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Entropy of Pleistocene till composition as an indicator of sedimentation conditions in Southern Lithuania

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The two most complete and stratigraphically most reliably identified Pleistocene sections in Southern Lithuania were chosen as the object of this study. Variations in relative entropy were assessed from the average data on the grain size, mineral and petrographic composition of the individual stratigraphically identified till beds. Data obtained in the current study showed that the relative entropy of till composition, which characterises the even distribution of the components according to relative parameters (such as the fraction intervals and, the number of minerals), indicates that the till composition was modified by matter dispersion (mixing) and condensation (concentration). The relative entropy of the content of different till components (grain size fractions, heavy and light minerals, petrographic groups) in glacial units of various ages is different and indicates different parameters of glacial dynamics and different routes of glacier movement. Also, the relative entropy of till composition in the direction of glacier movement shows repetitive patterns, which are predetermined by loading of the bottom layers of the glacier with till material up to its maximum concentration, followed by their settling. Ice loading with till material proceeds by grinding and mixing the transit and indigenous exarational material until the till mixture reaches its maximum density (volumetric weight) and becomes close to the optimum mixture.

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Key words: Southern Lithuania, Pleistocene till, relative entropy, sedimentology.

INTRODUCTION

The composition (grain size, mineral, chemical, and so on) of Pleistocene tills is traditionally used as a basis for stratigraphic division and comparison of Pleistocene strata. However, the highly variable composition seen in any one till section or in one till bed traced laterally forced us to apply various statistical methods (such as factor, cluster, correlation analysis), which enabled a more reliable definition of till composition for one or several components in comparable sections and areas. Some characteristics of the composition of any given till in a given section tend to be fixed and so reflect aspects of genesis, facies, uneven assimilation of source rocks, glacier dynamics, and post-sedimentational and other processes. We also examine the controls on the high density of basal till: do they reflect the static or dynamic pressure of a glacier during sedimentation (e.g. Lavrushin, 1980; Gaigalas, 1989), the grain size fraction ratio (e.g. Kriger, 1978), or the glacial genesis of deposits (e.g. Vereisky, 1978). Studies into similar processes in recent glaciers (Brodzikowski and Van Loon, 1991; Hindmarsh, 1996; Alley *et al*., 1997; Knight, 1997; Boulton *et al*., 1999, 2001; Stea and Pe-Piper, 1999; Knight *et al*., 2000; Khatwa and Tulaczyk, 2001; Lyså and Lønne, 2001; Müller and Schlüchter, 2001; Piotrowski *et al*., 2001; Waller, 2001) have helped understand the processes taking place in the lower part of a glacier. At the peripheries of continental glaciation, especially in buried older tills attainable only by drilling, compositional variations along glacier paths have been little studied. Here by applying data of integrated studies on till composition, we analyse relative entropy variations in the composition of stratigraphically identified till.

One of us has used relative entropy to evaluate the lithological variability of Pleistocene strata in Southern Lithuania (Baltrūnas, 1995). For the calculations, the deposits found in all borehole sections were divided into three groups: 1 — till deposits; 2 — clay and silt; 3 — gravel pebbly sand and sand. The maximum entropy H_m for the three-component system made up 1.0986. Entropy (H_r) and relative entropy ($R = H_r/H_m$) were calculated for each borehole section according to formulae given in

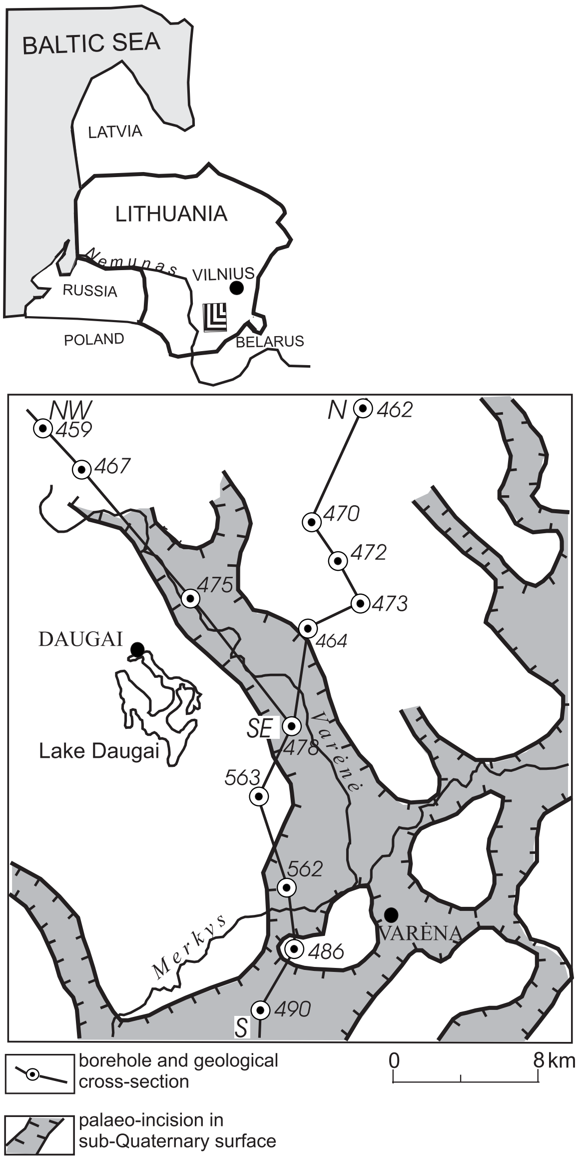


Fig. 1. Area of Pleistocene till composition entropy studies in Southern Lithuania

