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Characteristic of till formation during the Baltija (Pomeranian) Stage of the Nemunas (Weichselian) Glaciation in Lithuania

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Studies of the till structure and composition of the Baltija (Pomeranian) Stage of the Nemunas (Weichselian) Glaciation in Lithuania has enabled recognition of a multilayered till structure. This can be seen visually (colour, bed structure, interlayers, insertions of different composition and so on) and established from features determined by analytical and statistical methods (physical and mechanical properties, material composition, orientation and dip of longer axes of pebbles). Borehole log data from boreholes drilled during geological mapping showed heterogeneity within the subglacial till of the Baltija Stage and provided a preliminary picture of variations of its multilayered structure from S to N. This showed that two layers predominate in the subglacial till in the area of the South Lithuanian Phase while three layers are present in the area of the Middle Lithuanian Phase farther north. The petrographic composition of the gravel fraction as well as the orientation and dip of the long axes of pebbles measured in till beds in natural exposures and quarries further demonstrated the multilayered structure of the Baltija till. Research at key sections in areas of the subsurface extent of till of the East, South and Middle Lithuanian phases of the Baltija glacial recession confirmed the increase in the number of till layers from S to N. The physical and mechanical properties of the till also reflect its multilayered structure. Relative entropy values calculated for the grain-size frequency distribution of the Baltija till enabled evaluation of a change in its sorting along the direction of glacial ice advance from N to S. There is a correlation between the higher values of entropy of grain-size distribution and the rate of development of preferred orientation of longer axes of pebbles throughout the till section vertically. The formation of the multilayered structure of the Baltija till is ascribed to cyclic dynamics of the subglacial processes associated with the receding ice sheet; consequently, the number of subglacial till layers may be related to the marginal moraine ridges of different phases left by oscillation of the ice sheet margin during glacial recession.

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INTRODUCTION

Basal till plains and marginal moraine ridges of the Nemunas (Weichselian) Glaciation are widespread across most of Lithuania. There is a larger diversity of depositional facies of till, but these have been poorly studied to date. However, many properties of till are of uncertain origin and this hinders correlation of till units and the making of palaeogeographical interpretations. Available data on the rhythmic patterns of structure and composition within the till beds in the Quaternary succession of Lithuania and adjacent regions (Čepulytė, 1967; Gaigalas, 1971, 1979, 1989; 1995; Gaigalas and Marcinkevičius, 1973; Matveyev, 1976; Rzechowski, 1980; Halicka, 1986; Marcinkevičius, 1988; Āboltinš, 1989; Baltrūnas, 1995, 1996, 2002; Ber, 2000) relate such lithological variation to the multilayered structure of the till beds. Furthermore, the multilayered till structure invite an assumption of the subglacial till sedimentation mechanism as relating to repeated accumulation due to oscillations of ice at particular stages of glaciations. So the subglacial till layers should, theoretically, coincide with the marginal zones (end moraine ridges) of different phases of glacial recession.

The properties of till determining the character of such multilayered structure are usually related to glacial dynamics (Lavrushin, 1980; Gaigalas, 1989), genetic aspects (e.g. Vereisky, 1978; Dreimanis, 1989; Brodzikowski and van Loon, 1991; Šinkūnas and Jurgaitis, 1998; van der Meer *et al.*, 2003), variation of grain-size distribution (Kriger, 1978) or post-sedimentary and anthropogenic processes (e.g. Ignatavičius, 1986; Račkauskas, 2003). All these factors are considered

as having caused macroscopic, physical and mechanical differences between individual till layers in Lithuania (Baltrūnas, 2002). Valuable insights have been obtained in regions of present glaciation, especially as regards processes taking place within the bottom layers of the glacier (e.g. Lavrushin, 1980; Serebryanny and Orlov, 1989; Brodzikowski and van Loon, 1991; Hindmarsh, 1996; Alley *et al*., 1997; Czerwonka *et al*., 1997; Knight, 1997; Boulton *et al*., 1999, 2001; Stea and Pe-Piper, 1999; Knight *et al*., 2000; Khatwa and Tulaczyk, 2001; Lysså and Lønne, 2001; Müller and Schlüchter, 2001; Piotrowski *et al*., 2001; Waller, 2001; Stokes and Clark, 2002). This paper focuses on the till characteristic of the Baltija (Pomeranian) Stage of the Nemunas (Weichselian) Glaciation in relation to the glacial dynamics during deglaciation, and demonstrates the nature of the multilayered structure of this subglacial till to allow better interpretation of this phenomenon. For this purpose the structure, composition, physical and mechanical properties of tills were examined along a line which traverses the Last Glacial till units deposited during successive phases of glacial recession from the maximum of the Baltija (Pomeranian) Stage in Lithuania (Fig. 1).

SITES INVESTIGATED

Geophysical logs of radioactivity, electrical potential and electrical resistance in boreholes made during the geological mapping were studied to investigate the character of the multilayered structure of the Baltija till. Logs from 31 boreholes were analysed. The most complete logs of the Baltija till were obtained from boreholes in three areas situated around the towns of Prienai (East Lithuanian Phase) and Kaunas (South Lithuanian Phase) and on the till plain of the Middle Lithuania Phase (Fig. 1).

Till sections at exposures and in quarries located on surfaces formed during different glacial recession phases of the Baltija Stage of the Nemunas (Weichselian) Glaciation were studied (Fig. 1). The Baltija till in the area affected by the East Lithuanian Phase was investigated at Balbieriškis. The till outcrops there on the high left bank of the Nemunas River in the central part of the Simnas–Balbieriškis glaciolacustrine plain, which stretches between marginal moraine ridges of the East Lithuanian (maximum) and South Lithuanian phases of the Baltija Stage. The thickness of the macroscopically homogeneous bed of till overlain by varved clay reaches 5 m.

In the area affected by the South Lithuanian Phase two exposures, Rokai and Lašiniai, situated in between the marginal moraine ridges of the South and Middle Lithuanian phases of the Baltija Stage, were examined. The Rokai exposure is situated on the high right bank of the Jiesia River, the left tributary of the Nemunas River in the western part of Kaišiadorys–Garliava glaciolacustrine plain; here, the till, overlain by varved clay, is up to 5–6 m thick. The Lašiniai exposure is on the right bank of the Strėva River, the right tributary of the Nemunas River (Fig. 1).

The Baltija till in the area of the Middle Lithuanian Phase was investigated in the Paliepiai exposure and in the Klovainiai and Petrašiūnai quarries that lie between the marginal moraine ridges of the Middle and North Lithuanian phases. The Paliepiai exposure is on the left bank of the Šušvė River, the right tributary of the Nemunas River on the Middle Lithuanian till plain; here, the thickness of the Baltija till reaches 7 m. The Klovainiai sec-

