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Drumlins and related glaciogenic landforms of the Madliena Tilted Plain, Central Latvian Lowland

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Abstract

This paper presents new results on the morphometry and spatial distribution of the glaciogenic landforms and ice flow directions in the Madliena Tilted Plain that occupies the eastern part of the Central Latvian Lowland. Landforms were investigated by using topographic maps at scales of 1:25 000 and 1:10 000. There were identified and mapped 1461 glaciogenic landforms such as drumlins, end moraine ridges, eskers, ribbed moraines, marginal ridges, lateral shear margin moraines and recessional formations. Particular attention is given to the morphometry, spatial distribution, and the internal structure of drumlins. Glacial landscape of the study area was formed by the Zemgale ice lobe in course of deglaciation of the Late Weichselian Fennoscandian Ice Sheet, when the ice decay was interrupted by the reactivation of the Middle Lithuanian and the North Lithuanian glacial phases at the end of the Oldest Dryas (18–15 ka BP). The detailed study of the internal structure of the Brenceni drumlin suggests that it consists of glaciotectonically disturbed glacio-aquatic sediments and of a single till thrust sheet between sand sediments on the flank of the drumlin. Morphometric analysis of the drumlin field shows that the mean length of drumlins is about 850 m; the mean width indicates the average size 280 m, and the mean elongation ratio is 3.0. The obtained statistics compared to the morphometry of drumlins worldwide, show close similarity, so it coincides with the concept that in general morphometry of drumlins is mostly independent of their location and the characteristics of the ice streams.

Keywords (GeoRef Thesaurus, AGI): glacial features, drumlins, morphometry, glaciotectonics, deformation, ice movement, Weichselian, Madliena, Latvia

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1. Introduction

The Madliena Tilted Plain (further MTP) occupies the eastern part of the Central Latvian Lowland (Fig. 1). This glacial lowland is classified as divergent type lowland because it widens in the direction of ice movement (Zelcs, 1993a). Ice flow in the MTP, however, was convergent in some places, affected by the proximity of the Vidzeme Upland that caused lateral ice compression and formation of convergent drumlins.

The one of first attempts to study glaciogenic landforms of the study area was made by Zans (1936). He described and mapped landforms within Latvia and also observed three large eskers and marginal formations in the western part of the MTP. These marginal formations with north-south orientation were separated from closely existing drumlins with mostly north-west to south-east orientation by Aboltinš (1970), who described these landforms in details. The chain of marginal forms was attributed to the North Lithuanian (locally named as the Linkuva) ice-marginal zone (Aboltinš, 1970; Aboltinš et al., 1972).

The glaciogenic landforms in the study area was formed mostly by the Zemgale ice lobe of the Riga ice stream during oscillatory retreat of the Late Weichselian Scandinavian Ice Sheet in the two glacial phases – the Middle Lithuanian phase (locally named as the Gulbene phase and correlated with the Haanja phase in Estonia (Zelcs et al., 2011)), and the North Lithuanian phase (correlated with the Ottepaa/Sakala ice-marginal formation in Estonia (ibid). The mean absolute age of the Middle Lithuanian glacial phase is 13 600 ± 300 ^{10}Be years and 13 100 ± 300 ^{10}Be years for the North Lithuanian (Rinterknecht et al., 2006). Also other regional correlations of theses ice marginal zones are discussed in literature (e.g., Serebryanny & Raukas, 1966; Meirons et al., 1976; Aboltinš et al., 1977; Raukas

