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Till macro- and microfabrics of mega-scale glacial lineations of Mūša–Nemunėlis Lowland, north Lithuania

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Abstract. North Lithuania was chosen for a study of the "drumlinised" morainic surface produced during the Last Glaciation, typified as well-expressed mega-scale glacial lineations (MGSLs). The goal pursued in the present study was to investigate the morphology and macro- and microfabrics of some large glacial lineations to substantiate their formation mechanism. The geological structure of Quaternary strata of an area and the erosion depression of sub-Quaternary surface suggest favourable conditions for the glacier to rapidly fluctuate into the area during deglaciation of Late Glaciation. Investigations of Pleistocene tills observed in the MSGLs of the area preserved on the eastern and western margins of the study area show that these deposits are formed from the upper part of the Baltija Subformation – Middle Lithuanian till. According to two sets of grain sizes, MSGL tills are often notable for increased values of relative entropy. Therefore, morainic material deposited during the redeposition of the Baltija Subformation till was thoroughly mixed. The data on orientation and inclination of long axes of gravel and pebbles in the tills that form MSGLs, as well as the anisotropy of magnetic susceptibility (AMS) of microclast material suggest that the formation of MSGLs may have been influenced by directions of the local glacial stress that are different from the regional direction of glacial motion (about N–S). The change of macro- and microfabric of till confirms the formation of MSGLs during glacier erosion by groove-ploughing from the Baltija Subformation till. This occurred when basal ice carried over clast material to MSGL crests from interridge areas.

Keywords*: subglacial landform; lithostratigraphic division; Baltija Subformation; anisotropy of magnetic susceptibility*

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INTRODUCTION

Earlier observations enabled to assume that the Mūša–Nemunėlis Lowland (north Lithuania) was a landscape with abundant drumlins (Doss 1910; Hausen 1913; Mortensen 1924; Čepulytė 1956). Basalykas (1965) was the first to note the drumlinoid character of the study area, which is due to the retreating Mūša–Lėvuo ice lobe. Subsequent geomorphological investigations revealed the existence of marginal moraine ridges (Basalykas 1965) or glacial meltwater erosion landforms (Baublys *et al*. 1970; Mikalauskas and Mikutienė 1971) in the area. Moreover, drillings and till structure studies revealed flutings (Gaigalas and Marcinkevičius 1982; Gaigalas 1997). In later years, some authors of the present publication joined investigations where these landforms were treated as mega-scale glacial lineations (MSGLs) (Baltrūnas *et al*. 2014; Lozovskis *et al*. 2015). However, such treatment lacked data about the geological structure of Quaternary strata of the whole area and features of the formation mechanism of such landforms. To examine this problem, an area in north Lithuania (Pasvalys and Biržai districts) was chosen for our study due to the "drumlinised" morainic surface produced during the Last Glaciation, typified as well-expressed mega-scale glacial lineations (Fig. 1). The goal pursued in the present study was to investigate the morphology and macro- and microfabrics of some large glacial lineations to substantiate their formation mechanism.

INVESTIGATIONS OF MSGLs IN OTHER COUNTRIES

Two types of research should be emphasized regarding investigations of subglacial relief landforms from the perspective of MSGLs formation mechanisms. By analyzing the mechanism of ice movement taking part in this process, a hypothesis has been raised that rapid sliding was related to the creation of cavities and the occurrence of pressurized water inside these subglacial cavities (Lliboutry 1968). Increasing investigations and new data suggested that the elongated 'spouts' of primarily fast till ice movements occur at the axes in the depressions between the ridges and that slower ice movements occur at the ridge crests (Lavrushin 1976). The efforts to systemically categorize subglacial relief landforms and relate them to glacial processes should be mentioned (Sugden and John 1976; Aario 1977; Brodzikowski and van Loon 1991). The terms "fluted ground moraine", "drumlinised ridges" (Sugden and John 1976), and "fluting assemblage" (Aario 1977) are related to the transitional zone of glaciers – between erosion zone and "wastage" zone (Brodzikowski and van Loon 1991). In particular, connection of continuous subglacial bedforms to ice movement speed should be stressed (Stokes *et al*. 2013; Woźniak *et al*. 2019).

Referring to examples from Canada, Clark (1993) wrote that the zonation of a glacier can be regarded as a landform assemblage consisting of many components. In recent years, drumlins and more elongated MSGLs have been successfully mapped using LiDAR data in Finland. These colleagues describe new glaciomorphological mapping based on interpretation of