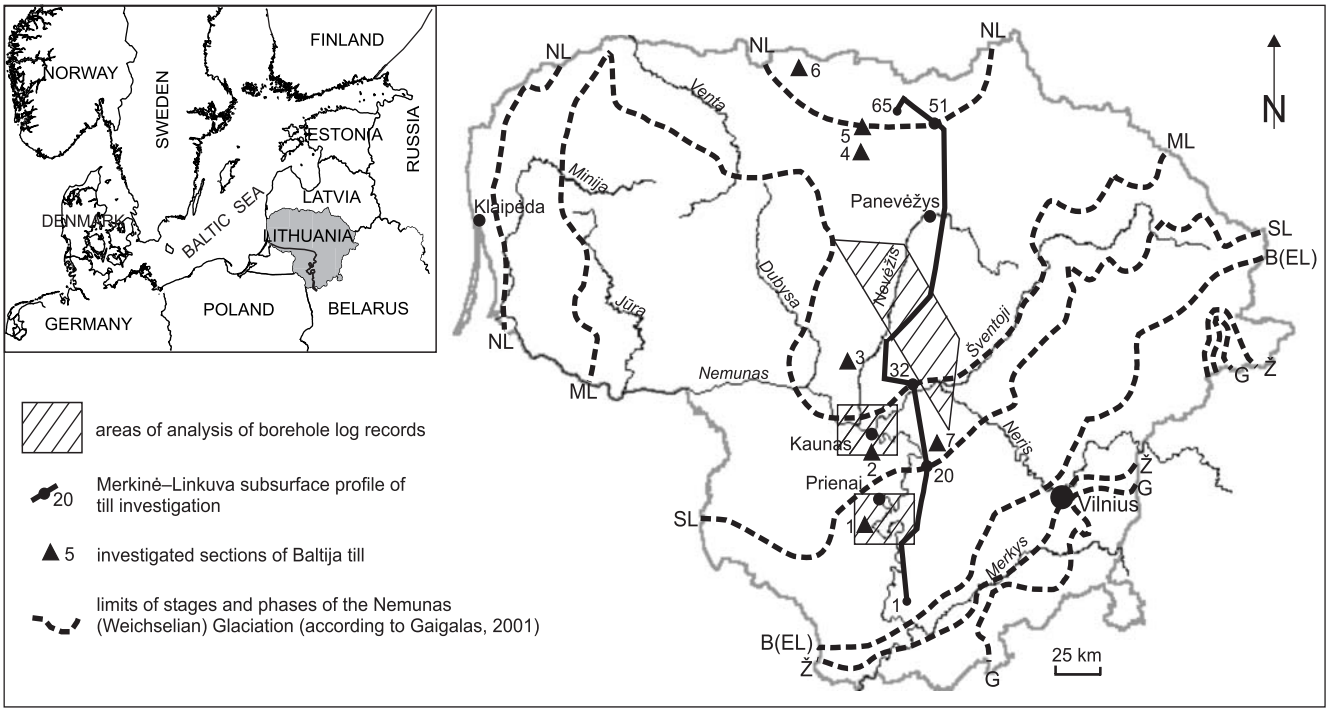

Fig. 1. Location of the sites investigated

Investigated sections of Baltija till: 1— Balbieriškis, 2 — Rokai, 3 — Paliepiai, 4 — Klovainiai, 5 — Petrašiūnai, 6 — Skaistgirys, 7 — Lašiniai; limits of stages and phases of the Nemunas (Weichselian) Glaciation (according to Gaigalas, 2001): G — Grūda (maximal) Stage, Ž — Žiogeliai Phase, B(EL) — East Lithuanian (maximum) Phase of the Baltija Stage, SL — South Lithuanian Phase, ML — Middle Lithuanian Phase, NL — North Lithuanian Phase

tion is located in the dolomite quarry that lies on the northern part of the Middle Lithuanian till plain in the Pakruojis district (Fig. 1), where a 3–3.2 m-thick layer of the Baltija till overlies the Upper Devonian dolomite. Less than 10 km to the north, a glacigenic succession up to 8 m-thick overlies the dolomite and marl beds in the Petrašiūnai quarry section.

The Skaistgirys section is situated in the dolomite quarry in area of the North Lithuanian Phase on the till plain near the Skaistgirys borough of the Joniškis district; here, the thickness of the Baltija till is 2–3 m.

Additional test boreholes were drilled using a vibro-drill on the Balbieriškis, Rokai and Paliepiai outcrops to examine the till beds. We have also used data earlier obtained, during the lithological investigations of till along the Merkinė–Linkuva subsurface profile (Baltrūnas *et al*., 1989; Baltrūnas, 1995, 2002); this profit, oriented N–S, crosses the Last Glacial till succession deposited during the different phases of glacial recession from the maximum of the Baltija Stage (Fig. 1).

METHODS

The character of the multilayered structure of the Baltija till was initially analysed using logs of radioactivity, electrical potential and electrical resistance from boreholes drilled during the geological mapping of the study area. Then, sections in natural exposures and quarries were examined and described in detail. The orientations and dips of pebble long axes in till beds were measured and samples were taken for petrographic and grain-size analysis of the till. Dip angle and orientation of long axes were measured for 50–100 clasts at each section.

The petrographic composition of pebbles was analysed following Gaigalas (1979) using the categories: crystalline rocks, sandstone, dolomite, Ordovician and Silurian limestone, limestone of other types, Mesozoic carbonates and group of other rocks. The petrographic indices were calculated according to the methods proposed by Ber *et al*. (1998), Gaigalas and Melešytė (2001), Pettersson (2002) and Lisicki (2003) .

Ten grain-size fractions of till material were obtained during granulometric analysis using the sieving and pipette methods. The relative entropy (R) was calculated using all 10 fractions and then 8 fractions after summing of the finest fractions. The results obtained and their interpretation have been discussed in earlier publications (Baltrūnas and Pukelytė, 2003; Baltrūnas and Gaigalas, 2004). The relative entropy was also calculated for Baltija till grain-size data obtained earlier along the Merkinė–Linkuva subsurface profile for 21 fraction and then after summing them for the same 8 fraction as in the other sites (Baltrūnas *et al*., 1989; Baltrūnas, 1995).

Samples of core from test boreholes made using a vibro-drill were taken for assessment of moisture content (W) and, from the Balbieriškis exposure, also for liquidity index (I_L). The apparent cohesion (c_u) of core samples was estimated using the vane test (Lancellota, 1995). The radioactivity of tills from some boreholes, natural exposures and quarries were examined using the Russian-made *RKSB-104 Geiger counter*. The subdivision of till sequences on the basis of dispersion and average values was controlled using the Student criterion.

RESULTS OF INVESTIGATIONS

ANALYSIS OF LOG RECORDS

Logs of radioactivity, electrical potential and electrical resistance from 31 boreholes drilled during geological mapping showed the multilayered nature of the Baltija till in subcrops of the East (maximum), South and Middle Lithuanian phases of the Baltija glacial recession (Table 1). Correlations of the logs

Table 1

The multilayered structure of the Baltija till in the areas of East Lithuanian (maximal) (EL), South (SL) and Middle (ML) Lithuanian phases of the Baltija glacial recession according to log data from the boreholes

Phase of the Baltija Stage	Number of borehole	Thickness of till [m]	Geomorphological position	Number of till layers according to:			Estimated number of till layers
				Ra	EP	Re	
EL	306	2.0	plain	1	1	1	1
	307	7.0	marginal zone	2	3	2	2–3
	312	4.3	plain	1	1	1	1
	313	1.5	plain	1	1	1	1
	317	1.3	end moraine	1	1	1	1
SL	159	11.0	plain	2	1	2	2
	162	5.3	plain	2	–	–	2
	178	8.9	plain	2	2	2	2
	185	9.0	plain	2	2	2	2
	188	22.4	plain	4	–	4	4?
	191	7.7	plain	2–3	1	2	2
	177	9.7	plain	1–2	2	2	2
	117	18.0	plateau	3–4	3–4	3–4	3–4
	120	11.4	plateau	3	3	3	3
	163	15.8	marginal zone	3	1	3	3
	164	17.3	marginal zone	–	≥1	≥2	≥2
	165	18.0	marginal zone	3–4	≥3	≥3	≥3
ML	151	15.8	plain	3–6	1?	2–3	3–4
	152	5.35	plain	2	2	2	2
	153	9.9	plain	3	2?	3	3
	155	11.3	plain	3–4	2?	3–4	3
	158	6.1	plain	3	2?	2	2–3
	167	6.2	plain	2	2	2?	2
	121	12.0	plain	–	3	–	3?
	124	12.4	plain	2–3	–	≥2	≥2
	126	12.5	plain	≥1	≥2	2	≥2
	179	15.0	plain	3	–	≥2	3
	184	12.8	plain	≥3	3?	–	3–4
	181	12.7	esker	≥2	≥2	≥2	≥2
	123	10.0	marginal zone	3	1–2	3	3
	156	5.0	marginal zone	2–3	2	2	2–3

