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Multilayered structure of the Dzūkija and Dainava tills and their correlation in South Lithuania

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Lithuanian Pleistocene tills have a multilayered structure, as established using borehole log data and various analytical methods. Locally it can be observed visually. The structure of the oldest Middle Pleistocene Dzūkija (Elster 1) and Dainava (Elster 2) tills was investigated in their areal stratotype in South Lithuania. Logs of three boreholes were chosen for detailed analysis. Their triangular distribution enables evaluation of the variation of till material in N to S and NW to SE directions. Grain-size analysis was performed for tills from all three boreholes and the index of relative entropy of grain-size was calculated. The composition of the Dzūkija and Dainava tills succession indicators advances referable to at least two glaciations and their stages. The Dzūkija tills were formed by glaciers advancing from the north across Devonian strata. The Dainava till were left by glaciers advancing from NW across Lower Palaeozoic and Mesozoic rocks. The macroscopically homogeneous upper layers of the Dzūkija till and the upper and lower layers of the Dainava till have a rhythmic multilayered structure revealed by log and grain-size data. The sedimentological nature of this rhythmicity is partly shown by variation analysis of the relative entropy of grain-size composition in vertical succession. The index of relative entropy, reflecting the degree of mixing, allowed the destination of four zones of entropy (better mixing) in the vertical succession. These zones sometimes correlate well between widely separated sections. Their presence may be explained by a repeated input of till material into the basal part of the glacier during its activation (stage, phase).

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INTRODUCTION

Lithuanian Pleistocene tills have a multilayered structure, which can be seen visually (colour, interlayers, patches, *etc.*) and is expressed in borehole log patterns and by measuring the dip angle and orientation of long axes of pebbles as well as by data obtained by various analytical (grain-size, geochemical, *etc.*) methods (Gaigalas, 1971, 1979; Baltrūnas, 1995, 2002; Baltrūnas and Gaigalas, 2004). There has been prolonged discussion about the origin of the multilayered structure of tills. It may have been predetermined by various factors: (1) repeated processes of sedimentation (beds of stages, phases, oscillations); (2) the sedimentary environment of the glacial deposits (supraglacial, englacial, subglacial, terminoglacial, *etc.*); (3) the movement of the glacier along major shear planes with slickensides and material transportation by blocks; (4) post-sedimentary processes (solifluction, rewashing, weathering, oxidation, reduction, *etc*; Kriger, 1978; Lavrushin, 1980; Dreimanis, 1990; Brodzikowski and Van Loon, 1991; Waller *et al.*, 2000; Waller, 2001; Lisicki, 2003; Adam and Knight, 2003 and others). The use of various statistical indices (correlation coefficients, relative entropy, *etc.*) of analytical data is important to help constrain the multilayered structure and for interpretation of sedimentary conditions.

This structural phenomenon has been specifically investigated in tills of the Baltija (Pomeranian) Stage of the Last Glaciation in Lithuania. Their multilayered structure has been related to the phases of dynamic activity of the glacier. The number of phases is mirrored by the rhythmic variation of the relative entropy of grain-size composition in the vertical succession (Baltrūnas *et al.*, 2005*a*, *b*). The present investigation has allowed the formulaton of a working hypothesis concerning the multilayered structure of the Lithuanian oldest Dzūkija and Dainava tills and their links with the glacial phases. Tills of this kind are deposits sporadically. They often lie in depressions in the sub-Quaternary surface and at the bottom of palaeo-incisions (Vonsavičius, 1967 and others). Their structure, lithology and stratigraphy were first summarised in 1971 (Kondratienė and Vaitiekūnas, 1971). Recently, the Dzūkija till