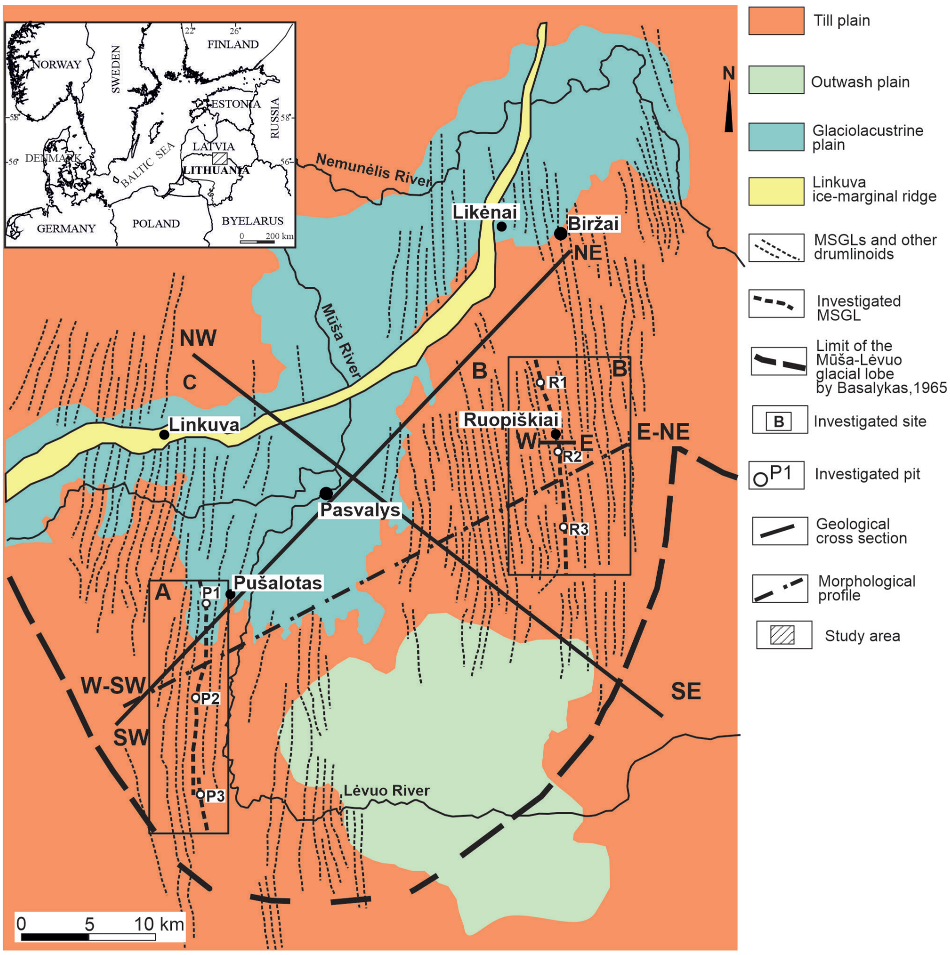

Fig. 1 Study area and geomorphology in the heartland of North Lithuania. Investigation sites: A – Pušalotas, B – Ruopiškiai

LiDAR data, and new classifications are performed according to a new Glacier Dynamic database provided by the Geological Survey of Finland (Putkinen *et al*. 2017; Sarala and Räisänen 2017). Special importance is given to research of subglacial forms performed in neighbouring Latvia (Lamsters and Zelčs 2015). Re-advances of the Zemgale Ice Lobe in the Central Latvian Lowland and Middle Lithuanian Plain during the Middle Lithuanian and North Lithuanian glacial phases created a subglacial bedform assemblage of drumlins, megaflutings, MSGLs, and ribbed moraines. Similar studies have also been performed on sea shelves and subglacial in Antarctica, Iceland and elsewhere (Jamieson *et al*. 2016; Hart *et al*. 2018; and others).

Another newly published paper (Spagnolo *et al*. 2014) presents a detailed morphometric analysis and comparison of 4043 MSGLs from eight palaeo-ice stream settings. This paper is the first compilation of MSGL morphometries, allowing for comparisons between different ice stream beds, including onshore and offshore, as well as in palaeo and modern settings. To test the hypothesis that subglacial bedforms comprise the size and shape continuum across many differently named types, 96,900 measurements of subglacial bedform size and shape have been recently analyzed (Ely *et al*. 2016).

Information about the internal structure of MSGLs is also important in examining the problem of MSGL formation. A relatively homogeneous thick basal till is exposed in the drumlins and flutes of the Weedsport drumlin and flute field in New York State. The drumlin field has AMS and pebble fabrics that are consistently oriented parallel to the streamlined bedforms (Gentoso *et al*. 2012). It is stressed that both fabrics, pebble and AMS, are concordant. Currently, three dominant theories of the formation of MSGLs are distinguished: (1) bed deformation and instability theory (Hindmarsh 1998; and others), (2) meltwater megafloods (Ó Cofaigh *et al*. 2010; and others), and (3) groove-ploughing (Clark *et al*. 2003; and others). With the help of our methods, it is realistic to test the groove-ploughing theory. Particular attention should be directed to observing whether sedimentary indicators of strain (e.g. till fabric) match that predicted by lateral deformation away from grooves (Clark *et al*. 2003). The authors do not deny the influence of meltwater on the formation of MSGLs.

METHODS

Morphometric parameters of MSGLs in Lithuania have been determined by cartometric measurements from topographic maps (1:10 000). A digital elevation model (DEM) with 2 m spatial resolution was used for microform analysis of some small areas in north Lithuania. The copyright of the DEM belongs to the National Land Service under the Ministry of Agriculture of the Republic of Lithuania and the Lithuanian Geological Survey under the Ministry of Environment.

The composition of Ruopiškiai and Pušalotas MSGLs and the thickness and sedimentological characteristics of depositional units were determined. Clast fabrics and samples for AMS were also taken from excavated pits in glacial till. The depth of pits was 1.20–1.50 m. The orientation and dip of long axes of 50 clasts with elongation ratios of ≥ 3:2 were measured in pits in MSGLs using a geological compass and applying methods outlined by Gaigalas (1979). The petrographic compositions of pebbles were analyzed following Gaigalas and Melešytė (2001) and using the following categories: crystalline rocks, sandstone, Devonian dolomite and dolomitized rocks, Ordovician and Silurian limestone, Devonian and Permian limestone, and a group of other rocks.

The relative entropy (R) of grain-size frequency distribution was also used in this study; it reflected the degree of mixing of till particles, which changed rhythmically throughout the vertical till sequences along the direction of ice advance (Baltrūnas and Gaigalas 2004; Baltrūnas *et al*. 2005). R was calculated for till grain-size data of Ruopiškiai MSGLs. R was evaluated for two grain-size fraction groups (mm): (1) >10, 10–5, 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, 0.005–0.002, 0.002–0.001, < 0.001, and (2) > 2, 2–0.05, 0.05–0.002, < 0.002.

Measurements of anisotropy of magnetic susceptibility (AMS)

AMS analysis is applied to investigate rock (deposit) fabrics. The AMS measurement of one rock specimen results in an ellipsoid of magnetic susceptibility (K) that is defined by the length and orientation of its three principal axes, Kmax > Kint > Kmin, which are the eigenvectors of the susceptibility tensor (Jezek and Hrouda 2004; Tarling and Hrouda 1993). The long axis of the magnetic susceptibility ellipsoid Kmax defines the magnetic lineation Kmin (short axis), which defines magnetic foliation. According to the expected model, magnetic lineation coincides with sedimentary or volcanic flow directions, whereas Kmin is perpendicular to the surface of flow (Cañón-Tapia 2004).