Ra — radioactivity, EP — electrical potential, Re — electrical resistance

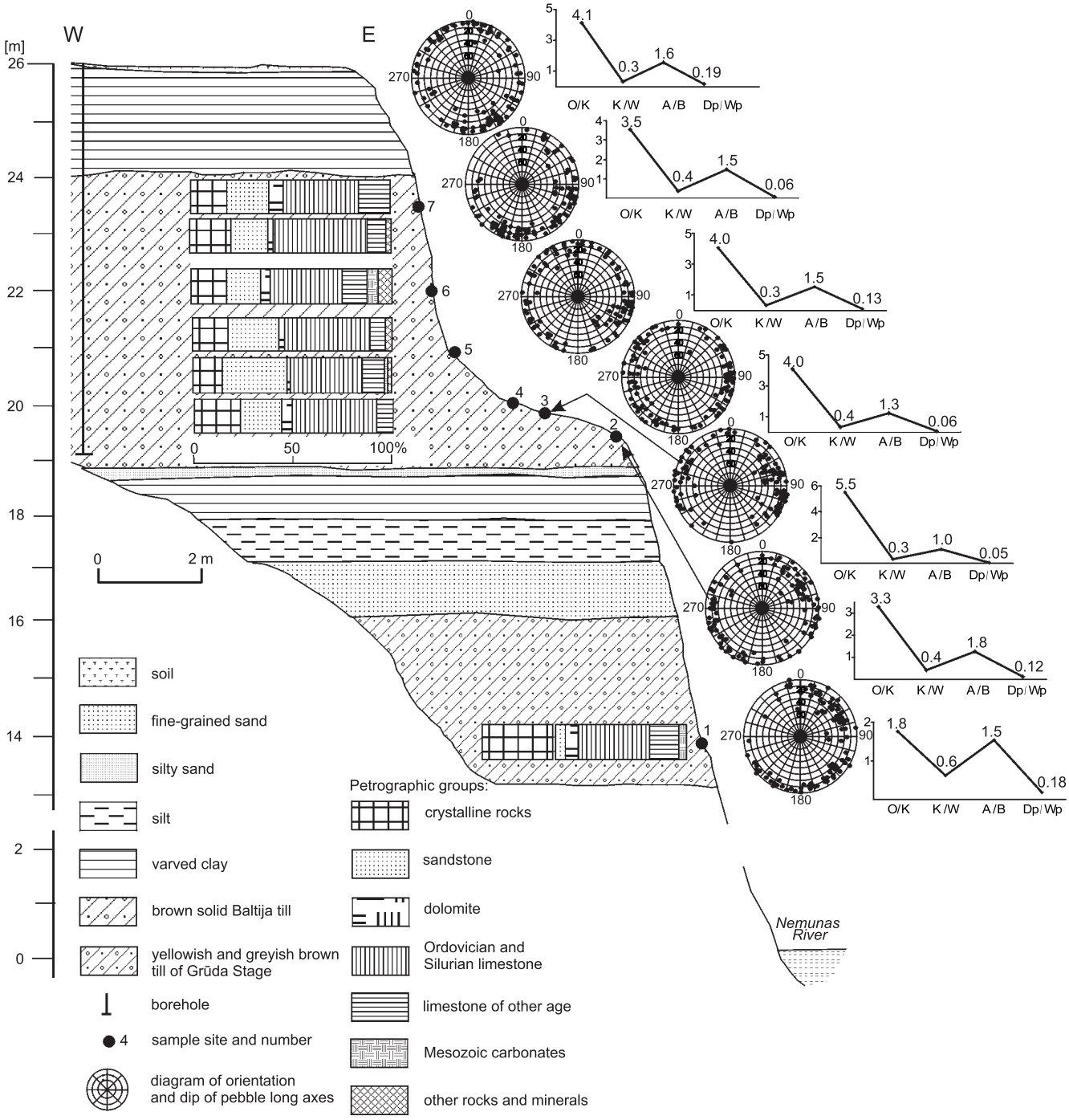

Fig. 2. Glacigenic deposit sequence in the Balbieriškis exposure

Petrographic coefficients: O/K — total of sedimentary rocks/total of crystalline rocks and northern quartz, K/W — total of crystalline rocks and northern quartz/total of limestone and dolomite, A/B — total of rocks non-resistant to destruction/total of resistant rocks, Dp/Wp — dolomite/Ordovician and Silurian limestone

shows that the multilayered till structure shows regular changes from S to N: two layers dominate in the area of the South Lithuanian Phase and a three layers are typical of the area of Middle Lithuanian Phase farther north.

INVESTIGATION OF TILL SEQUENCES

The 5 m-thick till bed in the Balbieriškis exposure is macroscopically homogeneous; the orientation and dip of the long axes of pebbles show vertical variations through the till section (Fig. 2). The preferred orientation of the long axes of pebbles in the lower part of the till bed (*ca.* 1 m thick) is dominantly E–W, although the dips may be to either E or W. The middle part of the till bed (1–2 m thick) is characterized by very weakly developed preferred, or random, orientation of the long axes. A well developed preferred orientation and dip to the S and SE was measured in the upper part of the section, although at the top of the till bed it again shows a more random character.

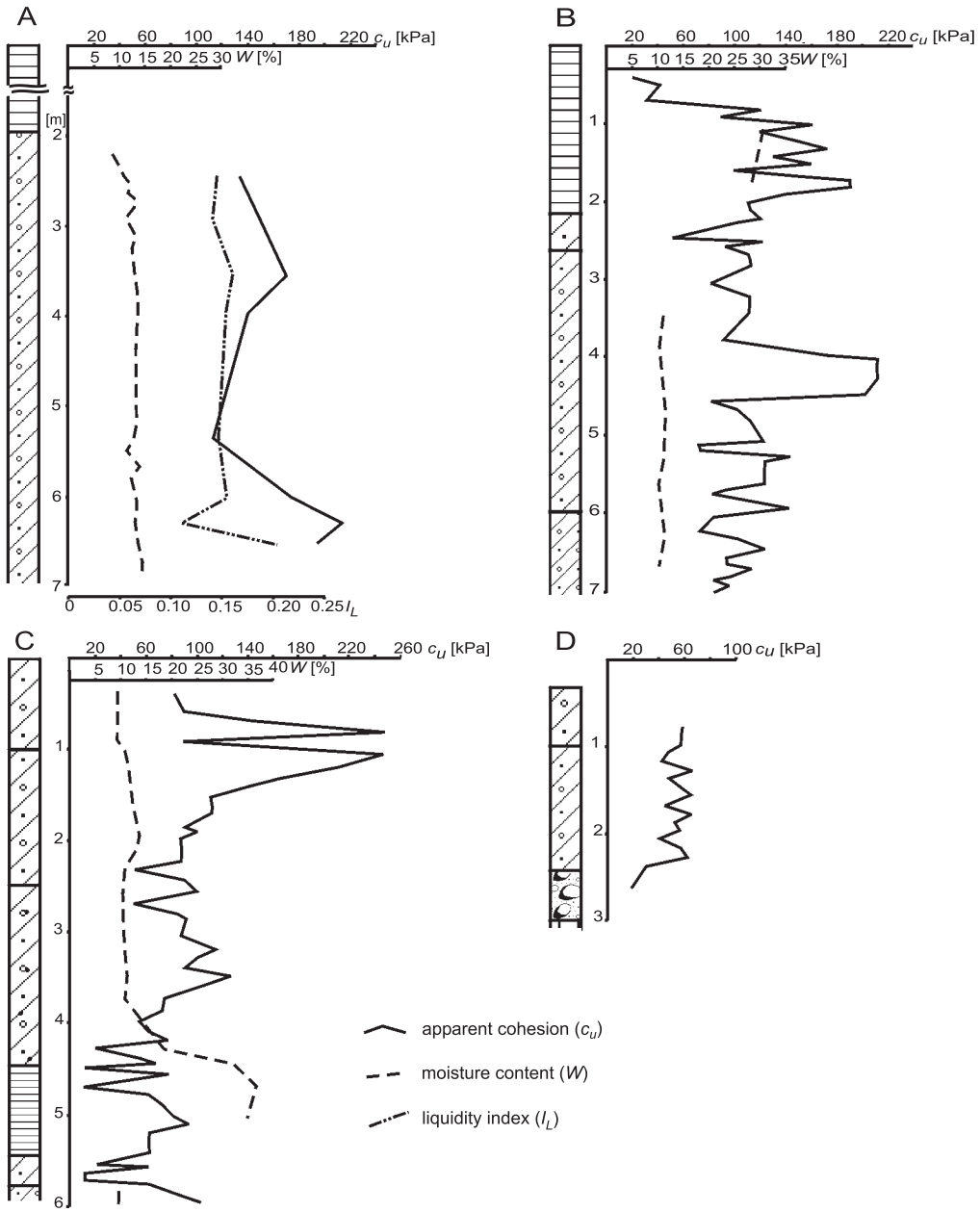

Fig. 3. Variation of physical and mechanical properties of Baltija till in the sections: A — Balbieriškis, B— Rokai, C — Paliepiai, D — Skaistgirys

Explanations as on Figures 2, 4, 5 and 8

The petrographic composition of gravel and pebbles is generally uniform throughout the till bed, although it differs strongly from the underlying more weathered till of the Grūda (Brandenburg) Stage, the maximal stage of Nemunas (Weichselian) Glaciation.

Physical and mechanical properties of till deposits sampled in the borehole drilled at this outcrop enable subdivision of the Baltija till bed into two parts (Fig. 3A). The lower part (1–1.25 m thick) of the till bed shows considerably higher values of apparent cohesion (175–215 kPa) and lower values of liquidity index (I_L) (2.12–0.16). The upper part of the till bed is characterised by consistent physical and mechanical properties: values of apparent cohesion range from 165 to 117 kPa and the values of liquidity index range around *ca*. 0.16, while values of moisture content (W) show a narrow range of 8.2–14.2%.

