Mramorny, two wind directions are observed. This is in agreement with modern winds during spring and autumn at these localities which have two predominant orientations (SW–NE and S–N, respectively, Gusthina… 1979). The same situation is expected for Toguchin where the modern wind direction also has bimodal character, but the number of samples is not enough to draw such a conclusion (Fig. 7). The difference in palaeowind directions for adjacently located sections Lozhok and Mramorny is probably connected with their different landscape position. Lozhok is located on a leeward slope of the river valley, while Mramorny is located on the windward slope of the watershed and is 30 m higher in altitude. A similar situation holds in the Kuznetsk depression where differences in the palaeowind direction are observed. Bachat is located in the middle of the Kuznetsk depression and is partially screened by the Salair ridge, so the wind intensity must be weakened. Novokuznetsk, in contrast, is located on the southwestern windward slope of the depression in the foothills of the Kuznetsk Ala-Tau mountain ridge where the atmospheric circulation is essentially affected by mountain relief.

Tatyshev has almost constant AMS patterns. The K_{max} AMS axes are similar to L1 and L2 at Belovo/Bachat and L2 at Kurtak. Since palaeosol unit PC2 derived its magnetic fabric from the underlying loess L3, it can be concluded that the main wind directions have generally not changed along the transect over the last 180 000 years respectively since OIS 6. The AMS pattern of palaeosol PC2 appears to be more distorted than in PC1 (Fig. 7, Belovo, Lozhok, Toguchin). The S ratio at Kurtak, Belovo and Lozhok is a little smaller in PC1 than in PC2. There is no difference at all between PC1 and the over- and underlying loess horizons at Tatyshev, in contrast to PC2. It is therefore suggested that pedogenesis was stronger during OIS 5 than during OIS 3. This is in agreement with observations from the central Chinese Loess Plateau. In China, the susceptibility of palaeosol L_1S_1, which is correlated with OIS 3 and PC1, is two times lower than that of palaeosol S1 (OIS5/PC2) (Sartori 2000).

Conclusions

- The magnetic composition of Siberian loess/palaeosol deposits consists of three main minerals: magnetite, maghemite and hematite. This qualitative composition is similar to other loess/palaeosol provinces in China and Alaska. Their variable concentration depends on climate and determines the magnetic properties of loess/palaeosol deposits and the mechanism of magnetic response on climatic changes ('Chinese', 'Alaskan' or 'Siberian'). Although the 'Siberian' mechanism is the superposition of the 'Chinese' and 'Alaskan' ones, from our viewpoint, it may be considered as a new individual mechanism due to its own peculiarities and advantages.
- In general, the 'Alaskan' wind-vigour mechanism predominates the magnetic enhancement in loess of the Siberian subaerial realm. 'Chinese' pedogenic mechanism plays a minor, but non-negligible role. Superparamagnetic minerals are formed and their presence is mainly indicated by high FD values in palaeosols. Both mechanisms are active and their relative contribution depend on local climate conditions. The Kuznetsk Ala-Tau mountain ridge is the geographical barrier between rather humid climate in the SW and a rather dry/cold climate in the NE. Correspondingly, the wind-vigour enhancement dominates in the NE, whereas in the SW pedogenic magnetic mineral enhancement gains in importance.
- According to present-day climate parameters, the Siberian subaerial realm is divided into different sub-zones. The magnetic parameters reflect this subdivision and suggest that the climate of the past 180 000 years has not changed to a greater or lesser extent. However, the amplitude of past global climate changes is also reflected in Siberian palaeosols. The marine oxygen isotope stage 3 is less pronounced in Siberia than stage 5, which is in agreement with observations on the Chinese Loess Plateau and other sedimentary record worldwide.
- The distribution of K_{max} axes reflects palaeowind directions in unaltered loess with a pristine sedimentary fabric. In palaeosols, however, the distribution of K_{min} and K_{max} axes is a sensitive indicator for the degree of pedogenesis.
- Humidity seems to be an important climate factor for the degree of pedogenesis. During the Late Pleistocene, the Kuznetsk depression was a region with its own local mild/humid microclimate due to its specific isolated geographical position. The climate was characterized by the optimal balance between humidification and temperature over the studied area, which is still retained in modern climate.

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References

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. *Russian Geology and Geophysics*, **38(6)**, 1065–1985.

Baranov, A. N. & Blinova, A. N. (eds). 1969. *Atlas of the USSR*. GUGK, Moscow. (In Russian)

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.

Burakov, K. S. 1977. Thermomagnetometer. *Izvestia AN SSSR. Fizika Zemli*, **5**, 92–96. (In Russian).