Many papers show that magnetic fabric provides a reliable strain indicator (Borradaile and Jackson 2004; Ferré *et al*. 2004; Hrouda 1979, 2002). AMS characteristics have been investigated in Late Pleistocene–Holocene sediments in China (Liu *et al*. 2005), in Pleistocene tills of drumlin fields in the USA (Gentoso *et al.* 2012; Hopkins *et al*. 2016; Iverson 2017), and in basal ice of a surge-type glacier (Fleming *et al*. 2013).

Samples from Ruopiškiai and Pušalotas MSGLs were collected from the excavated pits (depth 1.20–1.50 m) by pressing in special plastic boxes – cubes (ASC Scientific Co.). In total, 19–24 samples were collected. AMS was measured with an MFK1–B kappabridge (AGICO) in the Palaeomagnetic Laboratory of Nature Research Centre (Vilnius). AMS measurements were made along fifteen different directions (Jelinek 1977). Analysis of AMS data was performed using Anisoft 4.2 software.

STUDY AREA

The study sites lie in north Lithuania, where the Mūša–Nemunėlis Lowland is bounded from the north by the Linkuva Ridge (Karmazienė *et al*. 2013; The National Atlas of Lithuania 2014) and crossed by the rivers of Lėvuo and Mūša running northwards to the Zemgale depression in Lithuania and Latvia (Zelčs and Markots 2004; Lamsters and Zelčs 2013). The area is inclined northward, as it is the sub-Quaternary surface (Šliaupa 2004) (Fig. 2). This palaeo-surface consists of Upper Devonian rocks (dolomite and dolomitized rocks, marl, gypsum, clay, and sandstone) dipping WSW at a low angle. The sub-Quaternary surface dips northward from +40 m to +20 m, with +30 m AMSL prevailing. There are northward-dipping palaeo-incisions found in the middle part of

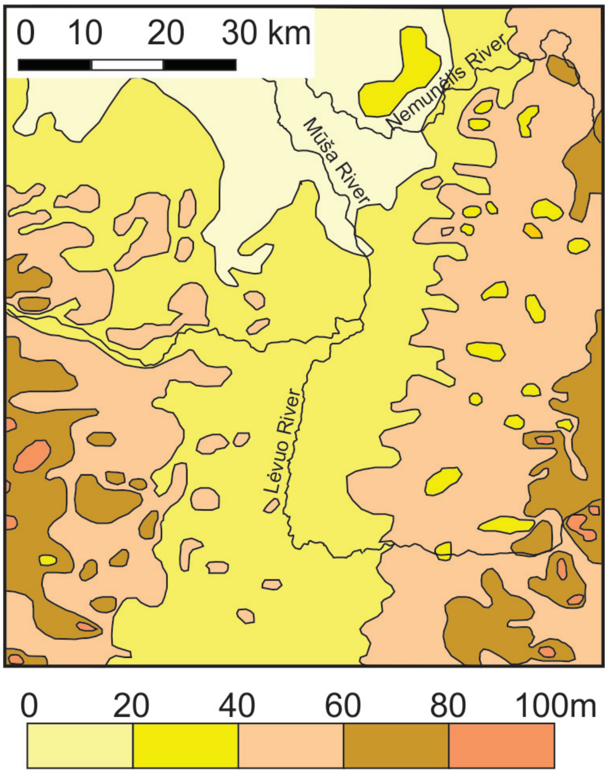

Fig. 2 Relief map of the sub-Quaternary surface in the heartland of North Lithuania (Šliaupa 2004)

the depression that approximately coincide with the present-day hydrographic network.

The thickness of the Quaternary (Pleistocene) rocks reaches 20–30 m with a minimum in river valleys (Jusienė 2007) (Fig. 3). Moraine deposits (tills) prevail in this section and are in relation to the erosional and depositional processes of the Penultimate (Medininkai, Saale) Glaciation and Last Glaciation (Late Nemunas, Late Weichselian). A significantly smaller amount of inter-till glaciofluvial and glaciolacustrine deposits are present, with the exception of 10–12 m thick glaciolacustrine sediments that are widely spread throughout the central part of the field area. We have chosen "drumlinised" morainic surface of the Last Glaciation in Pasvalys and Biržai districts, which can be typified as well-expressed mega-scale glacial lineations (MSGLs).

RESULTS AND INTERPRETATION

The digital elevation models recently obtained from LiDAR data enable interpretation of glacial lineations in the heartland of north Lithuania as MSGLs (Fig. 4). However, there are some visual differences that we can explain. At the Pušalotas site, MSGLs are lower in relief and wider, with small descents along crests, compared to MSGLs at the Ruopiškiai site (Fig. 4 A, B; Fig. 5). At the Pušalotas site (total width of MSGL area 18–20 km), the absolute height of crests rises to 48–55 m, whereas in the Ruopiškiai site (total width of MSGLs area 20–22 km), absolute heights of MSGL crests rise to 58–65 m. The MSGL ridges in the Pušalotas site are affected by the abrasion of the glaciolacustrine basin and subsequent erosion. The north Lithuanian (Linkuva) marginal ridge subdivides MSGLs into two parts. This occurs north of Pušalotas (Linkuva township) and Ruopiškiai (Likėnai resort town) (Fig. 1, Fig. 4 C). Lamsters and Zelčs (2015) interpret this feature as an imbricate thrust that was formed on the glacier margin. The authors of this paper concentrated on investigations of MSGL till.

