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Lithology and palaeomagnetic record of Late Weichselian varved clays from NW Russia

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A lithological and palaeomagnetic analysis of Late Weichselian glaciolacustrine deposits from two ancient periglacial lakes was carried out in the valley of the Shuja (S Karelia) and Ust-Pjalka (S–E Kola Peninsula) rivers, NW Russia. The rhythmic structure of the varved clays is interpreted as turbiditic with systematic differences between the proximal and distal areas of accumulation. In the proximal area the textural and structural properties of the deposits towards both distal and (partly) lateral directions are described. It is shown that the proximal varve successions are incomplete while distally they are continuous. The accumulation of one varve (DE rhythm, second order cycle) during one year is consistent with palaeomagnetic data. Significant differences in magnetic parameters and in the palaeomagnetic "records" of declination-inclination between proximal and distal varves are established. Analysis of palaeomagnetic properties was combined with lithological analysis in all sections. Locally, the varved clays in the proximal area could be used for palaeomagnetic research. Taking into account the erosion of underlying deposits by turbidity currents and inclination shallowing, these sediments could not precisely record palaeosecular variation (PSV). The distal varved clays (represented by the DE rhythms) are clearly most useful both for varve-clay chronology and PSV recovery. The palaeomagnetic declination and inclination records are correlated with chrono- and magnetostratigraphy scheme of NW Russia. This paper also examines lithology-dependent "inclination error" and anisotropy of magnetic susceptibility in glaciolacustrine sediments.

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INTRODUCTION

Two genetic hypotheses for varved clays have been dominant in the 20th century. Hence, two general genetic hypotheses for annual glaciolacustrine sedimentation have been developed. According to the hypothesis of De Geer (1912), glacial varved clays are constructed of summer (silty) and winter (clayey) layers, which reflect seasonal variations in a periglacial lake environment. During the summer, silt and clay are transported by glacial meltwater far from a glaciofluvial delta. They are then differentiated by grain-size through the water column. The silt accumulates during summer whereas clay is deposited mainly during winter. Thus a varve is a couplet of two layers accumulated during one year. In this manner it is possible to determine the duration of formation of a sedimentary succession in years. For instance, to estimate the timing of disappearance of the Scandinavian ice sheet the well-known Swedish clay varve chronology has been used (Ringberg, 1991; Brunnberg, 1995; Hang, 2001).

In the second interpretation varves are due to turbidity currents. The action of turbidity currents in periglacial lakes with different salinities was described by Kuenen (1951). Later, Banerjee (1973) showed that Canadian varved clays are similar to typical turbidites. On the model for deposition of British Colombia periglacial lake sediments, Shaw (1977) illustrated the transportation of clastic material to the basin by turbidity currents. Later it was established that the process of lacustrine sedimentation is complex (Catto, 1987; Kolka, 1996; Gruszka, 2001; Błaszkiewicz and Gruszka, 2005) and no single model can explain all the phenomena. The strict seasonality of couplet deposition in lacustrine environments has been challenged by several researchers, (e.g. Gilbert, 1975; Lambert and Hsu, 1979; Gilbert and Church, 1983; Catto, 1987; Ringberg, 1991; Van Der Meer and Warren, 1997), and the formation of multiple laminated units within a single season has been observed.

As regards the palaeomagnetic utility of varved clays, there is no common view as to the precision of the information recorded in glaciolacustrine deposits. Possible distortions in the "recording" of true geomagnetic directions have been analyzed in a number of papers (see summary in Verosub, 1977). Nevertheless no recommendations as to which type of glacial varved clays might be preferred for palaeosecular variation (PSV) investigations have been proposed. In palaeomagnetic research the term "varved clay" can encompass a wide range of varved deposits without reference to specific sedimentary environment. At the same time, the general usefulness of lacustrine varved clays for PSV investigations has been estabilished (e.g. Bakhmutov and Zagny, 1990; Saarnisto and Saarinen, 2001). This paper provides new data on the remnant magnetization of varved clays with particular attention to the textural and structural features of the deposits. The material is taken from two former periglacial lakes of Late Weichselian age.

This study examines the phenomenon of turbidity currents in relation to varved clays and investigates the acquistion of a palaeomagnetic signal in glaciolacustrine sediments.

METHODS

FIELDWORK AND LABORATORY TREATMENT

A few exposures were selected for sampling and investigation of the varved sequences. Each section was thoroughly cleaned. The primary description of the sections and the taking of monolith samples were done in field. The samples were placed into the boxes 50×15×10 cm in size, with 5 cm overlapping between the long axes of monoliths, and then wrapped in a plastic sheet. In addition to the monoliths, oriented specimens (5×5×5 cm or 2×2×2 cm) were sampled for palaeomagnetic studies. For determination of the direction of transport by turbidity currents the strikes and dips of foreset laminae in C units of turbidite units were measured.

In the laboratory the monolith sample surface was cleaned and overlapping parts of sections were visually correlated. Then a paper strip was attached to the surface and the thickness of each element (layer) was noted. The lithological description of the sediment sequences was done using a binocular microscope. Grain-size composition was analyzed by sieving and pipette analysis. The quantities of Fe^{2+} and Fe^{3+} were determined by chemical analysis of the clayey parts of the varves.

PALAEOMAGNETIC ANALYSES

Four hundred and fifty-five cubic specimens were taken from 5 exposures in the Ust-Pjalka palaeobasin (3–4 specimens from each sampling level). The number of cubic specimens from 98 sampling levels of the Shuja section was 529.

The natural remanent magnetization was measured by a *LAM-24* astatic magnetometer (Institute of Geophysics National Academy of Sciences of Ukraine) and *2G Enterprise* cryogenic magnetometer accompanied by an alternating field (AF) demagnetizer (Institute of Geophysics, Polish Academy of Sciences). A pilot collection (one sample from every five levels) was subjected to stepwise AF-demagnetization. Demagnetization results were analyzed using principal component analysis (Kirschvink, 1980) by means of a PDA program package (Lewandowski *et al.*, 1997). The bulk susceptibility and its anisotropy were measured by the *KLY 2* kappabridge in 15 different positions, and L, F, P, T parameters were calculated from the principal components using the *Aniso* program (Jelinek, 1973, 1977).

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

During decay of the Scandinavian ice sheet on the NE of the Baltic Shield glacio-lacustrine sedimentation occurred in palaeobasins of different size and shape, depending on their precursor depressions (Kolka and Korsakova, 2000). The present study is focused on the deposits from the Ust-Pjalka (S–E Kola Peninsula,) and Shuja (South Karelia) former periglacial lakes (Fig. 1).

The Ust-Pjalka glaciolacustrine deposits accumulated in a narrow N–S elongated palaeobasin (9 km long, 1 km wide,) which was situated in front of a cluster of ice-marginal deposits and occupied the middle part of the valley of the Ust-Pjalka River. In the south the deposits interfinger with those of a glaciofluvial delta of the Neva marginal system (Fig.1A.1–2). Taking into account the lowest and highest absolute altitude of the Precambrian basement in the depression the maximum water depth in the axial part of the palaeolake was estimated as 30–50 m, decreasing to the margins of the depression (Kolka, 1996). At present the glaciolacustrine deposits are exposed along the river and occur in two terraces. The upper terrace is mainly constructive, being 150–145 m a.s.l.; the lover terrace is predominantly erosional, being 142.5–140 m a.s.l. This circumstance enabled us to establish the lithological changes and magnetic characteristics of sediments in different parts of the Ust-Pjalka glaciolacustrine system. Clastic material was transported to the basin from a glaciofluvial delta bordering the lake in the south (Bakhmutov *et al.,* 1993; Kolka, 2004).

The Shuja glaciolacustrine deposits (Fig.1B.1–2) were formed in an extensive isometric terminoglacial basin immediately adjacent to a stripe of marginal landforms of the Neva stage of the Weichselian Glaciation (Ekman and Iljin, 1991). Presently the deposits underlie a large glacial plain rimmed to the north-west, west and south-west by the boulder-pebble-gravel end-moraine ridges. The Neva band of the marginal landforms also includes gravelly-sandy glaciofluvial deltas. The deltas together with eskers were formed in glaciofluvial channels, flowing normal to the glacier margin. The main input of the material to the periglacial lake was through these channels. Turbidity currents were generated on the frontal slopes of the deltas and transported clastic material into the periglacial lake (Kolka, 1996, 2004). A portion of the sediment was transported into the palaeobasin by meltwaters emerging out of glaciofluvial channels from the front of the glacier lobe. In the latter case the transported material was accumulated in the immediate vicinity of the marginal ridges as gravelly-sandy deposits with scattered boulders.

