Geological Quarterly, 2024, 68, 31
DOI: http://dx.doi.org/10.7306/gq.1759

Glaciomorphological features of the North and Middle Lithuania lowlands

Violeta PUKELYTĖ[1], Valentinas BALTRŪNAS[1,*] and Bronislavas KARMAZA[1]

[1] Nature Research Centre, Laboratory of Quaternary Research, Akademijos Str. 2, LT-08412 Vilnius, Lithuania; ORCID: 0000-0002-4913-5657 [V.P.], 0000-0002-9504-1416 [V.B.], 0000-0001-8423-8005 [B.K.]

Pukelytė, V., Baltrūnas, V., Karmaza, B., 2024. Glaciomorphological features of the North and Middle Lithuania lowlands. Geological Quarterly, 2024, 68, 31; http://doi.org/10.7306/gq.1759

Associate Editor: Wojciech Granoszewski

Glaciomorphological features of the North and Middle Lithuania lowlands are described and interpreted. The ridged relief of the morainic plain in the NW part (Akmenė district, North Lithuania) is characterized by mega-scale glacial lineation (MSGL) forms, testifying to the active movement of the glacier; they do not correlate with the sub-Quaternary palaeosurface. The relief structure of the Nevėžis Moraine Plain located farther south includes areas of obscure MSGL that were affected by glaciolacustrine accumulation and abrasion, glaciofluvial accumulation and erosion, as well as intensive land drainage (amelioration) in the 20th century. Typical MSGL forms in the Mūša-Nemunėlis Moraine Plain and relicts of MSGL forms in the Nevėžis Moraine Plain, as well as patterns of orientation and inclination of macroclast long axes due to mixing of the moraine material (till), reflect the dynamics of the sliding glacier. These features show that the moraine plains of Middle and North Lithuania were formed by an actively moving glacier, which left an identifiable till layer when geological and hydrological conditions allowed.

Key words: Last Glaciation, moraine plain, MSGL, till, Lithuania.

INTRODUCTION

Expressive forms of glacial relief in Lithuania have had their original morphological form and structure changed by later glaciofluvial erosion, glaciolacustrine abrasion, glaciokarst, solifluction and other processes, as well as by human agricultural activities. Therefore, identification of the primary genesis of these landforms is often difficult. The situation is similar on other moraine plains formed by the ice streams and lobes of the Last Scandinavian Ice Sheet and Laurentide Ice Sheet (in Germany, Poland, Belarus, Latvia, Canada, and elsewhere; e.g., Karabanov and Matveyev, 2011; Zelčs and Nartišs, 2014; Lamsters and Zelčs, 2015; Spagnolo et al., 2016; Lang et al., 2018; Roman, 2019; Lamsters et al., 2021; Szuman et al., 2021 a, b, c, 2023).

A comprehensive monograph published 53 years ago (Gudelis and Gaigalas, 1971) is perhaps the only one devoted to detailed analysis of the structure and morphogenesis of these moraine plains. Over the past five decades, study has continued, expanding the research database (Gaigalas, 1979; Kudaba, 1983; Mikalauskas, 1985 and others). Initially, the parallel low and long moraine ridges recorded to the south of the Linkuva Ridge were called drumlins (Doss, 1910; Hausen, 1913). Later, these relief forms were associated with the marginal annual accumulation of the degrading glacier lobe or with erosion by glaciofluvial streams (e.g., Basalykas, 1965; Baublys et al., 1970; Kudaba, 1971; Mikalauskas and Mikutienė, 1971). Data from boreholes, though, show that this relief formed in a subglacial environment (Gaigalas and Marcinkevičius, 1982). Similar results were obtained in subsequent studies that interpreted these relief forms as mega-scale glacial lineation (MSGL) (Baltrūnas et al., 2014, 2020). Although some data suggested a fast-moving glacier of the Middle Lithuanian Phase (Basalykas, 1965; Kudaba, 1971; Gaigalas, 1971, 1979; Vaitonis, 2000; Guobytė, 2001, 2002), there were also indications of the passive nature of the Last Glaciation. Čepulytė (1962), and Bitinas (2011, 2012) proposed that areal degradation of the glacier prevailed in Lithuania during the deglaciation. Studies of MSGL and similar glacial landforms in Lithuania and other countries are discussed in Lamsters and Zelčs (2015), Baltrūnas et al. (2020), Lamsters et al. (2021), and other publications.

Continuing the research noted above, we have recently studied a similar, only geomorphologically less pronounced, ridge relief in the NW part of the Mūša-Nemunėlis Moraine Plain (Akmenė district), and the geology and geomorphology of the Nevėžis Moraine Plain, to evaluate the glaciomorphological features of the North and Middle Lithuania lowlands. The following tasks were involved: (1) determination of the genesis and

* Corresponding author, e-mail: valentinas@baltrunas.lt
Received: March 12, 2024; accepted: August 5, 2024; first published online: November 6, 2024

geological structure of the ridged relief in the NW part of the Mūša-Nemunėlis Morainic Plain; (2) evaluation of the terrain distribution characteristics of mega-scale glacial lineation (MSGL) and its palaeodynamic significance in interpreting the activity of the ice sheet during of the Middle Lithuanian Phase of the Baltija Stage of the Last (Late Nemunas, Late Weichselian) Glaciation. The Mūša-Nemunėlis and Nevėžis Moraine plains in the North and Middle Lithuania lowlands stand out clearly on the geomorphological map (The National Atlas..., 2014) and schematized depiction of this part of Lithuania (Fig. 1).

REGIONAL SETTING

The Middle and North Lithuanian morainic plains are built of glacial till, which probably formed during the Middle and North Lithuanian phases of the Baltija Stage. The North and Middle Lithuania lowlands are a continuation of the Central Latvia Lowland, which to the south pass into the SW Lithuanian glacio-lacustrine lowlands (Fig. 2). To the east these plains are bounded by the Baltic Highlands, and to the west by the Žemaičiai Upland. The area of the North and Middle Lithuania lowlands is characterized by formerly pronounced glacial erosion, a low thickness of Quaternary deposits, and the absence of older Pleistocene till. In this area, the central part of the sub-Quaternary surface consists of Upper Devonian rocks (dolomite, sandstone, marl, gypsum) (The National Atlas..., 2014), and in the NW part, Lower Carboniferous (sandstone), Upper Permian (limestone), and Lower Triassic (clay) are found, more rarely Middle Jurassic sands and silts. In the southern part, Lower Triassic (clay) and Upper Jurassic (sand, silt) deposits are found. In the northern and central part of the area, the thickness of the Pleistocene strata ranges from 2–3 to 20 m, and at the edges of the area it increases to 50 m, rarely up to 100 m. The glacial tills predominantly date from the Last Glaciation, more rarely the Medininkai till of the Middle Pleistocene. The Last Glaciation succession consists of Grūda Stage and Baltija Stage tills of variable thickness and Baltija Stage tills (Baltrūnas et al., 2005).