The 5–6 m-thick till bed in the upper part of the Rokai exposure is overlain by varved clay (Fig. 4). The orientation and dip of the long axes of clasts vary slightly throughout the till section (Fig. 4). The middle part of the till displays no preferred orientation, whereas the orientation and dip of pebble long axes in the lower part (*ca*. 1 m thick) suggest that the till accumulated during ice advance. However, the petrographic composition of the coarse fraction of the till bed is more variable, especially in the transition from the lower to the middle part. A gradual upwards increase in radioactivity (10–16 μR/h) was observed.

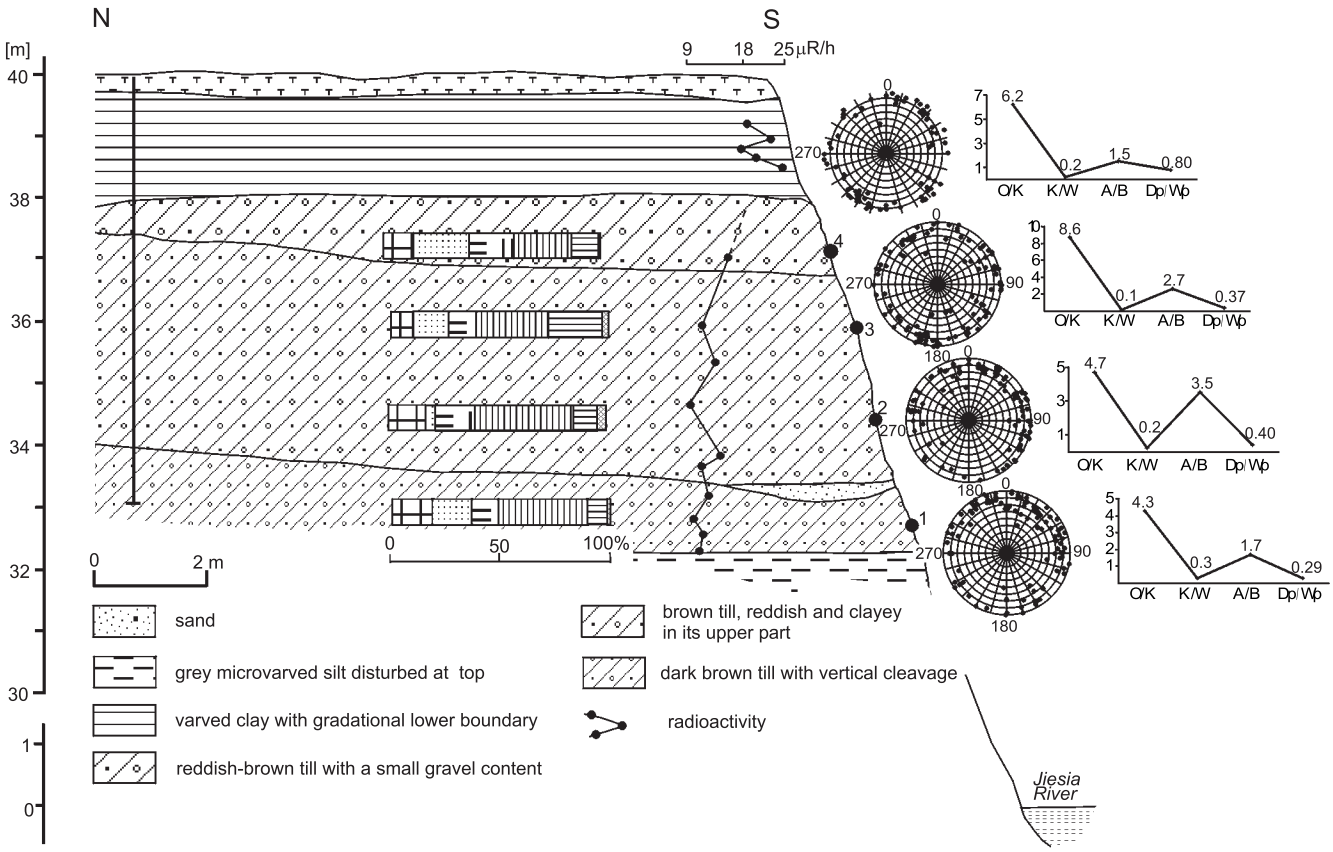

Fig. 4. Glacigenic deposit sequence in the Rokai exposure

Other explanations as on Figure 2

The moisture content values (*W*) measured in the borehole are consistent (9.6–10.4%) throughout the till bed (Fig. 3B). However, the values of apparent cohesion at a depth of 3.9–4.5 m range from 190 to 225 kPa, while in the upper and lower parts of the till bed they are much lower and weakly variable (85–160 kPa).

In the Lašiniai section earlier investigations (Baltrūnas, 1995, 1996, 2002) demonstrated that the multilayered structure of the till reflects two glacial advances during the Baltija Stage.

The lower part (*ca*. 1.0 m thick) of the Paliepiai exposure (Fig. 5) is composed of the Grūda till. The orientation and dip of pebble long axes in the lower part (*ca*. 1.5 m thick) of the Batija till section (total thickness up to 7 m) in the Paliepiai exposure are dominantly from the north. The middle part of the till sequence (*ca*. 3 m) is characterized by more random orientation and dip directions of pebble long axes. A dark brown clay layer separates the middle and upper parts of the till sequence. This glaciolacustrine clay interlayer is 0.4 m where exposed and 10 m away in a borehole it reaches 1.1 m thick. The till which overlies the clay is laminated for 0.6 m. The long axes of pebbles are clearly N–S orientated with a dominant dip to the north. In its upper part (1.5 m thickness) the till is clayey, friable and shows a similar orientation and dip of pebble long axes; it grades upwards into sand of variable grain-size.

The petrographic composition of the till coarse fraction is consistent throughout this sequence but differs strongly from the underlying greyish brown till of the Grūda Stage.

Values of radioactivity reflect the heterogeneous character of the till. Both in the borehole and in the upper part of the exposure these do not exceed 9–18 μR/h, though in the exposure they notably decrease downwards.

The values of apparent cohesion of till (Fig. 3C) in the upper part of the borehole (up to 1.5 m in depth) average 160 kPa; in the depth interval 1.5–4.5 m they vary over a considerably smaller interval (50–120 kPa) and drop to 60–100 kPa beneath the clay interlayer. The values of apparent cohesion show that the sequence may be subdivided in to three layers of different till strength, the moisture content shows low variation within an interval of 8.9–13.5%.

In the Klovainiai quarry the till bed (3–3.2 m thick) is pale and yellowish-brown, friable in its upper part (0.3 m thick), and gradually grades into solid brown till in its lower part (0.5 m thick) that overlies an Upper Devonian dolomite (Fig. 6). A preferred orientation of pebbles long axes is not developed in the lower part of the till bed, but the dips are mainly towards the NW, N or NE. However, a NW–SE orientation in the upper part is apparent with almost equal proportions of dips to opposite directions. The content of crystalline rocks and sandstone in the till decreases upwards whereas the content of dolomite and limestone of other types increases. The proportion of Ordovician and Silurian limestone is somewhat smaller in the middle part of the till sequence.

The 4.5–5 m-thick till bed overlying the Upper Devonian dolomite in the lower part of the section in Petrašiūnai quarry