Miller and Kahn (1965). Schemes of relative entropy (lithological variability) of Pleistocene deposits were compiled for certain areas, while nothing the characterises of the sub-Quaternary and recent surfaces. In practice, the entropy of function is more often used to assess the degree of sorting for deposits of various origins and for determination of sedimentation zones/facies (e.g. Brieva and Montes, 1995; Neupauer and Borchers, 2001).

An attempt was also made to assess changes in relative entropy (further designated as *R*) for Pleistocene till grain size composition along a glacial transport path (Baltrūnas, 1995, 2002). The average grain size composition (8 fractions) of stratigraphically identified tills were studied in detail and their *R* (calculated) was used for this purpose. Comparison of till grain size *R* values in three remote areas showed that in the direction of glacier movement (or close to it) *R* values increased slightly in all the 5–6 till strata studied. The increase in *R* value per kilometre was similar for all tills. However, changes in *R* values of grain size composition for some tills in the same areas were found to vary greatly. Data averaging for some areas was assumed as incorrect, concealing useful information. Therefore, continuing studies are planned, emphasising certain borehole sections and examining different grain size groups and the results of other analyses.

METHODS

We have applied the method of relative entropy, which has long been used in geology (Miller and Kahn, 1965), for assessment of till composition variations in the direction of glacier movement. This is an application of a function used in thermodynamics. The thermodynamic states can be equilibrium or non-equilibrium ones (Kaladė *et al*., 1982). A system is at thermodynamic equilibrium when it enters a certain state and cannot break it by itself. The parameters in such a state do not vary. A system is in non-equilibrium when parameters vary or their stability is supported from the outside. Such systems are notable for transfers of, for example, mass, energy, electric charge, and so on. If we treat till (a mixture of different components) formed by a glacier as a multicomponental system, the equilibrium state system model can be applied for deposited till, while the non-equilibrium model is applied for till under formation by a glacier. In the current study, deposited till was treated as an isolated system in a relative equilibrium state. Entropy *H* as a function of the state is expressed as $H = -\Sigma p_i \log p_i$, where p_i is part of the i-th component in a system, and $\Sigma p_i = 1$. The relative entropy used expresses the ratio of the system entropy observed to the system's maximum entropy: $R = H_r/H_m$. This expression is convenient for comparison of different systems (tills) and for their graphic representation.

A well-studied area of 1200 km^2 around Daugai and Varėna (Southern Lithuania) was chosen for the analysis (Fig. 1). The target of the study was the most complete Pleistocene cross-section elaborated on the base of four boreholes (Fig. 2) with the most reliable stratigraphical identification as well as a north-south aligned profile through the Middle Pleistocene Žemaitija (Odra, Drenthe, Dnieper) till spanning 10 boreholes (Fig. 3). The subdivision and correlation of the strata were based on traditional biostratigraphic and lithostratigraphic criteria (Gaigalas, 1979, 1989, 1995; Baltrūnas, 1995, 2002; Kondratienė, 1996). The *R* variations were evaluated according to averaged data on grain size, mineral and petrographic composition for certain stratigraphically identified till strata. The grain size *R* was evaluated for three grain size fraction groups (mm): (1) 5–2, 2–1, 1–0.5, 0.5–0.25, 0.25–0.1, 0.1–0.05, 0.05–0.01, 0.01–0.005, < 0.005; (2) 5–1, 1–0.1, 0.1–0.05, < 0.05; (3) 5–1, 1–0.1, 0.1–0.01, and < 0.01. The mineral composition *R* was analysed for the 0.25–0.1 mm fraction, separately for light and heavy minerals. In addition, *R* was analysed for the coarse fraction (10–5 mm) of the petrographic composition.