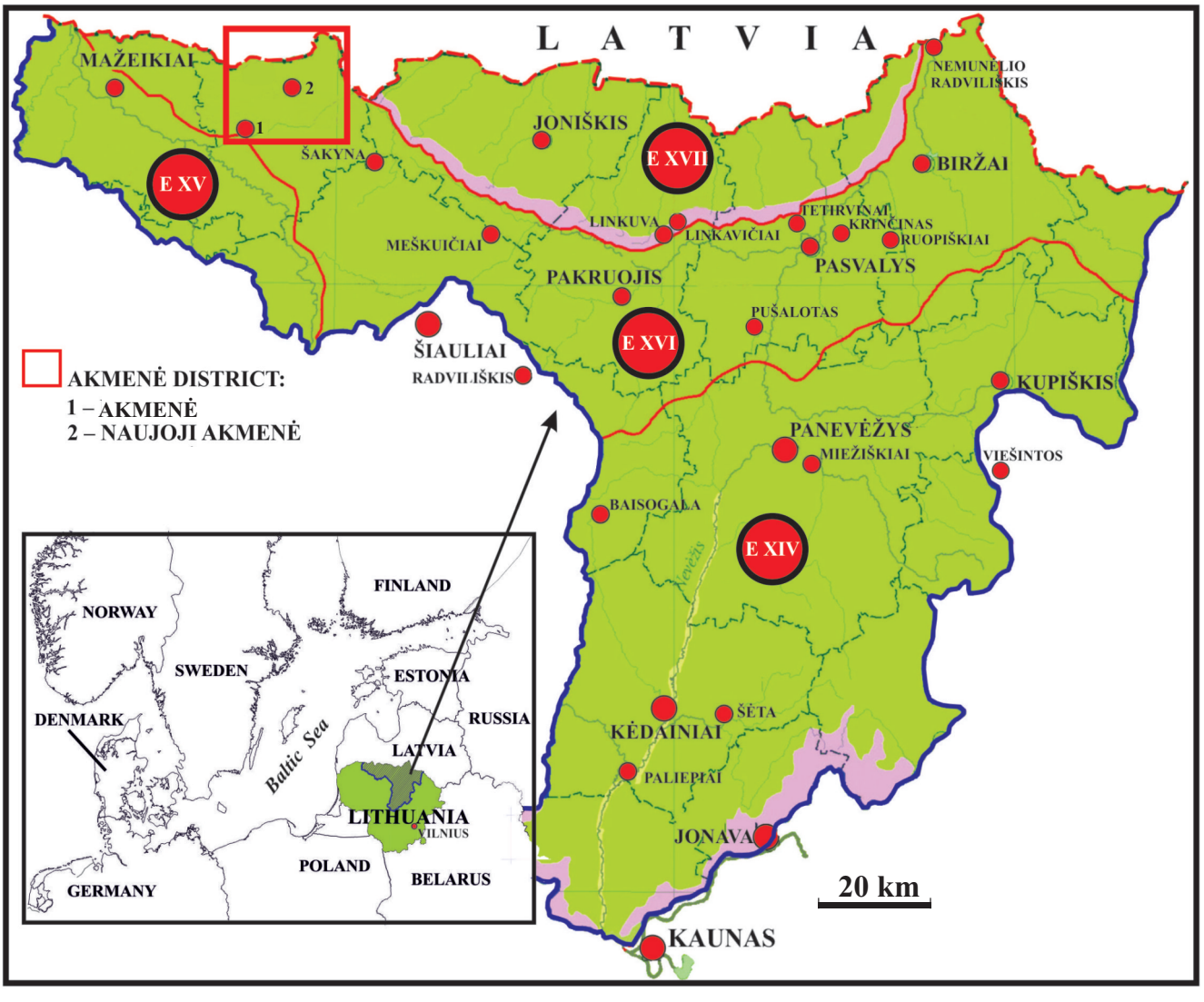

Fig. 1. Location of the area investigated and schematic geomorphological map of the North and Middle Lithuanian lowlands (based on The National Atlas, 2014)

E XIV – Nevėžis Moraine Plain, E XV – Venta Midstream Moraine Plain, E XVI – Mūša-Nemunėlis Moraine Plain, E XVII – Žiemgala (Zemgala) Moraine Plain; red rectangle – geomorphological map of the ridged moraine plain in the Akmenė district (Fig. 3)

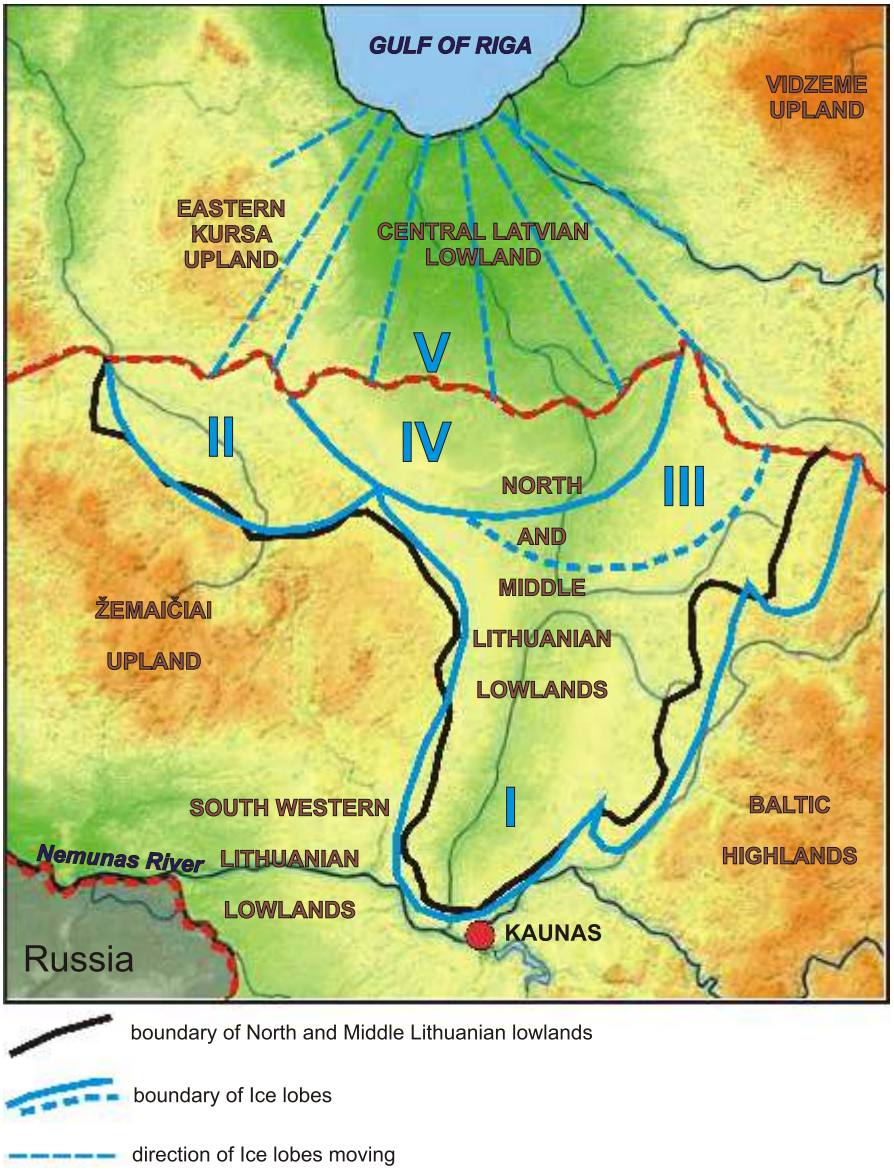

Fig. 2. Former ice lobes of the North and Middle Lithuanian lowlands: I – Nevėžis Ice Lobe, II – Venta Midstream Ice Lobe, III – Mūša-Lėvuo Ice Lobe (by Basalykas, 1965), IV – Žiemgala (Zemgala) Ice Lobe, V – Zemgala Ice Lobe moving in different directions (by Zelčs and Markots, 2004)

METHODS

The genesis of the Last Glaciation deposits was investigated by taking samples from till exposures for analyses of grain-size and petrographical composition. Pebble petrographic compositions were analysed according to the Gaigalas methodology (Gaigalas, 1979; Gaigalas and Melešytė, 2001) and using the following categories: crystalline rocks, sandstone, Devonian dolomite, and dolomitized rock, Ordovician and Silurian Limestone, Devonian and Permian Limestone, and a group of other rocks. The calculated mean vector is usually close to the regional characteristics of the petrographic composition of the layer studied. Clast fabric measurements were also made in glacial till exposures. The orientation and dip of long axes of 50 macroclasts with elongation ratios of ≥3:2 were measured using a geological compass and applying methods outlined by Gaigalas (Gaigalas, 1979; Gaigalas and Melešytė, 2001). The stereograms were compiled manually, and show every measuring point. The azimuth and dip of the long axes of macroclasts were estimated statistically (Jolliffe, 2002). Eigenvalues are fundamental in assessing the variance in data. The significant difference between the two eigenvalues (4 591.65 and 22 162.85) indicates that there is a major axis of variation. Given that isotropy is a measure of uniformity in all directions, a value of 0.207 shows significant anisotropy, which is useful for applications requiring an understanding of directional variance. This is suitable for identifying the degree of stretching in the data. High elongation is needed for applications where understanding the shape and directional tendencies of data is crucial. Data from geological mapping, and hydrogeological and mineral exploration boreholes from the geological archive of the