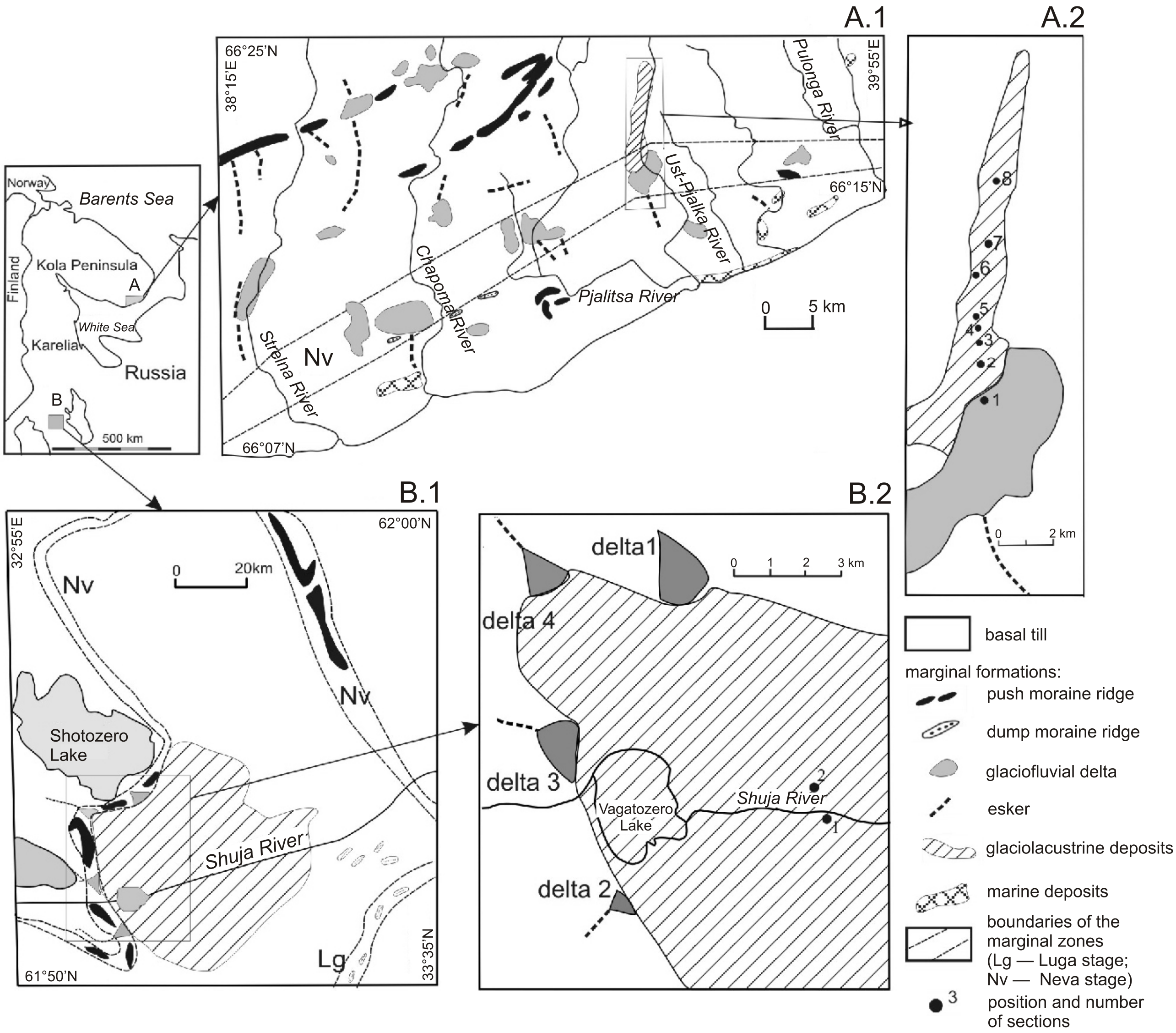


Fig. 1. Location of the study areas; Ust-Pjalka (A.1–2) and Shuja (B.1–2) in the context of Quaternary deposits

LITHOLOGY

DESCRIPTION OF THE CROSS-SECTIONS

UST-PJALKA GLACIOLACUSTRINE DEPOSITS

Eight sections across the glacial lake deposits have been studied in detail (Fig.1A.2). Figure 2A shows their correlation based on the interpretation of palaeomagnetic and geological and geomorphologic data (Bakhmutov *et al.,* 1993). Section 1–5, 7 and 8 are confined to the lower river terrace. They consist of sediments deposited along the approximately N–S trending axis in the deeper part of the palaeolake. Section 6 occurs on the upper terrace, near to the coastal part of the lake. These sediments therefore accumulated in shallower parts of the palaeolake.

Section 1 is represented by laminated sandy deposits of a glaciofluvial delta. The lower part of section 2 (interval 1.52–4.0 m) is represented by cross- and parallel-bedded sandy deposits of a glaciofluvial delta. The sediments in the upper part of section 2 (int. 0.3–1.55 m), in sections 3, 4, 5 and 7, not reaching the base of the glacial lacustrine sequence consist of laminated silts and clays. The silty parts of the succession have a complex structure with different styles of bedding and a range of grain-sizes. They are graded laminated, horizontally laminated or cross-bedded silt layers and horizontal interbedded silt and clay layers. The laminated silts are interbedded with clay layers. The different styles of lamination could be represented by Bouma cycle terminology. Graded beds represent Bouma A, coarse-grained horizontally laminated silt is Bouma B, cross-bedding silt is Bouma C, horizontally interlaminated silt and clay layers is Bouma D, while non-laminated clay is Bouma E. The thicknesses of the silty parts of sections 2–5 and 7 vary from 3.0 to 25.0 cm. The thicknesses of the clayey part E vary from 1.0 to 4.0 cm. A typical section through the interbedded silt and clay layers is shown in Figure 2B.1.

Earlier, the silt and clay interbeds, confined to the contact with the glaciofluvial deposits (glaciofluvial delta deposits in our case) were named as bottom or proximal varves (Ringberg, 1991).

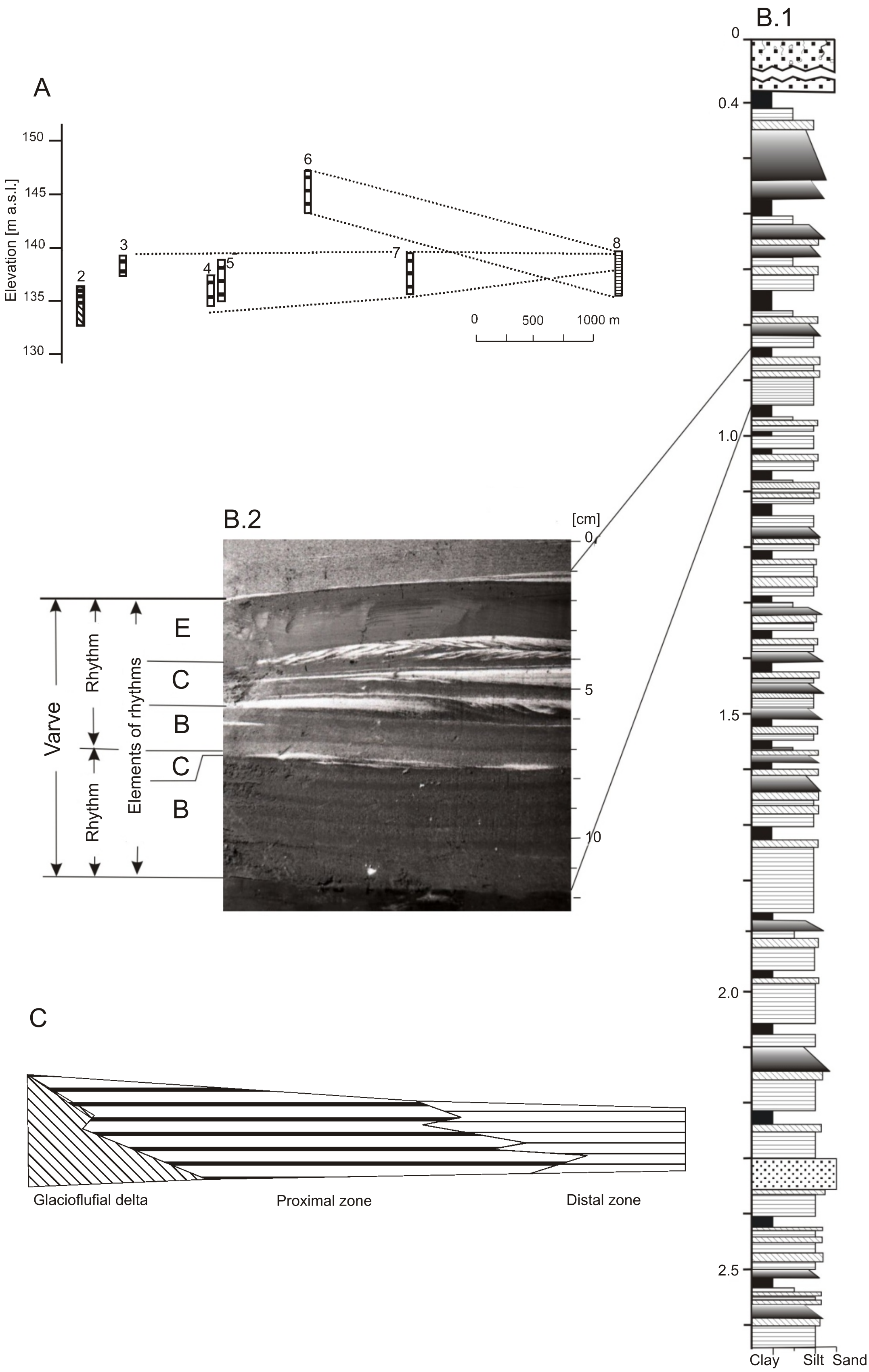


Fig. 2. Correlation of the sections (A); lithological log of section 4 (B.1); inner structure of the proximal varve, composed of two abbreviated rhythms, section 4, int. 84–94 cm (B.2); and schematic longitudinal section of the Ust-Pjalka glaciolacustrine deposits (C)

Section 8 comprises the entire lacustrine sequence which is represented by classical varves only. We named these distal varves.

Thus two glaciolacustrine facies could be distinguished in the Ust-Pjalka clayey deposit: proximal varves and classic varves. The former are confined to the proximal part of the glaciofluvial delta and to the lowest parts of the sections. The latter are confined to the distal part of the deposit and to the upper parts of sections (Fig. 2C).

SHUJA GLACIOLACUSTRINE DEPOSITS

Two sections in the central part of the Shuja palaeolake are represented by glaciolacustrine deposits (Fig.1B.1–2). According to the structure and thickness of rhythmic units they could be divided into two parts (Fig. 3). The lower parts are mainly composed of proximal varves (with thicknesses up to 0.6 cm), whereas the upper parts comprise mainly distal varves (0.3–0.4 cm thick) interbedded with proximal varves.