PLEISTOCENE TILL COMPOSITION ENTROPY AND ITS VARIATIONS

The stratigraphically most complete profile with the most reliable identification of Pleistocene strata drawn connecting

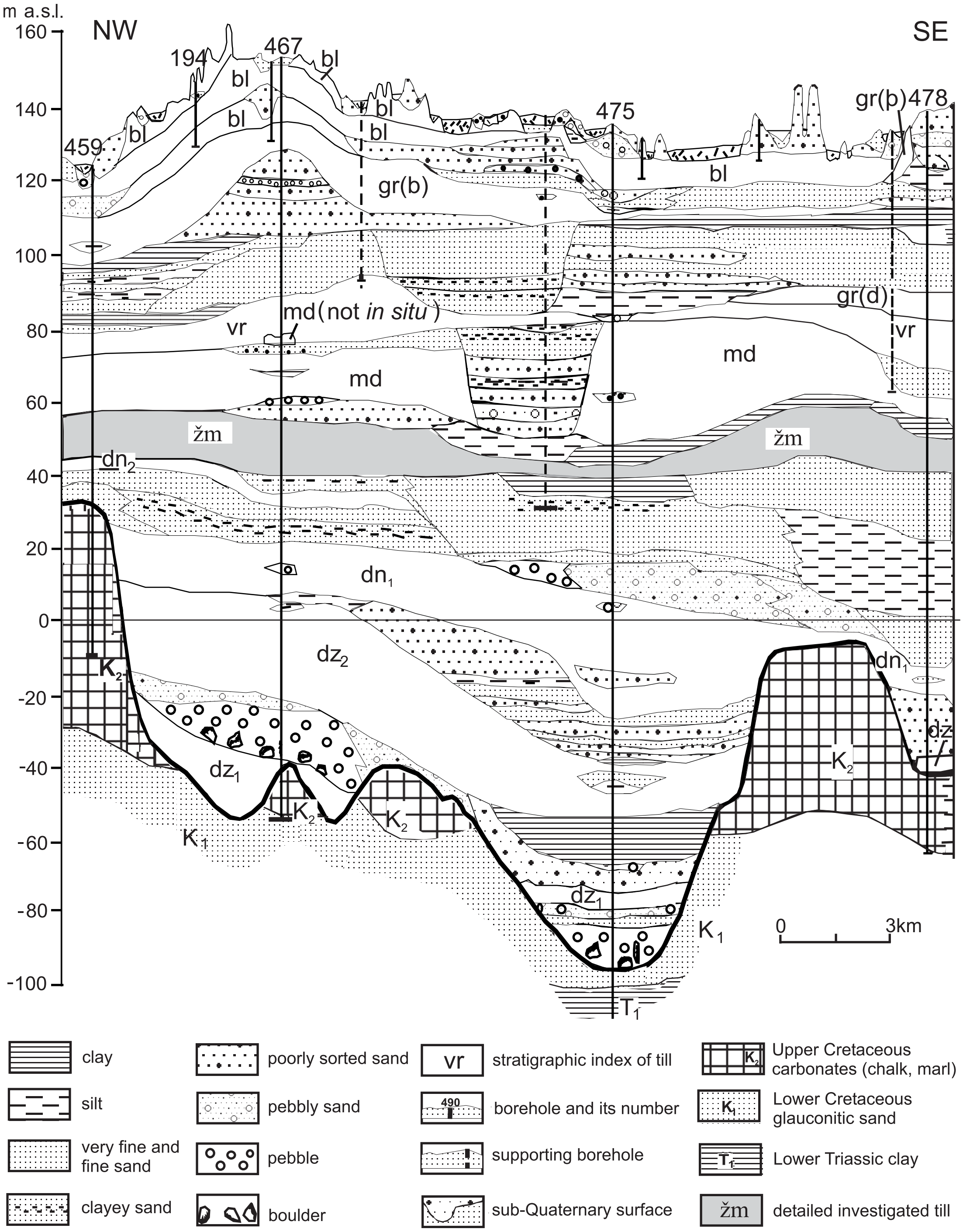


Fig. 2. NW–SE geological cross-section of Pleistocene deposits

Stratigraphical index of till: dz_1 and dz_2 strata — Dzūkija till; dn_1 and dn_2 strata — Dainava till; žm — Žemaitija till (grey in cross-section); md — Medininkai till; vr — Varduva till; gr(d), gr(b) and gr(žg) strata — Grūda till; bl — Baltija till

four boreholes (459, 467, 475, and 478) (Baltrūnas, 1995, 2002) has been analysed. This cross-section is NW–SE aligned along a palaeo-incision in a buried sub-Quaternary surface through calcareous, clayey and sandy deposits or even reaching clayey Triassic (no. 475) deposits in some sites (Fig. 2). The Pleistocene deposits reach a depth of 262.5 m (borehole 490 — Fig. 3) comprise Middle and Upper Pleistocene glacial, glaciofluvial, glaciolacustrine, as well as of the reliably identified Butėnai (Mazovian, Holsteinian, Likhvin) and Merkinė (Eemian, Mikulin) interglacial deposits. Detailed lithostratigraphical studies enabled distinction of 11 till strata belonging to the Dzūkija (Elster 1, San 1, Don), Dainava (Elster 2, San 2, Oka), Žemaitija (Odra, Drenthe, Dnieper), Medininkai (Warta, Moskva), Varduva (Świecie, Kalinin), Grūda (Leszno-Poznań) and Baltija (Pomerania, Ostaszkow) Formations and Subformations (Baltrūnas, 2002).