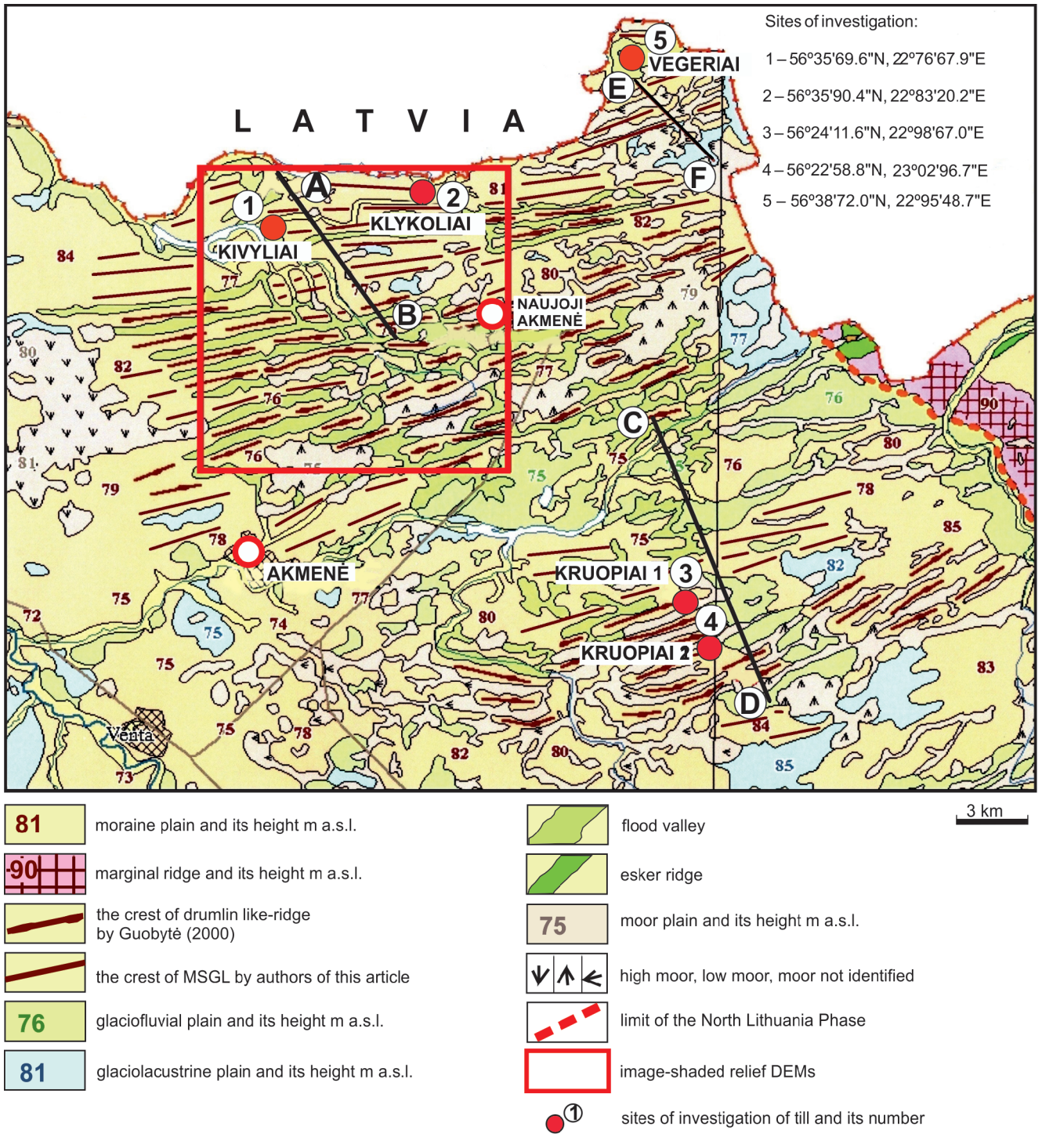

Fig. 3. Geomorphological map of the ridged moraine plain in the Akmenė district [Kivyliai, Klykoliai, Kruopiai, and Vegeriai places; by Guobytė (2000), Lithuanian Geological Survey under Ministry of the Environment]

Geological-geomorphological cross-sections (see Fig. 5): A–B – Kivyliai, C–D – Kruopiai, E–F – Vegeriai; rectangle – image shaded-relief DEMs between Kivyliai and Akmenė (see Fig. 4)

Lithuanian Geological Survey under the Ministry of Environment were used to study the structure and composition of the morainic plains. Morphometric parameters of MSGLs in Lithuania were 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 places sites (Kivyliai, Baisogala, and others) in northern and middle Lithuania. The copyright of the DEM belongs to the Lithuanian Geological Survey of the Ministry under Environment. The composition of MSGLs and the thickness and sedimentological characteristics of depositional units were determined. Macroclast fabrics were also taken from excavated pits and exposures in glacial till.

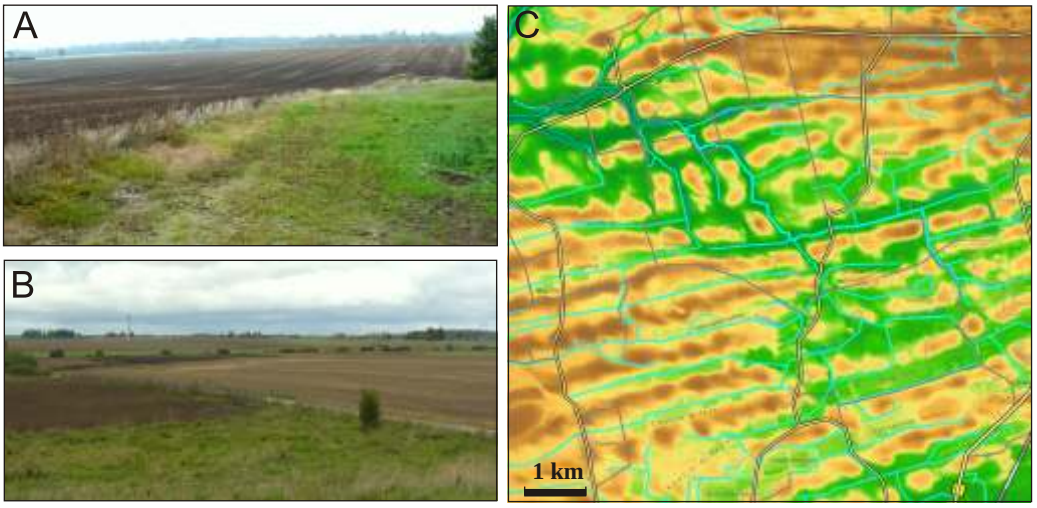

Fig. 4. MSGLs in the Akmenė district: A – weakly ridged relief near the Kivyliai site, B – weakly ridged relief near the Kruopiai site, C – image shaded-relief DEMs between Kivyliai and Akmenė (see Fig. 3)

The copyright of the DEMs belongs to the Lithuanian Geological Survey under Ministry of the Environment

RESULTS

GEOMORPHOLOGICAL FEATURES OF THE MŪŠA-NEMUNĖLIS MORAINE PLAIN IN ITS NE PART (AKMENĖ DISTRICT)

Such features include the orientation and dip of the long axes of macroclasts, as well as the formation of specific relief forms – MSGLs. The results of a study of these relief forms in the NE part of Mūša-Nemunėlis Morainic Plain have been published (Baltrūnas et al., 2020). The results are now presented in the NW part of Mūša-Nemunėlis Moraine Plain (Akmenė district; Fig. 3).

The research was conducted in two MSGLs that extend from the ENE to the WSW, are situated between the villages of Kivyliai and Kruopiai, and are located 8–10 km from Naujoji Akmenė town (Akmenė district). The MSGLs are lengths up to 16–18 km long and 0.3–0.6 km wide, with the height varying from 3 to 8 m, predominant height of 4–5 m (Figs. 4 and 5). The ridge is affected by erosion with small descents along its crest. The absolute height of the crest is relatively flat: in the ENE part – rise to 83–90 m a.s.l., and in the WSW part – rise to 76–86 m a.s.l.

GEOLOGICAL STRUCTURE OF MSGL FORMS AND RELATIONSHIP WITH THE SUB-QUATERNARY PALAEOSURFACE

Data on the structure and composition of the MSGLs and sub-Quaternary palaeosurface in this area come from abundant mineral exploration and hydrogeological boreholes. Their descriptions allow geological cross-sections (AB and CD) to be drawn across the MSGL terrain at the NW and the SE fringes of the former ice lobe (Fig. 5). These geological sections show that beneath the central part of the glacial depression, the relief is less fragmented and so less affected by erosive and abrasive processes. The palaeoincisions of the sub-Quaternary surface are commonly filled with sand and gravel deposits, which are overlain by several layers of till up to the present surface. The resulting geological sections do not show a direct relationship between the location of the sub-Quaternary palaeosurface and the moraine ridges (MSGLs).

Useful information (sections of boreholes, topography) was found in the reports of the exploration of the Vegeriai limestone deposit prepared by Stonkus and Laurinaitytė (1963) and Stankevičius (1994). The relationship of the MSGL location to the sub-Quaternary surface is partly illustrated by the SE–NW geological cross-section passing through the limestone deposit for mining, almost perpendicularly crossing the MSGL shapes on the sub-Quaternary surface. This section crosses the glacial erosion palaeosurface of the Upper Permian Limestone and the Upper Jurassic sand. It shows no correlation between the MSGL forms and the sub-Quaternary palaeosurface and its constituent rocks. To the north of this geological cross-section, a parallel narrow (100–150 m wide) and relatively deep (up to 19–21 m) till-filled palaeoincision crosses Permian Limestone. Similar palaeoincisions up to 20–30 m deep in the surface of Permian rocks have long been recorded from this place (Kadūnas, 1976).