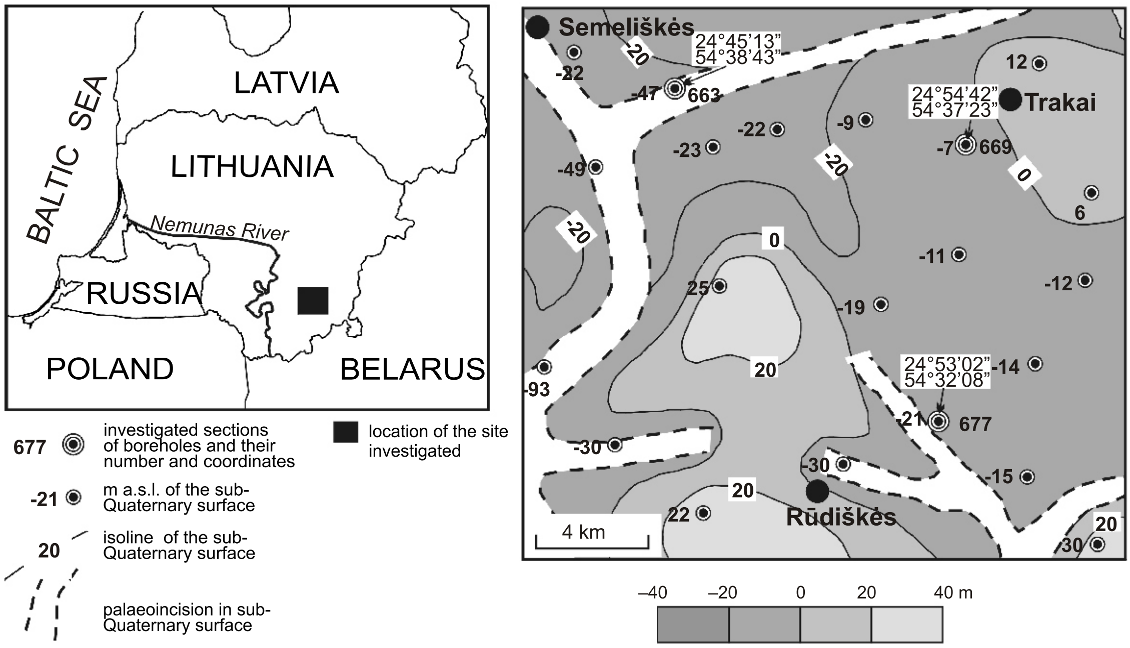

Fig. 1. Location of the site investigated

has been correlated with Elster 1 (San 1, Don, isotope stage 14–16) and the Dainava till with Elster 2 (San 2, Oka, isotope stage 12) tills, based on features of their lithological and geochemical composition and sometimes on data from the Turgeliai interglacial deposits (Ferdynandowski, Voigstedt, Konachowski; Gaigalas and Satkūnas, 1994; Satkūnas and Kondratienė, 1995; Ber, 2000, 2006).

The areal stratotype of the Dzūkija and Dainava tills of South Lithuania (Trakai District, Fig. 1) was chosen for a detailed study (Kondratienė, 1993). The tectonic structure of this region and features of the Quaternary system have been discussed in a previous publication (Šliaupa and Bitinas, 1986). The stratigraphic interpretation proposed by the authors has been taken as a basis for the present study.

The aim of the present work was to evaluate the multilayered structure of the Dzūkija and Dainava tills in this region. The following tasks were set:

— to establish the stratigraphic subdivision and correlation of the Dzūkija and Dainava tills successions;

— to determine features of the multilayered structure of these tills successions on the basis of grain-size composition and on the pattern of variation of their relative entropy;

— to evaluate the possibilities of correlating individual layers within these tills.

METHODS

Logs of three boreholes from the areal stratotype of South Lithuania (Trakai District WSW of Vilnius) were chosen for analysis (Kondratienė, 1993). The boreholes define a triangular area and thus enable variation in the till material to be assessed from N to S and from NW to SE (Fig. 1). The distance between the boreholes is 10–15 km. 54 samples were taken from the cores of all three boreholes for grain-size analysis: 23 from the Dzūkija till and 31 from the Dainava till. Two samples with anomalous values of some fractions from boreholes 669 and 677 were eliminated from some calculations. Clastic material coarser than 5 mm was not included into the samples because of their small mass (200 g). The statistical parameters of the distribution of fractions and the correlation coefficients were calculated using *Excel* and *Statistics* programs. For the regional characteristics of the tills, published data were also used (number of samples — 41; Šliaupa and Bitinas, 1986). 23 samples of the Dzūkija till and 31 samples of the Dainava till were taken for detailed analysis. The statistical generalization was based on 22 and 30 samples respectively. According to the sample size determining method, the chosen number of samples (sample size) for the intended experiment was regarded as sufficient. The minimal sample sizes (N) for the Dzūkija and Dainava tills were determined, taking into account the average x of relative entropy, the variation coefficient v, the significance level t (0.95) and the measurement bias of average λ according to the formula $N = (tvx/100\lambda)^2$. The requisite sample size for the chosen measurement bias of relative entropy average ($\lambda = 2\%$) was 12 (of R_1) and 15 (of R_2) samples for the Dzūkija till and 12 (of R_1) and 14 (of R_2) samples for the Dainava till. Due to structural nature of the drillcore analysed, the sample size was enlarged to the maximum.

The grain-size fractions of till material were obtained during granulometric analysis using the sieving and pipette methods (mm): 5.0–2.0; 2.0–1.0; 1.0–0.5; 0.5–0.25; 0.25–0.1; 0.1–0.05; 0.05–0.01; 0.01–0.005; 0.005–0.001; <0.001. The relative entropy was calculated for all the ten fractions and for eight fractions (combining the finest particles into one fraction of <0.01 mm). Evaluation and interpretation issues regarding this technique have been recently discussed in Baltrūnas and Pukelytė (2003), Baltrūnas and Gaigalas (2004) and Baltrūnas *et al*. (2005*a*).

The multilayered structure of tills was first determined on the basis of archived borehole logs. Analysis of these logs has shown that the multilayered structure of thick till successions is evident and sometimes correlatable between distant sections. Based on archived material, stratigraphic interpretation of the petrographic composition of gravel and pebbles was carried out and some coefficients (for example, *k* — the ratio of dolomite content and the sum of Ordovician and Silurian limestone) were calculated using the method of Gaigalas (1979).

STRATIFICATION AND COMPOSITION OF THE DZŪĶIJA AND DAINAVA TILLS

The sub-Quaternary relief of the region and its geological structure have been described (Šliaupa and Bitinas, 1986; Šliaupa, 2004). The areal stratotype of the tills is situated on the lowest (–10 – –20 m b.s.l.) level of the sub-Quaternary surface. This level lies between the middle level of the sub-Quaternary surface (+20 – +30 m a.s.l.) and solitary elevations (+50 – +62 m a.s.l.) in the east and a deep palaeoincision in the west (–100 – –156 m b.s.l.). Borehole 663 goes to the bottom (–47 m b.s.l.) of another steep-side palaeoincision (Fig. 1). In the NE, the sub-Quaternary surface is composed of Upper Permian limestone (borehole 669) which in the western and southern directions dips beneath the Lower Triassic mudstones and sandstones (borehole 663) and Lower Cretaceous glauconitic sand (borehole 677). A fault, trending NE–SW, cuts off the subcrop of Triassic and Permian deposits.