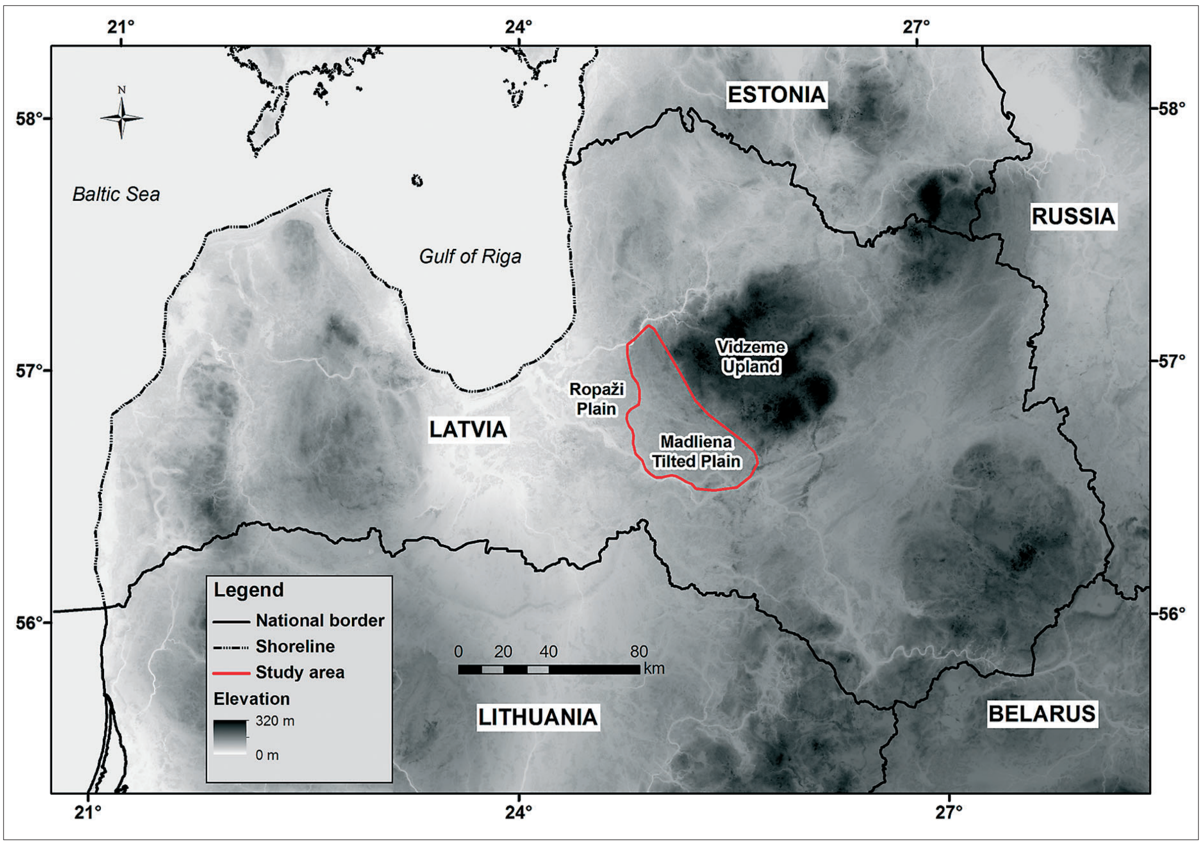

Fig. 1. Location of the study area (Shuttle Radar Mission Model (SRTM) at background).

et al., 1995; Zelcs & Markots, 2004; Kalm, 2006; Rinterknecht et al., 2006; Raukas et al., 2010). Since Zans (1936) identified the Linkuva marginal formations in Latvia and Lithuania, and Serebryanny & Raukas (1966) attributed them to the North Lithuanian glacial phase, this become the only cross border correlation that has not been changed contrary to the rest of glacial phases.

The purpose of this study was to map glaciogenic landforms, obtain their morphometric parameters, explore internal composition, establish direction of ice movement, and find relations of landform morphology and spatial arrangement to the topography and lithology of the bedrock surface. Most attention was paid to the morphometry and internal composition of drumlins.

2. Study area

The MTP (Fig. 1) is bordered by the Vidzeme Upland along its eastern side and the Ropazi Plain along the western side. The northern and southern boundaries of the MTP are marked by the Gauja and Daugava River valleys. The hypsometric position of the relief surface ranges from 120 m a.s.l. to 40 m a.s.l. towards the southwest. The maximum surface elevation value of 142 m a.s.l. occurs on the Keipene Ridge that is interpreted as lateral shear margin moraine. This moraine ridge rises up to 42 m above surrounding terrain. In general, the MTP is characterized by low local topography. Relative height of landforms seldom exceeds 20 m.

Glacial morphology in the MTP (Fig. 2) is dominantly composed of subglacial and ice-marginal landform assemblages including drumlins, ribbed moraines, recessional moraines, end moraines and complex marginal ridges. The last ones are the ice-marginal formations of the Middle Lithuanian phase. Drumlins of this glacier reactivation phase and their unmodified appearance attest the areal deglaciation in this part of the MTP. When ice decay was interrupted by the reactivation of the Zemgale ice lobe during the North Lithuanian glacial phase, the Linkuva push moraine formed between active ice lobe and the masses of dead ice. Such model was proposed by Zelcs et al. (1990) and supported by Bitinas et al. (2004). Afterwards frontal deglaciation prevailed when the ice masses retreated from the North Lithuanian phase ice-marginal zone. This is supported by the presence of the recessional moraines, ribbed moraines and eskers widespread up-ice of the North Lithuanian ice marginal line.

Thickness of the glacial sediments varies from 5 m to 60 m, on average it is 20 m. The Pleistocene deposits are composed mainly of the Late Weichselian till with interlayers of glacio-aquatic sediments. Two till beds can be encountered in the area under consideration. These till beds occurring upglacier from the Linkuva push moraine were interpreted by Savvaitov & Straume (1963) as deposits of the LGM and the North Lithuanian phases but Zelcs & Markots (2004) pointed out that upper till unit was deposited during the Middle Lithuanian phase and has been fragmented due to subglacial deformation in course of the subsequent glacier reactivation.

The MTP is situated on an uneven slope of bedrock. The bedrock surface declines from 100 m to 0 m a.s.l. towards the southwest. The bedrock is composed of Upper Devonian siliciclastic and carbonatic sedimentary rocks, mostly by sandstone, clay and dolomite. Overall the bedrock is made of spatially varying material therefore it is tricky to establish bedrock influence on distribution, spatial arrangement and morphology of drumlins and other forms. It is assumed that formation of drumlins was initiated by mosaic bed deformation, caused by varying characteristics of bedrock and Quaternary sediments.