PETROGRAPHICAL COMPOSITION AND LONG AXES ORIENTATION AND DIP OF THE MACROCLASTS

The till forming the MSGL is usually light brown and yellowish brown, with gravel, pebbles, cobbles and boulders, locally from a depth of 3–5 m being a darker grey-brown and grey, and is most likely of the first (Grūda) Stage of the Last Glaciation. According to Stankevičius (1994), at the Vegeriai site the Permian Limestone is covered by till characterized by a typical mixture of macro- and microclasts. The total content of silt particles (0.01–0.001 mm) ranges from 18 to 35%, and of clay particles from 5–15%.

Petrographic and long-axis orientation investigations of the MSGL till macroclasts (5–20 mm) of the Akmenė district were performed on opposite sides of the former ice lobe (see Fig. 3) – on the north side near Kivyliai and Klykoliai villages and the south side near Kruopiai village. The Kivyliai site is a 0.8 m deep excavation in a MSGL ridge, where light brown till is exposed. The Klykuoliai observation site is a new reclamation well 0.2–0.7 m in diameter revealing a very steeply dipping dark

brown (lower part) and grey (upper part) till. On the slopes of excavated ponds at the Kruopiai 1 and the Kruopiai 2 sites, tills 0.2–0.7 m and 0.3–0.8 m thick were studied (Figs. 6 and 7). Measurement data at all four study sites show quite different glacio-sedimentation conditions (as regards the magnitude of stress preserved in the deposits). The Kivyliai and Klykoliai sites are situated on the ridge of the same MSGL. The Kivyliai site shows a WSW–ENE direction corresponding to the direction of the MSGL ridge, while in the Klykoliai site the direction of long axes is perpendicular to the process of check in the subglacial environment. At the Kruopiai 1 and Kruopiai 2 – located in parallel adjacent MSGL ridges, the fixed orientation of the macroclasts in the diagrams is perpendicular to the long axes of the MSGL ridges. This may be related to subglacial lateral pressure on both MSGL slopes.

The petrographical composition of the macroclasts is close to that of the Baltija Subformation till in northern Lithuania, especially the increase in Devonian dolomite, and Permian and Devonian limestone, compared to that of the Grūda Subformation (Gaigalas, 1979; Baltrūnas et al., 2005, 2020). The influence of rocks in the shallow sub-Quaternary surface is observed in the composition of the Baltija till, which Baltija till at Kivyliai site contains many other limestones because the sub-Quaternary surface includes Upper Permian rocks. Meanwhile, in the Klykoliai site on the same MSGL, the brownish-grey sandy till is rich in Devonian dolomite, and Ordovician and Silurian limestone, indicating a thick layer of Lower Grūda till. In the nearby Kruopiai site the petrographic compositions of the samples taken on different MSGLs are similar to each other and correspond to the overall petrographic composition of the regional till.

GEOMORPHOLOGICAL AND GEOLOGICAL FEATURES OF THE NEVĖŽIS MORAINE PLAIN

RELIEF FEATURES OF THE SOUTHERN FOOTHILLS OF THE LINKUVA RIDGE

The Linkuva Ridge marks the extent of the ice sheet during the North Lithuania Phase of the Last Glaciation (see Fig. 8). It divides the large Middle Lithuania Lowland into smaller moraine plains: in the southern part the Nevėžis and Mūša-Nemunėlis Moraine Plain, and in the northern part the Žiemgaliai (Zemgale) Moraine Plain. The height of the ridge in the NW part is 97.9–94.4 m a.s.l. Farther east, it gradually descends and

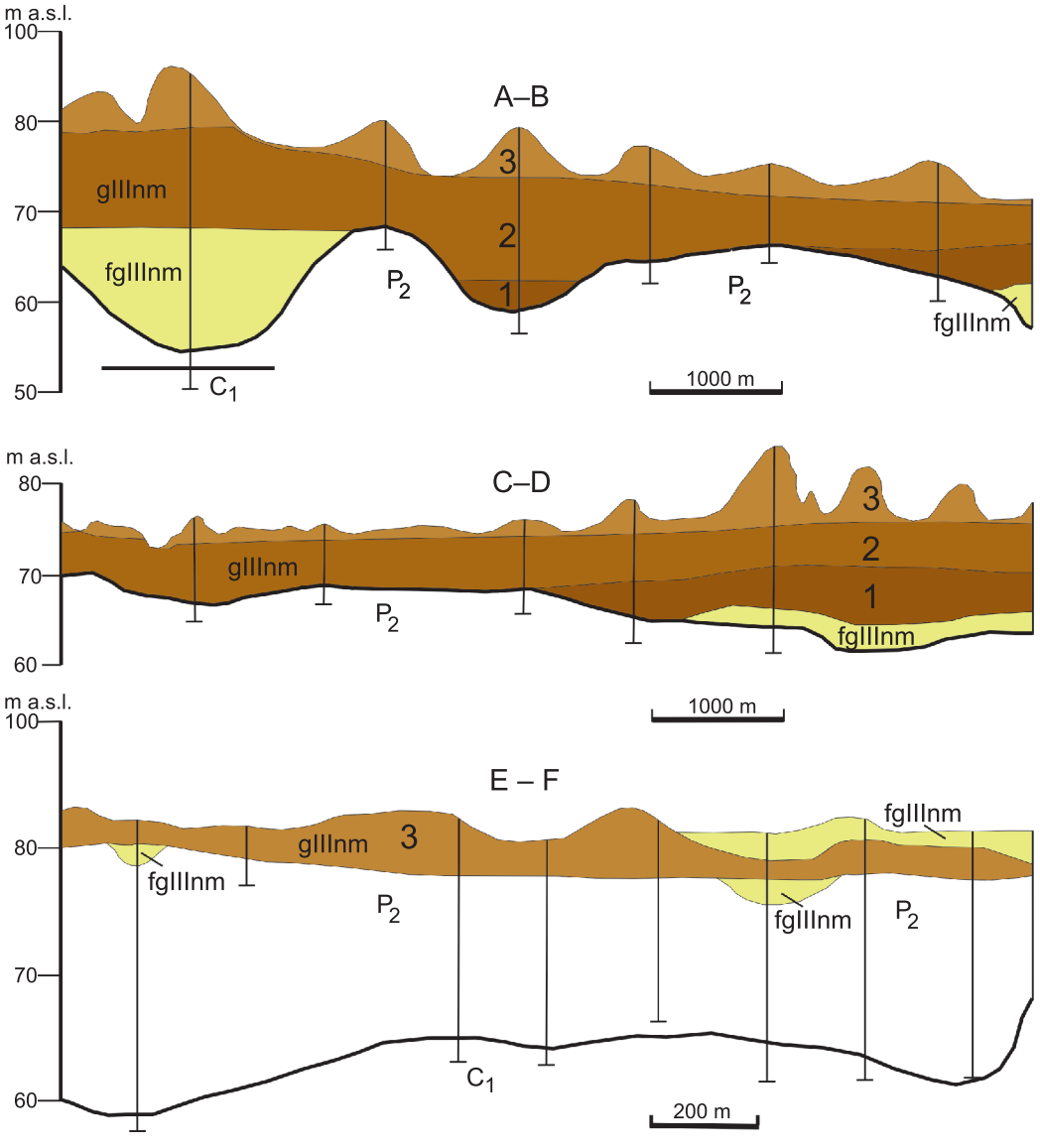

Fig. 5. Geological-geomorphological cross-sections through MSGL distribution in the Akmenė district (see Fig. 3): A–B – Kivyliai, C–D – Kruopiai, E–F – Vegeriai

Geological index: C_1 – Lower Carboniferous (sand and sandstone), P_2 – Upper Permian (limestone), gIIInm – glacial deposits of the Nemunas Subformation (till), fgIIInm – glaciofluvial deposits of the Nemunas Subformation (sand, gravel); thin lines in cross-section hypothetically separate tills of the Last Glaciation: 1 – till of Grūda Stage, 2 – till of Baltija Stage, 3 – till of Middle Lithuanian Phase; vertical line – borehole

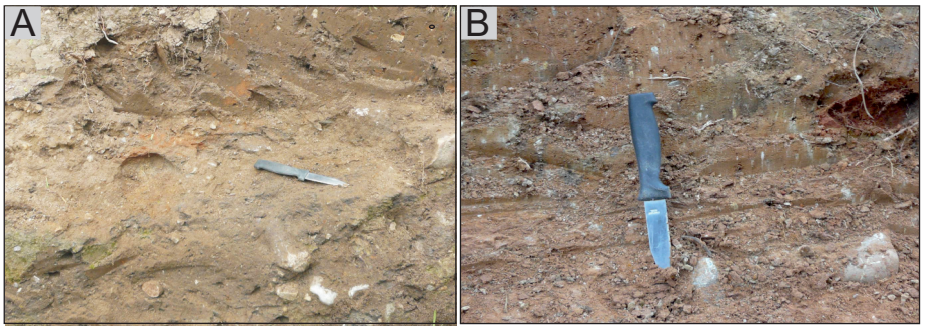

Fig. 6. The visible structure of the MSGL till at the Kivyliai (A) and Kruopiai-2 (B) sites