Investigation of tills in the Pušalotas reference site

Research was conducted on one MSGL that extends from N to S, is situated between the villages of Pušalotas and Daukniūnai, and is located 18–30 km southwest of Pasvalys town. The MSGL is 22 km long and 0.3–1.0 km wide, with the height varying from 1 to 3–4 m (see Figs 4 and 5). The ridge is affected by abrasion and erosion with small descents along its crest. The absolute height of the crest is relatively flat (rise to abs. 49.8–51.4 m). Samples were collected at the northern tip (pit P1), in the middle section (pit P2), and in the southern section (pit P3) of the MSGL, and till

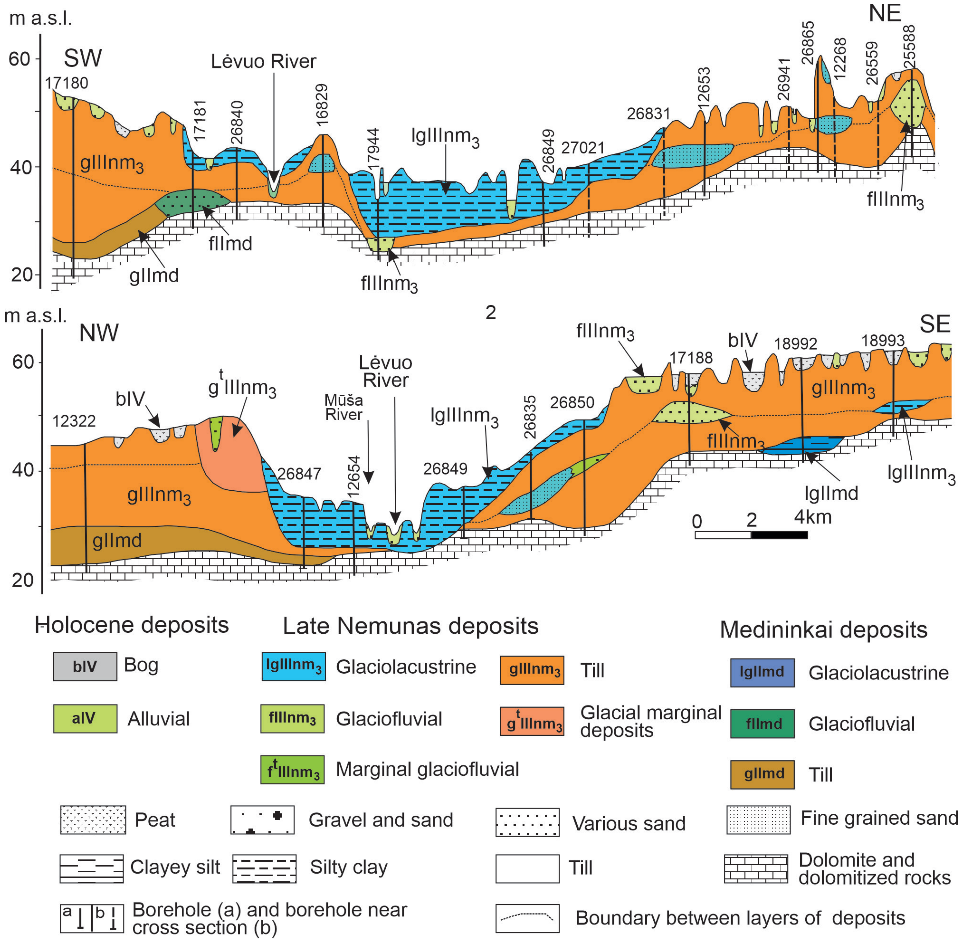

Fig. 3 Structure of Pleistocene deposits in the study area of the Mūša–Nemunėlis Lowland. The geological cross-sections (SW–NE and NW–SE) are by Jusienė (2007)

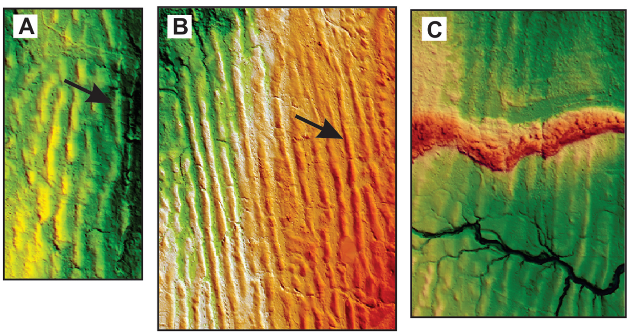

Fig. 4 MSGLs in the Pušalotas site (A), Ruopiškiai site (B) and Linkuva Township (C). Images are shaded-relief DEMs. The copyright of the DEMs belongs to the National Land Service under the Ministry of Agriculture of the Republic of Lithuania and the Geological Survey of Lithuania

investigations were performed in the pits. These investigations included long axis orientation and dip inclination of macroclast material, as well as petrographic composition studies, and anisotropy of magnetic susceptibility (AMS) analyses (Fig. 6).

The depth of pits is 1.20–1.30 m. In all the pits, till is yellowish brown, compact, massive, with gravel, cobbles and boulders, carbonaceous. In the upper part (down to 0.50–0.70 m) sandy till is weathered or degraded, non-carbonaceous. The lower boundary of the weathered part is uneven and obscure.

Macrofabric analysis of till in the Pušalotas MSGL. The majority of macroclasts are composed of sedimentary rocks: Devonian dolomite and dolomitized rocks (37.9–48.9%), Devonian and Permian limestone (10.0–20.0%), and Silurian and Ordovician limestone (17.8–32.5%). The proportions of sandstone, marl and other lithologies are smaller (Fig. 6). The content of crystalline rocks (magmatic and metamorphic) ranges from 7.5–16.3%. In the Ruopiškiai MSGL, crystalline rocks (avg. 22.6%) and Devonian and Permian limestone (avg. 24.5%) are more abundant than in the Pušalotas MSGL (Lozovskis *et al*. 2015).