The nature of the sub-Quaternary surface has influenced the distribution and composition of the Dzūkija and Dainava tills. The broad lowest level of the palaeosurface is associated with the thick and extensive accumulation of till material. The Dzūkija till is only locally present, in depressions of the sub-Quaternary relief. The Dainava till is widespread. According to published and archival data, the average (*N* = 41) grain-size composition of the Dainava till in the region is as follows: 5–2 mm — 1.6%; 2–1 mm — 2.6%; 1–0.5 mm — 3.7%; 0.5–0.25 mm — 10.8%; 0.25–0.1 mm — 23.5%; 0.1–0.05 mm — 19.8%; 0.05–0.01 mm — 14.6%; 0.01–0.005 mm — 4.8%; <0.005 mm — 18.6% (Šliaupa and Bitinas, 1986). Similar results were obtained also in the new investigations (Fig. 2, Table 1). The new data show that in general the Dzūkija and Dainava tills are similar in grain-size composition (Fig. 2). The average value of sand and gravel (2–0.1 mm fraction) for the Dzūkija and Dainava tills is 42.4 and 41.6%, of silt (0.1–0.01 mm fraction) 44.4 and 40.8% and of clay (<0.01 mm) 13.2 and 17.6% respectively.

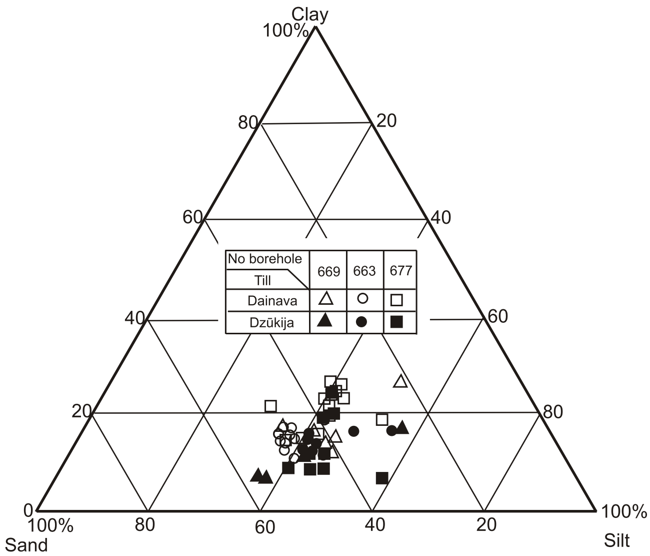

Fig. 2. Grain-size characteristics of the Dzūkija and Dainava tills in boreholes 663, 669 and 677

The petrographic composition of the gravel fraction shows three dominant groups of rocks: crystalline rocks, Devonian dolomite, Ordovician and Silurian limestone (Figs. 3–5). The ratio of Devonian dolomite and Ordovician and Silurian limestone (*k*) in the Dzūkija and Dainava tills is a useful index indicating differing directions of glacier advance. The increased content of Devonian dolomite and the reduced content of Ordovician and Silurian limestone clasts (*k* = 0.53–2.71; 1.18 on average) of the Dzūkija till indicate glacier advance from the north across Devonian strata. The reversed proportions of these rocks (*k* = 0.16–0.91; 0.33 on average) in the Dainava till indicates glacier advance from the NW across the Baltic Sea floor. This index is more suitable for stratigraphical subdivision than for correlation of the sections. The results obtained are in good agreement with data previously obtained from the tills (Gaigalas, 1979, 1995*a*). Clasts of Permian limestone, Triassic sandstone, Mesozoic carbonates (chalk marl, chalk) and locally phosphorite, flint and calcite are likely derived from local rocks

Table 1

Average grain-size composition [%] of the Dzūkija and Dainava tills in boreholes 663, 669 and 677

Index of till	No. borehole	Sample number	Fraction [mm]									
			5–2	2–1.0	1.0–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	< 0.001
dn	669	6	5.03	2.62	4.40	8.78	18.27	21.15	23.30	4.68	7.11	4.67
	663	11	1.73	1.90	4.63	12.42	26.27	21.78	16.81	4.36	5.43	4.67
	677	13	2.53	2.06	3.74	8.57	21.29	21.20	19.71	6.69	7.98	6.24
dz	669	4	2.76	2.12	4.41	11.45	24.89	25.35	18.59	2.89	4.93	2.61
	663	9	1.57	1.48	3.66	10.35	24.59	23.41	21.05	4.33	5.54	4.01
	677	9	1.52	1.82	3.86	10.01	24.50	24.68	19.83	4.72	5.40	3.65