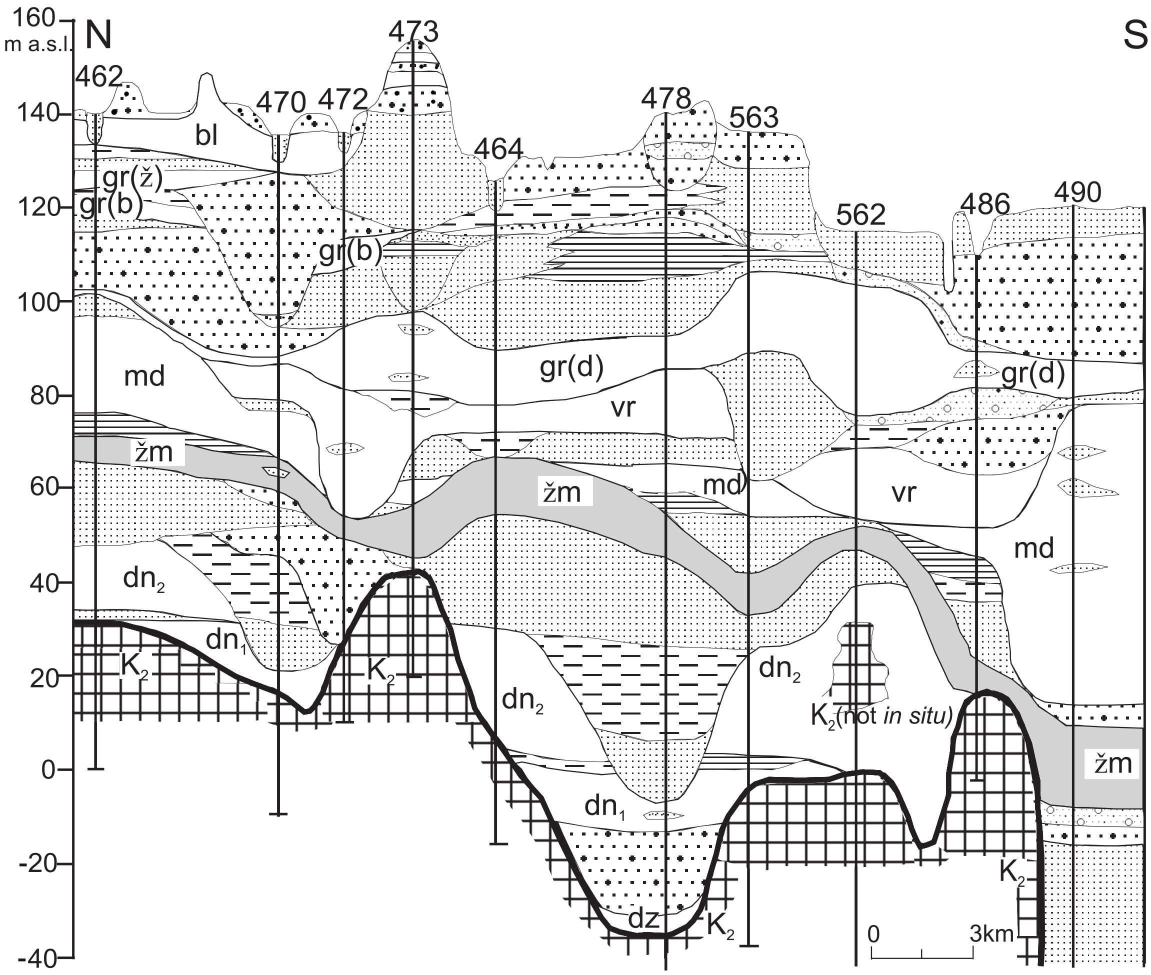


Fig. 3. N–S geological cross-section of Pleistocene deposits

For explanations see Figure 2

Table 1 shows that grain size *R* values for separate fractions in all tills are similar and range from 0.662 to 0.919, with values of 0.850 to 0.890 prevailing. The least *R* variation amplitude (0.768–0.919) was observed in 9 fraction groups, while the maximum range in *R* variations (0.662–0.901) was found in the second group of fractions. This is mostly related to the prevalence of the < 0.05 mm fraction in some tills, which decreases the uniformity of quantitative distribution among the fractions. The mean *R* value is the highest for the first group of fractions (0.875), slightly lower (0.865) in the third group and the lowest

Table 1

Variations of relative entropy *R* for Pleistocene till grain size composition along the NW–SE geological cross-section (boreholes 459, 467, 475, 478)

Index of till	*R* of 9 fractions (I version)				*R* of 5 fractions (II version)				*R* of 5 fractions (III version)			
	459	467	475	478	459	467	475	478	459	467	475	478
bl	0.833	0.889	0.873	–	0.879	0.887	0.862	–	0.915	0.875	0.850	–
gr	0.880	0.884	0.872	0.919	0.873	0.787	0.854	0.892	0.879	0.859	0.854	0.909
vr	0.869	0.859–0.888	–	0.890	0.824	0.795	–	0.839	0.863	0.860–0.868	–	0.893
md	0.891	0.907	0.887	0.892	0.862	0.884	0.871–0.890	0.891	0.872	0.881	0.877–0.899	0.889
žm	0.853	0.895	0.768	0.894	0.895	0.885–0.901	0.662	0.892	0.851	0.857	0.716	0.900
dn_2	0.838	–	–	–	0.864	–	–	–	0.843	–	–	–
dn_1	–	0.889	0.879–0.903	0.789	–	0.878	0.870–0.891	0.663	–	0.869	0.865–0.885	0.799
dz_2	–	0.895	0.893	–	–	0.892	0.868	–	–	0.885	0.884	–