The crest of the MSGL is characterized by a well-developed fabric. In the northern part of the MSGL (pit P1), macroclasts are orientated W–E. In the middle part (pit P2), they are oriented SSW and NNW, and in the southern part (pit P3), they are oriented NE–SW. The dip of the long axis in the dominant direction is variable (between 0–54°), and the dominant dip is between 0–30° (Fig. 6). All fabrics investigated on the crest of the MSGL display low isotropy indices and low -to-medium elongation indices with the exception of pit P1 fabric, which shows the highest

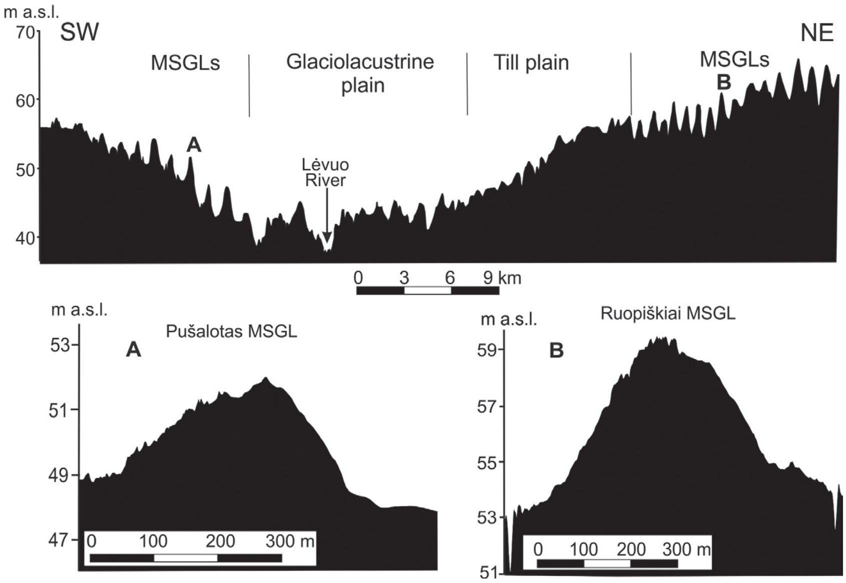

Fig. 5 Morphological profiles across the Pušalotas MSGL (A) and the Ruopiškiai MSGL (B)

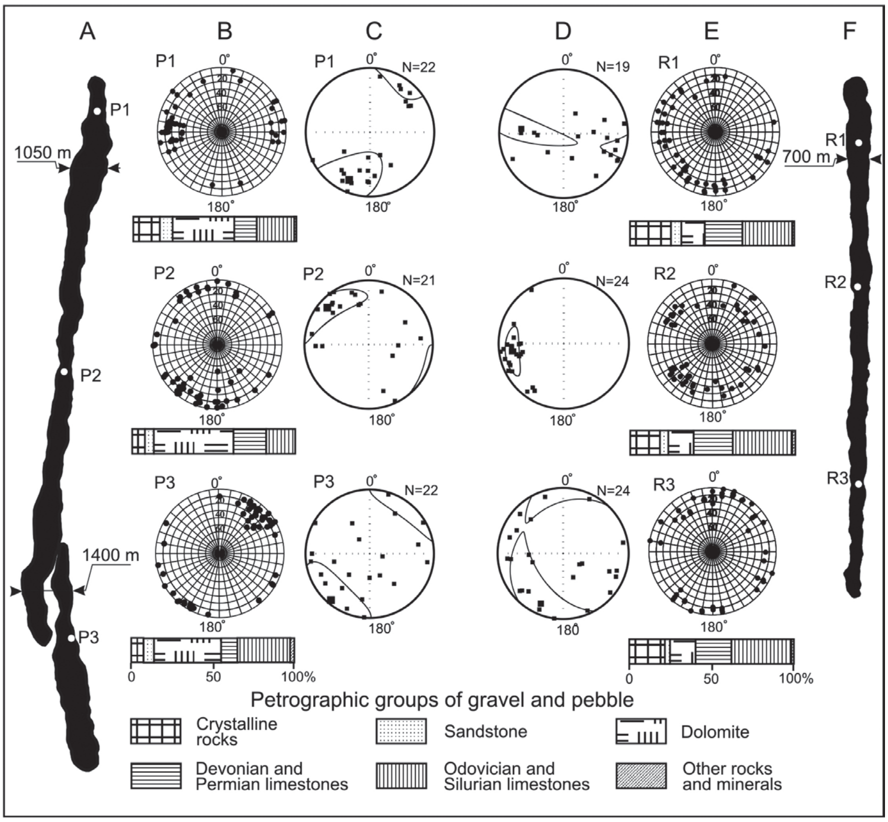

Fig. 6 Petrographical composition, orientation and dip of macrofabric long axes (B, E) and microfabric AMS directional results (C, D) in the investigated till of the Pušalotas MSGL (A) and Ruopiškiai MSGL (F). P1, P2, and P3 and R1, R2, and R3 – investigation pits. In C and D the small symbols represent specimen eigenvectors, whereas the large squares represent the mean eigenvectors of Kmax. N – number of samples

elongation value of all the measured fabrics. These data indicate that the Pušalotas MSGL experienced a different direction of local glacial stress. The direction of macrofabric depends on the formation mechanism that could differ from ice flow direction. The diversity of directions is evidenced by a study of another object (see Fig. 8).

Microfabric analysis of till in the Pušalotas MSGL. AMS analysis generated results presented in Fig. 6 and Table 1. In pit Pušalotas-1 (P1), the dominant (main) direction of glacial flow was 203°/20°, but it can be distinguished from 197°/38° (P1/1) and 40°/20° (P1/2) directions. It is likely that the glacier briefly pressed. In pit Pušalotas-2 (P2), the main di-

Table 1 AMS parameters for dominant (P1, P2, P3) and separate (P1/1, P1/2, P2/1, P2/2, P3/1, P3/2) directions of till in the Pušalotas MSGL and parameters for dominant (R1, R2, R3) directions of till in the Ruopiškiai MSGL (see Fig. 6)