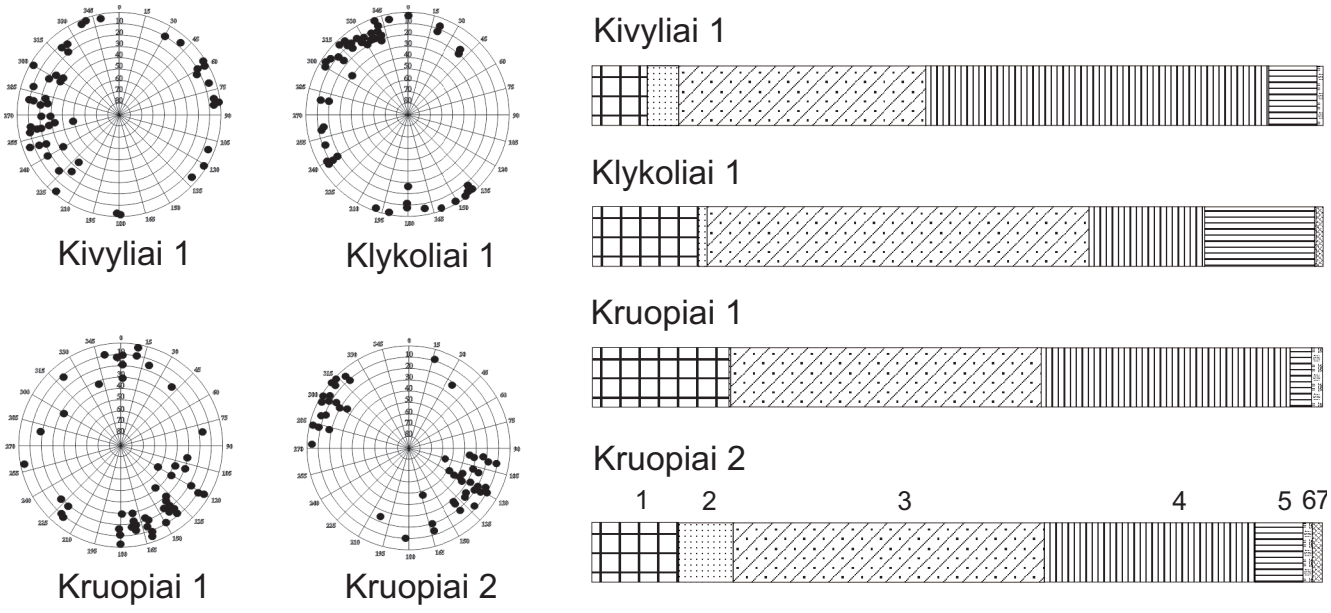

Fig. 7. Fabric of macroclasts (at left) and petrographical composition of macroclasts (at right) of MSGL till of the Kivyliai, Klykoliai, and Kruopiai sites

Petrographic groups: 1 – crystalline rock, 2 – sandstone, 3 – Devonian dolomite and dolomitized rock, 4 – Devonian and Permian limestone, 5 – Ordovician and Silurian limestone, 6 – marl, dolomitic marl, 7 – other rocks

reaches 87.5–84 m a.s.l. in Rudiškiai, 81.7–80.8 m a.s.l. in Linkuva, 77.7–74 m a.s.l. in Linkavičiai, 60.9–55.8 m a.s.l. in Tetirvinai, and 56.8–52 m a.s.l. in Nemunėlio Radviliškis. The southern foot of the ridge also has a downwards trend in the same direction, but is characterized by two major local depressions at Naujoji Akmenė-Kruopiai and Pasvalys-Krinčinas, and a less pronounced one between them, at Šakyna-Rudiškiai (see Fig. 8). These glacier bed depressions apparently testify to advanced of a glacier with three small lobes, the last two of which merged into one large Nevėžis Ice Lobe. The relief profiles reveal the fine ridges of the southern foothills of the Linkuva Ridge, which is related to the MSGLs of the morainic plain described in the previous section (see profiles A–B and C–D in Fig. 4). The North Lithuania (Linkuva) Marginal Ridge subdivides the MSGLs into two parts – north of Pušalotas (Linkuva township) and Ruopiškiai (Likėnai Resort) (Baltrūnas et al., 2020). Lamsters and Zelčs (2015) interpret this feature as an imbricate thrust that formed at the glacier margin.

PREVALENCE OF MSGLs IN THE ZONE OF THE NEVĖŽIS ICE LOBE

Data from studies of well-expressed MSGLs in the Naujoji Akmenė area (the NW part of Mūša-Nemunėlis Plain), previously studied in the Pasvalys-Biržai area (the NE part of the Mūša-Nemunėlis Plain) (Baltrūnas et al., 2020) indicate their formation in the subglacial environment of a relatively fast-moving glacier. Careful analysis of the terrain structure of the morainic plain showed areas of obscure MSGLs that were affected by glaciolacustrine accumulation and abrasion, glaciofluvial accumulation and erosion, as well as intensive land drainage (amelioration) in the 20th century. These include Šakyna township to the south of Naujoji Akmenė town, Meškučiai township to the north-east of Šiauliai town, Baisogala township to the south-west of Panevėžys town, Šėta township to the east of Kėdainiai town, and Miežiškės township to the east of Panevėžys town (Figs. 1 and 8). For example, in the SE-aligned

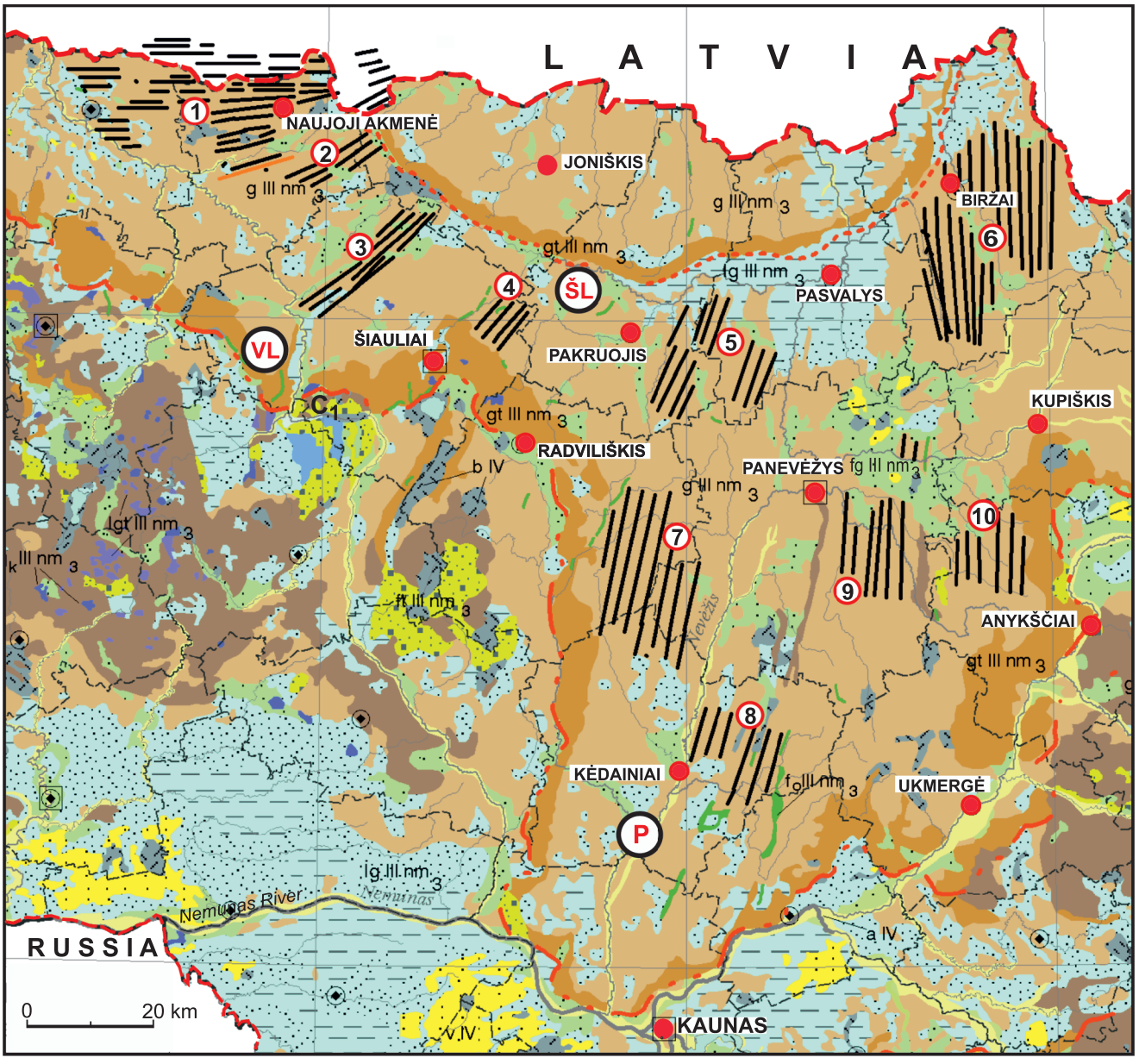

Fig. 8. Places with widespread MSGLs or their relicts in the North and Middle Lithuanian lowlands (black hatching): 1 – Kivyliai-Klykoliai, 2 – Kruopiai, 3 – Šakyna, 4 – Meškučiai, 5 – Pušalotas, 6 – Ruopiškiai, 7 – Baisogala, 8 – Šėta, 9 – Miežiškės, 10 – Troškūnai; ŠL – limit of North Lithuanian Phase – Linkuva Ridge, VL – limit of Middle Lithuanian Phase, P – Paliepiai exposure (see Fig. 10)