The greatest part of the MTP is occupied by drumlins that form the Madliena drumlin field. Drumlins in this area have been recognised by Aboltinš (1970) and Straume (1979). According to Russian terminology and due to relatively low topography, these streamlined landforms were named as "uval moraines" (ibid. and also Zelcs (1993a, b). Later they have been classified as "convergent drumlins" or "crumlins" (Zelcs, 1998, 2001). The Madliena field comprises 880 drumlins covering an area of 1248 km^2. The length of the field is 70 km, whereas the width increases from 5 km in the north up to 33 km towards the south and decreases to 18 km at the distal end. The western side of the Madliena drumlin field is transgressively covered by the Linkuva ice-marginal formations.

3. Methods

In this study the elevation data for identification and digitization of the glacial topographic features were derived from the topographical maps at scales of 1:25 000 and 1:10 000 with main contour intervals of 5 and 2 m, respectively. Mapping from the topographical maps was accomplished by visual interpretation of the landforms and by on-screen digitizing directly into a GIS by using ArcView software. Also, the geological maps of Quaternary deposits and geomorphological maps at scales of 1:50 000 and 1:200 000 were used to interpret some landforms.

There were mapped 1500 glaciogenic landforms such as drumlins, end moraines, recessional moraines, lateral shear margin moraines, ribbed moraines, marginal ridges and eskers (Fig. 2). The interpretation of landforms was based upon spatial arrangement, orientation of longitudinal axes and internal structure of individual landforms. For background information on possible genesis and internal structure of landforms were used geological maps of Quaternary deposits, geomorphological maps, borehole data from Latvian Geological Fund and data from Aboltiņš (1972), Straume (1979) and Zelcs (1993a, b).

The landform mapping resulted in the data

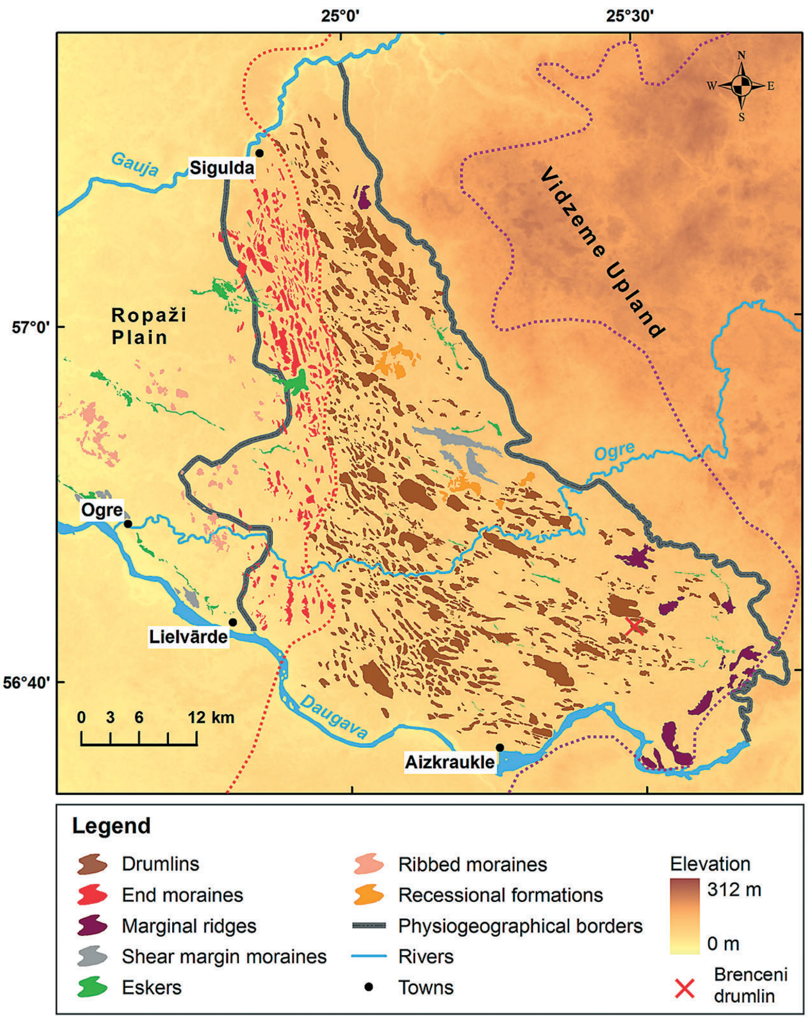

Fig. 2. Glacial morphology of the Madliena Tilted Plain (SRTM at background). Ice marginal positions: L = North Lithuanian (Linkuva), G = Middle Lithuanian (Gulbene).

being stored in GIS layers as shapefiles: the layers containing landforms mapped at the break of slope as GIS polygons and conforming to the LKS92/ Latvia TM projection. The polygons of the drumlins were also transformed to single lines, drawn automatically as the longest lines inside of the polygons. These single lines have automatically computed attributes of their length and azimuth. There were obtained also other morphometric parameters of the drumlins, as the width, elongation ratio, perimeter and area for geospatial and statistical analysis. The length and width were also calculated from automatically obtained perimeter and area by using Euler's approximation, adapted by Clark et al. (2009). The calculated values were compared to manually measured values for 100 drumlins and correlation was very close (Spearmen correlation coefficient 0.98 for length and 0.93 for the width). A geographic information system (ArcView) was used to collect a range of parameters on the drumlins. Shape parameters of each drumlin were compiled into an attribute table including the length and width, which were measured from the GIS polygons, and elongation ratio. Elongation ratio was calculated by GIS from length/width parameters. There were done also spatial analyses on obtained morphometric parameters with a purpose to observe connection between them and topography and lithology of the bedrock surface.