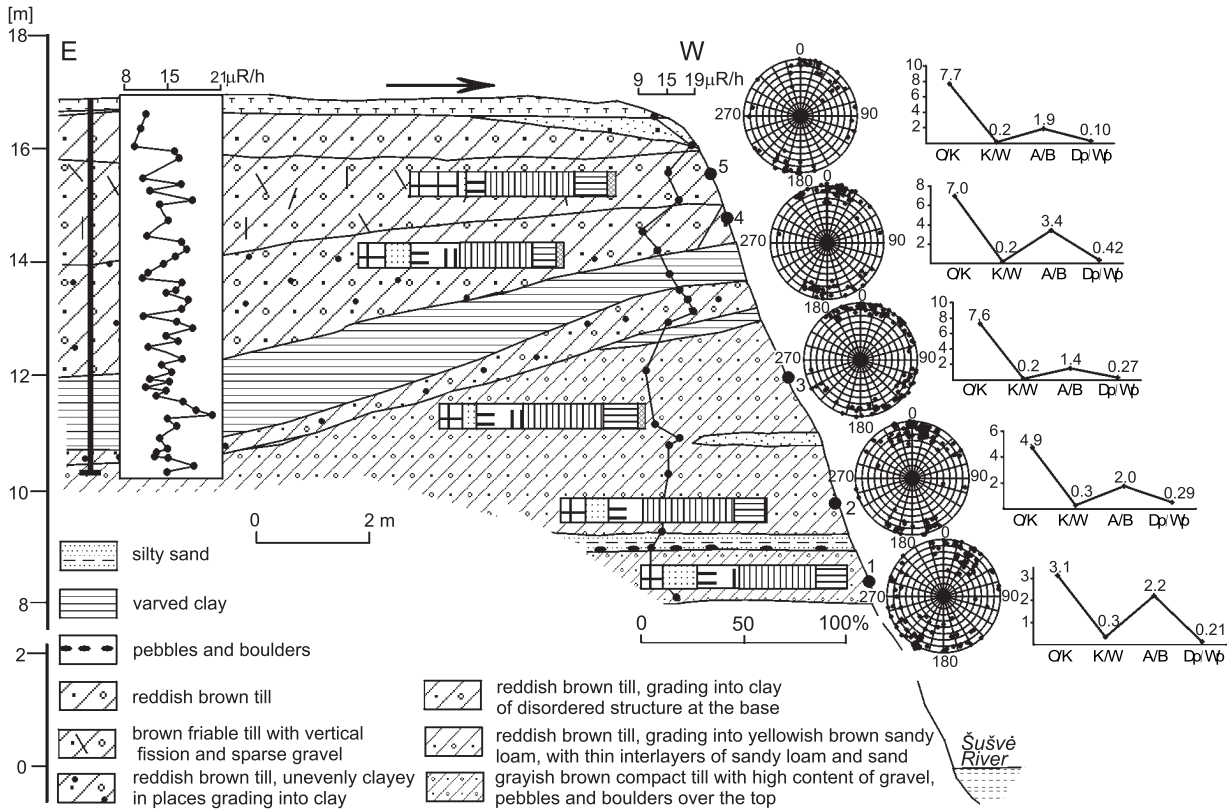

Fig. 5. Glacigenic deposit sequence in the Paliepiai exposure

Other explanations as on Figures 2 and 4

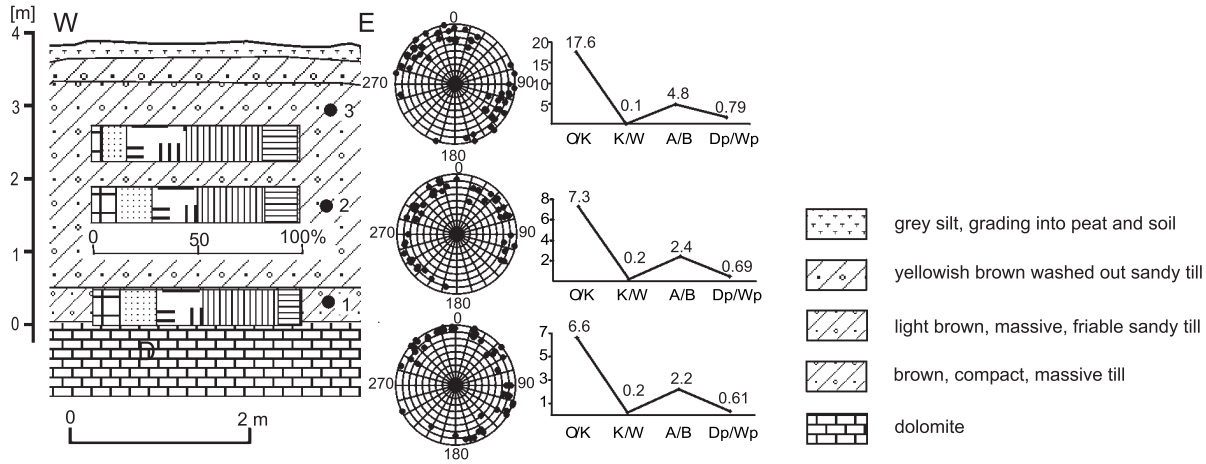

Fig. 6. Glacigenic deposit sequence in the Klovainiai quarry

Other explanations as on Figure 2

(Fig. 7) is dark brown in the lower and upper parts of the bed and grey and yellowish grey in the middle part where it contains a large amount of coarse material. This till bed, widespread in Northern Lithuania, is usually attributed to the Grūda Stage of the Last Glaciation (Gaigalas and Marcinkevičius, 1982; Marcinkevičius, 1988).

The bed of pale brown sandy till of the Baltija Stage *ca*. 4.0 m thick, in two layers separated by glaciolacustrine silt and very fine-grained silty sand, occurs at the top of the sequence. Unlike the underlying older till which has a poorly developed preferred pebble orientation, the lower layer of the Baltija till displays a well developed preferred orientation of clast dip to the north, becoming more scattered in the upper layer of the till.

All three till layers have different petrographic compositions of the gravel fraction. The Grūda till contains a large proportion