INTERPRETATIONS

UST-PJALKA GLACIOLACUSTRINE DEPOSITS

To explain the genesis of successions in the Ust-Pjalka clay deposit we assume that the limnoglacial varves were formed by turbidity currents generated on the frontal slope of the glaciofluvial delta. The nature of these depended on the sediment accumulation on the frontal slope of delta. Each turbidity current deposited one continuous or reduced Bouma rhythm. According to the conceptual model of "varve" genesis it includes the all material deposited in one year. Therefore the varve is the result of all turbidity currents generated during one year.

The deposits exposed in sections 2–7 are similar to typical turbidit. A complete assemblage consists of 5 elements (ABCDE) and corresponds to the full succession recognised by Bouma (1962). Table 1 shows the structure, composition and grain-size of a complete rhythm from section 5 (interval 380–390 cm).

As one can see from Table 1, the median grain-size becomes finer towards the top of the profile. This is consistent with the idea that the elements A, B, C and D are produced by a decelerating turbidity current. The uppermost clay layer E was partly deposited in summer directly from a turbidity current, and partly in winter from longer-lived suspension (Banerjee, 1973). This is confirmed by the difference in color of the summer and winter components of the element rhythm E: the lower component is greenish-grey and resembles the silty element D whereas the upper one is reddish-brown. The difference in colour is related to the oxidation of iron because winter water is highly saturated with oxygen. The Fe_2O_3 to FeO ratio in the green clay is 1.3 (the mean value of four analyses), whereas in brown clay the ratio is up to 1.9 (the mean value of three analyses).

In the deposits of sections 2–7, as in most turbidites, complete Bouma successions are rare. There are many abbreviated rhythms, lacking one or more components (Fig. 2B.2). This the individual manner of braking of each turbidity current (Allen, 1984), and also the erosive capability of the succeeding turbidity currents.

Altogether 26 Bouma unit combinations were identified in the proximal zone (Table 2). Table 2 shows 14 such combinations in the southern part, 20 in the central part and 11 in the most distal northern part and in the adjacent shallow part of the proximal zone. Such a distribution of rhythm types probably results from the varying dynamics of the turbidity currents.

Two broad groups can be discerned in the proximal area (Fig. 4A). The first group consists of Bouma units A, B and C; the second one comprises elements D and E. The components of the first group tend to decrease in a distal (northern) direction while these of the second group show a concomitant increase. This pattern is consistent with current understanding of facies distribution along a turbidite transport path (Gradziński *et al.*, 1980, Allen, 1984). Bouma units A, B and C consequently disappear with the distance from the delta while units D and E become ubiquitous. The distal zone of the Ust-Pjalka glaciolacustrine deposits thus only comprise units D and E.

The presence of scours and apparent lithological unconformities in the sections, indicates that the turbidity currents locally eroded the underlying sediments. As a result, the sections have been significantly attenuated.

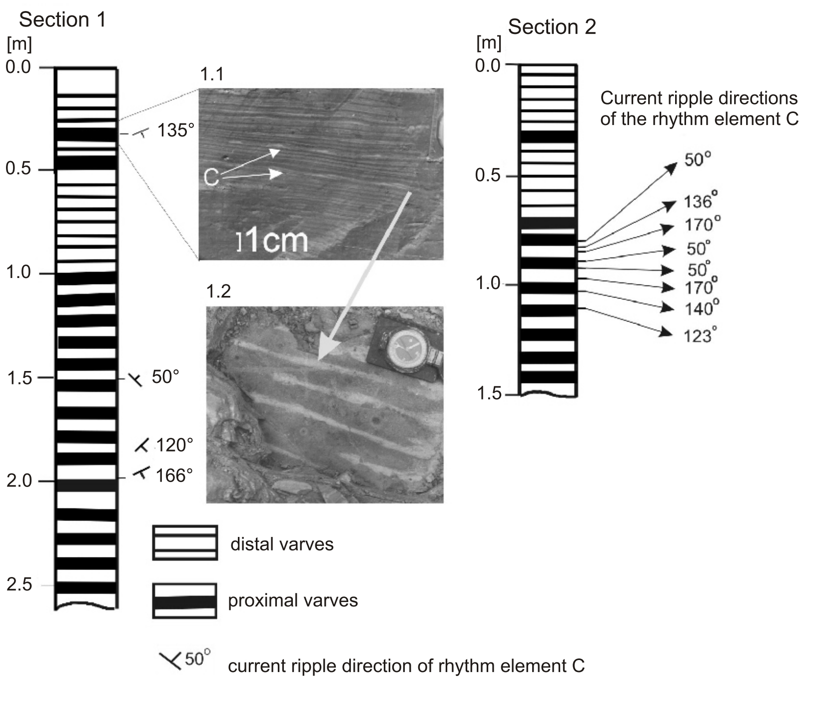


Fig. 3. Schematic sections of the Shuja glaciolacustrine deposits

1.1. — interbedding of the proximal and distal varves in the interval 0.28–0.38 m, section 1; 1.2. — planar view of rhythm element C, interval 0.32 cm; the light stripes are the ripple crests

Table 1

Composition, structure and grain-size of an ABCDE rhythm from the proximal part of the Ust-Pjalka glaciolacustrine deposits (section 5, depth interval 380–389.5)

Ele-ments of the rhythm	Structure	Grain-size distribution [mm/%]					
		<0.001	0.005–0.001	0.01–0.005	0.05–0.01	0.05–0.1	>0.1
E	Structureless	35.42	28.12	10.41	11.88	6.88	7.29
D	Parallel interbedding of silt and clay layers	10.1	41.98	18.75	23.34	3.75	2.08
C	Cross-lamination	3.95	14.58	33.76	46.21	1.50	–
B	Parallel lamination	12.08	13.75	24.17	47.92	2.08	–
A	Graded lamination	9.79	13.54	16.46	53.96	2.50	3.75

Table 2

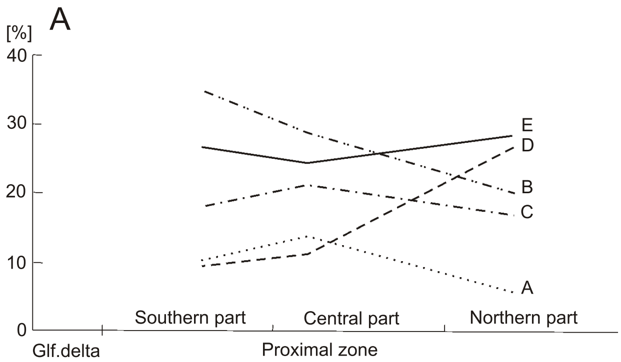
Distribution of various types of rhythms in deposits of the proximal zone of the Ust-Pjalka glaciolacustrine deposits

Rhythms	Deep part of palaeobasin			Shallow part of palaeobasin	Total in the proximal zone
	Southern part, sections 2, 3	Central part, sections 4, 5	Northern part, section 7	Section 6	
ABCDE	–	1/1.0	–		1/0.26
BCDE	1/2.3	4/4.0	16/27.6		21/5.53
ABC	1/2.3	1/1.0	–		2/0.53
AB”D	–	–	–	1/0.57	1/0.26
A”CD	–	–	–	1/0.57	1/0.26
BCD	1/2.3	2/2.0	–	5/2.82	8/2.10
CDE	2/4.5	–	1/1.7	1/0.57	4/1.05
BC	8/18.2	22/21.8	8/13.8		38/10.00
DE	–	3/3.0	15/25.9	4/2.25	22/5.79
A”CDE	–	3/3.0	2/3.4		5/1.32
AB”DE	–	1/1.0	2/3.4		3/0.79
ABC”E	–	2/2.0	–		2/0.53
AB”E	2/4.5	2/2.0	1/1.7		5/1.32
A”C”E	–	1/1.0	–		1/0.26
A””DE	–	9/8.9	4/6.9		13/3.42
BC”E	2/4.5	13/12.9	2/3.4	2/1.13	19/5.00
B”DE	5/11.4	5/4.9	6/10.3	3/1.69	19/5.00
A”C	2/4.5	4/4.0	–		6/1.58
A””D	–	–	–	34/19.21	34/8.95
A”””E	2/4.5	6/5.9	–		8/2.10
B””E	8/18.2	8/7.9	–	7/3.96	23/6.05
BD	–	–	–	114/64.41	114/30.00
CD	–	–	–	5/2.82	5/1.32
A	2/4.5	3/3.0	1/1.7		6/1.58
B	4/9.1	9/8.9	–		13/3.42
E	4/9.1	2/2.0			6/1.58
Total	44/99.9	101/100.2	58/99.8	177/100	380/100

The numerator and denominator show the amount and percentage of rhythms respectively; parenthetic mark in rhythm symbol denotes absent elements of the rhythm; for the locations of the sections see Figure1

Proximal varves comprise one or more complete or abbreviated rhythmic units (Fig. 2B.2). Varves are normally 1.0 to 15.0 cm thick (maximum thickness is up to 40 cm). Some varves are composed of a varied number of rhythmic units that change down current. Figure 4B shows that the varves of the southern and central parts of the proximal area resemble one another in this respect: the share of varves composed of one to two rhythms is 34–42%; of three rhythms is 12–18%; of four rhythms 6–8%. The varves of the northern part have a simpler structure; 73% are represented by a single rhythm; 23% by two rhythms; 2% by three rhythms and 2% by four rhythms. If we assume that each rhythm was formed by one flow, this simple structure signifies that not all the flows generated on the frontal delta slope, had reached the northern peripheral part of the proximal area. Even those flows that reached this northern periphery had lower speeds than those in the central part, as indicated by variations in average varve thickness. Moreover, there was less erosion of the underlying sediments then in the central and southern parts. Consequently in the northern part element E of the rhythm is preserved much more often then elsewhere.