Sample code	Number samples, N	Mean magnetic susceptibility, K_m (10^{-6}SI)	Magnetic lineation, L	Magnetic foliation, F	Anisotropy degree, P	Shape parameter, T	Long axis, K_{max} (°)	Short axis, K_{min} (°)
P1	22	1.38E–4	1.015	1.022	1.036	0.191	203/20	314/43
P1/1	15	1.39E–4	1.026	1.038	1.046	–0,166	197/38	335/43
P1/2	7	1.34E–4	1.033	1.024	1.058	–0.164	40/20	275/57
P2	21	1.00E–4	1.010	1.023	1.033	0.374	312/14	45/17
P2/1	15	0.96E–4	1.019	1.025	1.045	0.134	319/19	178/66
P2/2	5	1.10E–4	1.031	1.007	1.038	–0.647	82/38	196/28
P3	22	3.63E–5	1.006	1.002	1.008	–0.566	220/6	127/23
P3/1	15	3.58E–5	1.009	1.002	1.012	–0.596	226/6	322/43
P3/2	6	3.78E–4	1.003	1.006	1.009	0.274	174/66	279/7
R1	19	8.24E–5	1.006	1.022	1.028	–0.564	276/35	11/6
R2	24	1.24E–4	1.022	1.036	1.058	0.243	260/21	104/67
R3	24	1.12E–4	1.001	1.017	1.018	0.894	204/18	87/55

rection of glacial flow was 312°/14°, and it is comparable to 319°/19° (P2/1), which corresponds to P2. However, the other flow direction recorded in P2 was 82°/38° (P2/2 differs from the previous direction). In pit Pušalotas-3 (P3), the main direction of glacial flow was 220°/6°, and it is comparable to 226°/19° (P3/1) but different from the flow direction of 174°/66° (P3/2).

Investigation of till in the Ruopiškiai reference site

A typical geomorphological area with previously investigated MSGLs was chosen 15–18 km eastward of Pasvalys town, in the village of Ruopiškiai (see Fig. 1**)**. More detailed investigations were performed in one MSGL landform that is 16.5 km long and 200–700 m wide and has a relative height of 4–6 m. Its primary crest is oriented NNW (prevailing azimuth is 352°, changing to 348° in its northernmost part), and it gradually rises from its northern tip (abs. 53 m) towards the southern end (abs. 58.2 m). Samples were taken at the northern tip (pit R1), in the middle part (pit R2), and in the southern part (pit R3) of the MSGL. Till investigations in the moraines were performed, including long-axis orientation and dip inclination of macroclast material, as well as petrographic composition studies and anisotropy of magnetic susceptibility (AMS) analyses (Fig. 6).

The depth of pits is – 1.20–1.30 m. In all the pits, till is brown, massive, structure-less, with gravel, cobbles and boulders, carbonaceous. In the upper part, till is low-carbonated.

Macrofabric analysis of till in the Ruopiškiai MSGL. The majority of macroclasts are composed of sedimentary rocks: Devonian dolomite and dolomitized rocks (14.3–15.6%), Devonian and Permian limestone (21.9–24.7%), and Silurian and Ordovician limestone (30.4–37.4%). The proportions of sandstone, marl and rocks of other lithology are smaller (Fig. 6). The content of crystalline rocks (magmatic and metamorphic) ranges from 18.2–25.9%.

The crest of the MSGL is characterized by a well-developed fabric. In the northern part of the MSGL (pit R1), the macroclasts are orientated W–NW and SW. The clasts are oriented SW and SE in the middle part (pit R2), and the macroclasts are oriented N–NE and S–SW in the southern part (pit R3). The dip of the long axis in the dominant direction is variable (between 0–41°), and the dominant dip is between 6–28° (Fig. 6). All fabrics investigated on the crest of the MSGL display low isotropy indices and low-to-medium elongation indices. These data indicate that the Ruopiškiai MSGL experienced different directions of local glacial stress.

Microfabric analysis of till in the Ruopiškiai MSGL. AMS analysis generated results presented in Table 1 and Fig. 6. In pit R1, the dominant (main) direction of glacial flow was 276°/35°. In pits R2 and R3, the main directions were 260°/21° and 204°/18°, respectively.

Attention should be paid to the results of AMS investigations across the Ruopiškiai MSGL (Baltrūnas *et al*. 2013). A new generalization of data was made (Fig. 7). The mean AMS long-axis orientation of samples from the western slope of the landform are almost perpendicular (W–E) to the long-axis orientation of the MSGL with mean plunges ≤ 20°. The mean AMS microfabrics recorded from the eastern slope of the landform display rather different mean orientations: the lower microfabric shows meridional orientation, and the upper one shows NE–SW direction with low dips. Both AMS microfabrics recorded from the crest of the MSGL display similar mean orientations NE–SW with dips around 25°. AMS microfabric of the next quarry section displays two different mean orientations (NW–SE and NE–SW) with low plunges. Sedimentary indicators of strain in till fabric can testify to lateral deformation. These orientations deviate rather significantly from the average macroclast long-axis orientation of the sites (Fig. 7). A comparison of orientation of macroclast and microclast material of till shows that often directions are approximately perpendicular. These data suggest that the formation of the MSGL landform may have been influenced by a direction different from the regional direction of glacial motion (about N–S).

Lithostratigraphic division and correlation of tills in the Ruopiškiai reference site

A previously completed and more detailed investigation along entire MSGLs revealed a possible mechanism for their formation (Gaigalas and

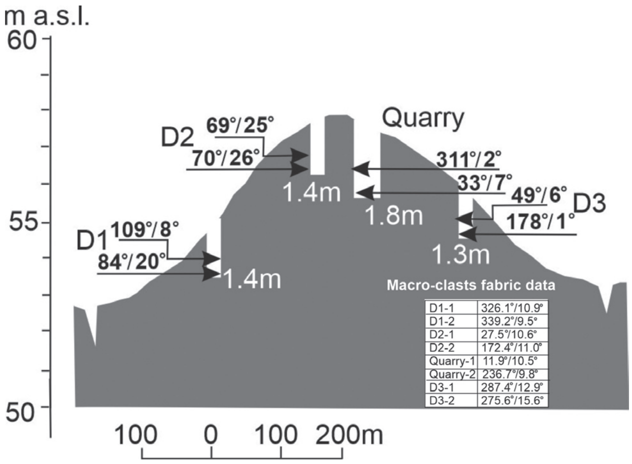

Fig. 7 Micro-clast fabric (AMS results) and macro-clast fabric of till across the Ruopiškiai MSGL. D1, D2, D3 and Quarry – investigation pits and quarry. 109°/8° – mean long axis orientation (°)/mean dip (°)