Table 2

Variations of relative entropy *R* for Pleistocene till mineral and petrographic composition along the NW–SE geological cross-section (boreholes 459, 467, 475, 478)

Index of till	*R* of heavy minerals				*R* of light minerals				*R* of petrographic groups			
	459	467	475	478	459	467	475	478	459	467	475	478
bl	0.711	0.627	0.708	–	0.402	0.462	0.451–0.483	–	0.852	0.833	0.864	–
gr	0.740	0.747	0.692	0.656	0.418	0.428	0.468	0.311	0.794	0.828	0.950	0.841
vr	0.727	0.775	–	0.669	0.419	0.415	–	0.472	0.843	0.838	–	0.888
md	0.718	0.758	0.693	0.642	0.386	0.455	0.450–0.521	0.508	0.830	0.848	0.852	0.821
žm	0.734	0.738	0.672	0.635	0.435	0.455	0.531	0.487	0.859	0.842	–	0.817
dn_2	0.719	–	–	–	0.501	–	–	–	0.908	–	–	–
dn_1	–	0.749	0.694	0.661	–	0.445	0.504	0.495	–	0.772	0.834	–
dz_2	–	0.725	0.682	–	–	0.460	0.483	–	–	0.830	0.805–0.873	–

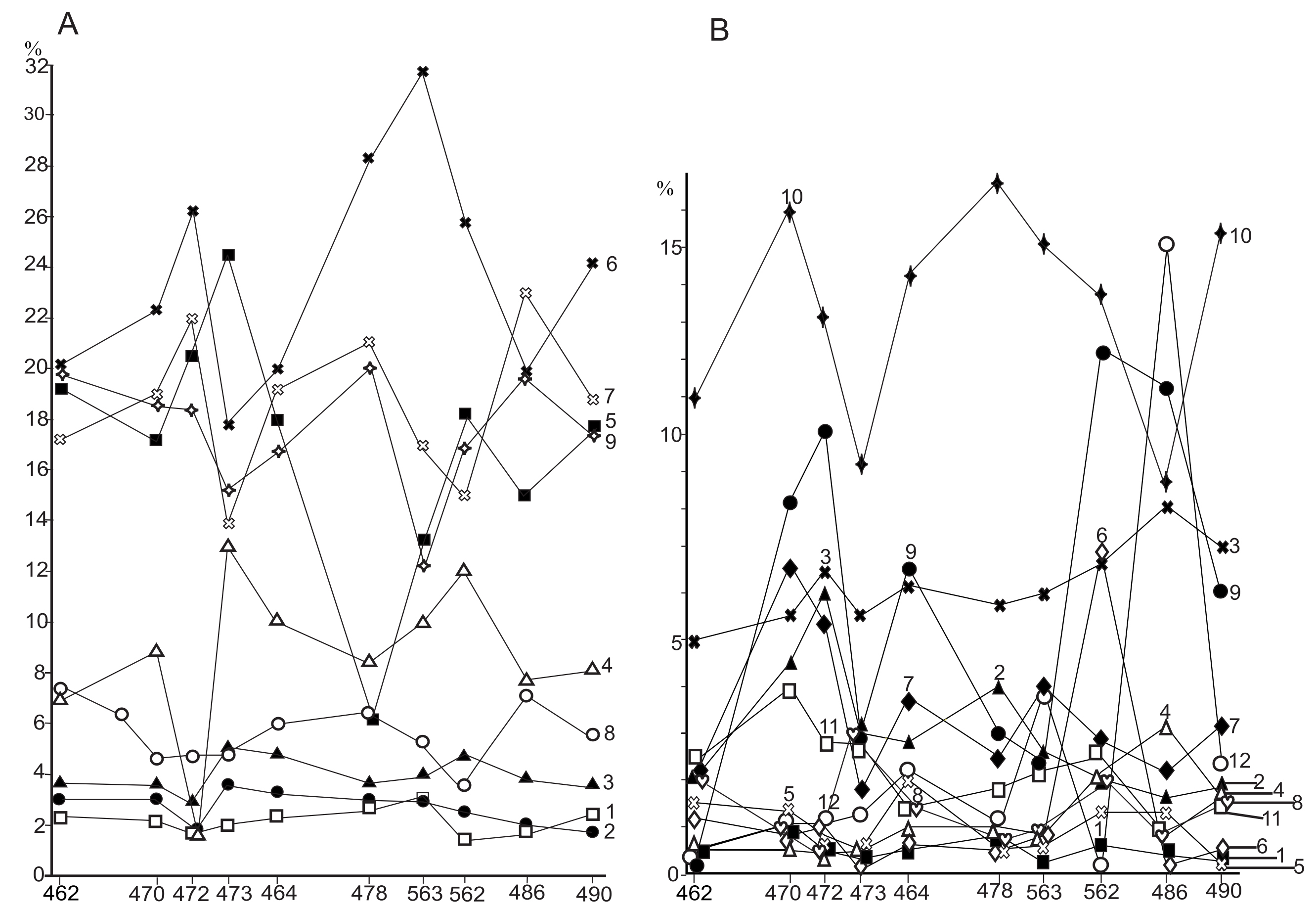
(0.852) in the second group, showing a more uniform quantitative distribution of better fraction numbers in all the Pleistocene thickness. A relatively high *R* value (0.846) was observed in the petrographic composition of the 10–5 mm gravel fraction, where the uneven quantitative distribution of components seems due to a low content of sandstone and Mesozoic carbonates (Table 2). The *R* of approximately 20 heavy minerals (0.25–0.1 mm) shows a significantly higher mean value, (0.703) than the *R* of light minerals, with quartz prevailing in the latter.