Geological map according to Guobytė (2022)

and 23 km long profile of Baisogala place, the relief ridge is more pronounced between the 9 and 20 km (Fig. 9). The height of the moraine plain near Baisogala is 95–96 m a.s.l. and in the east the marginal ridge of Baisogala reaches 110 m a.s.l. The morainic ridged plain descends to the east and reaches 50 m a.s.l. The barely visible length of the ridges, oriented SSW, reaches 15–20 km, the width – 0.3–0.6 km, and the relative height in places reaches 3.1–3.9 m.

If Kėdainiai is situated in the central axial part of the Nevėžis Ice Lobe, then Baisogala is related to the "stuck" part of this lobe between the lateral ridge of Radviliškis on the western side and the lateral ridge of Viešintos on the eastern side. The

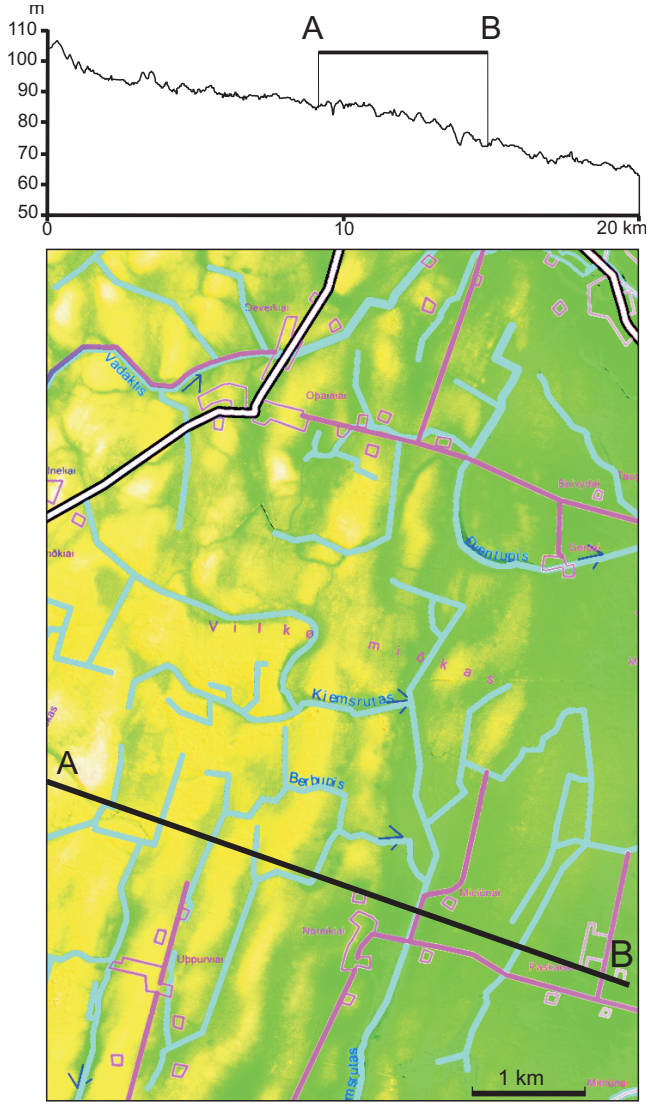

Fig. 9. Hypsometric profile of Baisogala (top) through the MSGL relicts on the Nevėžis Moraine Plain (see Fig. 8) and image of MSGL relicts of south-east Baisogala township (below)

The image is a DEM-shaded relief, the copyright of the DEMs belongs to the Lithuanian Geological Survey under Ministry of the Environment

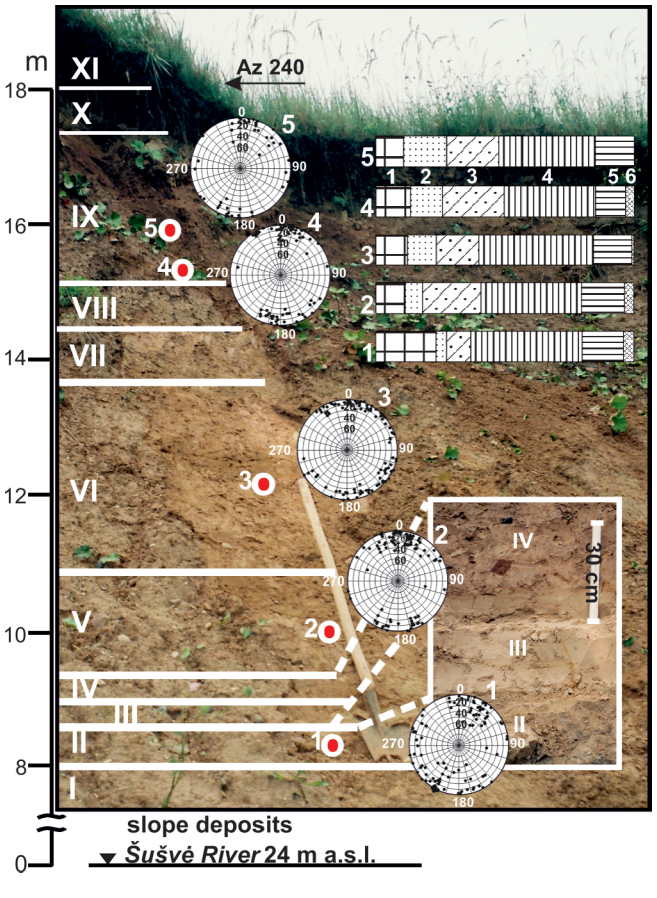

Fig. 10. Glacigenic deposits and orientation and dip of till macroclast long axes in the Paliepiai exposure (for site see Fig. 8): I – slope deposits; II – greyish brown compact till with a high content of pebbles and boulders at the top; III – yellow sand, very fine, in lower part silty; IV – yellowish brown till; V, VI – reddish brown till, grading into yellowish brown sandy loam, with thin interlayers of sandy loam and sand; VII – reddish brown till, grading into clay with a disordered structure at the base; VIII – varved clay; IX – reddish brown till, in middle part brown friable till with vertical fissures and sparse gravel, in lower part reddish brown till, unevenly clayey in places grading into clay; X – various sand; XI – soil; petrographic composition of till macroclasts (1–5 samples): 1 – crystalline rock, 2 – sandstone, 3 – Devonian dolomite and dolomitized rock, 4 – Devonian and Permian limestone, 5 – Ordovician and Silurian limestone, 6 – other rocks

Radviliškis Ridge correlates with the shallowly buried sub-Quaternary surface elevation southern spur (70–80 m a.s.l.), and the Viešintos Ridge, with a similar elevation also of its southern spur (70–80 m a.s.l.) (Šliaupa, 2004; see Fig. 11).

The latter situation is well-captured by the Paliepiai exposure to the SW of Kėdainiai town. It is located on the left bank of the Šušvė River (the right tributary of the Nevėžis River). Petrographic analysis of the macroclast material showed that the lower grey-brown till of the Grūda Stage (Subformation) differs significantly from the higher-lying layered Baltija till in smaller quantities of Devonian dolomite and sandstone and a higher content of crystalline (magmatic and metamorphic) rocks and Mesozoic marl and phosphorite (≤0.8%; Fig. 10).

In this exposure, the till succession of the Baltija Stage (Subformation) reaches a thickness of 7 m. The fabric of the lower part of the till (~1.5 m thick) was formed by an actively moving glacier from the north. The middle part (~3 m), characterized by a wider spread of orientation of clasts and their rough inclination in opposite directions, most likely formed without dynamic effects. A 0.4 m thick layer of chocolate-coloured clay occurs in the exposure above this part. Above the glaciolacustrine clay, the till (~0.6 m) is stratified, with a significant orientation of clasts aligned north to south with their predominant inclination to the north. Above this till that was formed by a moving glacier lies a more homogeneous, clayey, friable till, ~1–1.5 m thick, with a much lower gravel content. This till grades upwards into 0.5 m of predominantly fine sand. The main differences between the layers of the Baltija Stage are the upper layer of the Middle Lithuanian Phase, which is characterized by the highest content of Devonian sandstone and siltstone, as well as the pronounced N–S orientation of the clast material and the longitudinal inclination to the north (Fig. 10).