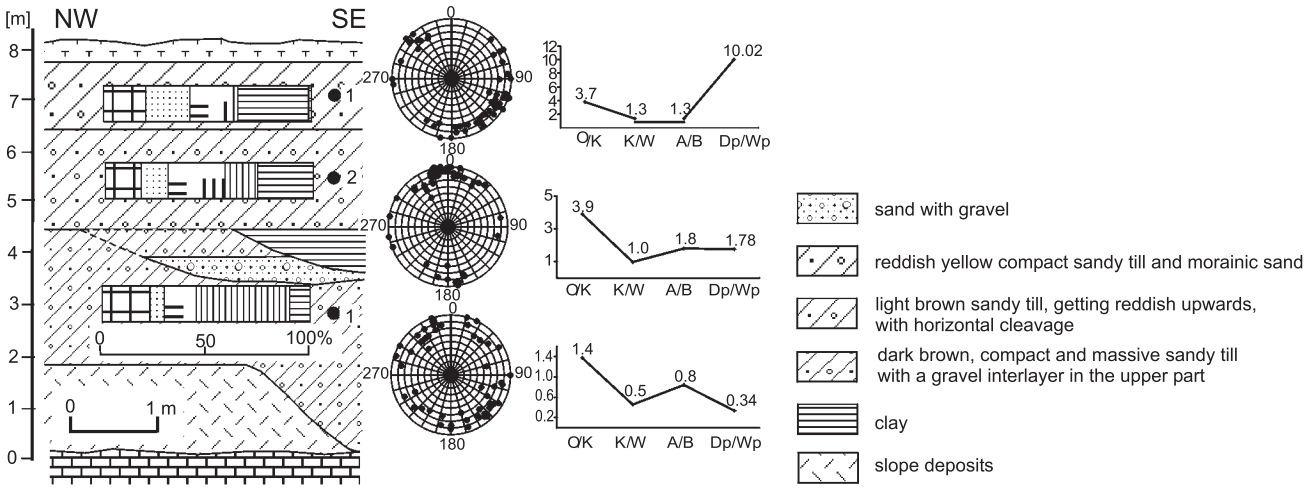

Fig. 7. Glacigenic deposit sequence in the Petrašiunai quarry

Other explanations as on Figures 2 and 6

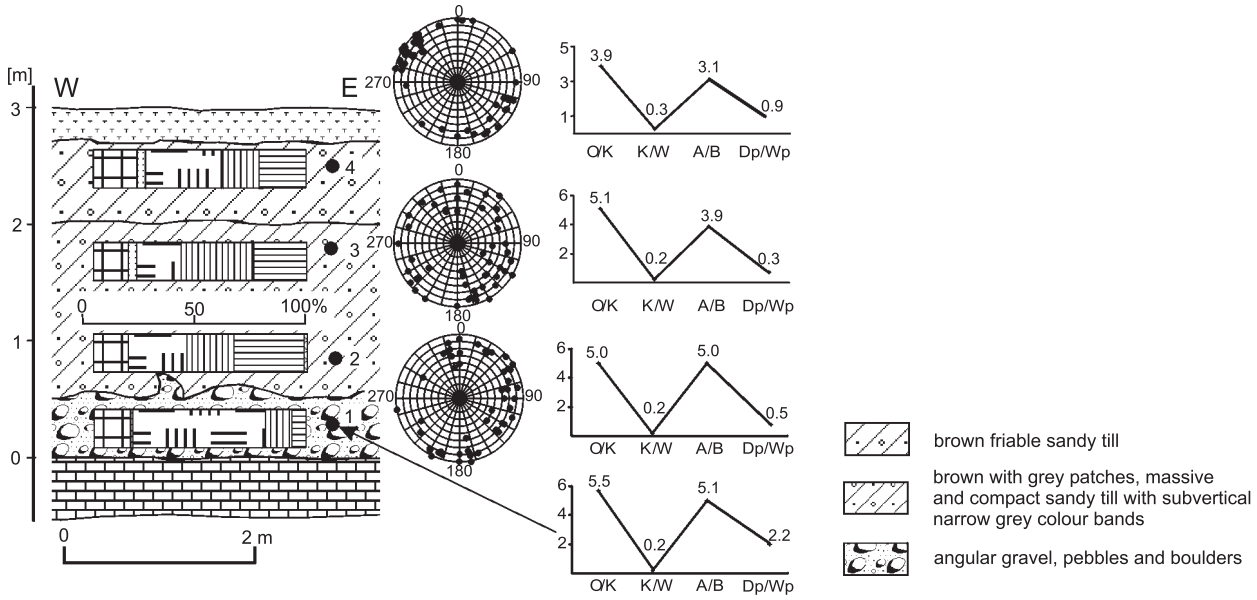

Fig. 8. Glacigenic deposit sequence in the Skaistgirys quarry

Other explanations as on Figures 2 and 6

of Ordovician and Silurian limestone and a small quantity of other limestone types, sandstone and dolomite. The lower till layer of the Baltija Stage differs from the upper one in a higher content of Ordovician and Silurian limestone and dolomite and a reduced content of sandstone and limestone of other types.

In the lower part of the Skaistgirys glacigenic section a bed *ca*. 0.5 m thick of unsorted yellowish grey till with a high content of angular dolomite clasts (60–65%) 1–3 cm in diameter occurs (Fig. 8). In places this turns sandy or grades into morainic sand that overlies the Upper Devonian dolomite. This till bed underlies a layer 2–3 m thick of brown, massive, compact sandy till. The lower boundary of the underlined bed is sharp and very irregular.

A preferred orientation of pebble long axes is generally developed only in the lower and upper parts of the section. The orientation of long axes in the middle part of section is random, indicating till accumulation beneath passive ice. The middle part of the till bed is notable for its considerably higher content of Ordovician and Silurian limestone and smaller content of dolomite.

The values of apparent cohesion (Fig. 3D) in the upper part of the sequence down to a depth of 2.25 m range within a rather

narrow interval: 42–67 kPa. Downwards, the values of apparent cohesion of the sandy till drop sharply to 16–30 kPa.

TILL LITHOLOGY ALONG THE MERKINĖ–LINKUVA SUBSURFACE PROFILE

The variation in till composition across phases of Baltija glacial recession was investigated along the N–S oriented Merkinė–Linkuva subsurface profile (Baltrūnas *et al*., 1989; Baltrūnas, 1995, 2002) that crosses the Last Glacial till successions deposited during different phases of glacial recession from the maximum of the Baltija Stage (Fig. 1). The tills of the East and South Lithuanian phases appear similar according to the majority of criteria used (petrographic, mineral and chemical compositions) in comparison to tills of the Middle and North Lithuanian phases which compositionally are closely related to each other. However, the grain-size distribution data suggests that the till of the East Lithuanian phase (less clayey) is more comparable with the till of the Middle Lithuanian phase. The same could be said about the tills of the South and North Lithuanian phases (more clayey). A comparison of values of relative entropy showed that the highest values of relative entropy are characteristic of the till of the East Lithuanian (maximal) Phase (Table 2).

Along the profile investigated the values of relative entropy decrease considerably in the area of South Lithuanian Phase, increase in the area of the Middle Lithuanian Phase and again decrease in the area of the North Lithuanian Phase (Fig. 9). The sharp reductions in relative entropy values are related to the marginal zones of the North, Middle and South Lithuanian phases.

DISCUSSION

The multilayered structure of the till beds in Lithuania have been described (Čepulytė, 1967; Gaigalas, 1971, 1979, 2001; Gaigalas and Marcinkevičius, 1973; Marcinkevičius, 1988; *etc*.), but the reasons for this phenomenon have been little discussed. Possible causes that have been considered are: sliding of ice along shear planes; interaction of neighbouring glacier lobes, and superposition of the till beds left by them; ice margin fluctuation during glacial recession; differences in till genesis (by lodgement, melt-out, flow and so on); and the effects of post-sedimentary processes (e.g. compaction, weathering).

Usually, clear characteristics of lodgement tills or basal tills are absent or are dominated by other characteristics (Brodzikowski and van Loon, 1991); such subglacial tills show a mixed character and may be referred to as till complexes. The characteristics of the Baltija till suggest consideration of it as subglacial till complexes composed of alternating layers of lodgement and melt-out till.

Analysis of the till sequences in the Balbieriškis, Rokai and Paliepiai exposures and Klovainiai, Petrašiūnai and Skaistgirys quarries confirms the multilayered structure of the Baltija till originally indicated by the log data. Furthermore, the number of till layers are different in areas affected by different phases of the Baltija glacial recession. The number of till layers determined at exposures accords with the number distinguished in borehole log records.

The nature of till composition variation throughout the areas affected by different phases of the glacial recession, as investigated along the Merkinė–Linkuva subsurface profile, may

Table 2

Mean relative entropy of grain-size frequency distribution of the Baltija till for the areas reflecting different glacial phases along the Merkine–Linkuva subsurface profile

Phases of the Baltija Stage	Number of samples	Fraction <0.01 mm [%]	Relative entropy (*R*)	
			21 fraction	8 fractions
EL	14	27.1	0.8584	0.8844
SL	17	34.9	0.8088	0.8560
ML	19	25.5	0.8371	0.8723
NL	15	39.9	0.7651	0.8396

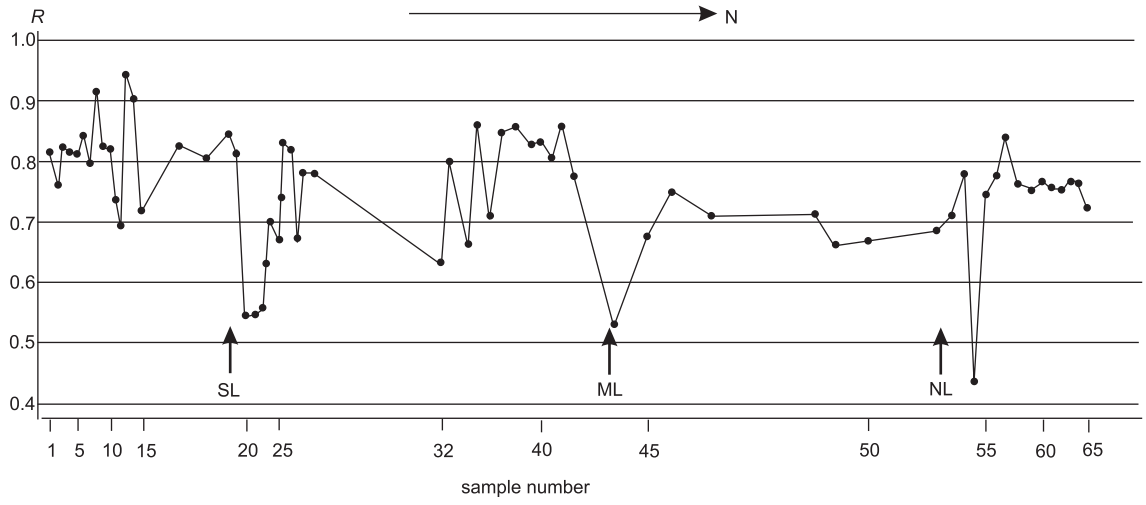

Fig. 9. Variation in relative entropy (*R*) of the grain-size frequency distribution of the Baltija till along the Merkine–Linkuva subsurface profile

SL, ML, NL — limits of South, Middle and North Lithuanian phases of the Baltija Stage respectively; see Figure 1 for a location of the profile

Table 3

Median grain-size (*Md*) and relative entropy (*R*) of grain-size distribution (10 fractions) of the Baltija till

Sites	Number of samples	Fraction <0.01 mm [%]	*Md* [mm]	*R*
Rokai	4	21.30	0.049	0.8642
	3	25.49	0.071	0.9159
	2	23.26	0.067	0.8420
	1	19.16	0.153	0.9263
Lašiniai	10	34.00	0.047	0.8695
	9	24.00	0.073	0.9090
	8	24.60	0.077	0.9109
	7	20.50	0.094	0.9152
Klovainiai	3	23.57	0.076	0.9109
	2	23.49	0.069	0.9026
	1	25.41	0.070	0.9190
Petrašiūnai	3	6.74	0.178	0.8617
	2	24.95	0.068	0.9244
	1	18.36	0.090	0.9107
Skaistgirys	4	17.95	0.091	0.9232
	3	19.36	0.085	0.9098
	2	21.82	0.075	0.9097
	1	6.93	0.269	0.9180

explain the overall stratigraphic variation in till properties, but it does not explain the variation within the till of a single phase.