Lateral changes in the structure of proximal varves are distinct. A total of 177 rhythms of 11 types (Table 2) have been distinguished in section 6. As noted above these sediments were formed in the lateral, shallower part of the palaeobasin. The varve thickness in section 6 ranges from 0.5 to 3.0 cm, being 1.2 cm of average. All varves are represented by a single rhythm. Their major feature is the reduction of element E. Its thickness is small



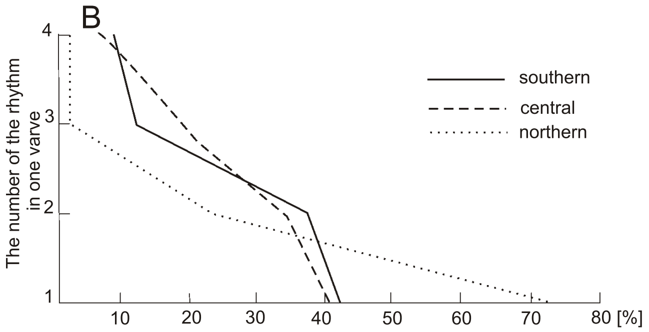


Fig. 4A — variation in the percentage of each element of the ABCDE rhythm in the deposits of the proximal zone, with distance from the glaciofluvial delta; B — number of rhythms in the varves of the proximal area

(0.1–0.2 cm) and it shows a tendency to disappear towards the top. Thus, lower in the section element E is found in 20 % of the rhythms but at the top it is found in only 3–4%. This trend can be explained by a decrease in lake depth. As a result more and more clayey particles were carried from the coastal areas to the deeper and quieter part of the lake. This is supported by the predominance of silt in the deposits of section 6 (Table 3). Palaeomagnetic data (Bakhmutov *et al.*, 1993) indicate that the deposits of section 6 were accumulated at the same time as the deposits of the complete varve of section 8. The record here is fragmentary. We inform that peripheral segments of turbidity currents contained less clastic material than the central part. Consequently, the varve internal structure became simpler towards the shallow area of the palaeobasin.

Distal varves were studied in section 8. Here all the varves are represented only by DE units. Here in the distal part of the palaeobasin deposition was from low energy turbidity currents (unit D and the lower part of unit E) and from suspension (unit E).

The "summer" silty layer (unit D) is usually thicker than the "winter" clayey one (unit E). In some exceptions the thickness of "winter" layer is greater. Section 8 comprises a total of 606 couplets varying in thickness from 0.2 to 2.0 cm, being 0.5 cm on average. The relative proportion of clay decreases from bottom to top of the section profile (Table 4). Lake level lowering during accumulation may be the reason for this.

SHUJA GLACIOLACUSTINE DEPOSITS

The deposits of the Ust-Pjalka palaeobasin stem from a single glaciofluvial delta, from which most supply to the basin occurred. But locally a few deltas may supply a glacial lake (Kolka and Gorbunov, 1990). We here consider varve clay deposits from the Shuja River valley in south Karelia (Kolka, 2004). Here proximal and distal areas have not been distinguished because interactions of turbidity currents from different directions have influenced the structural-textural features of each section. At least four glaciofluvial deltas supplied clastic material to the center of the Shuja basin (Fig.1B.1–2).

According to the structure and thickness of varves section 1 could be divided into two parts with the boundary at about 1.1m (Fig. 3). The lower part is mainly constructed of typical proximal varves (with an average thickness of 0.6 cm) whereas the upper part comprise mainly distal varves (0.3–0.4 cm). The proximal varves of the Shuja glaciolacustrine deposits consist of 13 rhythms (Table 5). This complex structure of the varves can be explained by the existence of at least two directions of supply from turbidity currents. We suggest that these developed on the frontal slope of the glaciofluvial delta that bordered the palaeobasin. The accumulation occurred at different flow speeds with local erosion of underlying sediments. As the ice retreated, one of the meltwater sources may have disappeared, to produce a simpler succession in the upper part of the section.

Table 3

Grain-size of varve clay from the section 6 of Ust-Pjalka glaciolacustrine deposits

Sample No.	Sample depth [cm]	Grain-size distribution [mm/%]					
		> 0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001
1	0.95–0.975	0.45	6.45	43.26	22.38	16.46	11.0
2	1.17–1.22	0.13	4.08	46.54	22.37	15.33	11.55
3	1.85–1.88	0.2	8.96	51.32	17.35	15.39	6.78
4	2.36–2.41	0.22	8.82	39.71	17.92	19.18	14.15
5	2.60–2.65	4.97	15.97	36.21	12.69	17.3	12.86
6	3.15–3.18	4.11	12.62	43.12	16.65	13.92	9.55

Table 4

Grain-size of varve clay of the distal part of Ust-Pjalka glaciolacustrine deposits (section 8)

Sample No.	Sample depth [cm]	Grain-size distribution [mm/%]					
		>0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.00	<0.001
1	0.8	0.2	0.1	50.4	21.1	16.7	11.5
2	1.3	0.1	4.7	38.6	19.9	21.1	15.6
3	1.7	0.1	0.1	35.6	20.6	25.5	18.1
4	2.6	0.1	0.7	39.8	19.3	25.5	14.5
5	3.0	0.2	2.7	18.0	15.4	36.2	27.5

Here 77.5% of varves are represented by DE rhythms only. Nevertheless 8 different types of rhythms resembling typical proximal varves are distinguished in the upper part (Table 5).

Both the upper and lower parts of section 1 contain evidence of turbidity currents from different directions. Thus why the new rhythms CE and C appear in addition to those in the Ust-Pjalka deposits. Different orientations of ripple layers in the rhythms of element C and alternation of distal and proximal varves also indicate the interaction of turbidity currents. Measurement of current ripple direction in the C elements in proximal varves (Fig. 3, section 1) shows (from top to bottom) flow directions of 135°, 50°, 120° and 166°. In section 2 in the central part of the Shuja palaeobasin measurements indicate four main directions, coinciding with the directions of section 1 (Fig. 3, section 2).

Thus the complete geochronological "record" could be established in the distal area of the periglacial basin and partially in the distal part of the proximal area. In the last of these the succession may be incomplete. Estimation the duration of sedimentation in the proximal area has not been possible. Varved clays of the distal area should be considered as suitable for varve chronology and, as shown below, are most useful for palaeomagnetic research.

PALAEOMAGNETIC STUDIES

STABILITY OF REMANENT MAGNETIZATION AND MAGNETIC MINERALOGY

The natural remanent magnetization (NRM) of the Shuja samples ranged from 10 to 50 mAm^{-1} and mean susceptibility ranged from 20 to 80×10^{-5} SI. In the Ust-Pjalka samples the highest and lowest values are associated with the proximal and distal areas respectively and have a wide range of values.

Table 5

Distribution of various types of rhythms in deposits of the Shuja's glaciolacustrine deposits

	Mostly proximal varved clays (depth 1.0–2.5 m)		Mostly distal varved clays (depth 0.0–1.0 m)	
Rhythms	Amount	[%]	Amount	[%]
BCDE	35	13.11	16	5.9
BCD	2	0.75	–	–
BC	4	1.5	–	–
BC"E	8	3.0	1	0.37
BD"E	50	18.73	8	2.95
BE""	8	3.07	8	2.95
CDE	36	13.48	17	6.27
CD	6	2.25	1	0.37
CE"	2	0.75	10	3.69
DE	104	38.95	210	77.49
B	6	2.25	–	–
C	3	1.12	–	–
E	3	1.12	–	–
Total	267	100	271	100

Figure 5 shows the results of stepwise AF- demagnetization of typical samples from Shuja (Fig. 5A) and Ust-Pjalka (Fig. 5B). Orthogonal diagrams indicate univectorial stable remanence. The 5–10 mT AF-demagnetization field erased the viscous component. The medium destructive field (MDF) during AF-demagnetization of NRM varies between 50–90 mT in the Shuja samples and 35–150 mT in the Ust-Pjalka samples. After demagnetization of the pilot collection, the remaining samples were demagnetized in a 20 mT peak of AF. Magnetic cleaning did not noticeably change the NRM directions of samples. After 150 mT AF-demagnetization field 15–20% of NRM in the Shuja samples (10–50% of NRM in Ust-Pjalka samples) still remained indicating a mixture of low and high coercivity minerals.

The magnetic mineralogy investigations of the Ust-Pjalka varves indicated a mixed composition of magnetic fractions (Petrova *et al*., 1995). Thermomagnetic curves (Fig. 6A, B) show the presence of hematite whereas the $J_s(T)$ and $J_{rs}(T)$ behaviors indicated curve bends near 150°C, 350–400°C and Tc near 560°C (Petrova *et al.,* 1998; Fig.6C). During second heating these bends disappear and Tc comes close to the Tc of hematite. The acquisition curves of IRM (Fig. 6D) demonstrate that 2.0 T is an insufficient field for saturation of samples from the lower part and confirmed the presence of hematite-type magnetic minerals in the samples. But sediments from the upper part of the same section (Fig. 6D) were saturated in a field of 1.2 T. More data about the magnetic mineralogy in different levels were reported by Petrova *et al*. (1995, 1998). The magnetic behaviour of the deposits shows that hematite, maghemite and magnetite are the carriers of remanent magnetization in these varved clays. In addition, the presence of greigite cannot be exluded. In certain intervals the chemical remanent magnetization due to pigment took place along with depositional (postdepositional) remanent magnetization (Petrova *et al.,* 1995). However these deposits have been admitted to the study of "palaeomagnetic records".