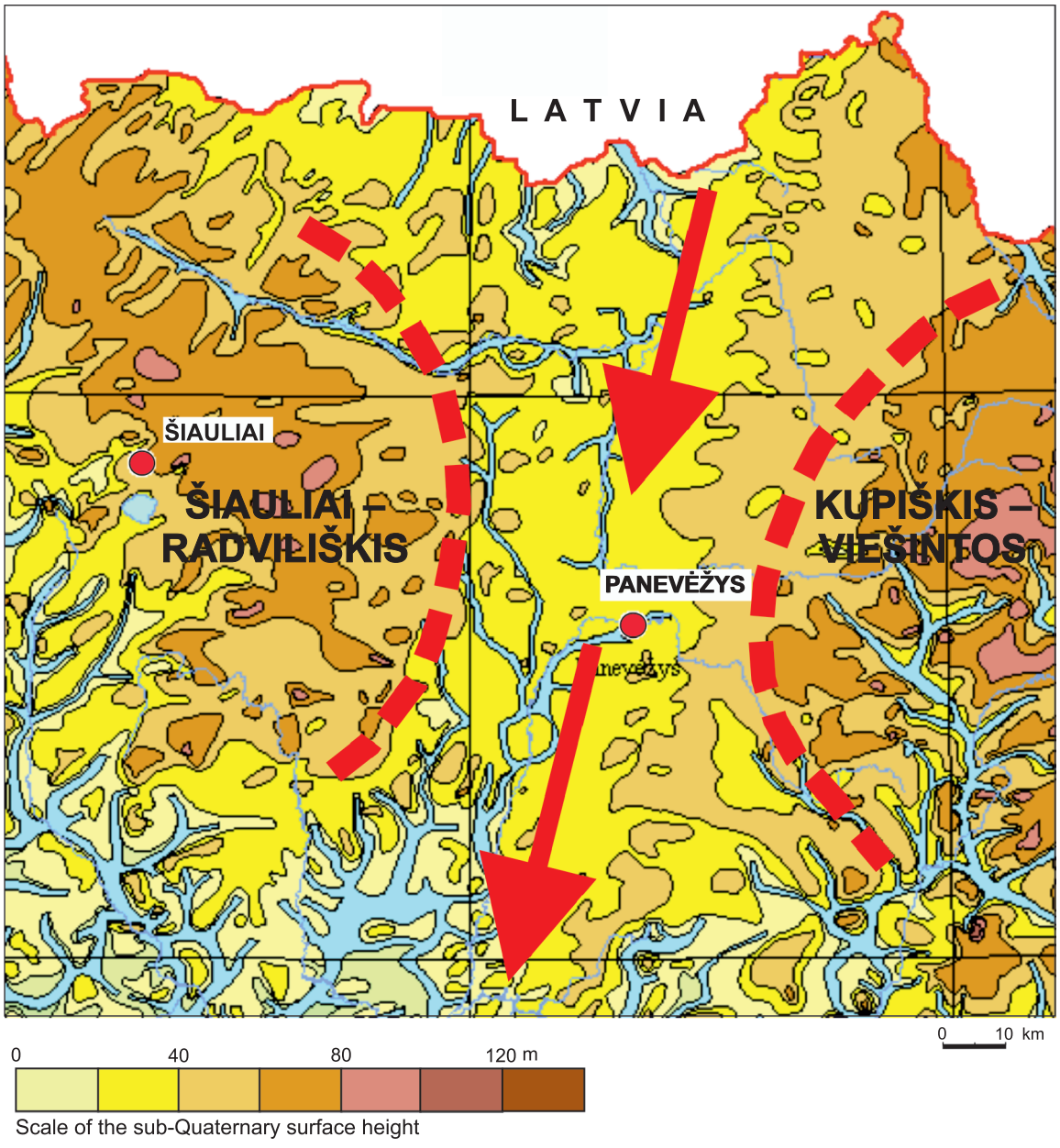

Fig. 11. Elevations of sub-Quaternary surface of Šiauliai-Radviliškis and Kupiškis-Viešintos indicate the direction, velocity and subglacial processes of the Nevėžis Ice Lobe

The map of the sub-Quaternary surface of North and Middle Lithuania by Šliaupa (2004); palaeoincisions in the sub-Quaternary surface are marked in blue

DISCUSSION

STAGES AND TIME OF FORMATION OF THE PLAINS AREA

The prevalent till formed in the Baltija Stage as well as the formation of specific relief forms (MSGLs) formed after the Inter-Stage Grūda-Baltija warming testify to the dynamic activity of this glacier. The moraine plains of Middle and North Lithuania that formed during deglaciation are the result of several steps. The beginning of the formation of these moraine plains may be attributed to the Middle of the Venta and Mūša-Lėvuo Ice lobes, by which time the glacier had probably advanced to northern Lithuania (Basalykas, 1965). In the second step, the Mūša-Lėvuo Ice Lobe, under pressure from the north-expanding Ice Stream of Riga, advanced into the lower depression of the sub-Quaternary palaeosurface to the present confluence of the Nemunas and Neris rivers near Kaunas. The “penetration“ between the elevations of the sub-Quaternary surface from the western side (Šiauliai-Radviliškis) and the eastern side (Kupiškis-Viešintos) had a significant impact on the glaciodynamics of this ice lobe and on the intensity of subglacial processes (Fig.

11). This led to an increase in glacier velocity and subglacial MSGL-forming processes at these elevations.

During the third stage, passive (areal) deglaciation resulted in accumulation and abrasion processes of the glaciolacustrine basins, as well as in glaciofluvial erosion and sedimentation, which largely destroyed or transformed the MSGL forms formed during glacial advance. Active penetration of the Nevėžis Ice Lobe into middle Lithuania is indicated by the geological and geomorphological maps of Lithuania compiled by Guobytė (2001, 2002), where the boundary of the distribution of the Nevėžis Ice Lobe "cuts off" the marginal tills of previous phases.

Geological and geomorphological maps of Lithuanian Quaternary deposits (Guobytė, 2022; Fig. 8) show that there are widespread glaciofluvial and glaciolacustrine deposits on the Nevėžis Moraine Plain. This indicates that sedimentation, erosion, and abrasion processes took place in this area during the Late Ice Age, which largely leveled or destroyed the low MSGL forms. Land reclamation in the 20th century contributed to this. Eskers fixed in the southern part of this plain also testify to intense ice melting processes during deglaciation of the ice lobe. Kame terraces on the southern slope of the Linkuva Ridge indicate the separation of the Nevėžis Ice Lobe from the source area of the glacier (Karmazienė et al., 2013).

^{10}Be surface exposure ages of boulders in Lithuania suggest that the duration of formation of the MSGLs studied was up to several hundred years. The ^{10}Be ages from the Middle Lithuanian and the North Lithuanian moraines (13.5 ±0.6 ^{10}Be ka and 13.3 ±0.7 ^{10}Be ka) indicate a relatively slow retreat of the Riga Ice Stream margin (Rinterknecht et al., 2008). These data are not contradicted by subsequent studies over a large area (Tylmann et al., 2022). In the region occupied by the Riga Ice Stream (up to the maximum extent during the Pomeranian Stage) ^{10}Be ages range between 13.2 ±1.2 ka and 17.1 ±2.0 ka (Tylmann et al., 2022).

FEATURES OF THE SUBGLACIAL PROCESSES

That the moraine plains of Middle and North Lithuania were formed by a relatively fast-moving glacier is shown by previously studied MSGLs (Baltrūnas et al., 2014, 2020). Studies of similar subglacial relief forms indicate increased glacier velocity, for example, in Canada (Stokes et al., 2013). Changing macrofabric of till (variable orientation and dip) corroborates the formation of MSGLs during glacial erosion by groove-ploughing. This occurred when basal ice carried clast material to MSGL crests from interridge areas. The data presented by Stokes et al. (2013) strongly favor a subglacial bedform continuum primarily controlled by ice velocity; however, it is inconsistent with the duration of ice flow and the fact that new bedforms are continually being created, remolded, and, ultimately, erased. Given that the Dubawnt Lake Ice Stream only operated for a relatively short period of time (just a few hundred years) (Stokes and Clark, 2003), a further implication is that MSGLs (and subglacial bedforms more generally) are likely to have been created over time-scales of decades rather than centuries (Stokes et al., 2013).