Marcinkevičius 1982; Baltrūnas *et al.* 2014; Lozovskis *et al.* 2015). The present paper uses and generalizes the results from the abovementioned publications. Special attention is, however, given to the west-east geological section, which has seven boreholes that cross four typical MSGLs. After comprehensive borehole investigations were completed, the data were applied and generalized by new statistical methods, and the lithostratigraphic model of the geologic section changed radically; thus, allowing for another explanation of MSGL formation (Fig. 8). According to till grain size and other physical-mechanical parameters, three assemblages of deposits are selected and compared with the following lithostratigraphical units: Grūda Subformation ($gIIInm_3^{gr}$), Baltija Subformation ($gIIInm_3^{bl}$), and Middle Lithuanian Member ($gIIInm_3^{ml}$) (Satkūnas *et al.* 2007; Guobytė, Satkūnas 2011).

The Grūda till is usually notable for its low content of clay (fr. < 0.002 mm – 11.5–14.8%), higher content of sand (fr. 0.05–5.0 mm – 68.6–65.7%), high moisture content, overconsolidation ratio and liquid limit, and void ratio significantly lower (18.1–18.4) than in the Baltija till (Table 2). A comparison of the Baltija till with the Middle Lithuanian till illustrates that the Middle Lithuanian till contains less clay and more sand and it is notable for an anomalously high silt content, which slightly increases porosity and fluidity.

Calculations of the relative entropy of grain-size components show that rather low relative entropy (R2) of 13 fractions is characteristic of the lower (Grūda) till and that R2 is slightly higher in the upper till that fills MSGL landforms. The middle (Baltija) till is notable for varying values of relative entropy. Another calculation of relative entropy for four fractions (R1) shows the highest values (0.948–0.906) fixed in two boreholes drilled in the MSGL site of the Baltija Subformation till and in one case in the

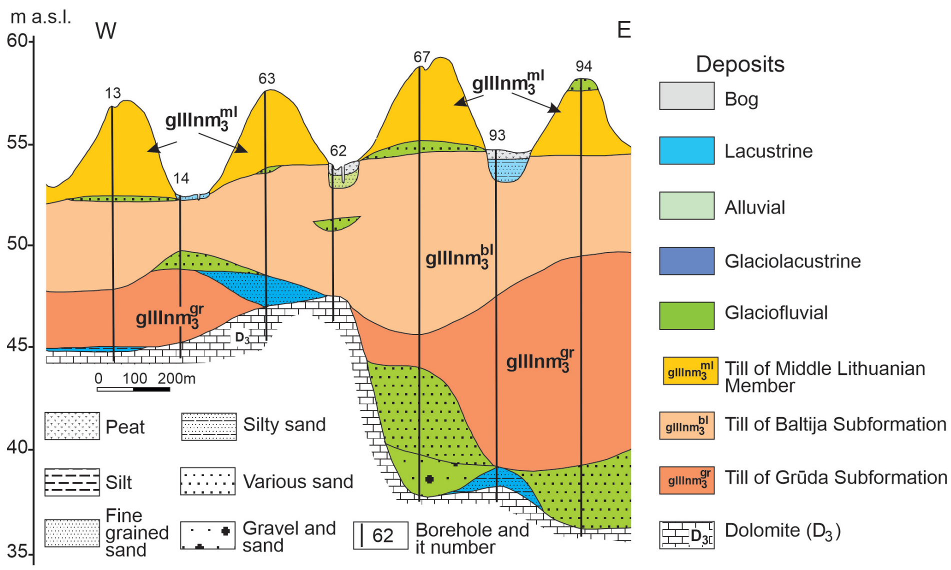

Fig. 8 Geological cross-section (W–E) across the MSGLs in the Ruopiškiai site

Table 2 Characteristics of tills for two boreholes (Nos 94 and 67) drilled in MSGLs in the Ruopiškiai site (see Fig. 8). Index of till: Grūda Subformation ($gIIInm_3^{gr}$), Baltija Subformation ($gIIInm_3^{bl}$), and Middle Lithuanian Member ($gIIInm_3^{ml}$)

No bore-hole	Depth, m	Fractions (mm), %			Ratio 0.05–0.002/ < 0.002	Relative entropy		Physical-mechanical parameters		Stratigraphical index
		> 0.05	0.05–0.002	< 0.002		R_1	R_2	Liquid limit	Plasticity index	
94	2.6	55.4	26	18.6	1.4	0.911	0.918	0.104	0.092	$gIIInm_3^{ml}$
94	5.1	52.8	29	18.2	1.59	0.882	0.896	0.107	0.075	$gIIInm_3^{ml}$
94	6.7	51	27	22	1.23	0.855	0.879	0.111	0.086	$gIIInm_3^{bl}$
94	8.6	52.7	25	22.3	1.12	0.846	0.865	0.113	0.076	$gIIInm_3^{bl}$
94	12.0	65.7	20	14.3	1.4	0.778	0.854	–	–	$gIIInm_3^{gr}$
94	13.5	65.7	19.5	14.8	1.32	0.772	0.840	0.089	0.072	$gIIInm_3^{gr}$
94	17.0	66.5	19	14.5	1.31	0.706	0.824	0.086	0.077	$gIIInm_3^{gr}$
67	1.5	54	32	14	2.28	0.857	0.895	–	–	$gIIInm_3^{ml}$
67	3.5	56	29	15	1.93	0.899	0.902	–	–	$gIIInm_3^{ml}$
67	5.0	54.1	29	16.9	1.72	0.899	0.885	0.113	0.071	$gIIInm_3^{bl}$
67	7.5	54.5	28	17.5	1.6	0.880	0.892	0.108	0.075	$gIIInm_3^{bl}$
67	10.0	53.7	24.4	21.9	1.11	0.907	0.899	0.111	0.072	$gIIInm_3^{bl}$
67	11.7	54.6	24	21.4	1.12	0.887	0.899	0.119	0.088	$gIIInm_3^{bl}$
67	13.5	57.6	23	19.4	1.19	0.834	0.898	0.113	0.071	$gIIInm_3^{gr}$

lower part of the Grūda Subformation till. The lowest values of relative entropy (0.700–0.778) are fixed for borehole No 94 in the Grūda till and in borehole No 63 in the upper part of the MSGL till. In general, according to both sets of fractions, the MSGL till is often notable for a higher relative entropy, i.e. the material is more thoroughly mixed.

