Sborník geologických věd	Antropozoikum 23	Pages 49–54	– fig.	3 tabs.	– pl.	ČGÚ Praha 1999	ISBN 80-7075-272-6 ISSN 0036-5270

Pleistocene pedogenesis and climatic history of Western Siberia

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Received October, 1996

Key words: Loess-paleosol sections, Pleistocene, Pedogenesis, Climate, Pedocomplexes, Western Siberia

Zykina, V. S. (1999): Pleistocene pedogenesis and climatic history of Western Siberia. – Sbor. geol. Věd, Antropozoikum, 23, 49–54. Praha.

Abstract: Principal loess-paleosol sections of West Siberia are located in southern acccumulation regions. Nine major pedocomplexes and loess units are present in the subaerial deposits of West Siberia above the Brunhes/Matuyama palaeomagnetic boundary. Accumulation of each loess unit was followed by a pedogenesis phase. The altered loess deposits differed in terms of degree of pedogenesis between the Lower, Middle and Upper Pleistocene. The Early Pleistocene soil formation phases were characterized by a prolonged duration, a higher heat balance and humidity. Soils of subboreal meadow-forest and forest-steppe types are typical of this period. The Middle Pleistocene pedogenetic phases were shorter, though the climate was similar to that of the Early Pleistocene, but became more continental. Soils typologically close to modern ones of West Siberia characterise that time. The Late Pleistocene phases of soil formation were of a much shorter duration. Soils of steppe and dry steppe type formed under a less warm and drier climate than previously. Each Late Pleistocene pedogenesis was followed by a cold and wet cryogenic phase.

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INTRODUCTION

The West Siberian Quaternary subaerial deposits are widely distributed in the regions stretching as a wide belt from the Urals to Altai, Salair and Sayan Mountains. The subaerial formation has a complex facial development. Volkov (1971) demarcated the regions where there has been accumulation of aeolian sand and silty deposits respectively. The loess sections located in the region provide the most complete climato-stratigraphical and palaeogeographical information. They record the history of most of the Pleistocene in terms of climate and natural environment change, and provide the basis for prediction of future trends of climatic changes.

Analysis of the subaerial formation and its structural peculiarities indicates a climatically controlled cyclic structure (Volkov 1980, 1983, Zykina 1980, 1986, Volkov - Zykina 1991). The cyclicity is represented by three major stratigraphical units, formation of which were determined by definite climatic cycles. Each cycle began with a dry and cold climatic phase when loess accumulated, followed by moderate conditions similar to the present ones promoting pedogenesis and concluded by a cold and wet phase, which brought about cryogenic distortion of the soil cover. Each subsequent climatic cycle proceeded on a qualitatively different level principially controlled by the ratio of heat and water supply.

The study of cycles reflecting the main climatic rhythms has been the basis for the stratigraphical classification of the loess deposits of Western Siberia (Tab. 1) (sine1983, 1990, Volkov et al. 1990).