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

One of the main problems in palaeomagnetic studies of recent sediments is the "record" of true ancient geomagnetic field direction. Identification of disrupted zones, e.g. due to sampling, or sedimentological disturbances, e.g. caused by bioturbation, are problems in the palaeomagnetic investigation of soft sediments. In this context the study of the varved clays from the Ust-Pjalka and Shuja periglacial lakes is important because the alteration of magnetic parameters in direct relation to the processes of sedimentation in different zones of the lake could be traced. In addition to visual description of the varved clay fabric we used magnetic fabric analysis (Blunk, 1989). The analyses of anisotropy of the magnetic susceptibility (AMS) could specify stress-induced variations of remanent magnetism (Schmitz, 1984) and secondary fabric in homogeneous clays (Blunk, 1989). Parameters often used in studies of magnetic fabric are the shape, orientation and size of the anisotropy ellipsoid (Tarling and Hrouda, 1993). According to Blunk (1989), the primary magnetic fabric of lake sediments is invariably of oblate type, i.e. $0<T<1$.

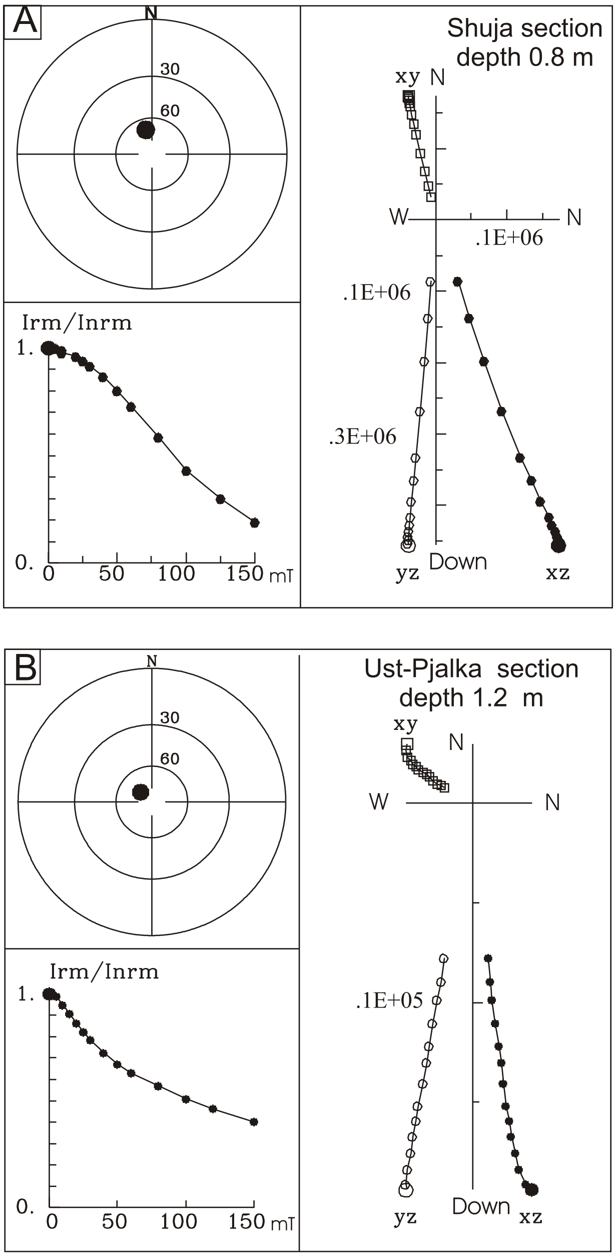


Fig. 5. Examples of typical AF-demagnetization behavior of samples from the Shuja (A) and Ust-Pjalka (B) sections

The plots in the lower left corners show decay of NRM intensity during demagnetization; the stereoplots (upper left corners) and orthogonal diagrams (right) indicate that the direction of remanence is stable; orthogonal diagrams are shown in the horizontal plane *xy* represented by squares, and in two vertical planes: *xz* represented by solid circles and *yz* represented by open circles

The data from sequence 1 in the Shuja periglacial lake display no deformed sediments (primary fabric; Fig. 7). The grains are well oriented with minimum axis (K3) normal to the depositional plane and with the maximum axis (K1) parallel to the flow. The analyses of the principal directions of AMS ellipsoids of the samples from different levels indicate that the directions of maximum axis K1 in proximal clays are about 160° (Fig. 8A) whereas the directions K1 in distal clays are about 60° (Fig. 8B). This is consistent with field measurements of palaeocurrent directions in section 1 (Fig. 3) that are 135°, 50°, 120° and 166°. Field measurements of current ripples in section 2 (Fig. 3) basically show the same directions of flow 50° and 170°. Thus they are close to the K1 AMS-directions. Some samples from the proximal zone show that K1 AMS-directions typical of the distal area and conversely, a few samples with peculiar K1 AMS-directions resembling those from the distal zone are placed in the proximal part of the section. Hence the succession of glaciolacustrine accumulation could be established. First clastic material was delivered basically towards 340° NW–160° SE from delta 1. Simultaneously a smaller quantity of clastic material was delivered from delta 2 with flow direction of 240° SW–60° NE. Later, with the beginning of distal varved clay accumulation, transportation of clastic material from delta 1 was considerably reduced and occurred mainly at 240° SW–60° NE from delta 2.

The AMS data from the Ust-Pjalka periglacial lake show both primary and secondary fabric. In section 8 together with a primary fabric, a secondary fabric below 3.75 m (Fig. 9) has been determined. The portions of primary and secondary fabric according to the shape parameter T are marked on Figure 9 with a dashed line. But deformed varves are tracked below 3.2 m (dotted line). The directions of K1 and K3 axes of the AMS ellipsoid for all samples of section 8 (Fig. 10A) and only for samples from the upper 3.2 m (Fig. 10B) are zones in which the sediment is visibly contorted. Therefore declination-inclination data from lower than 3.2 m must be excluded from following PSV interpretations.

The data from section 6 are displayed only for primary fabric (Fig. 10C). The directions of the maximum axis K1 both in sections 6 and 8 are close to longitudinal and taking into account the geological context show an easterly direction of water flow.

PALAEOMAGNETIC RECORDS

Structural and textural differences of deposits from proximal and distal areas are emphasized by differences in their palaeomagnetic parameters. This is primarily caused by sedimentation type flow speed in different zones of the basin. The heavy fraction of fine-grained sandy and silty particles was deposited mostly at high flow speeds near the glaciofluvial delta and partialy was transported to the central deepest zone, while the fine clayey particles were deposited almost everywhere, although showing a concentration in the peripheral part furthest from the delta. Our palaeomagnetic investigation was primarily aimed at obtaining information about the "record" of the ancient magnetic field direction in lithologically heterogeneous sediments.

PROXIMAL ZONE OF THE UST-PJALKA PERIGLACIAL LAKE

The clays of sections 3 and 5 (Fig. 2A) are characterized by scattered magnetic parameters in neighboring levels and even in samples of the same level (Fig. 11). The NRM and magnetic susceptibility (k) values become higher on approaching the delta. In both sections NRM and k slightly decrease from bottom to top.

The mean inclinations of samples are 10–15° less then the geocentric axial dipole GAD inclination for this area (78.5°). This inclination error is comparable with those estimated by other authors who studied varved clays (e.g. Barton *et al.*,