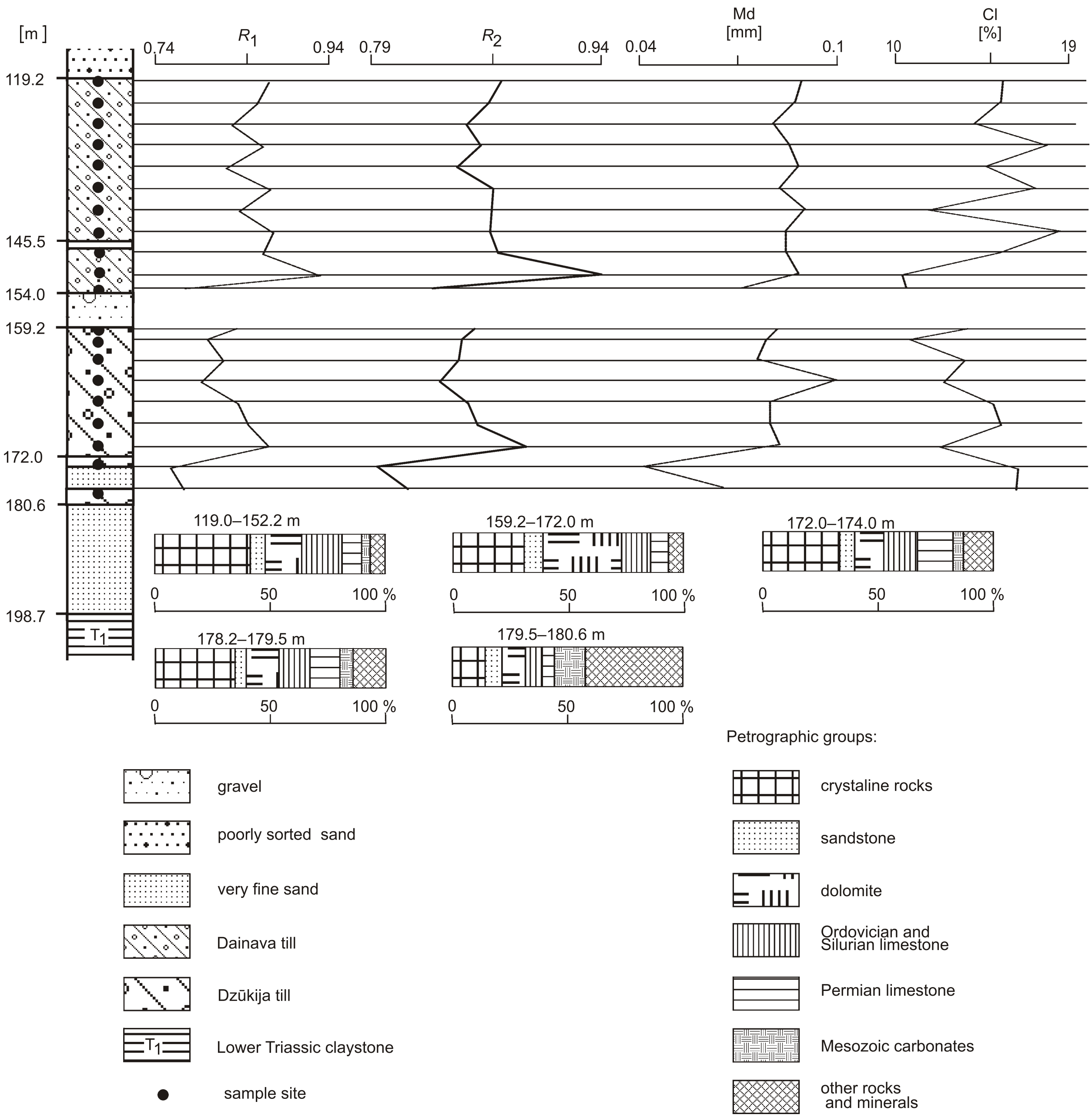

Fig. 3. Sequence of Middle Pleistocene deposits in borehole 663

R_1 and R_2 — variation in relative entropy of the grain-size composition of the Dzūkija and Dainava tills for the 10 fractions and for the 8 fractions; Md — variation of the median grain-size; Cl — variation of fraction less 0.01 mm

(Figs. 3–5). The Dzūkija till often immediately overlies the sub-Quaternary surface (Figs. 4 and 5). Therefore, its lower part is greenish grey, locally with 3 cm-thick interlayers of Lower Cretaceous green glauconitic sand (borehole 669). Cretaceous phosphoritic sandstone clasts abound (up to 34%) in the till (borehole 663). The petrographic data suggests that blocks of brownish grey and greenish grey Dzūkija till lie within the lower part of the Dainava till (borehole 677; the interval of 139.7–143.5 m).

GRAIN-SIZE COMPOSITION OF THE TILLS AND VARIATION PATTERNS IN THEIR RELATIVE ENTROPY

Grain-size analysis of the tills has shown typical compositions, i.e. sandy till in which the clayey fraction (<0.01 mm) accounts for 13.64–20.21% (Gaigalas, 1995*b*). Only in two samples was the content of clay fraction anomalously high — 41.44