EARLY PLEISTOCENE

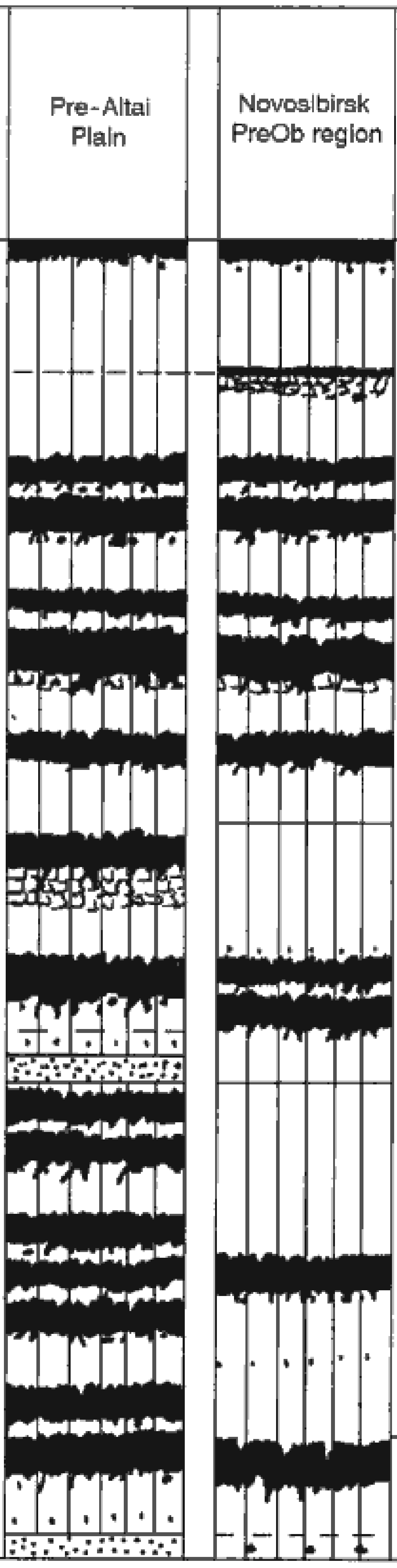
The study of loess-paleosol sequences has allowed the evolutionary direction and intensity of pedogenesis associated with the Pleistocene climate changes in the south of West Siberia to be revealed. The sedimentary sequence is classified according to the Russian stratigraphic scheme (see Table 1).

Three pedocomplexes were established for the Early Pleistocene period: Evsino (ev), Belovo (bl) and Shadrikhino (shd). The pedocomplexes consist of 2–3 soils separated by loess. Their structure confirms the directional and phased developmental character of the soil formation processes from the initial stage towards the mature and the final stages. The features of the latter stages are the most completely reflected in the pedocomplex structure (Zykina 1986, Zykina - Kim 1986). Traces of the initial phase of soil-formation are generally not well preserved. They are masked by later stronger pedogenetic phase. Only specific micromorphological features indicate their presence in the soil profile.

The first and pronounced Early Pleistocene warming stage in West Siberia corresponds to the development of steppe chernozems, characterised by high content of clay (< 0.001 up to 42 %) and ferruginous (Fe_2O_3 up to 6.2 %, Al_2O_3 up to 17.1 %) fractions (see Table 2) in East Kulunda, the Pri-Altai Plain and the Novosibirsk

Table 1. Chronostratigraphy of subaerial deposits of the West Siberian Plain

Russian scale: System	Russian scale: Series		Northern-Siberian stratigraphic scale	South-Siberian loess-soiles stratigraphic scale (pc - pedocomplex, ls-loess)	Paleomagnetism	Oxygen isotope stages	Assemblages of mammals
QUATERNARY	Holocene			Modern soils (hl)	Brunhes	1	
	PLEISTOCENE	UPPER	Sartan	Bagan ls (bg)		2	Middle-Upper Pleistocene fauna
				Sumino pc (sm) *14±0.2			
				Eltsovka ls (el) *19±0.8			
			Karginsk	Iskitim pc (is) *25±0.4		3	
			Ermakovo	Tulino ls (tl)		4	
			Kazantsevo	Berdsk pc (br) 130±10	Blake	5	
		MIDDLE	Tazov	Susun ls (sz) 140±14		6	
				Kolnihian pc (kn)		7	
				Chulym ls (cl)		8	
			Shirta	Charysh pc (cr)		9	
			Samarovo	Shibaevo ls (shb)		10	
			Tobol	Shipunovo pc (shp)		11	
		LOWER	Nisjamy	Morozovo ls (mr)		12	Vjatkino (Tiraspol)
			Tiltim	Shadrihino pc (shd)		13	
			Azovy	Danilovo ls (dl)		14	
			Talagaika	Belovo pc (bl)		15	
			Mansi	Salair ls (sl)		16	
	Eopleistocene		Gornofilino	Evsino pc (ev)		17	
			Kochkovo	Loess	Matuyama	18	



Pri-Ob Plateau, and luvisolic brown soils in the Kuznetsk Basin (Table 3). It corresponds to the Evsino interglacial, correlated with the Oxygen Isotope Stage 19. These soils are characterized by well-expressed pedological features associated with significant humidity and high groundwater levels. Soil development was dominated by intensive humus accumulation; this is confirmed by a significant thickness of the accumulative horizon and the humus-humate content and a high C_{ha} : C_{fa} ratio (2.0–1.6 see Table 2).