During the fieldwork the internal structure of the glaciogenic landforms were examined in exposures located in sand and gravel pits. The most work was done in the Brenceni sand pit, where the internal composition of drumlin was studied in detail. There were done directional measurements of planar structural elements of the strata composing the drumlin. The internal composition was tested also by coring and radiolocation using ground penetrating radar.

To specify the direction of ice flow in the research area, 55 measurements of glacial striations in Turkalne dolomite quarry were done and visualised in StereoNet plot. Also, the average mean orientation of the drumlin longitudinal axis was calculated.

4. Results

The mapped landforms are shown in Fig. 2. The database includes 1461 glaciogenic landforms in total. It comprises 880 drumlins, 312 end moraine ridges, 161 individual esker ridges and 108 other forms like ribbed moraines, marginal ridges, shear margin moraines and recessional formations.

Statistics on length, width and elongation ratios (length/width) for the mapped drumlins are presented in Table 1. The average mean length of the drumlins is found to be about 850 m; the mean width reaches almost 280 m. The mean elongation ratio is 3.0. Most drumlins (ca. 68 %) are between 200 and 1500 m in length; between 100 and 600 m in width; and 1.5 to 5 times as long as they are wide. The most frequent length is 400 m, the width is 100, and the elongation ratio is 2.5. The longest drumlin is 5.91 km long, and the widest is 1.68 km wide. These measurements are not normally distributed around the mean value; all have a strong positive skew and are markedly peaked.

Table 1. Morphometric statistics for drumlins of the Madliena Tilted Plain.

	Length (m)	Width (m)	Elongation ratio
Min	71	42	1,3
Max	5907	1681	8.8
Average mean	843	278	3.0
Standart deviation	674	165	1.1
Median mean	648	245	2.7
Skewness	2.9	2.4	1.6
Kurtosis	12.7	11.4	4.0

Fig. 3 illustrates the drumlin length against width. The strongest clustering is at the smallest sizes. There is a close linear relationship that gives the Pearson correlation coefficient of 0.83 and the Spearmen rank correlation coefficient of 0.86. It is clearly seen that longer drumlins tend also to be wider but this relationship decreases for drumlins with bigger size. The biggest drumlins can vary greatly in size, for example, a 5 km long drumlin, may have a width between 600 and 1700 m.

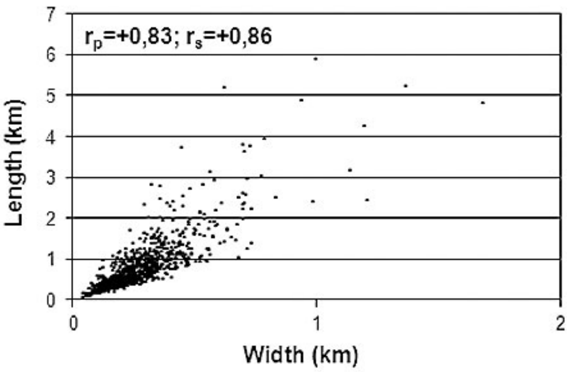

Fig. 3. Drumlin width plotted against length (r_p is Pearson and r_s is Spearmen correlation coefficient).

The detailed studies from the Brenceni sand pit show some peculiarities of the drumlin internal composition. The Brenceni drumlin (Fig. 4) is 1.91 km long, 0.78 km wide and with the elongation ratio of 2.45. The drumlin is situated in the SE part of the Madliena drumlin field (see location in Fig. 2), and it is distal part of ice flow trunk.

Up to 10 m high exposure (Fig. 5), that is located on the NW flank of the Brenceni drumlin in its proximal part with the face approximately perpendicular to the long-axis of the drumlin, reveal its internal structure. The sediments (Fig. 5) exposed in this part of the drumlin can be grouped into two facies: deformed sand (Sd) and matrix supported, massive, deformed diamicton (Dmm(d)). The exposure mainly consists of fine to medium grained sand that is disrupted by the overthrusted scale of subglacial deformation till. The overthrusted scale-like body is up to 1.5 m thick. It is thickening in the direction of the inter-drumlin depression, with the exception of the very distal part. According to the measurement results alongside displacement surface (see resulting stereo plot in Fig. 5.), over-