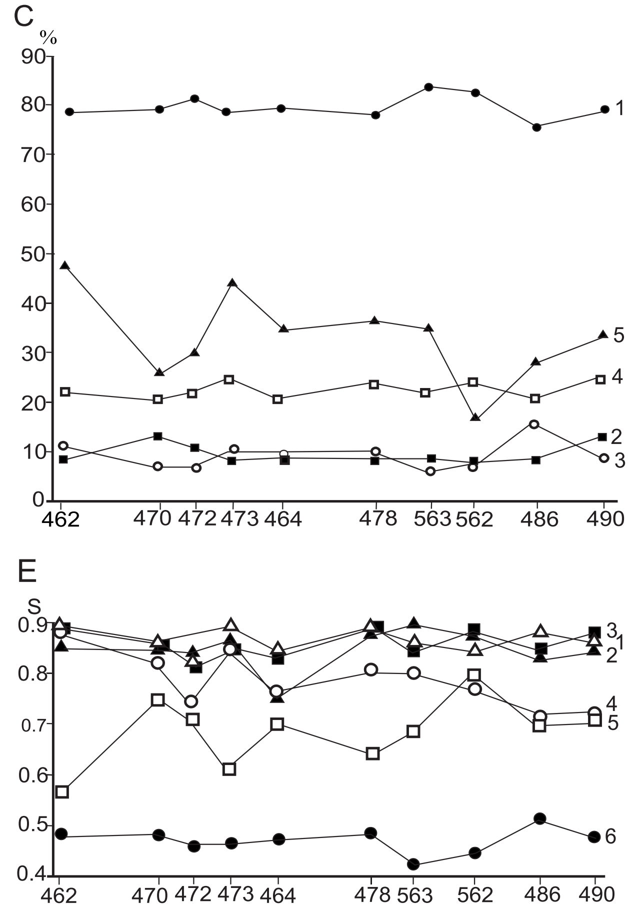
Differences in till component *R* values for different tills identified stratigraphically are also obvious. The *R* value for all three grain size groups is the highest in the Medininkai till, and is somewhat lower in the Baltija and Grūda tills. The lowest *R* value is characteristic of the Žemaitija (1-st and 3-rd fraction groups) and the Varduva till (2-nd fraction group). The highest *R* values were found for the petrographic composition of the 5–10 mm fraction and for the heavy mineral composition in the Varduva till, while the highest values for light minerals were observed in the Dainava and Žemaitija tills. The lowest petrographic composition *R* values were typical of the lower part of the Dainava till, while heavy mineral *R* and light mineral *R* values were characteristic of the Baltija and Grūda tills, respectively. The application of mean *R* values for definitions of individual tills are only general, however, since they do not show changes in *R* values taking place vertically or areally.

Changes in till composition *R* for strata along a NW–SE transect are distinctive. Thus moving from borehole 459 (at Butrimonys) to borehole 467 (Sibiriškės), the 9–fraction *R* values increased in all tills by 0.0007–0.009. *R* values were found to decrease by 0.001–0.01 per kilometre from borehole 467 (Sibiriškės) to borehole 475 (Vaikantonys), but further, from borehole 475 (Vaikantonys) to borehole 478 (Gailiai) *R* increased again. Such repetitive variations, but sometimes in the opposite direction, were observed in *R* values for the four larger fractions, heavy and light minerals, and gravel petrographic composition.