The microstructure of the humic horizon confirms the complex aggregation and the presence of organic substance in the form of humous within the humus-clayey plasma. Besides the complex aggregates, there are nodules of organic-clay substance with concentric texture, mottles and patterned structures of iron oxides indicating a meadowy character and periodic water saturation in the soils. Humus accumulation, clay formation, gleying and enrichment in Fe_2O_3 oxides are characteristic features of lessivage. Crotovinas, created by rodent faunas, in the soil horizons are typical of the Early Pleistocene Tiraspol Complex (Zykina - Krukover 1988). The stratigraphical classification of the pedocomplex is also confirmed by the Brunhes/Matuyama reversal, which has been recorded above the pedocomplex (Pospelova - Gnibidenko 1982, Volkova et al. 1985), between the soils

(ARKHIPOV et al. 1973) and beneath the pedocomplex (MOTUZKO - FAUSTOV 1972).

The climate of that time was characterized by a high heat-supply and a higher precipitation than today. A similar climate for the given interval is reconstructed in Central Europe, in the Caucasus (ZUBAKOV - BORSENKOVA 1993) and in the Ukraine (ARTUSHENKO - TURLO 1989).

The subsequent Belovo Pedocomplex (Oxygen Isotope Stage 17–15) is represented by luvisolic and chernozemic soils with illuviation, gleying and clay aggregation textures (Tab. 3). In general, the soils are similar to those of the Evsino Complex, with similar soil-formation processes dominating. The incorporated small mammalian fauna corresponds to the Tiraspol Complex of the Early Pleistocene. The climate in Western Siberia at that time was temperate, with a high water and heat supply. The very end of the Early Pleistocene (i.e. the early Middle Pleistocene of the international stratigraphical scale) was marked by formation of the Shadrikhino fossil soil of the chernozemic, brown chernozemic and brunisolic types (Table 3). Their microstructure is characterized by a complex aggregation of soil plasma, humus concentrations in isotropic zones, humus clayey plasma and scaly structure of clayey substance. The micromorphologic structure indicates that chernozems formed under forest-steppe conditions with humate form of organic substance and $C_{ha} : C_{fa}$ ratio > 1 (Table 2). The soils are characterized by a significant clay content (fraction < 0.001 up to 40 %) and mineral grain corrosion, and reflect conditions of a temperate-warm and humid climate.

MIDDLE PLEISTOCENE

Middle Pleistocene climatic fluctuations in West Siberia are evidenced by three pedocomplexes: Shipunovo (shp), Charyshian (cr) and Koinikhian (kn). Typologically, the soils are close to modern soils distributed in the area and differ from the Early Pleistocene soils by reduced thickness of profiles and humus horizons and the particular nature of soil-formation process. The Shipunovo Complex (correlated with Oxygen Isotope Stage 11) is represented by chernozems of meadow steppes, leached chernozems and meadow chernozem soils (Table 3). These soils usually have a morphologically well-expressed genetic profile and the microstructure typical of chernozems and high absolute values of $C_{ha} : C_{fa}$ ratio (Table 2).

The Charyshian Pedocomplex (Oxygen Isotope Stage 9) is characterized by polygenetic soils, the lowest part of which is a texture-differentiated palaeosol horizon typical of brown and grey forest soils. The horizon is enriched with Fe_2O_3 and Al_2O_3, and has a significantly increased silt content. The unit is micromorphologically distinguished by the abundance of clay occurring in form of laminated accumulations (sometimes with humus inclusions), filling pores and interaggregate interspaces. All the above features are typical of podsolization and lessivage processes. The upper soils of the pedocomplex are represented by meadow-steppe chernozems (Table 3). They are characterized by a deep-humified profile, low amount of silt and oxides, a humate-humus composition with a very high value of humic acids, $C_{ha} : C_{fa}$ ratio well above 1.0, a high porosity, weak plasma mobility, and the scale and skeletal forms of optical clay orientation (ZYKINA 1986, DERGACHEVA - ZYKINA 1988).