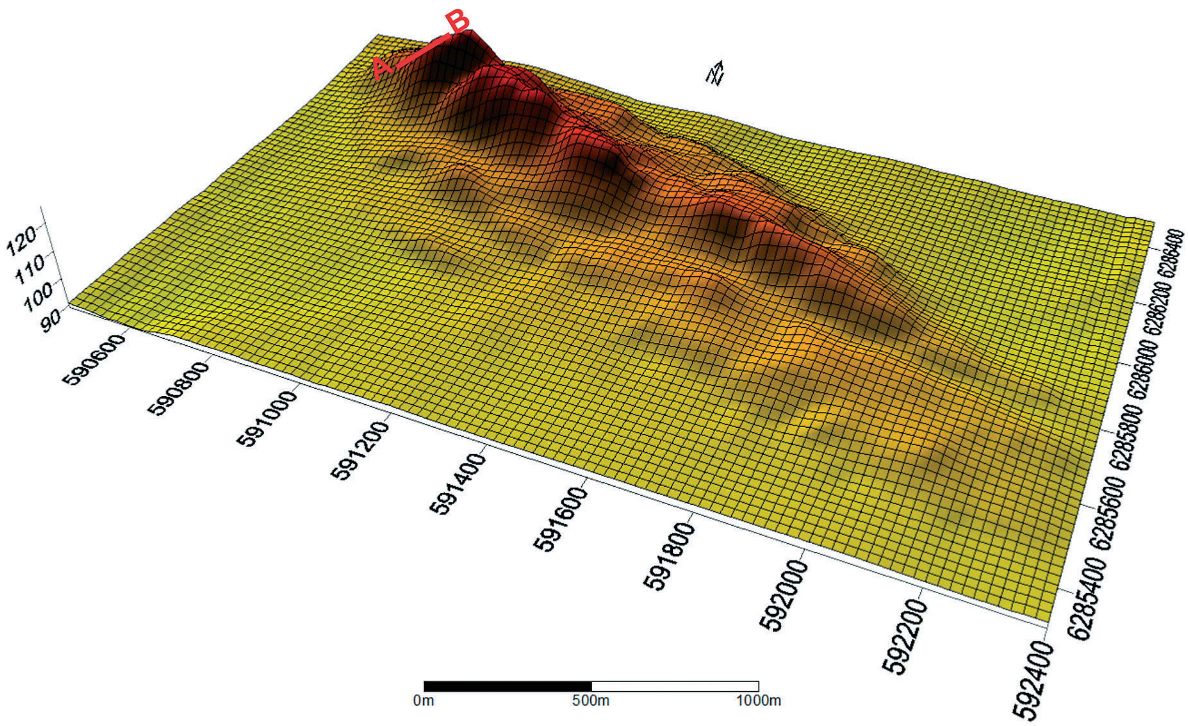

Fig. 4. Morphology of Brenceni drumlin. See location in Fig. 2. Ice movement from NW to SE. Location of a section A–B is shown by red line. Coordinates in LKS92/Latvia TM.

thrust direction is from SW. The overthrusted scale contains highly attenuated, folded and boudinaged sand laminae in the lower part (Fig. 6A). The sand above and below overthrust also is glaciotectonically deformed. The right part of the exposure is composed of deformed sandy material that forms tight slightly overturned fold. Such deformation structure is also seen in smaller exposures closer to the crest of the drumlin.

Another type of sediment deformation is found under the same drumlin in the other exposure on the SW flank of the drumlin (Fig. 6B). About five metres thick fine sand underlies thin till layer that contains a small-sized, compact silt raft. The structure of silt block is intact and lithological boundary with till is sharp. There is no significant sediment homogenization.

The overall internal composition of the Brenceni drumlin is characterized as follows. The highest is the proximal part (32 m). It is mainly composed of the stratified up to 27 m thick (as shown by boreholes made by geological survey of the sand pit) fine sand sediments with interlayers of till. The data from ground penetrating radar profiles, done by

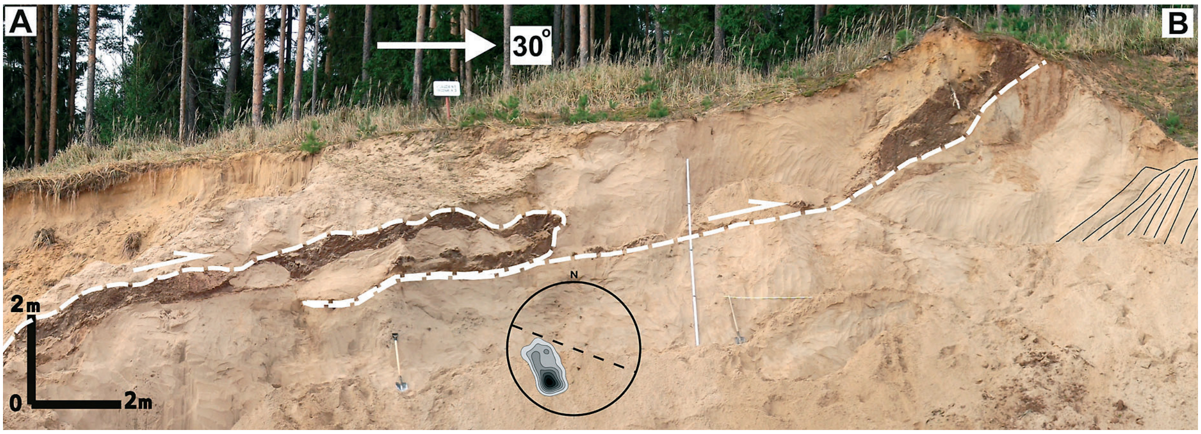

Fig. 5. Exposure in the proximal slope of the Brenceni drumlin (see location in Fig. 4 (A – B)) showing overthrusted scale of till between sand and resulting stereo plot of measurements alongside overthrust displacement surface (V1=232°, S1=0,90, n=23, lower hemisphere projection, 2 contour interval). The orientation of the longitudinal axis of the Brenceni drumlin is shown in the stereo plot by black dotted line. Shear zone is shown by white dotted line and deformation structures in sand by black line.