Commonly, increased values of the relative entropy of the grain-size distribution in the till correlates with more strongly aligned pebble long axes in the till. For example, the lower part of the till in the Rokai exposure (South Lithuanian Phase of the Baltija Stage), showing a strongly preferred orientation and dip of the long pebble axes to the north, also shows increased values of the relative entropy of till grain-size distribution (Fig. 4, Table 3).

The increased values of the relative entropy and well-developed preferred orientation of the long axes of the coarse fraction are also characteristic of the lower part of the Baltija till in the Klovainiai and Petrašiūnai quarries (Middle Lithuanian Phase) and of the upper part in the Skaistgirys quarry (North Lithuanian Phase) (Figs. 6–8).

The more strongly developed preferred orientation of long axes of pebbles indicates that the till sedimented from the ice of an active glacial stream. In the case of the Paliepiai section (Fig. 5), the preferred orientation and dip of pebble long axes show that the lower part of the till bed (*ca*. 1.5 m thick) was formed by an active ice sheet advance from the north. The middle part of the sequence (*ca*. 3 m thick), characterized by more random orientation and dip directions of pebble long axes, presumably formed by the melting of passive ice loaded with till material. The *ca*. 1.5 m thick layer of laminated till above the clay layer shows a return to accumulation from active ice, as shown by the obvious N–S orientation of pebbles and their dip to the north.

Modelling studies by Christoffersen and Tulaczyk (2003) show that horizontal advection of ice can trigger a switch from basal melting to basal freezing even under relatively warm ice sheet conditions. This can cause uneven consolidation of till with depth. Thus, basal melting and basal freezing could alternate and so cause till sedimentation from active and passive states of ice sheet respectively. In such situations, the repetition of composition and other features throughout the till sequence can be explained by cyclic loading of bottom layers of the glacier with till material (Fig. 10). This phenomena may have been associated with ice sheet activation and stabilization phases which are geomorphologically marked by end moraines formed in ice-marginal zones. Such processes could have occurred time-transgressively in a submarginal melting bed zone several hundred kilometres wide (Punkari, 1997). The formation of the multilayered structure of the Baltija till succession may be related to the cyclic dynamics of subglacial processes in the receding ice sheet, and consequently the number of subglacial till layers may be related to the marginal moraine ridges of different phases left by oscillation of the ice sheet margin during glacial recession. The layers of the till succession and the rhythmic change in its properties and composition may reflect the intensity of till material loading.

CONCLUDING REMARKS

Investigations of till beds left by the Baltija Stage of the Nemunas (Weichselian) Glaciation in Lithuania showed that the Baltija till has a multilayered structure, which can be ob-

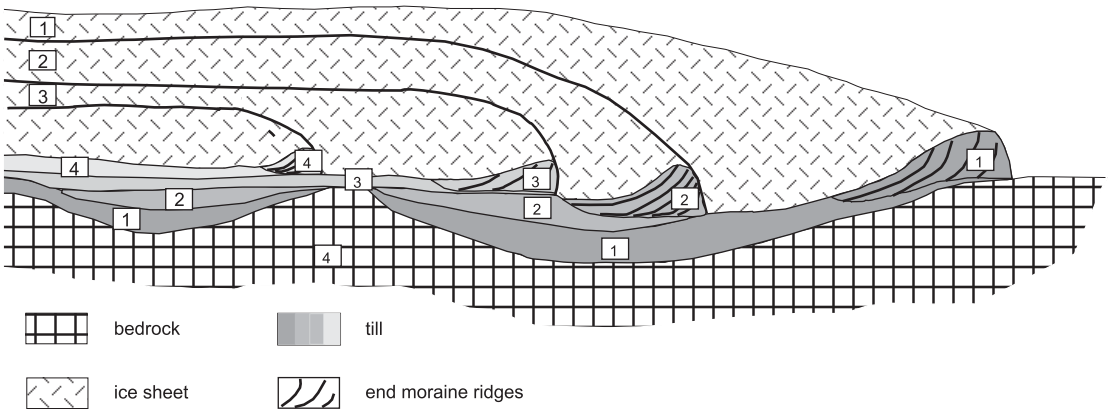

Fig. 10. Formation of multilayered structure during 1–4 stages of glacial recession

served visually (colour, structure, interlayers and patches of different composition and so on) and on the basis of features recorded analytically and evaluated statistically (physical and mechanical properties, composition and degree of mixing, orientation and dip of pebble long axes, *etc.*). Borehole log records (radioactivity, character of the changes of electrical potential and electrical resistance) reflect the heterogeneity of the Baltija till and provide a preliminary view of the variations in the multilayered structure along the direction of ice sheet advance. A bi-layered till structure predominates in the area of the South Lithuanian Phase and a tri-layered structure occurs in the northern zone of the Middle Lithuanian Phase. The multilayered structure of the till is also reflected in changes in the preferred orientation and dip of clast fabric and in the petrographic composition of the gravel fraction. Research carried out on more complete sections in the areas of the East, South and Middle Lithuanian phases revealed an increase in the number of till layers from S to N up the ice flow direction.

The relative entropy of the grain-size frequency distribution, reflecting the degree of mixing of till particles, changes rhythmically throughout the till sequences vertically and along the direction of ice sheet advance. Increased values of the relative entropy of the grain-size distribution of the till coincide with a more pronounced preferred orientation of pebble long axes in the till.

The formation of the multilayered structure of the Baltija till succession may be related to the cyclic dynamics of subglacial processes in the receding ice sheet, and consequently the number of subglacial till layers may be related to the marginal moraine ridges of the different phases left by oscillation of the ice sheet margin during glacial recession. The layers of the till succession and the rhythmic changes in its properties and composition likely reflect the intensity of till material loading.

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REFERENCES

ĀBOLTINŠ O. (1989) — Glaciostructure and the glacial lithomorphogenesis (in Russian). Rīga. Zinātne.

ALLEY R. B., CUFFEY K. M., EVENSON E. B., STRASSER J. C., LAWSON D. E. A. and LARSON G. J. (1997) — How glaciers entrain and transport basal sediment: physical constraints. Quater. Sc. Rev., **16** (9): 1017–1038.

BALTRŪNAS V. (1995) — Pleistocene stratigraphy and correlation (in Lithuanian with English summary). Academia. Vilnius.

BALTRŪNAS V. (1996) — Multinomiality — specific property of Pleistocene tills in Lithuania (in Russian with English summary). Lithosphere, **5**: 58–64.

BALTRŪNAS V. (2002) — Stratigraphical subdivision and correlation of Pleistocene deposits in Lithuania (methodical problems). Inst. Geol. Vilnius.

BALTRŪNAS V. and PUKELYTĖ V. (2003) — Variability peculiarities of relative entropy of Pleistocene till grain-size in South Lithuania (in Lithuanian with English summary). Geologija, **42**: 45–50.

BALTRŪNAS V. and GAIGALAS A. (2004) — Entropy of Pleistocene till composition as an indicator of sedimentation conditions in Southern Lithuania. Geol. Quart., **48** (2): 115–122.

BALTRŪNAS V., ŠINKŪNAS P. and JURGAITIS A. (1989) — A comparative lithological-geochemical analysis of moraine deposits of the Lithuanian Baltic stage (in Russian with English summary). Geologija, **10**: 121–134.

BER A. (2000) — Pleistocene of north-eastern Poland and neighbouring areas against crystalline and sedimentary basement (in Polish with English summary). Pr. Państw. Inst. Geol., **170**.

BER A., JANCZYK-KOPIKOWA Z. and KRZYSZKOWSKI D. (1998) — A new interglacial stage in Poland (Augustovian) and the problem of the age of the oldest Pleistocene till. Quater. Sc. Rev., **17**: 761–773.

BOULTON G. S., DOBBIE K. E. and ZATSEPIN S. (2001) — Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. Quater. Internat., **86** (1): 3–28.

BOULTON G. S., VAN DER MEER J. J. M., BEETS D. J., HART J. K. and RUEGG G. H. J. (1999) — The sedimentary and structural evolution of a recent push moraine complex: Holmstrømbreen, Spitsbergen. Quater. Sc. Rev., **18** (3): 339–371.