The Koinikhian Pedocomplex (Oxygen Isotope Stage 7) consists of one or two chernozems. They are often gleyed in the upper part and contain secondary carbonate features in the accumulative horizon, which are probably associated with an increasing aridization of the climate (ZYKINA 1986, VOLKOV - ZYKINA 19091). Humus accumulation, carbonization and gleying were the dominant soil-forming processes.

In summary, during the Middle Pleistocene, humus accumulation, lessivage and podsolization were most intensive pedogenic processes, corresponding to a warm and wet climate with reduced duration of pedogenesis comparing to the Early Pleistocene.

LATE PLEISTOCENE

Three soil formation phases are evident in the Late Pleistocene loess-palaeosol record; these correspond to the Kazantsevo (Mikulino, Eem) interglacial, the early Zyriansk (Krutitsk, Brorup/Ammersfort) interstadial and the Karginsk (Brjansk, Stillfried B, PK I) interstadial (ZYKINA et al. 1981, ZYKINA 1990). The lower (last interglacial) soils of Berdsk Complex (br_1) were formed in a forest-steppe zone of Western Siberia. According to palynological data (VOLKOVA 1977), biotic zones at that time moved northward by 500–700 km and summer temperatures were 4–5 °C higher than the present ones. The soil cover of the area was represented by a leached chernozem, usually in complexes with meadow-chernozemic and meadow soils. Meadow gley soils developed in the central Irtysh River region in flat and poorly drained areas (Table 3).

The chernozemic soils have double humic profiles differentiated by type A_1, $B_{t,ca}$, C_{ca}. The humus horizon reached thicknesses of up to 1.2 m, which is not typical for modern chernozems of West Siberia. Intensive humus accumulation processes were characterized by humate humus composition with prevailing humic acids, bound with Ca, by high $C_{ha} : C_{fa}$ ratios and a significant optical density of humic acids.

The microstructure of humus horizons confirms their aggregation, high porosity, spongy structure and prevalance of dark-coloured grained humons (ZYKINA et al.

Table 2. The main granulometric and chemical properties of fossil soils of different ages in the south-east Siberia

Horizons		Fraction size, mm (hor. A-B)		Al_2O_3, %	Fe_2O_3, %	SiO_2/R_2O_3	$C_{ha} : C_{fa}$	$\frac{0.001, \% C}{E_{\lambda-454 nm}}$
		< 0.001, %	< 0.01, %	(hor. A-B)	(hor. A-B)	(hor. A-B)	(hor. A)	(hor. A-B)
Sumino		32.0	47.0	14.0	4.7	6.2	no def.	no def.
Iskitim	IS_2	29.6; 26.2	50.7; 41.2	17.1; 16.9	4.3; 4.5	6.5; 5.6	1.21; 1.30	0.16
	IS_1	29.4; 30.4	49.5; 47.1	17.7; 17.5	5.6; 6.1	5.2; 5.3	1.19; 1.88; 2.65	0.27–0.36
Berdsk	BR_2	30.0; 28.4	41.5; 41.7	16.4; 17.4	6.7; 5.6	5.4; 5.3	1.05; 1.56	0.29–0.30
	BR_1	34.2; 41.5	56.5; 58.0	15.7; 18.6	6.3; 7.3	5.3; 4.7	1.21; 1.62	0.28–0.38
Koinihian	KN	39.6	58.4	17.3	5.5	5.5	no def.	0.10
Charysh	CR	38.2; 41.2	62.9; 64.0	16.5; 18.5	6.2; 7.1	6.2; 5.4	1.51; 2.64	0.28
Shipunovo	SHP	38.2; 39.7	62.3; 61.0	14.6; 15.9	5.1; 4.7	5.6; 5.5	1.83; 2.28	0.28–0.32
Shadrichian		41.9; 50.3	60.4; 61.7	16.5; 15.9	5.9; 5.7	5.2; 6.2	1.46; 1.19	0.36
	BL_3	43.5; 39.0	66.8; 59.8	20.5; 19.9	6.9; 6.8	4.4; 4.1	1.90	no def.
Belovo	BL_2	51.7; 41.2	61.5; 59.2	19.5; 15.8	6.9; 5.9	5.1; 4.6	3.25	no def.
	BL_1	43.1; 38.3	66.0; 57.0	18.5; 19.3	7.0; 6.4	4.4; 3.8	3.25	no def.
Evsino	EV_2	40.1	66.3	17.1	6.0	5.0	2.0	no def.
	EV_1	41.2	64.5	16.5	6.2	4.4	1.65	no def.