The data available from analytical investigations and statistical parameters were used to perform new lithostratigraphic divisions and correlation of sections. The Grūda till is found to have a variable thickness that is the largest (9.5–10 m) in a palaeo-incision (boreholes Nos. 93 and 94) of a sub-Quaternary surface. The Baltija till consists of two members. The lower part remains nearly intact according to its thickness (up to 8–10 m) and exhibits rare sand interlayers (up to 0.5 m thick). The upper part is not solid and contains only elevated MSGLs. The upper part also resembles the lower part in terms of grain size composition; however, it has a higher sand content and porosity and contains more clay, particularly in the top part (Table 2). The setup and composition of till in the geological reference section enables us to assume that the two-member character of the Baltija till is related with Baltija Subformation and its Middle Lithuanian Member.

DISCUSSION

Previous investigations in north Lithuania were based on mapping and borehole drilling, which provided data that lead to similar conclusions. Specifically, parallel flat valleys and ridges resembled in their shape and origin the lithomorphogenetic range of flutings and drumlinoids, but these ridges were formed under the joint impact of glacier erosion and deposition occurring at varying velocities (Gaigalas, Marcinkevičius 1982). Investigations completed in northern Canada confirm the importance of sediment supply for MSGL formation; they provide the material necessary for the formation of ridges (Ó Cofaigh *et al*. 2013). The MSGL of the Lake Dubawnt palaeo-ice stream is at least partially erosional (cf. Stokes *et al*. 2013) and related to the overriding and reworking of pre-existing sediments. This is actually consistent with the formational theories that invoke at least partial erosion and reworking of material from between ridges, e.g. groove-ploughing of ice keels and/or subglacial streams directed along inter-ridge grooves. This statement is partly supported by Fig. 7 of our paper, which shows different directions of the local glacial stress in MSGL formation. Gentoso *et al*. (2012) described and sampled six drumlins and five flutes and found that flute fabrics were stronger and more unidirectional than those of drumlins. As we can see in the case of our investigated MSGLs, the image of macro- and microfabric is even more complex.

Having investigated MSGLs in Latvia, Lamsters and Zelčs (2015) agree with Ó Cofaigh *et al*. (2013) in that MSGLs were formed by sediment erosion from preexisting substrate and shallow subglacial deformation, which is partially compatible with the formation of MSGLs by groove-ploughing, but do not present data about the internal structure which could support or decline the mentioned hypothesis. Attention should be paid to the results of AMS investigations across the Ruopiškiai MSGL (Baltrūnas *et al*. 2013). A new generalization of data was made, which suggests that the formation of the MSGL landform may have been influenced by a different direction of subglacial lateral pressure rather than by the regional direction of glacier motion (about N–S) (see Fig. 7). A comparison of macro- and microfabric of till shows that often directions are approximately perpendicular. This can be the result of two stages of MSGL formation: relics of primary (regional) direction and glacial erosion by groove-ploughing. AMS provided specific useful information regarding the kinematics of deformation within subglacially deformed sediments (Fleming *et al.* 2013). Investigation of modern-day sedimentary environments on the glacier margin provides important information on the sediments and relief generated by retreating glaciers. For example, orientation and dip of long axes of debris in basal ice of the Russell Glacier are caused by directions and, possibly, the modes of glacier ice movement: plasticity (ice creep) and the movement by planes of internal cleavage (Baltrūnas *et al*. 2009). According to Clark *et al*. (2003), because of flow acceleration and convergence in ice-stream onset zones, the ice-base roughness elements experience transverse strain, transforming them from irregular bumps into longitudinally aligned keels of ice protruding downwards. Where such keels slide across a soft sedimentary bed, they plough through the sediments, carving elongate grooves and deforming material up into intervening ridges. The size of keels of ice and the distance between them is related to the subglacial relief and glacial crevasse.

Changing macro- and microfabric of till (variable orientation and dip) confirms the formation of MSGLs during glacier erosion by groove-ploughing. This occurred when basal ice carried over clast material to MSGL crests from interridge areas. The data presented by Stokes *et al*. (2013) strongly favour a subglacial bedform continuum primarily controlled by ice velocity; however, it is confounded by the duration of ice flow and the fact that new bedforms are continually being created, remoulded, and, ultimately, erased. Given that the Dubawnt Lake ice stream only operated for a relatively short period of time (just a few hundred of years: Stokes and Clark, 2003), a further implication is that MSGL formations (and subglacial bedforms more generally) are likely to have been created over time-scales of decades rather than centuries (Stokes *et al*. 2013).

CONCLUSIONS

1. The geological structure of Quaternary strata of the area and the erosive depression of sub-Quaternary surface suggest favourable conditions for the glacier to rapidly fluctuate into the area during deglaciation of Last Glaciation.

2. Investigations of Pleistocene tills observed in the MSGLs of the area preserved on the eastern and western margins of the study area show that these deposits are formed from the upper part of the Baltija Subformation – Middle Lithuanian till.

3. According to two sets of grain sizes, MSGL tills are often notable for increased values of relative entropy. Therefore, morainic material deposited during the redeposition of the Baltija Subformation till was thoroughly mixed to MSGLs.

4. The data of orientation and dip of long axes of gravel and pebbles in the till and the anisotropy of magnetic susceptibility (AMS) of microclast material show that the formation of MSGL landform may have been influenced by directions different from the regional direction of glacial motion (about N–S).

5. The change of macro- and microfabric of till confirms the formation of MSGLs during glacier erosion by groove-ploughing from the Baltija Subformation till. This occurred when basal ice carried over clast material to MSGL crests from interridge areas.

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