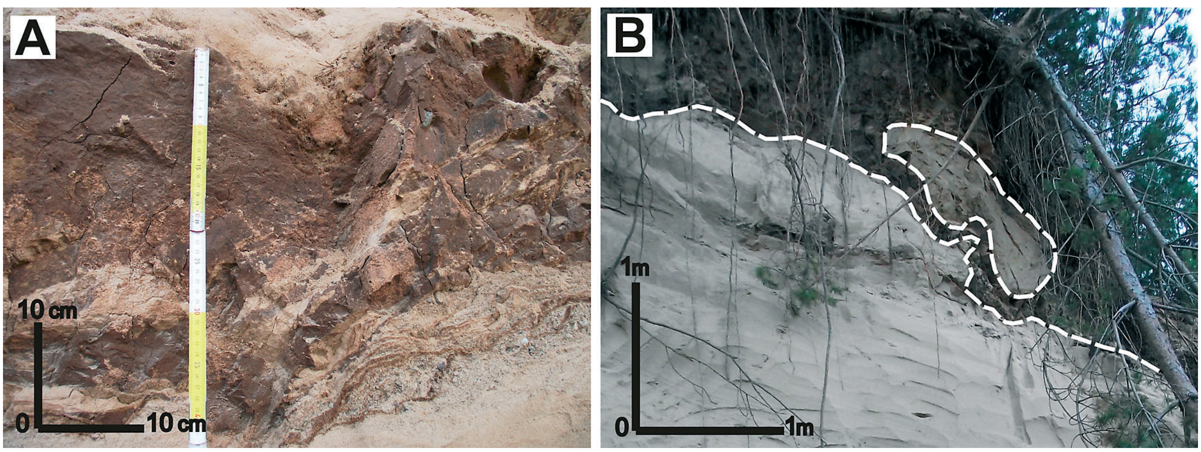

Fig. 6. A close view of the subglacial shear deformation structures in the till overthrust on the SW flank of the Brenceni drumlin (A; for location, see Fig. 5). Silt raft inclusion at the base of till indicating low homogenization of till and low deformation rates, another exposure in the SW flank of the Brenceni drumlin (B).

author, also reveal the stratified sediments with interlayer of till in the proximal part of drumlin as mentioned above. The very central part of the drumlin consists of basal till, at least 5 m thick, as it is proved by coring. The upper meter of till is more compacted than lower that is more sandy. The upper distal part of drumlin is composed of stratified sediments with a thin capping of till, as discovered by ground penetrating radar and coring. At least in the proximal part, the SW flank of drumlin consists of thrusts of sand and deformation till.

5. Discussion and interpretation

Drumlins are widely distributed and form several drumlin fields in the glacial lowlands of Latvia. Their formation has been considered as a result of multiphase glaciotectonic deformation (Zelcs, 1993a; Zelcs & Dreimanis, 1997). The current investigation and previous studies (Zelcs, 1993a, b) of the internal structure of these landforms carried out in the territory of the Madliena drumlin field reveal that they are also complex glaciotectonic formations that are originated as a result of the reactivation of the Zemgale ice lobe during the Middle Lithuanian phase.

The obtained morphometric statistics of drumlins (Table 1) compared to the statistics of drumlins worldwide (summarized by Clark et al., 2009), show close similarity. So it coincides with the concept that, in general, morphometry of drumlins is mostly independent of their location and the characteristics of the ice streams. There have not been observed interconnection between drumlin morphometry and topography and lithology of the bedrock surface.

The mentioned exposure situated along the proximal slope of the Brenceni drumlin (Fig. 5) shows clear evidence of subglacial shear deformation. The deformation strain increases upward in the overthrusted till scale. The upper zone is made of homogenized till, but the lower part is glacial diamicton, where folded and boudinaged sand and gravel laminae are incorporated in till (Fig. 6A). It reflects a shear zone in a deformable glacier bed. In the lower part, the diamicton has the highest heterogenity. It conforms to medium strain rates, as defined by Boulton (1996). According to interpretation of sediment deformation beneath glaciers by Boulton et al. (2001), the individual fold structures and boudins found in the shear zone of the Brenceni drumlin can be considered as evidence of separate successive phases of deformation, i.e. folding and attenuation events. The thickness of the shear zone is less than 10 cm. It is supposed that after formation of the overthrust, occurred coupling of the ice with its bed and, overthrust was folded into isoclinal recumbent fold. Measurements of planar contacts in the shear plane between till and sand (Fig.5) indicate on the ice stress that was directed from inter-drumlin depression during formation of drumlin flank. It is assumed that almost vertically bedded sandy sediments (see the right corner in Fig. 5) represent a core of the Brenceni drumlin and it is formed by upward squeezing of this material out of glacier bed. The core of the drumlin could be interpreted as diapiric fold.

Formation of mentioned silt raft (Fig. 6B) in the section of results agrees with the explanation of Piotrowski & Kraus (1997), who interpreted such clusters as parts of the substratum that has been included into the glacier base, transported some distance and then redeposited together with the till matrix. Because the intact structure of the silt block, sharp till/sand lithological boundary and no significant sediment homogenization, it is quite certain that till have been subjected only to very low deformation rates after incorporation of the silt cluster.