1981). Accumulation of the clay fraction and Al_2O_3, Fe_2O_3 in the illuvial horizon along with practically no SiO_2 redistribution down the profile, the presence of illuviation cutans, coatings around the mineral skeleton and margins of aggregates can be explained by lessivage processes, along with $CaCO_3$ leaching down the profile. Mature Ca (illuvial) horizons of the soils, a variety of carbonate microforms (fine grained and micrograined calcite in the form of nodules, isolated crystals, halos around the pores) evidence the carbonate migration processes. Thus, fossil soils of the Kazantsevo interglacial were formed under the influence of humus accumulation, carbonate migration, clay forming and lessivage processes. The great thickness of the accumulative horizon, the genesis diversity and intensity of soil formation are similar to the Middle Pleistocene soils. The soil structure, nevertheless, was also similar to the present one, but the original climate was warmer and more humid (Zykina 1990, Arkhipov et al. 1995). Rodent fauna from the Kazantsevo interglacial soils, i.e. *Citellus* sp., *Lagurus lagurus* and *Allactaga* sp., corresponds to steppe and forest-steppe habitats.

The Zyriansk (early Last Glacial) soil formatiom phase, including the upper soils of the Berdsk Complex (br_2), was characterized by forest-steppe soils with a pedogenic profile and humus horizons half the thickness of the last interglacial soils. The soil cover consisted of chernozem-like soils with a poorly differentiated profile of the A-BC type. There are no chernozems equivalent to modern forms due to the short soil forming intverval and a less favourable climate. The soils differ from the previous soils by the high contents of humic acids and a low content of humin, and a great amount of carbon (54–55 %, Dergacheva - Zykina 1988) in the humic acids. Humus formation processes proceeded in warm, but more arid conditions than in the previous pedogenetic stages. The $C_{ha} : C_{fa}$ ratio is typical for steppe and forest-steppe soils. Humic acids have high values of the optical density coefficient close to those of the present steppe soils. The content of silica oxides, the silt fraction proportions are uniform down the soil profile, indicating the absence of elluvial-illuvial process. The microstructure of humus horizon is typical of chernozemic soils with a high content of biogenic aggregates, a well-expressed porosity and spongy structure, prevalence of dark dispersed humones and dark-brown thin dispersed humus. Humus accumulation and carbonization have been main processes in the Zyriansk interstadial soils. The first process is evidenced by stable forms of humic acids and dark-coloured granular humons in the microstructure; the second is expressed by the variety of carbonate forms in the soil profile. The overall character of the soil structure indicates a changing climate tending towards aridization and cooling.

The mid-Last Glacial Karginsk soil formation interval, corresponding to Oxygen Isotope Stage 3 (^{14}C dates of 35 000 to 20 000 yr. BP, Zykina et al. 1981), is divided into early and late phases. They correspond to the Iskitim Pedocomplex, consisting of two soils, that differ from the Kazantsevo soils in that they have thinner humic horizons and soil profiles overall. In turn, they are similar to the Zyriansk soils in terms of soil structure, main pedogenic processes and soil formation interval. Most soils are chestnut coloured and greyish chernozem-like soils (Table 3).