ŽEMAITIJA TILL COMPOSITION ENTROPY AND ITS VARIATIONS

To better understand changes in relative entropy determined for till composition in the direction of glacier movement, the Middle Pleistocene Žemaitija till cross-section, the most complete in the area, was studied in detail. This cross-section is 42 km long and goes from N to S across 10 boreholes from borehole 462 (at Režnyčia) to borehole 490 (Lavysas) (Figs. 1 and 3). At depths of between 60 and 110 m this profile shows units 4 to 18-m thick, most often of brown dolomite containing till loam and sandy loam with rare lenses of sand and clay and Cretaceous rock fragments. In the direction of glacier movement, the basal of the till descends down from +65 to –7 m. The juxtaposition of the till with the sub-Quaternary surface formed of Cretaceous rocks (chalk, marl) was observed only at two sites (boreholes 473 and 486). In four sites (boreholes 462, 470, 478, and 490) the till overlies Butėnai (Holsteinian, Likhvin) interglacial lake deposits identified by pollen analysis. Depending on the thickness of till, 1–10 samples were taken for analysis. The till composition *R* values obtained for each borehole were averaged into one or two values. In the direction of glacier movement, the variations of *R* determined for three grain size fraction groups, heavy and light minerals and gravel petrography are notable for a rhythmic repetition, sometimes of antipodal character (Fig. 4). This probably indicates accumulation of "heavy" till material at similar distances (each 5–15 km apart), where the moving ice produced till material of the highest concentration and mass, possibly because the till grain size composition is close to the optimal mixture with the highest density of deposits. This is supported by a comparison of our data with physical and mechanical data on the formation and composition of Central Lithuanian till of the last glaciation. The latter work shows that grain size composition of till deposits of the Central Lithuania formed during the Last Glaciation is identical or close to the grain size of optimal mixtures, hence, causing the high density of tills (Marcinkevičius, 1988).





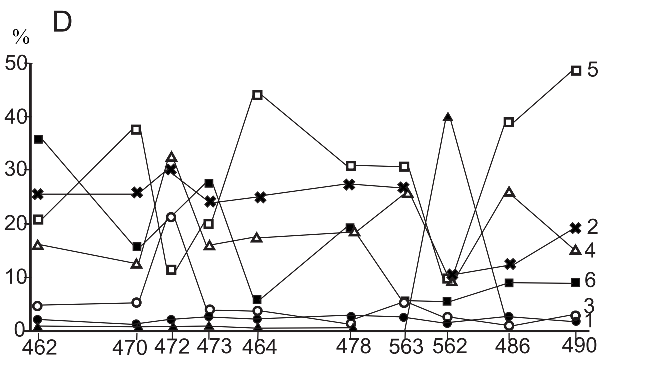


Fig. 4. Middle Pleistocene Žemaitija (Odra, Drenthe, Dnieper) till composition and changes in its relative entropy along a N–S geological cross-section (see Fig. 3)

A — variations in grain size fractions (mm) (1 — 5–2, 2 — 2–1, 3 — 1–0.5, 4 — 0.5–0.25, 5 — 0.25–0.1, 6 — 0.1–0.05, 7 — 0.05–0.01, 8 — 0.01–0.005, 9 — < 0.005); **B** — variations in the 0.25–0.1 mm fraction of heavy minerals (1 — zircon, 2 — pyroxene, 3 — epidote, 4 — staurolite, 5 — biotite, 6 — glauconite, 7 — phosphates, 8 — iron oxides, 9 — pyrite, 10 — magnetite and ilmenite, 11 — leucoxene, and 12 — dolomite); **C** — variations in the 0.25–0.1 mm fraction of light minerals, garnet and hornblende (1 — quartz, 2 — feldspar, 3 — carbonates, 4 — garnet, 5 — hornblende); **D** — variations in the 10–5 mm fraction of petrographic groups (1 — 5–2 mm fraction, 2 — crystalline rocks, 3 — sandstone, 4 — dolomite, 5 — Ordovician and Silurian limestone, 6 — other limestone types); **E** — variations of relative entropy for 9 grain size fractions (1), 5 grain size fractions (2, 3), heavy minerals (4), light minerals (5) and petrographic groups (6)

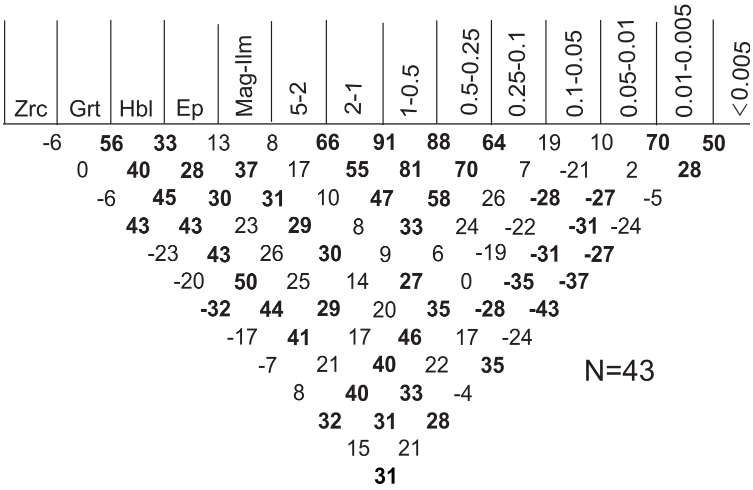


Fig. 5. Correlative links ($r_{xy}\ 10^{-2}$) among grain size fractions (mm) for the Middle Pleistocene Žemaitija (Odra, Drenthe, Dnieper) till and the 0.25–0.1 mm fraction of some heavy minerals