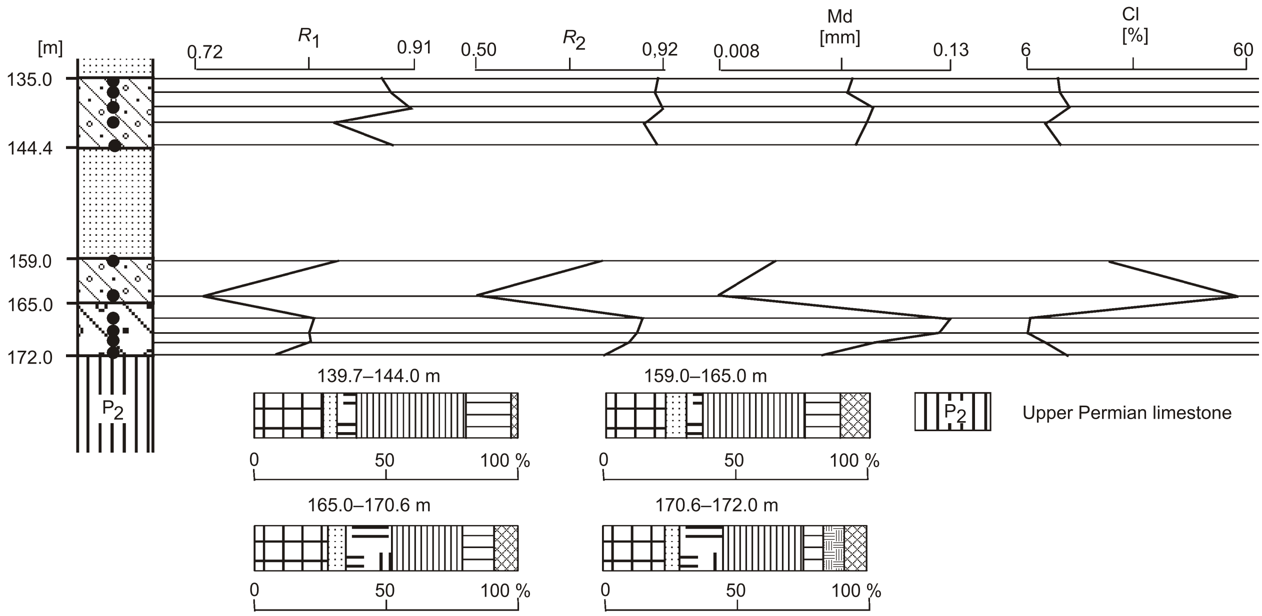

Fig. 4. Sequence of Middle Pleistocene deposits in borehole 669

Other explanations as in Figure 3

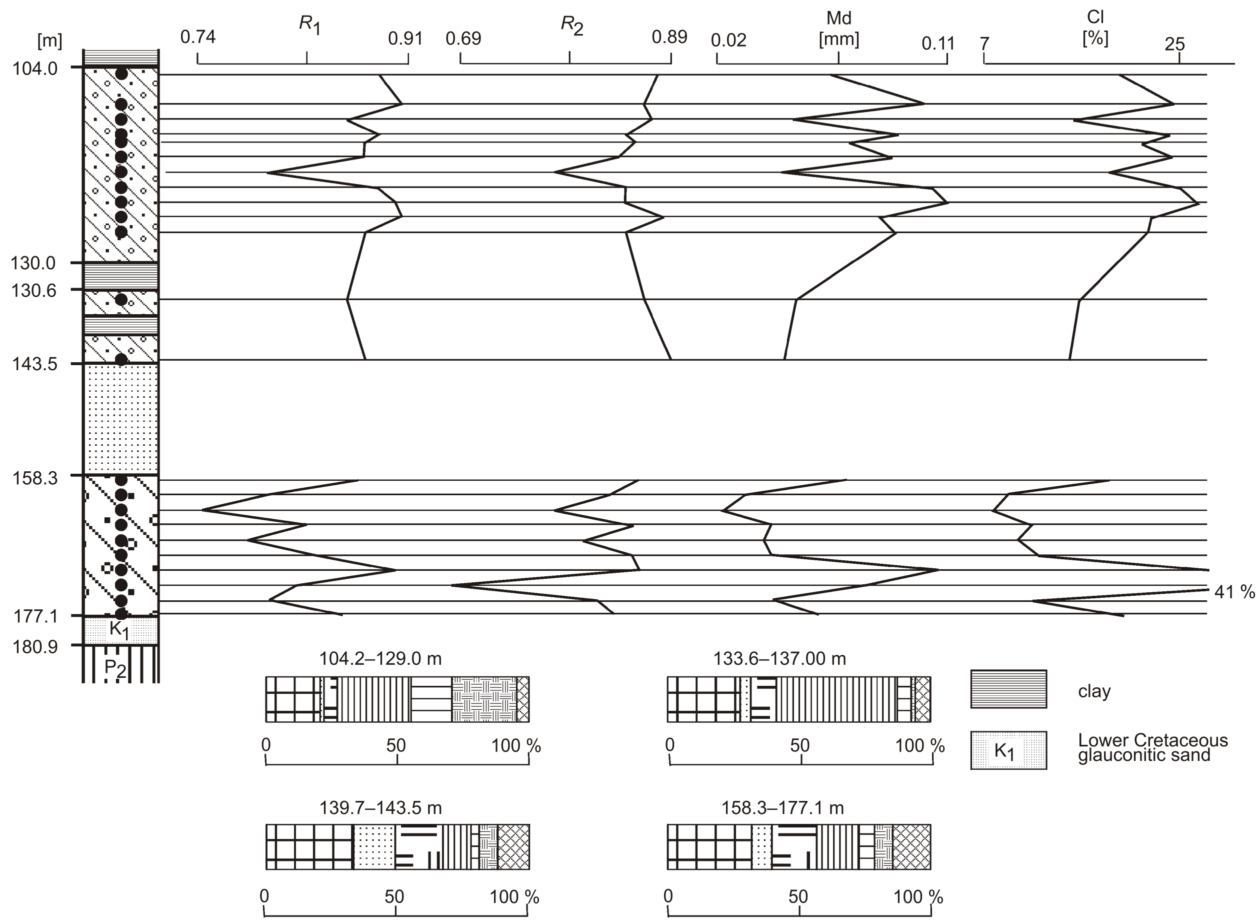

Fig. 5. Sequence of Middle Pleistocene deposits in borehole 677

Other explanations as in Figure 3 and 4

and 59.17% (Figs. 3–5). Data from these samples were not included in the statistical generalizations (Table 1). The averaged differences between the Dainava and Dzūkija tills are clear. The Dzūkija till contains less clay. Its median value of grain-size composition and the values of the 0.25–0.1 and 0.1–0.05 fractions are higher. Higher concentrations of some heavy minerals in these fractions have been observed in South Lithuania (Klimašauskas, 1965, 1967; Klimašauskas and Prakapaitė, 1971). The median (Md) of the grain-size composition and the clay fraction (Cl = fraction <0.01 mm) in part of the succession till varies rhythmically and across a wide range (Figs. 3–5).