The lack of the profile differentiation by main components the prevalence of humus in humic acids, bound with Ca, low amounts of fulvic acids and humines, a high dispersity coefficient (particularly in the early Karginsk soils), the microstructure analogous to chernozem and chestnut coloured soils are the most typical characteristics of the Iskitim Pedocomplex. Humus ac-

Table 3. Interregional correlation of the Pleistocene soils of the West Siberian Plain

System	General Scale	pedocomplex	Ob Plateau	Novosibirsk area	Kuzneck Basin	Central Irtysh Basin
PLEISTOCENE	HOLOCENE	hl	Chernozem ordinary	Chernozem leached, grey forest soil	Chernozem leached	Soddy podzolic
	LATE	is	Chernozem like; Meadow chernozemic	Chernozem like; Meadow chernozemic	Chernozem like	Soddy gley
		br_2	Chernozem like	Chernozem like		
		br_1	Chernozem ordinary; Chernozem leached	Chernozem ordinary; Chernozem leached	Chernozem ordinary; Chernozem leached	Meadow gley
	MIDDLE	kn	Chernozem	Chernozem	Chernozem	
		cr	Chernozem; Brownish-grey		Chernozem-brown	Chernozem podzolized
		shp	Chernozem leached	Chernozem; Meadow chernozemic	Chernozem-brown; Chernozem leached	
	EARLY	shd	Chernozem of meadowy steppes; Meadow		Chernozem-brown	Grey forest podzolized
		bl	Meadowy; Meadow chernozemic	Brown forest soil	Chernozem-brown	
		ev	Meadowy; Meadow chernozemic	Meadowy	Meadow cinnamon	

cumulation, carbonization and sometimes gleying and lessivage were the dominant soil formating processes.

The early Karginsk soils have more mature pedogenic profiles than their late Karginsk counterparts due to their greater duration of formation as indicated by the more developed structure of the humus horizon and the illuviation features. Small mammals found in both Iskitim soils (*Citellus* sp., *Citellus erythrogenus* Brandt and *Microtus* sp.) are typical of open steppe areas. The climate here was colder and more arid than today, a pattern similar to that of Ukraine as evidenced by palynological and palaeopedological data (Sidorenko - Turlo 1986, Artushenko - Turlo 1989).

Conclusions

The Pleistocene climatic history of West Siberia is well illustrated by the loess-palaeosol record. The final stage of pedogenesis was a cryogenic phase that disturbed the soils under a wet and cold climate (gleying, solifluction and frost wedges) in lower parts of the humus horizons. Palynological data show distribution of open areas without forests with a wide range of herbs and grasses with *Ephedra* and *Poa arctica* (Zykina et al. 1981). Green sphagnum mosses were significant among spores, *Botrichium borealis* was also present. The flora shows cold climatic conditions close to those of forest-tundra.

During the climatic optimum of the Late Pleistocene warm phases, the environment was similar to the present with distribution of forest-steppe or steppe landscapes, later replaced by cold forest-tundra during stadials. A gradual reduction of heat and water balance during the Pleistocene promoted an increase in continentality. In the south of West Siberia, soils characteristic of subboreal pedogenesis developed in response to cooling and aridization and shortening of pedogenic intervals.

The West Siberian Quaternary loess deposits with buried palaeosols are well correlated with the oxygen isotope stages of the Pacific core V-28-238 (Volkov 1983, Volkov - Zykina 1991). The Evsino Pedocomplex is correlated with Stage 19 at the Brunhes/ Matuyama boundary. The following pedocomplexes should correspond to the subsequent interglacials (Table 1). The Kazantsevo interglacial soil corresponds to Stage 5e, the early Zyriansk interstadial to Stage 5a and the Karginsk interstadial to Stage 3. The ^{14}C dates from subaerial deposits from the late Last Glacial sections confirm the suggested correlation.

Acknowledgement
The research has been supported by the Russian Foundation of Fundamental Investigations (RFFI), grant No. 96-05-64844.

Recommended for print by M. Tomášek

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