BRODZIKOWSKI K. and VAN LOON A. J. (1991) — Glacigenic Sediments. Elsevier. Amsterdam.

CHRISTOFFERSEN P. and TULACZYK S. (2003) — Signature of palaeo-ice stream stagnation: till consolidation induced by basal freeze-on. Boreas, **32**: 114–129.

CZERWONKA J. A., DOBOSZ T. and KRZYSZKOWSKI D. (1997) — Till stratigraphy and petrography of the northern part of Silesia (southwestern Poland). Geol. Quart., **41** (2): 209–242.

ČEPULYTĖ V. (1967) — Multilayer Würm moraine and its position in the sections of Pleistocene formation. In: On Some Problems of Geology and Palaeogeography of the Quaternary Period in Lithuania (in Russian with English summary) (ed. M. Kabailienė): 135–148. Mintis. Vilnius.

DREIMANIS A. (1989) — Tills: their genetic terminology and classification. In: Genetic Classification of Glacigenic Deposits (eds. R. P. Goldthwait and C. L. Matsch): 17–84. Balkema. Rotterdam.

GAIGALAS A. (1971) — Texture, structure and the genetic varieties of the ground-moraines (in Russian). In: Structure and Morphogenesis of the Middle Lithuanian Morainic Plain (eds. V. Gudelis and A. Gaigalas): 28–87. Mintis. Vilnius.

GAIGALAS A. (1979) — Glaciosedimentation cycles of the Lithuanian Pleistocene (in Russian with English summary). Mokslas. Vilnius.

GAIGALAS A. (1989) — Composition of macro-detrital material and moraine structure (in Russian with English summary). In: Moraines as a Source of Glaciological Information (ed. V. M. Kotljakov): 19–38. Nauka. Moscow.

GAIGALAS A. (1995) — Glacial history of Lithuania. In: Glacial Deposits in North-East Europe (eds. J. Ehlers, S. Kozarski and Ph. Gibbard): 127–135. Balkema. Rotterdam.

GAIGALAS A. (2001) — Stratigraphy and geochronology of the Upper (Late) Pleistocene (in Lithuanian with English summary). In: Stone Age in South Lithuania (According to Geological, Palaeogeographical and Archaeological Data) (ed. V. Baltrūnas): 7–24. Inst. Geol. Vilnius.

GAIGALAS A. and MARCINKEVIČIUS V. (1973) — Vidurio Lietuvos neopleistoceno pagrindiniĺ morenĺ fizinės ir deformacinės savybės (Padubysio, Čiukiškių ir Tūtiškių atodangų pavyzdžiu)(in Lithuanian with German and Russian summary). Geografinis metraštis, **12**: 23–36. Mintis. Vilnius.

GAIGALAS A. and MARCINKEVIČIUS V. (1982) — Bedded structure and genesis of forms of hollow-ridge glacial relief in North Lithuania (in Russian with English summary). Geologija, **3**: 69–79.

GAIGALAS A. and MELEŠYTĖ M. (2001) — Spread and composition of the deposits of Nemunas Glaciation (in Lithuanian with English summary). In: Stone Age in South Lithuania (According to Geological, Palaeogeographical and Archaeological Data) (ed. V. Baltrūnas): 46–54. Inst. Geol. Vilnius:

HALICKA A. (1986) — An outline of petrography of moraines of the Vilna region (in Polish with English summary). Pr. Muz. Ziemi, **38**: 13–46.

HINDMARSH R. C. A. (1996) — Sliding of till over bedrock: scratching, polishing, comminution and kinematic-wave theory. Ann. Glaciol., **22**: 41–48.

IGNATAVIČIUS V. (1986) — Changes of physical and mechanical properties of moraine loams under the action of technogenic water (in Lithuanian with English summary). Geologija, **7**: 122–129.

KHATWA A. and TULACZYK S. (2001) — Microstructural interpretations of modern and Pleistocene subglacially deformed sediments: the relative role of parent material and subglacial processes. J. Quater. Sc., **16** (6): 507–517.

KNIGHT P. G. (1997) — The basal ice layer of glaciers and ice sheets. Quater. Sc. Rev., **16** (9): 975–993.

KNIGHT P. G., PATTERSON C. J., WALLER R. I., JONES A. P. and ROBINSON Z. P. (2000) — Preservation of basal-ice sediment texture in ice-sheet moraines. Quater. Sc.Rev., **19** (13): 1255–1258.

KRIGER N. I. (1978) — Formation of physico-mechanical properties of a moraine (till). In: Material Composition of Ground Moraines. Materials of the International Symposium (in Russian) (eds. E. V. Shantser and Yu. A. Lavrushin): 134–154. Moscow.

LAVRUSHIN Yu. A. (1980) — Some general problems of morainic sedimentogenesis (in Russian with English summary). In: Processes of Continental Lithogenesis (ed. E. V. Shantser): 123–135. Nauka. Moscow.

LANCELLOTA R. (1995) — Geotechnical engineering: 229–232. Balkema. Rotterdam.

LISICKI S. (2003) — Lithotypes and lithostratigraphy of tills of the Pleistocene in thee Vistula drainage basin area, Poland (in Polish with English summary). Pr Państw. Inst. Geol., **177**.

LYSÅ A. and LØNNE I. (2001) — Moraine development at a small High-Arctic valley glacier: Rieperbreen, Svalbard. J. Quater. Sc, **16** (6): 519–529.

MARCINKEVIČIUS V. (1988) — Formation of physical and mechanical peculiarities of the moraines of the last glaciation in Middle Lithuania (formation of the composition of moraine deposits) (in Russian with English summary). Geologija, **9**: 125–136.

MATVEYEV A. V. (1976) — Anthropogene glacial formation of Belarus (in Russian). Nauka i tekhnika. Minsk.

MÜLLER B. U. and SCHLÜCHTER C. (2001) — Influence of the glacier bed lithology on the formation of a subglacial till sequence-ring-shear experiments as a tool for the classification of subglacial tills. Quater. Sc. Rev., **20** (10): 1113–1125.

PETTERSSON G. (2002) — Weichselian glaciations in the middle Noteć River region, northwest Poland. LUNDQUA Thesis 47. Lund Univ.

PIOTROWSKI J. A., MICKELSON D. M., TULACZYK S., KRZYSZKOWSKI D. and JUNGE F. W. (2001) — Were deforming subglacial beds beneath past ice sheets really widespread. Quater. Internat., **86** (1): 139–150.

PUNKARI M. (1997) — Subglacial processes of the Scandinavian Ice Sheet in Fennoscandia inferred from flow-parallel features and lithostratigraphy. Sediment. Geol., **111** (1–4): 263–283.

RAČKAUSKAS V. (2003) — Influence of pollution by chemical substances upon the strength parameters of glacial soil (Šiauliai area). Abstract of Ph.D. thesis: 8–12. Vilnius Univ.

RZECHOWSKI J. (1980) — An attempt of lithostratigraphical subdivision of the Vistulian Glaciation tills in Poland. Quater. Stud. Poland, **2**: 107–120.

SEREBRYANNY L. R. and ORLOV A. V. (1989) — Sedimentational approach to the studies of moraines. Modern moraine-forming processes and settings. Analysis of the glacier formation and reconstruction of glaciodynamic settings (in Russian with English summary). In: Moraines as a Source of Glaciological Information (ed. V. M. Kotljakov): 65–137. Moscow.

STEA R. R. and PE-PIPER G. (1999) — Using whole rock geochemistry to locate the source of igneous erratics from drumlins on the Atlantic coast of Nova Scotia. Boreas, **28** (2): 308–325.

STOKES Ch. R. and CLARK Ch. D. (2002) — Are long subglacial bedforms indicative of fast ice flow? Boreas, **31** (3): 239–249.

ŠINKNŪAS P. and JURGAITIS A. (1998) — Lithogenetic aspects of glacigenic sedimentation investigations (in Lithuanian with English summary). Geologija, **23**: 99–104.

VAN DER MEER J. J. M., MENZIES J. and ROSE J. (2003) — Subglacial till: the deforming glacier bed. Quater. Sc. Rev., **22**: 1659–1685.

VEREISKY N. G. (1978) — Engineering-geological peculiarities of ground moraines of the Russian plain (in Russian). In: Material Composition of Ground Moraines. Mat. Internat. Symp. (eds. E. V. Shantser and Yu. A. Lavrushin): 155–165. Moscow.

WALLER R. I. (2001) — The influence of basal processes on the dynamic behaviour of cold-based glaciers. Quater. Internat, **86** (1): 117–128.