Calculations of the relative entropy of grain-size composition for the 10 and 8 fractions (R_1 and R_2) have shown that this index in till stratigraphy also varies rhythmically (Figs. 3–5). A comparison of the average values of this index showed that the relative entropy for the 10 and 8 fractions in all three boreholes was higher in the Dainava than in the Dzūkija tills (Table 2). This difference was especially distinct with respect to the relative entropy of the 10 fractions. The relative entropy increases with the amount of mixing level in the tills, i.e. the content of all fractions equalizes (Baltrūnas and Pukelytė, 2003; Baltrūnas and Gaigalas, 2004). The correlation coefficient (r) between the relative entropy and the clay fraction Cl in the Dzūkija and Dainava tills revealed considerable differences between the indices of relative entropy for the 10 and the 8 fractions and for different boreholes (Table 3). The differences might have been caused by an unequal and sometimes small number of samples. A positive correlation is more typical between the entropy index for the 10 fractions and for the clay fractions in both kinds of till. A negative correlation is typical of the entropy index for the 8 fractions in clay fraction. It is also obvious that the correlation coefficient of one and the same till is different in different sections (r_1 and r_2). A correlation between the clay fraction (Cl) of all samples and the relative entropy index (R_1) of the 10 fractions is positive — the correlation coefficient $r = 0.61$ (Fig. 6). This is related to the fractions (0.01–0.005; 0.005–0.001; <0.001 mm), distinguished in the clay fraction (<0.01 mm), which are more helpful in identifying higher entropy zones (better mixing). Meanwhile, there is no correlation between the clay fraction (C1), not sub-divided into fractions, and the index of relative entropy (R_2) of the 8 fractions. An increase in the 0.1–0.25 and 0.05–0.01 mm fractions was observed in zones of a lower relative entropy.

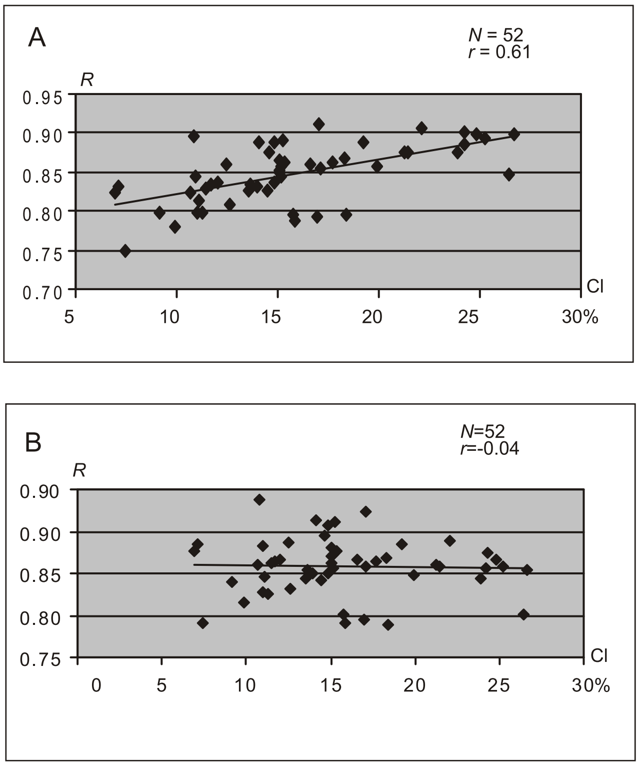

Fig. 6. Character of correlation between relative entropy for the 10 grain-size fractions and for the fraction <0.01 mm (A), between relative entropy for the 8 fraction grain-size and fraction less than 0.01 mm (B)

Table 2

Average, standard devation and variation coefficients of grain-size relative entropy of the Dzūkija (dz) and Dainava (dn) tills

Index of till	Sample number	Average		Standard deviation		Variation coefficient [%]	
		R_1	R_2	R_1	R_2	R_1	R_2
dn	30	0.8663	0.869	0.0293	0.0323	3.38	3.71
dz	22	0.8203	0.8434	0.0328	0.0293	3.99	3.47

R_1 — relative entropy of grain-size for 10 fractions, R_2 — relative entropy of grain-size for 8 fractions

Table 3

Comparison of mean relative entropy of grain-size for the 10 fractions (R_1) and for the 8 fractions (R_2), fraction less than 0.01 mm (Cl), median grain-size (Md), correlation coefficient between R_1 and Cl (r_1), R_2 and Cl (r_2) of the Dzūkija (dz) and Dainava (dn) tills

Index of till	No. bore-hole	Sample number	R_1	R_2	Cl [%]	Md	r_1	r_2
dn	669	6	0.8781	0.8896	16.45	0.08	–0.23	–0.04
	663	11	0.8477	0.8649	14.45	0.09	0.23	–0.22
	677	13	0.8767	0.8630	20.91	0.07	0.49	–0.24
dz	669	4	0.8174	0.8542	10.44	0.10	–0.94	–0.99
	663	9	0.8226	0.8400	15.49	0.17	–0.31	–0.56
	677	9	0.8231	0.8420	13.78	0.08	0.92	0.65

THE ORIGIN OF THE MULTILAYERED STRUCTURE IN THE TILLS: DISCUSSION

The Dzūkija and Dainava till successions of South Lithuania are composed of a few beds of glacial deposits. These beds are associated with repeated glacier advances. Based on this assumption, the lower and the upper beds of the Dzūkija and Dainava tills, separated by inter-till (inter-phase and inter-stage) deposits, have been distinguished (Baltrūnas, 1995, 2002; Baltrūnas and Gaigalas, 2004). The study area includes the upper beds of the Dzūkija glaciation and the lower thin and upper beds of the Dainava glaciation. The multilayered structure of these macroscopically homogeneous beds was originally determined using borehole log data which locally allows correlation between different till sections (Fig. 7). The logs of radioactivity, electrical potential and electrical resistance logs from boreholes 663, 669 and 677, drilled during geological mapping, showed a multilayered structure in the Dzūkija and Dainava tills. The log correlations show, variability of the multilayered till structure, though also a marker level.