Chlachula, J. 1999. Loess-palaeosol stratigraphy in the Yenisey basin, Southern Siberia. *Sbornik Geologickych Ved,. Journal of geological sciences. Anthropozoic*, **23**, 55–70.

Chlachula, J., Evans, M. E. & Rutter, N. W. 1998. A magnetic investigation of a Late Quaternary loess/palaeosol record in Siberia. *Geophysical Journal International*, **132**, 128–132.

Chlachula, J., Rutter, N. W. & Evans, M. E. 1997. A late Quaternary loess-palaeosol record at Kurtak, southern Siberia. *Canadian Journal of Earth Sciences*, **34(5)**, 679–686.

Davitaya, F. F. & Pastukh, V. P. (eds) 1960. *Climatic Atlas of the USSR. V. 1.* GUGK, Moscow. (In Russian).

Dearing, J., Livingstone, I. & Zhou, L. P. 1996. A Late Quaternary magnetic record of Tunisian loess and its climatic significance. *Geophysical Research Letters*, **23**, 2, 189–192.

Derbyshire, E., Billard, A., Vliet-Lanoe, B. V., Lautridou, J.-P. & Cremaschi, M. 1988. Loess and palaeoenvironment: some results of European joint program of research. *Journal of Quaternary Science*, **3**, 147–169.

Dobrovolsky, V. V. 1976. *Soil Geography and Basic Pedology*. Prosveshenie Publishing, Moscow. (In Russian).

Dunlop, D. J. & Özdemir, O. 1997. *Rock Magnetism: Fundamentals and Frontiers*, Cambridge University Press, Cambridge.

Foronova, I. V. 1999. Quaternary mammals and stratigraphy of the Kuznetsk Basin (South-Western Siberia). *Sbornik Geologickych Ved. Anthropozoic*, **23**, 71–99.

Florindo, F., Zhu, R., Guo, B., Yue, L., Pan, Y. & Speranza, F. 1999. Magnetic proxy climate results from the Duanjiapo loess section, southernmost extremity of the Chinese loess plateau. *Journal of Geological Society*, London, **104**, 3, 645–659.

Frechen, M. & Yamskikh, A. F. 1999. Upper Pleistocene loess stratigraphy in the southern Yenisei Siberia area. *Journal of Geophysical Research*, **156**, 3, 515–525.

Guo, B., Zhu, R. X., Florindo, F., Ding, Z. L. & Sun, J. M. 2002. A short, reverse polarity interval within the Jaramillo subchron: Evidence from the Jingbian section, northern Chinese Loess Plateau. *Journal of Geophysical Research*, **107**, 2124–2124.

Gusthina, A. G. (ed). 1979. *Atlas of the Novosibirsk Region*. GUGK, Novosibirsk. (in Russian).

Heller, F. & Evans, M. E. 1995. Loess magnetism. *Reviews of Geophysics and Space Physics*, **33**, 211–240.

Heller, F. & Liu, T. S. 1986. Paleoclimatic and sedimentary history from magnetic susceptibility of loess in China. *Geophysical Research Letters*, **13**, 1169–1172.

Hus, J. J. 2003. The magnetic fabric of some loess/palaeosol deposits. *Physics and Chemistry of the Earth*, **28**, iss. 16–19, 689–699.

Jelínek, V. 1977. *The Statistical Theory of Measuring Anisotropy of Magnetic Susceptibility of Rocks and Its Application*. Brno, Geofyzika.

Jelínek, V. 1981. Characterisation of magnetic fabric of rocks. *Tectonophysics*, **79**, 63–67.

Jordanova, D. & Jordanova, N. 1999. Magnetic characteristics of different soil types from Bulgaria. *Studia Geophysica et Geodaetica*, **43**, 303–318.

Jordanova, N., Jordanova, D. & Karloukovski, V. 1996. Magnetic fabric of Bulgarian loess sediments derived by using various sampling techniques. *Studia Geophysica et Geodaetica*, **40**, 36–49.

Kukla, G. F., Heller, F., Liu, X. M., Xu, T. S. & An, Z. S. 1988. Pleistocene climates in China dating by magnetic susceptibility. *Geology*, **16**, 811–814.

Lagroix, F. & Banerjee, S. K. 2002. Paleowind directions from the magnetic fabric of loess profiles in central Alaska. *Earth and Planetary Science Letters*, **195**, 99–112.

Liu, X., Xu, T. & Liu, T. 1988. The Chinese loess in Xifeng. II: A study of anisotropy of magnetic susceptibility of loess from Xifeng. *Geophysical Journal of the Royal Astronomical Society*, **92**, 349–353.