Zrc — zircon, Grt — garnet, Hbl — hornblende, Ep — epidote, Mag-Ilm — magnetite and ilmenite; numbers in bold show a significant correlation for q = 0.05; N — number of samples

The heavy mineral composition *R* and the grain size fraction and petrography *R* showed an antipodal character. The heavy mineral *R*, as a rule, increases with the grain size fraction while the petrography group *R* decreases. The fact that heavy mineral proportion in a narrow range of fractions (e.g., 0.25–0.1 mm) depends on the total grain size composition of the rock is supported by our earlier works (Baltrūnas, 1995, 2002) and correlation analyses of the Žemaitija till in the area studied (Fig. 5).

The intercomponent comparison of till composition *R* values in the direction of glacier movement, as well as characteristics of the sub-Quaternary surface partly explain some variations. For instance, a decrease in the nine grain size fraction S for borehole 472 is related to a sharp decrease in the 0.5–0.25 mm fraction and an increase in 0.25–0.1, 0.1–0.05 and 0.05–0.01 fractions, while for borehole 562 it is related to a decrease in the 0.05–0.01 and 0.01–0.005 mm fractions and an increase in the 0.5–0.25 and 0.1–0.05 mm fractions (Fig. 4A). As for heavy mineral distribution, these profiles are notable for a increase in mineral *R* due to a decrease in hornblende and an increase in pyrite and phosphates (borehole 472) and glauconite (borehole 562) (Fig. 4B, C). Regarding the petrographic composition, boreholes 472 and 562 show a sharp decrease in Lower Palaeozoic limestone and an increase in dolomites (borehole 472) and Mesozoic marl (borehole 562). Boreholes 473 and 486 within the till under study, reaching the sub-Quaternary surface, are notable for a 9–fraction *R* increase. Borehole 486 showed the lowest *R* of petrographic groups due to a sharp increase in Mesozoic marl (Fig. 4E).

The material presented above shows that the influence of sub-Quaternary surface rocks on the Žemaitija till composition in the profile studied is of a local character and is most pronounced in variations of the coarse-fraction composition. According to the 9-fraction *R*, the remainder of the till is evenly sorted, of high density and present in accumulation stage. The high concentration of till material in the lower layers of the ice, through favourable for abrasion of basement rocks, hampered the movement of ice layers and accelerated their transformation into a rather dense till mass poor in ice (e.g. Lavrushin, 1980; Gaigalas, 1989; Serebryanny and Orlov, 1989; Czerwonka *et al*., 1997; Ber, 2000; Khatwa and Tulaczyk, 2001; Muller and Schluchter, 2001; Piotrowski *et al*., 2001; Stokes and Clark, 2002). Thermal and hydraulic conditions in the near-bottom part of the glacier also affected sedimentation of till deposits (Serebryanny and Orlov, 1989; Alley *et al*., 1997; Knight, 1997; Boulton *et al*., 2001; Waller, 2001; *etc*.), which local could change the character of deposition. The most significant factor affecting mixing of basal till components and till density is, however, the glacial environment in the near-bottom part of the glacier. It is this environment that modified the formation and settling of the till deposits that were close to the optimal mixture, despite variation in dynamic, thermal and hydraulic conditions.

CONCLUSIONS

Calculation of relative entropy for Pleistocene till composition in Southern Lithuania and evaluation of its variation showed the following:

1. If a till (mixture of different components) being formed by a glacier is treated as a multicomponental system, an equilibrium system model can be applied to the deposited till and a non-equilibrium system model to the till being formed in the glacier. In this study the deposited till was treated as an isolated system in a relative equilibrium state. The two most complete and stratigraphically most reliably identified Pleistocene sections of Southern Lithuania were studied. Variations in relative entropy were assessed from the average data in the grain size mineral and petrographic composition of individual stratigraphically identified till beds.

2. Till composition relative entropy, which characterises the evenness of component distribution according to relative param-

eters (fraction intervals, minerals chosen, *etc.*) essentially reveals how till forms by grinding of the bed rock, and mixing, spreading and thickening (increasing concentration) of the debris. The relative entropy of various till components (grain size fractions, heavy and light minerals, petrographic groups) in glacial strata of different ages is different and indicates different parameters of ice dynamics and glacier transport directions.

3. Till composition relative entropy in the direction of glacier movement is characterised by (rhythmicity) in its changes (every 5–15 km), which seems most probably due to loading of the lower layers of the glacier with till material up to the maximum concentration and then settling of this material. This loading proceeds by grinding and mixing transit and local bedrock material to a till mixture the density (volumetric weight) of which is the highest, i.e. close to that of the optimal mixture. Till mixture of highest density is formed when the 9-fraction relative entropy approaches 0.9.

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