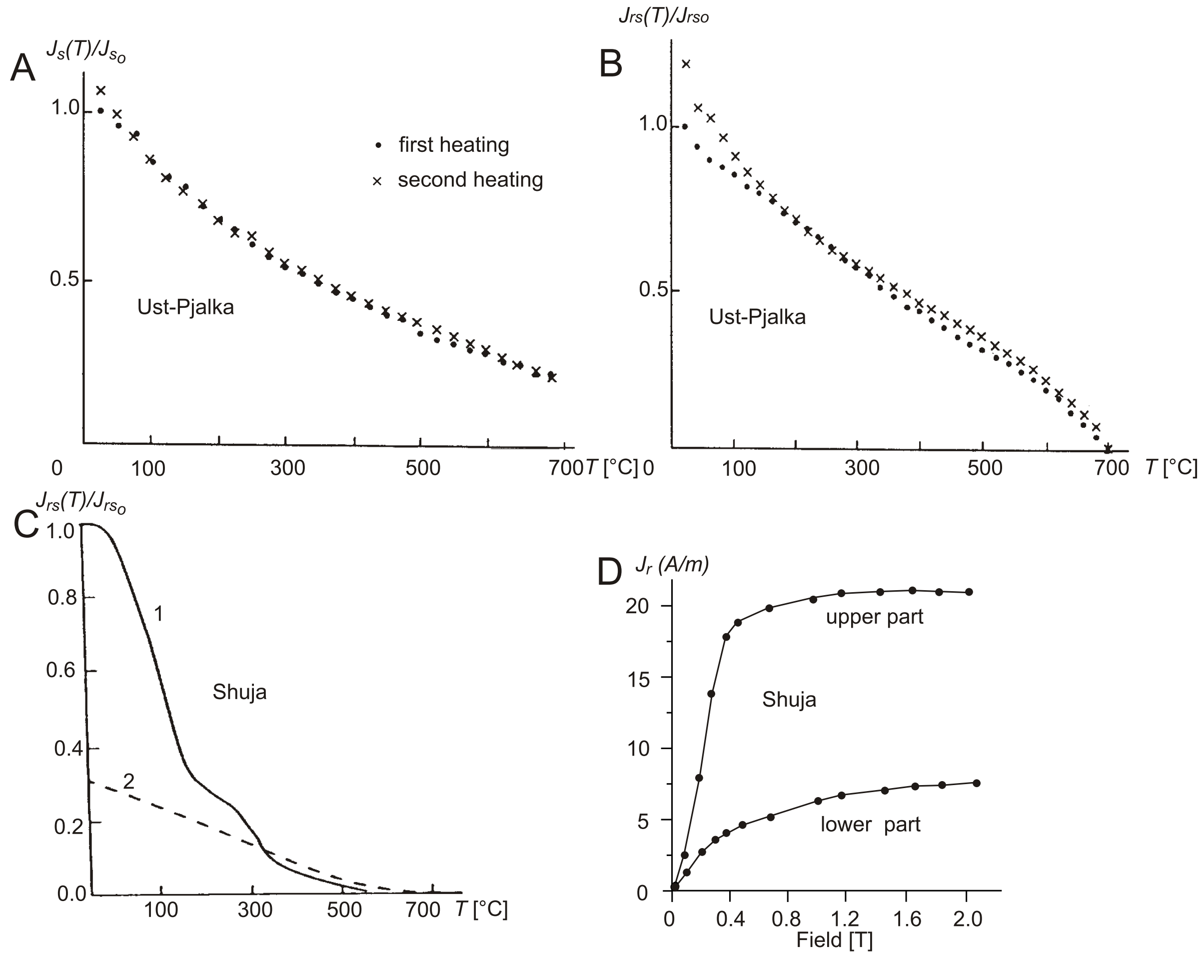


Fig. 6. A typical thermomagnetic $J_s(T)$ (A) and $J_{rs}(T)$ (B, C) and IRM acquisition (D) curves for Shuja and Ust-Pjalka varved clays

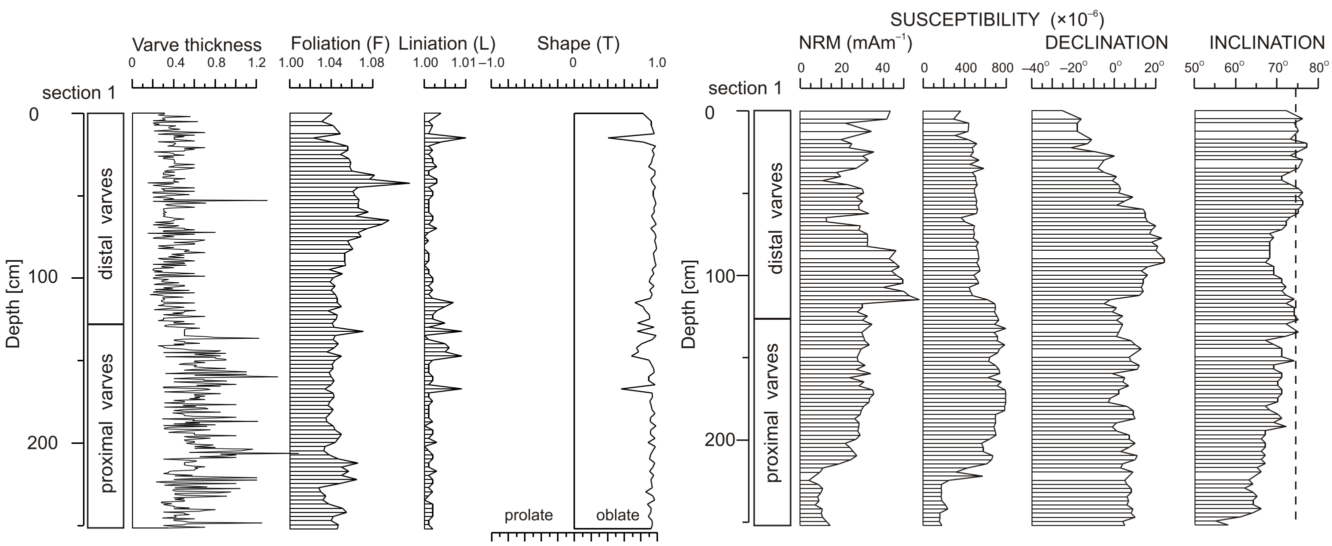


Fig. 7. Varve thickness, magnetic anisotropy parameters (foliation F, lineation L, shape parameter T), natural remanent magnetization (NRM), magnetic susceptibility (k), declination and inclination of sediments of section 1, Shuja periglacial basin

The dotted line in inclination indicates the GAD inclination

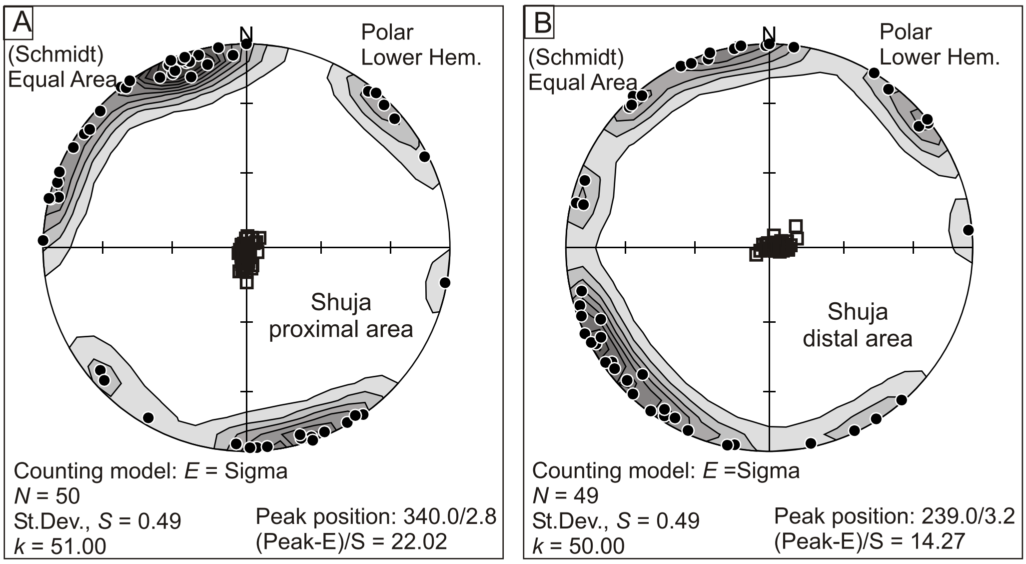


Fig. 8. Equal area projection of maximum K1 (filled circles) and minimum K3 (open squares) directions of AMS ellipsoids for the samples of section 1 of the Shuja proximal (A) and distal (B) areas

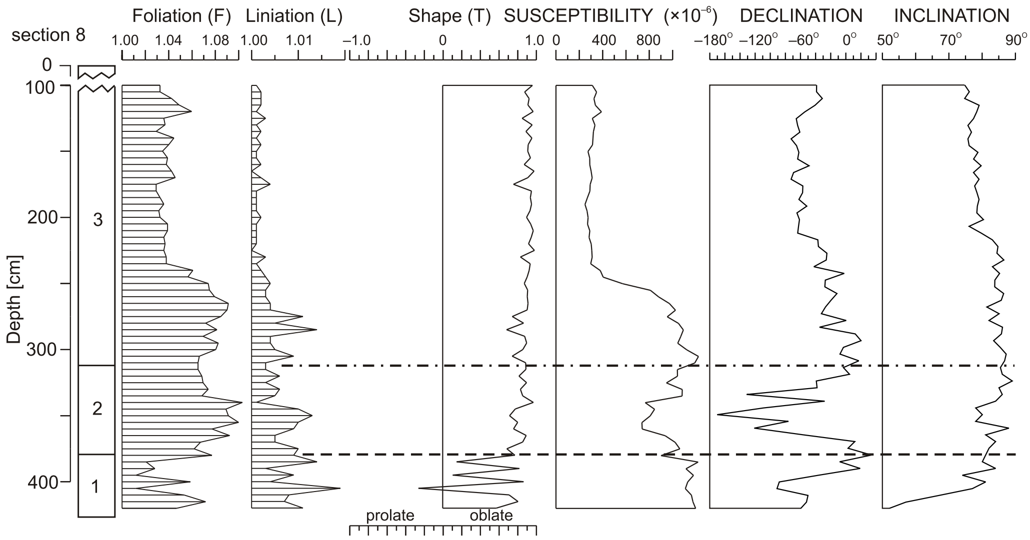


Fig. 9. Magnetic anisotropy parameters (foliation F, lineation L, shape parameter T), magnetic susceptibility, declination and inclination in section 8 of the Ust-Pjalka periglacial basin

The primary and secondary fabrics defined by shape parameter T and AMS ellipsoid axis directions are separated by dashed and dotted lines respectively

1980) and is probably controlled by the turbidity current velocity. The inclination errors related to flow velocity in the near-floor layers where the sediments were deposited. The absolute declination values are from 40°W to 60°W. The distinction of any declination-inclination variations in sections 3 and 5 seems impossible. Only at the bottom of section 5 is there a tendency for a declination shift eastwards.

At the bottom of section 6, located at the periphery of the proximal area, the NRM is 4–5 times less and *k* 2–3 times less than in sections 3 and 5 (Fig. 12). The sharp rise of NRM in the upper 2.5 m is associated with the pigmentation of the sediment changing from grey to brown. Above this level the samples become more stable to AF-demagnetization and this can be explained by the occurrence of hematite (Petrova *et al.,* 1995). This section provides a contrasting picture of variations in angular components. Changes in declination with amplitudes of *ca*. 100° have been recorded. The mean inclination values either approach the GAD inclination or even exceed it. These variations are not associated with changes in the scalar magnetic parameters NRM or *k*. The rhythms in section 6 are structurally most similar to those of distal zone sediments. Altogether 177 rhythms have been distinguished in this section. But the erosion produced by turbidity currents affected the underlying deposits and we are unable to estimate the duration of sedimentation. Nevertheless, these data seem contain information on geomagnetic field variations.