Liu, X. M., J. Shaw, T. S. Liu, F. Heller & M. Y. Cheng. 1994. Rock Magnetic Properties and Palaeoclimate of Chinese Loess. *J. Geomagnetism and Geoelectricity*, **45**, 117–124.

Lu, H. Y., Yang, W. F., Liu, X. D. & An, Z. S. 1998. Orbital tuned time scale for loess deposit in Luochuan of Central Chinese Loess Plateau. *Acta Geophysica Sinica*, **41**, 6, 810–816.

Maher, B. A. 1986. Characterization of soils by mineral magnetic measurements. *Physics of the Earth and Planetary Interiors*, **42**, 76–92.

Maher, B. A. 1998. Magnetic properties of modern soils and Quaternary loessic palaeosols: paleoclimatic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **137**, 25–54.

Maher B. A. & Thompson R. 1991. Mineral magnetic record of the Chinese loess and palaeosols. *Geology*, **19**, 3–6.

Maher, B. A. & Thompson, R. 1992. Paleoclimatic significance of the mineral magnetic record of Chinese loess and palaeosols. *Quaternary Research*, **37**, 155–170.

Maher B. A. & Thompson R. 1995. Paleorainfall reconstructions from pedogenic magnetic susceptibility variations in the Chinese loess and palaeosols. *Quaternary Research*, **44**, 383–391.

Mangerud, J., Svendsen, J. I. & Astakhov, V. I. 1999. Age and extent of the Barents and Kara ice sheets in Northern Russia. *Boreas*, **28**, 46–80.

Matasova, G., Petrovsky, E., Jordanova, N., Zykina, V. & Kapichka, A. 2001. Magnetic study of Late Pleistocene loess/palaeosol sections from Siberia: palaeoenvironmental implications. *Geophysical Journal International*, **147**, 367–380.

Matasova, G. G., Kazansky, A. Yu. & Zykina, V. V. 2002. Magnetic grain size in loess/soil deposits of Novokuznetsk section (Kuznetsk depression) as an indicator of climatic oscillations. *In*: Vaganov, E. A., Derevyanko, A. P., Grachev, M. A. (eds) *Main Legitimates of Global and Regional Changes of Climate and Environment in Late Cainozoic of Siberia*. IAIE SO RAN, Novosibirsk, 323–337. (in Russian).

Matasova, G. G., Kazansky, A. Yu. & Zykina, V. S. 2003. Superposition of 'Alaskan' and 'Chinese' proxy climatic signals recorded in magnetic properties of Upper and Middle Neopleistocene deposits in Southern West Siberia. *Russian Geology and Geophysics*, **44**, 607–619.

Moskvitin, A. I. 1940. Loess and loess-like deposits from Siberia. *Publishing of Geological Institute. Geological series*. **14(4)**, 1–83 (in Russian).

Nagata T. 1961. *Rock Magnetism*. Tokyo, Maruzen.

Näslund, J. O., Rodhe, L., Fastook, J. L. & Holmlund, P. 2003. New ways of studing ice sheet flow directions and glacial erosion by computer modelling – examples from Fennoscandia. *Quaternary Science Reviews*, **22**, 245–258.

Pan Y. X., Zhu, R. X., Shaw, J., Liu, Q. S. & Guo, B. 2001. Can relative paleointensities be determined from the normalized magnetization of the wind-blown loess of China? *Journal of Geophysical Research*, **106**, B9, 19221- 19232.

Protsuk, I. S. (ed.) 1978. *Altai Region Atlas*. GUGK, Moscow-Barnaul. (in Russian).

Rees, A. I. 1966. The effect of depositional slopes on the anisotropy of magnetic susceptibility of laboratory deposited sands. *The Journal of Geology*, **74**, 6, 856–867.

Reinders, J. & Hambach, U. 1995. A geomagnetic event recorded in loess deposits of the Tonchesberg (Germany): identification of the Blake magnetic polarity episode. *Geophysical Journal International*, **122**, 407–418.

Rolph, T. C., Shaw, J., Derbyshire, E. & Wang, J. T. 1989. A detailed geomagnetic record from Chinese Loess. *Physics of the Earth and Planetary Interiors*, **56**, 151–164.

Sartori, M. 2000. *The Quaternary climate in loess sediments: Evidence from rock and mineral magnetic and geochemical analysis*, Doctoral Thesis, Diss. ETH No. 13570, Zürich.

Schwertmann, U. 1988. Occurrence and formation of iron oxides in various pedoenvironments. *In*: Stucki, J. W., Goodman, B.A. & Schwertmann, U. (eds) *Iron in Soils and Clay Minerals*. D. Reidel Publishing, Dordrecht, Boston, Lancaster, Tokyo, 267–308.