The similarity to the Brenceni drumlin internal structure and composition is also reported from two drumlins in MTP by Aboltinš & Zelcs (1988), Zelcs (1993a, 1993b, 1998). The core of these drumlins represents the elongated injective fold built up of the sandy material that is overlain by basal, supposedly deformed lodgement till. Shear planes in the till are perpendicular to the direction of the long axis of the drumlin. It is assumed that the mentioned structures formed by glacial stress perpendicular to the crest of drumlin, like it is revealed in the Brenceni drumlin.

The formation of drumlins was affected by lateral ice compression along the western slope of Vidzeme Upland. The different properties of bedrock and Quaternary strata (properties are not directly proved) may have caused level variations of the pore water what resulted in spotty bed deformation and basal decoupling. The field observations of sand pits prove that the Late Weichselian Zemgale ice lobe flow emerged from a combination and fluctuation in time of subglacial bed deformation and basal sliding by mechanism mentioned by Rattas & Piotrowski (2003).

There have been identified also an area of ribbed moraines. This type of moraine is classified as Zemgale or Daugmale ribbed moraine (Zelcs, 1993a; Zelcs & Dreimanis, 1998). Although the main area of the Daugmale ribbed moraine locates in between the rivers of Daugava and Memele. Such type ribbed moraines are also found in the area between the rivers of Gauja and Daugava close to the proximal side of the belt of recessional moraine and Linkuva push moraine. At first mentioned landforms were attributed to marginal formations by Aboltinš (1970). Afterwards Straume (1979) interpreted these formations as ribbed moraines of the Labrador type, according to terminology suggested by Lavrushin (1976). The morphology of the ribbed moraines, which is characterized by two sets of ridges approximately perpendicular to each other, resulted from the transformation of Pre-Zemgale drumlin field (Zelcs, 1993a). The internal structure of the radial ridges consists of the laterally compressed folded thrusts (former structure of drumlins) but the transverse ridges consist of scale-like thrusts or megablocks. The internal composition is described as till units with interlayers of the glacio-aquatic deposits and rafts of the Devonian bedrock (Zelcs & Dreimanis, 1998).

As it is mentioned by Stokes et al. (2007) such ribbed moraine were formed during or immediately after the ice stream shut-down. The ribbed moraine is associated with development of basal freeze-on sticky spots (ibid). The location of the ribbed moraine suggests its formation during ice margin retreat from the Linkuva push moraine. As mentioned by many authors, the formation of the ribbed moraine is related to the boundary of cold and warm ice (e.g. Kleman & Hättestrand, 1999; Sarala, 2007). Instead of being related to the core area of glaciation, cold and warm ice boundary that coincided with a passive and active ice boundary, during formation of ribbed moraines in Latvia, existed close to the ice margin (Zelcs, 1993a; Zelcs & Dreimanis, 1998).

Landforms situated in the western part of the MTP were separated from drumlins by Aboltinš (1970), who attributed them to the Linkuva marginal formations and related landforms westerly from them as end moraines of the Plieni glacial phase. Landforms which were attributed to the Plieni glacial phase (ibid.) in the rest of the Central Latvian glacial lowland were re-interpreted as ribbed moraines by Zelcs & Dreimanis (1998). Later the Plieni glacial phase was no more recognized in the deglaciation history of Latvia (Zelcs & Markots, 2004; Zelcs et al., 2011). It is suggested by author that end moraines that are situated westerly from the Linkuva marginal formations due to their lower topography, spatial arrangement and orientation of the longitudinal axes can be termed as recessional moraines, which formed during the subsequent ice retreat from the Linkuva ice-marginal zone. Recessional moraines are few hundreds to 5 km long and by tens up to one thousand metres wide. A few hundreds of metres wide landforms are predominant. They are orientated on average from N to S. The distance between individual crests of recessional moraines is a few hundreds of metres. It is supposed to be equal to the retreat rate of the ice margin in a year. It also coincides with a rate of the deglaciation of the Onega area from the Luga moraine (between 14 250 and 12 750 cal. BP), which was 200 m per annum on average (Saarnisto & Saarinen, 2001). Above mentioned also supports the interpretation of recessional moraines, which formed by seasonal re-advance of the ice margin as suggested also by Bennett (2001) who defined such moraines as recessional push moraines.

Ice flow direction in the study area is reconstructed from active ice formations (mostly drumlins) and glacial striations found on dolomite surface. The orientation of drumlins changes from NNW-SSE in the N part of drumlin field to NW-SE in the central part. In the SW part, it is again NNW-SSE and in the SE part turns to WNW-ESE. A mean orientation is found to be from WNW (301.5°) to ESE (121.5°). It seems that three domains of differently orientated drumlins can be divided (the N, SW and SE parts of the drumlin field). It is suggested that the direction of the ice flow slightly changed due to uplift in the subglacial topography that truncated ice flow and facilitated its convergence in some areas. Also the distribution of possible shear margin moraines and recessional formations in the E part of the MTP could be attributed to the stagnation of the ice in the N part of the MTP; simultaneously active ice continued to flow in the central and southern parts of the MTP, thereby shear margin moraines formed between passive and active ice as it is defined by Stokes & Clark (2002).