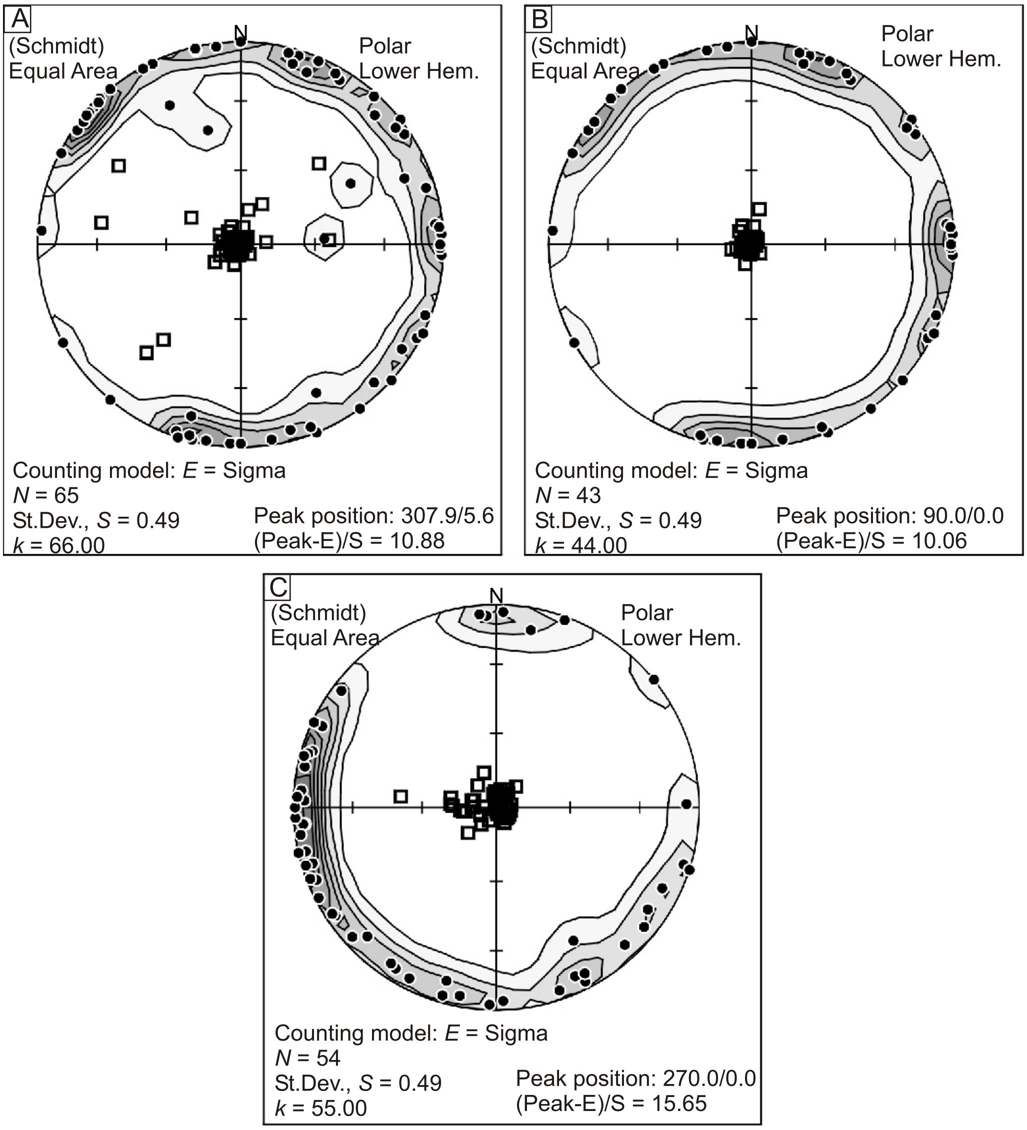


Fig. 10. Equal area projection of maximum K1 (filled circles) and minimum K3 (open squares) directions of AMS ellipsoids for the samples of the Ust-Pjalka periglacial basin

A — for all samples of section 8; **B** — for the upper 2.2 m of section 8 (upper dotted lines in Fig. 7); **C** — for all samples from section 6

DISTAL ZONE OF THE UST-PJALKA PERIGLACIAL LAKE

The palaeomagnetic record of declination and inclination in section 8 of the distal zone after removing the data below 3.2 m are shown in Figure 12. The NRM and *k* values reveal considerable variation from bottom to top, reflecting different hydrodynamic environments of sedimentation and probably magnetic mineralogy fluctuation. Towards the top of the section the NRM decreases by more then an order of magnitude and *k* decreases three-fold. The declination changes from 10°E to 50°W and inclination from 87° to 73°, the mean inclination value approaching the GAD inclination.

The different structure of clays in the proximal and distal areas and the absence of visibly marker layers and anomalous magnetic parameter horizons hinder the cross-correlation of the Ust-Pjalka sections. The only possible correlation is by comparison of the directions of remanent magnetization vectors and analyses of their variations through time. The data from sections 6 and 8 seem useful for correlation. The declination variations appear to be most informative, since: (1) we do not know the effect of "inclination error" which can vary from section to section depending on flow energy; (2) the amplitude of declination variations at this latitude is well above the inclination (in sections 6 and 8 they are about 100° and 10° respectively); (3) the samples have orientations in the horizontal plane and we can compare not only behavior of variations but also consider the absolute values.

A comparison of the absolute declination values for the proximal zone shows that sections 3 and 5 can be compared with interval 1.3 – 2.6 m of section 6 and interval 1.15–2.1 m of section 8. In the last one this interval includes *ca*. 200 DE rhythms and each rhythm probably representing one year. This number exceeds by several times the amount of varves distin-

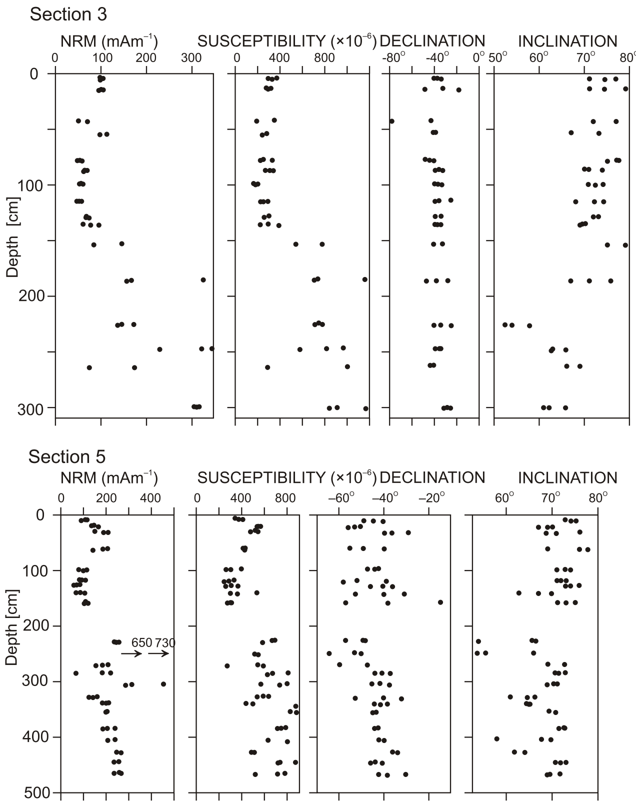


Fig. 11. Magnetic parameters (natural remanent magnetization NRM, magnetic susceptibility, declination and inclination) of the samples from sections 3 and 5 of the Ust-Pjalka periglacial basin

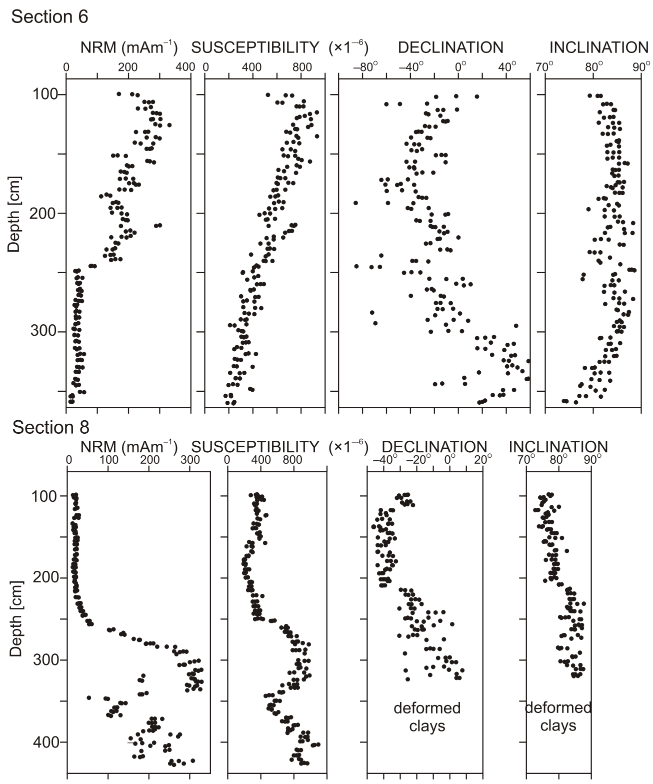


Fig. 12. Magnetic parameters (natural remanent magnetization NRM, magnetic susceptibility, declination and inclination) of the samples from sections 6 and 8 of the Ust-Pjalka periglacial basin

guished in section 3 and 5 and makes up only one-third of the total number of varves in section 8. Thus the clays in section 3 and 5 were deposited during a period of less than 200 years and their rhythms were completely or partly eroded by turbidity currents. Here the fragments of a single rhythm in sections 3 and 5 cannot be used to assess the sedimentation rate.