The grain-size composition in vertical section often has a rhythmic character. The sedimentological nature of this pattern is revealed by variations in the relative entropy of grain-size composition indicating the degree of mixing of the till material. Up to four higher entropy (better mixed) zones can be distinguished in the Dzūkija till stratigraphy and in the upper part of the Dainava till. These zones show good correlation in boreholes 663 and 677 where till beds are thick, and weaker correlation in borehole 669 where the till layer is thinner (Fig. 8).

The increased values in the relative entropy of till grain-size distribution are also reflected by changes in the preferred orientation and dip of the clast fabric (Baltrūnas *et al.*, 2005*a*). This association suggests that formation of the relative entropy zones was associated with glacier activation. The higher content of fine-grained sand and silt and the lower content of clay in the zones of lower entropy may be related to a passive, melting glacier. Thus, the presence of higher entropy zones in the till stratigraphy can be attributed to repeated input of extra till material during glacier activation stages or phases.

The successive subglacial depositional phases detected in the basal tills of the Lower Vistula valley in North Poland are noteworthy (Wysota, 2007). The three till facies must have been formed via complex subglacial sedimentary processes during the first Late Weichselian ice advance. The lowest till facies is interpreted as deformation till accumulated during the initial stage of ice advance. The middle facies represents the stagnation phase during the initial ice advance; it was deposited during recurrent periods of subglacial melt-out followed by meltwater sedimentation. The upper till facies was deposited by direct subglacial melt-out from stagnant ice. The grain-size composition of the Dzūkija and Dainava tills in South Lithuania is mostly comparable with the lowest till facies A (Wysota, 2007). Samples of till with a lower grain-size relative entropy can also be seen in the trigonal diagram and may be compared with the middle facies B which represents a stagnation phase of the glacier (Fig. 2).

The relative entropy of till composition in the direction of glacier movement is characterised by rhythmic variations, most probably caused by saturation of the lower layers of the glacier with till material to a maximum concentration and then settling of this material (Baltrūnas and Gaigalas, 2004). The saturation proceeded by grinding and mixing the material in transit and undergoing local erosion into a mixture of the highest density (volumetric weight), i.e. according to grain-size the tills are close to optimal mixtures (Vereisky, 1978; Marcinkevičius, 1988; Dundulis, 1997). When the relative entropy of nine fractions approaches 0.9 a till mixture of highest density is formed.

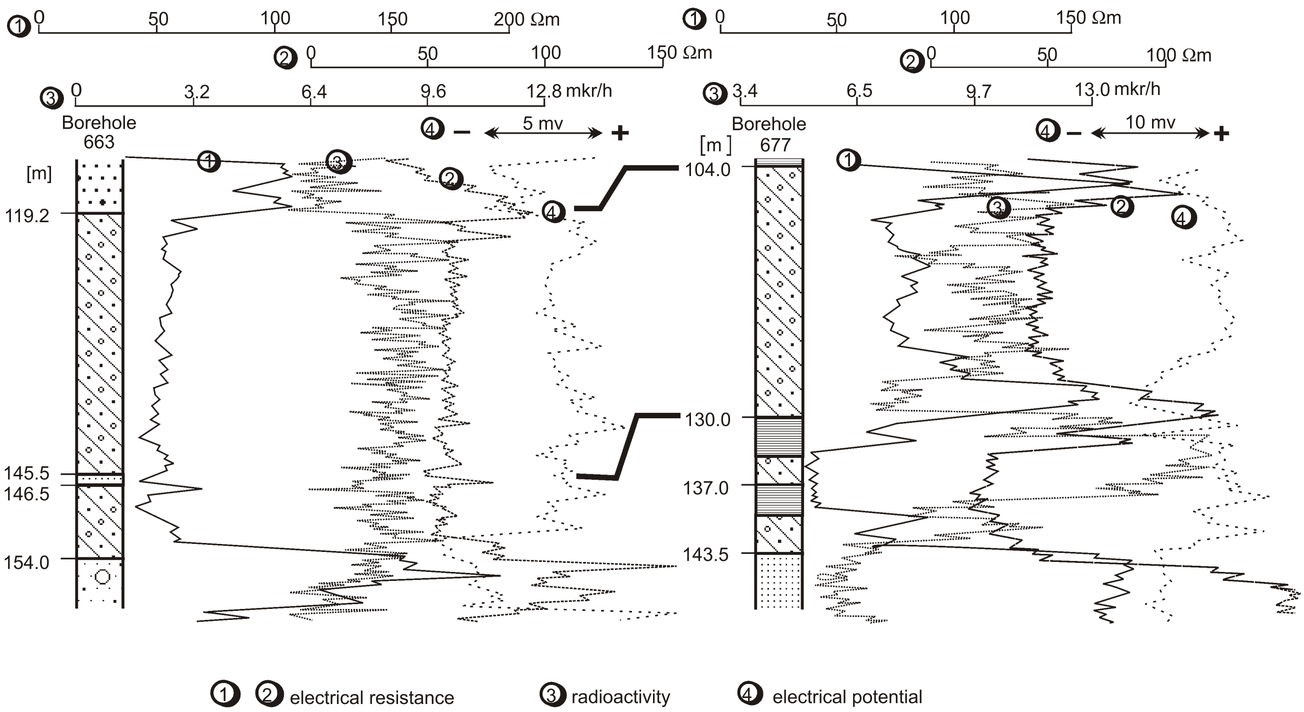

Fig. 7. Correlation of the Dainava till sequences according to log data from boreholes 663 and 677