The resulting azimuth (143°) of measured glacial striations in the Turkalne dolomite quarry (Fig.7), which is located close to one of the eskers in the Ropazi Plain, indicates on ice flow direction from NW to SE. This direction coincides with a general orientation of eskers. Similar measures from glacial striations have been published by Zans (1935) who reported on NW-SE striations near the town of Ogre. The WNW-ESE striations were found 10 km SE from Ogre. Small differences in orientation of glacial striations indicate on local variability of glacier stress.

The network of the past subglacial glaciofluvial systems can be identified now from esker systems what are found in the MTP and are widespread in the MTP adjoining area of the Ropazi Plain. Three esker systems stretch from approximately NW towards the proximal parts of the Linkuva end moraines and show ice meltwater activity shortly after stable position of Zemgale ice lobe during the Linkuva oscillation. Esker ridges are characterized by internal broadenings or deltas which can be associated with position of the retreating ice margin and fast deposition close to the ice margin from meltwater streams. According to borehole data subglacial channels cut in the dolomite bedrock are found in some places below esker ridges. That suggests about change in subglacial conditions from the process of erosion to the process of deposition. Such transition was described also by Johansson (2003) in Finland.

6. Conclusions

Comparison of obtained morphometric statistics of the drumlins under consideration to the morphometry of drumlins worldwide show close similarity,

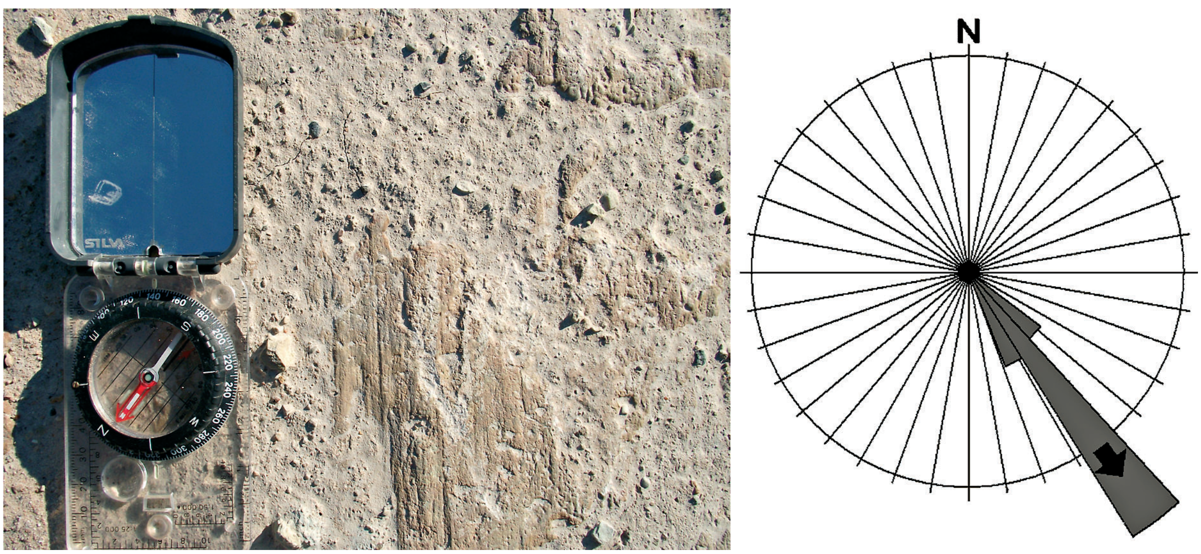

Fig. 7. Glacial striations on dolomite surface in Turkalne quarry and orientation of striations by StereoNet plot (number of measured striations is 55 and the mean azimuth is 143°, lower hemisphere projection).

supporting the concept that in general, the morphometry of drumlins is mostly independent of their location and the characteristics of the ice streams. Also no lithological or topographical control was found on the morphometry of mapped drumlins.

The Brenceni drumlin is a good illustration of multiphase formation of the drumlins. Supposedly glaciotectonic deformational structures that built up the drumlins of the MTP were created due to convergent ice flow pattern and lateral ice compression. The glacial structures observed in the Brenceni drumlin shows clear evidence of folding, thrusting and subglacial shear that indicates on subglacial stress direction from the inter-drumlin depression. Folded overthrust scale, inclusion of silt raft in a till layer, and in different ways glaciotectonically dislocated glacio-aquatic sediments show evidence of distinct deformation regimes that changed most likely due to pore-water level.

The distribution of glaciogenic landforms in the MTP can be used to establish the deglaciation pattern. Areal deglaciation was common during ice retreat from the Middle Lithuanian glacial phase. It was replaced by frontal deglaciation during ice retreat from the North Lithuanian phase. Areal deglaciation was featured also by lateral ice stagnation that at first occurred more closely to the lateral ice margin, while other parts of ice masses remained active, as it is inferred from difference in the orientation of drumlins and existence of lateral shear margin moraine.

Ice flow direction during the Middle Lithuanian glacial phase changed from the NNW-SSE in the N part of the MTP to the WNW-ESE in the SE part mostly due to influence of the subglacial topography; it remained approximately the same also during final ice retreat from the Linkuva ice-marginal zone, as it is reconstructed from the orientation of the glacial striations, ribbed moraines and eskers.

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