The distal varved clay section most completely reflects the chronological scale and is most appropriate for varvometric and palaeomagnetic investigations. In Figures 11 and 12 all the data are shown by depth scale. Section 8 contains 606 DE rhythms (annual laminated varved clays) and declination-inclination curves could be represented by a time scale. Thus the declination and inclination variations in section 8 correlate with palaeomagnetic data of section 6 and could be used for representation of geomagnetic field secular variations through time.

THE SHUJA PERIGLACIAL LAKE

Declination and inclination records in section 1 of the Shuja periglacial lake are shown in Figure 13. The mean inclination value is 71°, but for samples from proximal and distal varves (see Fig. 7) this value is 68° and 73° respectively. For this region the GAD inclination is 75°. Here the shallowing of inclination in proximal varves is less than in the Ust-Pjalka clays. The analyses of inclination values versus the anisotropy degree $P = K1/K3$ for proximal and distal clays are shown as two overlapping groups (Fig. 14). The amplitude of inclination variation is 16° and declination variation is more than 50° (from 17°E to 32°W).

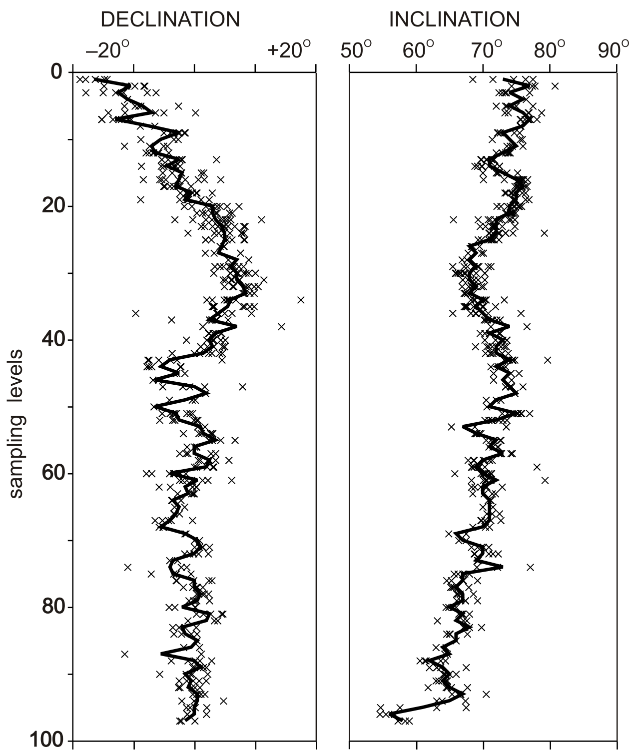


Fig. 13. Declination-inclination variations in the Shuja varved clays, section 1

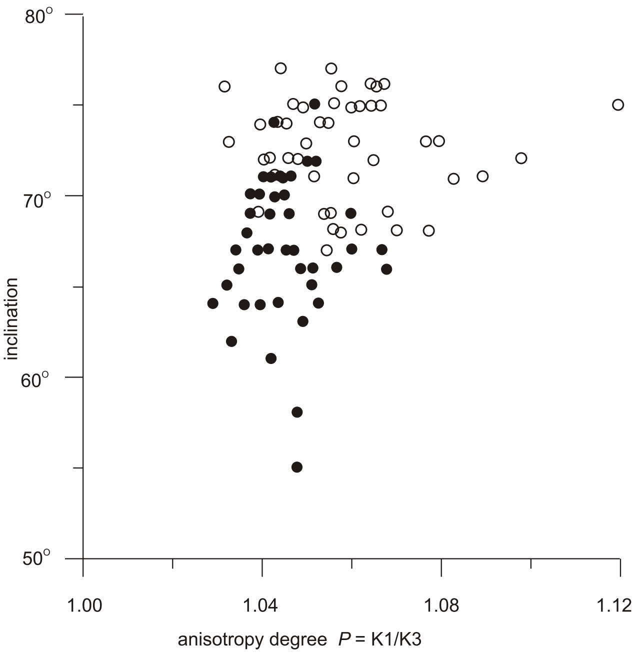


Fig. 14. Inclination *vs*. anisotropy degree *P* = K1/K3

Filled circles and open circles represent data from proximal and distal areas respectively

As mentioned above, the varves from the Shuja sections have a composite structure. From proximal and distal areas 267 and 271 couplets respectively were visually distinguished (Table 5). The upper part of the section is mostly composed of varves with monocyclic structure. From study of "hidden" periodicity of varve structures following Vyahirev (1997), from the proximal and distal areas 237 and 399 annual cycles were respectively determined. Therefore the conventional duration of sedimentation of these clays is 636 years. Hence the declination-inclination variations could be represented in a time sequence.

INTERPRETATION

The correlation of palaeomagnetic data obtained from the Ust-Pjalka (Fig.12) and Shuja (Fig.13) sequences with the chrono- and magnetostratigraphy scheme of NW Russia (Bakhmutov, 2000) is shown in Figure 15. Each point of this scheme represents the mean value for a 30 yr interval. The palaeomagnetic records are presented in our conventional duration of sedimentation of the Shuja and Ust-Pjalka clays of 636 and 606 years respectively. The suggested correlation of the Ust-Pjalka deposits with this scheme was used as a basis for comparison of the marginal glacial deposits of Keiva I and Keiva II with the marginal deposits of Karelia (Bakhmutov *et al*., 1993). The Keiva I succession corresponds to the marginal deposits of the Neva stage of the last glaciation. The correction of geochronological time scale (Bakhmutov, 2000) gives the age of the declination C peak at about 11950 BP varve years. According to recent palaeomagnetic data from neighbouring regions with new radiocarbon determinations the age of the C peak is about 13090 cal yrs BP (Saarnisto and Saarinen, 2001).

CONCLUSIONS

The detailed lithological and palaeomagnetic investigation of glaciolacustrine deposits from two different palaeobasins revealed many interesting features. The rhythmic structure of varved clays is similar to the rhythms of typical turbidites with substantial differences between proximal and distal areas.

The sedimentation rate for the proximal Ust-Pjalka varved clays (sections 3 and 5) of complex structure cannot be determined. These deposits contain time gaps while in the distal area they are represented by a continuous sequence. The varves become thinner and structurally simpler distally. The declination of the proximal clays corresponds to the 1.15–2.1 m interval of the

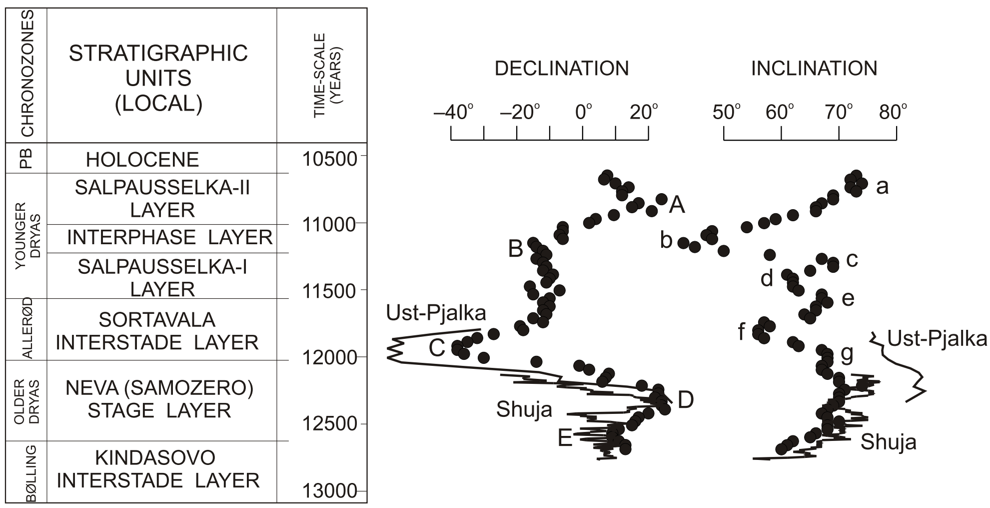


Fig. 15. Comparison of the declination-inclination records of the Ust-Pjalka and Shuja periglacial basins in the context of the chrono- and magnetostratigraphic scheme of Late Weichselian deposits in NW Russia (Bakhmutov, 2000)

Each point represents the average of 30-year intervals; declination and inclination peaks are given by upper and lower case letters respectively distal varved clays (section 8), which are represented by about 200 annual DE rhythms. It would be difficult to correlate the varves of the proximal area by the varve clay chronology method.

There are significant differences in the magnetic parameters (NRM and susceptibility) for proximal and distal areas. The palaeomagnetic records in proximal varved clays show scatters in inclination and declination values between neighboring levels and shallow inclination. Nevertheless in the proximal area either far from the delta (section 6 in the Ust-Pjalka clays) or in alterations of proximal and distal varves in the combined sequence (section 1 in the Shuja clays) the record of ancient geomagnetic field direction could be recovered with enough precision for secular variation investigation. The distal varved clays carry the primary palaeomagnetic records and could be used for palaeosecular variation studies. Thus only the distal varved clays are convenient both for geochronology and for palaeosecular variation recovery.

The presence of a mixture of magnetic minerals carrying remanent magnetization does not significantly affect the PSV record in the glaciolacustrine varved clays. Important information regarding the depositional processes could be gleaned from anisotropy of magnetic susceptibility measurements. The directions of current flows and transport of clastic material from different deltas are reflected in the AMS directions. Moreover the undeformed (primary fabric) and deformed (secondary fabric) sediments could be easily distinguished AMS parameters.

The features of PSV are similar to the main behavior of declination-inclination variations of the chrono- and magnetostratigraphic scheme for NW Russia (Bakhmutov, 2000; Fig. 15). This is consistent with the inferred duration of deposits of one couplet (the second order cycles, DE rhythms) during one year.

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