Explanations as in Figures 3 and 5

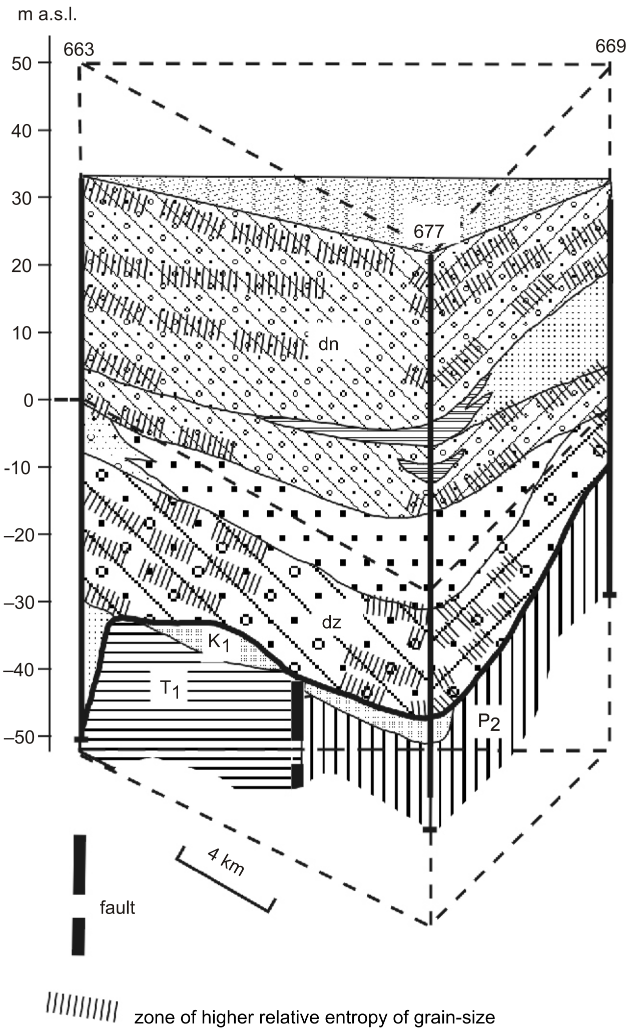

Fig. 8. Block diagram of Dzūkija and Dainava till strata in the site investigated

Explanations as on Figures 3–5

The number of new inputs of till material is probably reflected in the highest number of high entropy zones in sections, or it may be determined from the correlation of sections according to borehole log and other data. Sometimes these zones are separated by passive glacier till characterized by a worse mixing of material and orientation of the long axes of gravel and pebbles in the direction of glacier advance. The multilayered structure of subglacial tills can be controlled by alternating phases of active and passive mode inside the ice sheet, particularly in bedrock depressions. Glaciotectonic processes at the bedrock elevations deformed the soft-rock substrate and formed incorporation and deformation tills.

The number of subglacial till layers may be related to the marginal moraine ridges during glacial recession. This pattern was first recorded and analysed on an example of the Baltija (Pomeranian) Stage till of the Last Glaciation in Lithuania (Baltrūnas *et al.,* 2005*a*). This correlation is barely possible in the case of the Dainava and Dzūkija tills because the relief left by them was later eroded and covered by the more widespread Žemaitija (Odra, Dnieper) glacier.

The literature on the tills studied in Poland and Belarus show that there are 4–5 till and periglacial successions older than the Holsteinian (Mazovian, Alexandrian) Interglacial (Mojski, 1985; Velichkevich *et al*., 1997; Ber, 2000, 2006; Lindner *et al*., 2004; Sanko *et al*., 2005 and others). These till successions can be related to glaciations. In the till successions under consideration, Polish researchers have distinguished tills of older and younger stages, which can be correlated with zones of higher till entropy of grain-size composition in South Lithuania.

CONCLUSIONS

Investigations of the structure and composition of the South Lithuanian Dzūkija and Dainava tills successions allow the following conclusions:

1. The structure and composition of the oldest Lithuanian Middle Pleistocene Dzūkija and Dainava till successions are indicative of at least two glaciations and their stages. The Dzūkija till was formed by glaciers advancing from the north across an area of Devonian rocks. The Dainava till was formed by glaciers advancing from the north-west across an area underlain by Lower Palaeozoic and Mesozoic rocks.

2. The macroscopically homogeneous upper layers of the Dzūkija till, and the lower and upper layers of the Dainava till succession, have a rhythmic multilayered structure revealed by borehole log and analytical data. The multilayered structure of subglacial tills may be related to repeated phases of active and passive glacier behaviour, which formed specific tills inside the ice sheet, particularly in bedrock surface depressions.

3. The sedimentological nature of the rhythmicity of the till structure is partly revealed by analysis of relative entropy variations in vertical section. The index of relative entropy (indicating the degree of mixing) allowed the distinguishing up to four higher entropy zones in the stratigraphy till. These zones locally correlate well, even in distant sections.

4. The presence of these zones can be explained by repeated inputs of new till material in the basal part of active glacier ice. Saturation of the glacier with till material controlled the accumulation of subglacial till. Locally the zones are separated by deposited from till a passive glacier, usually marked by a poorer degree of mixing (lower relative entropy) of the till material and by other features.

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