Spassov, S., Heller, F., Kretzschmar, R., Evans, M. E., Yue, L. P. & Nourgaliev, D. K. 2003. Detrital and pedogenic magnetic mineral phases in the loess/palaeosol sequence at Lingtai (Central Chinese Loess Plateau). *Physics of the Earth and Planetary Interiors*, **140**, 4, 255–275.

Svezhentsev Yu. S., Lisitsin N. F. & Vasil'ev S. A. 1992. Radiocarbon chronology of the Yenisey Palaeolithic. In: *Chronostratigraphy of Palaeolithic of Northern, Central and Eastern Asia and America*. Publications of International Sympothium. RAN, Siberian Branch. Institute of History, Philosophy and Philology , Novosibirsk, 57–64 (in Russian).

Tarling, D. H. & Hrouda, F. 1993. *The Magnetic Anisotropy of Rocks*. Chapman & Hall, London.

Thistlewood, L. & Sun, J. 1991. A palaeomagnetic and mineral magnetic study of the loess sequence at Liujiapo, Xian, China. *Journal of Quaternary Science*, **6**, 13–26.

Vlag, P. A., Oches, E. A., Banerjee, S. K. & Solheid, P. A. 1999. The paleoenvironmental-magnetic record of the Gold Hill Steps loess section in central Alaska. *Physics and Chemistry of the Earth*, **24 (9)**, 779–783.

Volkov, I. A. 1971. Late Quaternary subaerial sedimentary association. Nauka Press, Moscow. (In Russian).

Volkov, I. A. & Zykina, V. S. 1984. Loess stratigraphy in the south-western Siberia. *In*: Velichko A. A. (ed.) *Late Quaternary Environments of the Soviet Union*. University of Minneapolis Press, Minneapolis, 119–124.

Yamskikh, A. F. 1992. Polycyclic terrace formation and stratigraphic subdivision of Quaternary deposits of river valleys from non-glacial zone of Near-Yenisey region in Siberia. Zodiac Publishing, Krasnoyarsk. (In Russian).

Zander, A., Frechen, M., Zykina, V. & Boenigk, W. 2003. Luminescence chronology of the Upper Pleistocene loess record at Kurtak in Middle Siberia. *Quaternary Science Review*, **22**, 999–1010.

Zhu, R. X., Coe, R. S. & Zhao, X. X. 1998. Sedimentary record of two geomagnetic excursions within the last 15,000 years in Beijing, China. *Journal of Geophysical Research*, **103**, B12, 30323–30333.

Zhu, R. X., Pan, Y. X. & Liu, Q. S. 1999. Geomagnetic excursions recorded in Chinese loess in the last 70,000 years. *Geophysical Research Letters*, **26(4)**, 505–508.

Zhu, R. X., Kazansky, A., Matasova, G., Guo, B., Zykina, V., Petrovsky, E. & Jordanova, N. 2000. Rock-magnetic investigation of Siberia loess and its implication. *Chinese Science Bulletin*, 45, 23, 2190–2197.

Zhu, R. X., Matasova, G., Kazansky, A., Zykina, V. & Sun, J. M. 2003. Rock magnetic record of the last glacial-interglacial cycle from Kurtak loess section, southern Siberia. *Geophysical Journal International*, **152**, 335–343.

ZYKINA, V. S. 1999. Pleistocene pedogenesis and climatic history of Western Siberia. *Sbornik Geologickych Ved,. Journal of geological sciences. Anthropozoic*, **23**, 49–53.

ZYKINA, V. S. & KIM, Y. V. 1989. Pedogenesis and loess sedimentation in Pleistocene in south-eastern part of West Siberia *In*: ARKHIPOV, S. A. & VOLKOVA, V. S. (eds) Pleistocene of Siberia. Stratigraphy and interregional correlations. SB RAS Publishing, Novosibirsk, **657**, 81–86. (In Russian).

ZYKINA, V. S., VOLKOV, I. A. & DERGACHEVA, M. I. 1981. The Upper Quaternary Deposits and Fossil Soils of Novosibirsk PreObje. Nauka, Moscow (in Russian).

ZYKINA, V. S., VOLKOV, I. A. & SEMENOV, V. V. 2000. Neopleistocene climatic reconstruction in West Siberia based on study of Belovo key section. *In*: VAGANOV, E. A. & DEREVYANKO, A. P. (eds.) *Problems of Reconstruction of Holocene and Pleistocene Climate and Environment in Siberia*, SB RAS Press, Novosibirsk, 229–249. (In Russian).