The sub-Quaternary surface influenced the accumulation of glacial deposits of the Grūda and Baltija stages of the Last Glaciation, especially on the formation of the Žemaičiai Upland and Baltic highlands. The Nevėžis Ice Lobe was active during Middle Lithuanian Phase "penetration" between these elevations. The speed of glacier movement can increase under several conditions, from characteristics of the glacier bed and topographical factors (in steep and narrow areas, glaciers can move faster due to increased gravitational effects) (Benn and Evans, 2010). The intensity of subglacial processes also increases, among which are ice sliding, ploughing, melting, erosion, and deposit transport. MSGL is the result of these processes.

The upper part of the Baltija Subformation till corresponds to an advance of the glacier during the Middle Lithuanian Phase. This is corroborated by the structure and pronounced orientation of the clasts in the direction of ice movement, as well as the shape of MSGL and their relicts in the moraine plain. This occurred when basal ice carried clast material to MSGL crests from interridge areas (Baltrūnas et al., 2020). The determination of the grain-size of the Baltija till in its the surface (upper) part and the calculation of its relative entropy have been effectively combined with this information (Baltrūnas et al., 2005), where the relative entropy of till grain-size composition, as an indicator of the mixing of macro- and microclasts, shows vertical variation related to glacier advance from north to south. This is corroborated by the correlation between the increased relative entropy and the more pronounced longitudinal orientation of the coarse-grained particles in geological sections. The increase in relative entropy and the decrease in the clay-silt fraction (<0.01 mm) are characteristic of morainic areas of the active glacier of the East Lithuanian (maximum Baltic Stage extent) and Middle Lithuanian phases, while the recessionary phases of the South Lithuanian and North Lithuanian (north of Linkuva Ridge) phases show the opposite relationship.

CONCLUSIONS

Investigations of the North and Middle Lithuania lowlands showed that the ridged relief of the moraine plain in the NW part (Akmenė district, North Lithuania) is characterized by features of mega-scale glacial lineation (MSGL) forms, testifying to active movement of the glacier. No correlation with sub-Quaternary palaeosurface features was observed in the arrangement of specific MSGL forms.

Analysis of the relief structure of the Nevėžis Moraine Plain located farther south showed areas of obscure MSGLs affected by glaciolacustrine accumulation and abrasion, glaciofluvial accumulation and erosion, as well as intensive land drainage (amelioration) in the 20th century.

Typical MSGL forms on the Mūša-Nemunėlis Moraine Plain and relicts of MSGL forms on the Nevėžis Moraine Plain, as well as patterns of the orientation and dip of the long axes of macroclasts and the relationship to mixing of the till indicate the dynamics of a moving glacier. These features show that the moraine plains of northern and middle Lithuania were formed by an actively moving glacier, which left an identifiable till layer under favourable geological and hydrological conditions.

Acknowledgements. This study was supported by the Lithuanian the Ministry Education, Science and Sport within the programme "Geo-environment and its resources in conditions of climate change and anthropogenic pressure, 2017–2021" (Order of the Minister No V-273, 24-04-2017). The authors are grateful under Lithuanian Geological Survey of the Ministry of the Environment for the opportunity to become acquainted with previous geological investigations and LiDAR data, which geologist V. Minkevičius helped to analyze. We are also grateful to the anonymous reviewer, and the reviewer J. Satkūnas for useful comments. We thank W. Granoszewski and J. Zalasiewicz for improving the paper.

REFERENCES

Baltrūnas, V., Karmaza, B., Dundulis, K., Gadeikis, S., Račkauskas, V., Šinkūnas, P., 2005. Characteristic of till formation during the Baltija (Pomeranian) Stage of the Nemunas (Weichselian) Glaciation in Lithuania. Geological Quarterly, **49** (4): 417–428. https://gq.pgi.gov.pl/article/view/7387/6037

Baltrūnas, V., Waller, R.I., Kazakauskas, V., Paškauskas, S., Katinas, V., 2014. A comparative case study of subglacial bedforms in northern Lithuania and south-eastern Iceland. Baltica, **27**: 75–92; https://doi.org/10.5200/baltica.2014.27.18

Baltrūnas, V., Karmaza, B., Katinas, V., Pukelytė, V., Karmazienė, D., Lozovskis, S., 2020. Till macro- and microfabrics of mega-scale glacial lineations of Mūša–Nemunėlis Lowland, north Lithuania. Baltica, **33**: 85–96; https://doi.org/10.5200/baltica.2020.1.8

Basalykas, A., 1965. Physical Geography of the Lithuanian SSR, II (in Lithuanian with Russian summary). Mintis, Vilnius.

Baublys, A., Beconis, M., Kudaba, Č., Mikalauskas, A., Mikutienė, L., 1970. Über das Relief des Muša–Beckens (in Russian with German summary). Geologija ir Geografija, **7**: 95–105.

Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation. Hodder Education, London. https://doi.org/10.4324/9780203785010

Bitinas, A., 2011. Paskutinis ledynmetis rytinės Baltijos regione (in Lithuanian). KU universiteto leidykla, Klaipėda.

Bitinas, A., 2012. New insights into the last deglaciation of the south-eastern flank of the Scandinavian Ice Sheet. Quaternary Science Reviews, **44**: 69–80. https://doi.org/10.1016/j.quascirev.2011.01.019

Čepulytė, V., 1962. Ledyninės akumuliacijos formř pasiskirstymas Pomeranijos-Baltijos stadijos ruože (in Lithuanian). Geografinis metraštis, **5**: 339–353.

Doss, B., 1910. Über das Vorkommen einer Endmoräne, sowie Drumlins, Åsar und Bänderton im nördlichen Lithauen. Zentralblatt für Mineralogie, Geologie und Paläontologie, Abteilung B. Geologie und Paläontologie, **22**: 723–731.

Gaigalas, A., 1971. Texture, structure and the genetic varieties of the ground-moraines (in Russian with English summary). In: Structure and Morphogenesis of the Middle Lithuanian Morainic Plain (eds. V. Gudelis and A. Gaigalas): 28–87. Academy of Sciences of the Lithuanian SSR, Vilnius.

Gaigalas, A., 1979. Glaciosedimentation Cycles of the Lithuanian Pleistocene (in Russian with English summary). Mokslas, Vilnius.

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

Gaigalas, A., Melešytė, M., 2001. Spread and composition of the deposits of Nemunas Glaciation (in Lithuanian with English summary). In: Stone Age in South Lithuania (according to geological, palaeogeographical, and archaeological data) (ed. V. Baltrūnas): 46–54. Institute of Geology, Vilnius.

Gudelis, V., Gaigalas, A. eds., 1971. Structure and morphogenesis of the Middle Lithuanian Morainic Plain (in Russian with English summary). Academy of Sciences of the Lithuanian SSR, Vilnius.

Guobytė, R., 2000. Project "Revision of geomorphological map M 1:200 000". Archive of Lithuanian Geological Survey, Inventory No. 5478, Vilnius.

Guobytė, R., 2001. Geomorphological map of Lithuania (in Lithuanian with English summary). Geologijos Akiračiai, **3**: 23–35.

Guobytė, R., 2002. Lithuanian surface: geology, geomorphology, and deglaciation (in Lithuanian with English summary). Ph.D. Thesis, Vilnius University.

Guobytė, R., 2022. Geological Map of Quaternary Deposits of Lithuania. Lithuanian Geological Survey.

Hausen, H., 1913. Über die Entwicklung der Oberflächenformen in den russischen Ostseeländern und angrenzenden Gouvernements in der Quartärzeit. Fennia, Societas Geographica Fennia, **34**: 1–142.

Jolliffe, I.T., 2002. Principal Component Analysis (2nd ed.). Springer. https://link.springer.com/book/10.1007/b98835

Kadūnas, V., 1976. Buried paleo-incisions in Zechstein limestone of northern Lithuania (in Russian with English summary). In: The Buried Paleo-incisions of Sub-Quaternary Rocks Surface of the South-East Baltic Region. Mokslas, Vilnius: 37–40.

Karabanov, A.K., Matveyev, A.V., 2011. The Pleistocene glaciations in Belarus. Developments in Quaternary Science, **15**: 29–35.

Karmazienė, D., Karmaza, B., Baltrūnas, V., 2013. Glacial geology of North Lithuanian Ice Marginal Ridge and surrounding plains. Baltica, **26**: 57–70. https://doi.org/10.5200/baltica.2013.26.0

Kudaba, Č., 1971. Morphology of the eastern slope of the Middle-Lithuanian Plain (in Russian with English summary). In: Structure and Morphogenesis of the Middle Lithuanian Morainic Plain (eds. V. Gudelis and A. Gaigalas): 161–172. Academy of Sciences of the Lithuanian SSR, Vilnius.

Kudaba, Č., 1983. The Uplands of Lithuania (in Lithuanian). Mokslas, Vilnius.

Lamsters, K., Zelčs, V., 2015. Subglacial bedforms of the Zemgale Ice Lobe, south-eastern Baltic. Quaternary International, **386**: 42–54. https://doi.org/10.1016/j.quaint.2014.10.006

Lamsters, K., Karušs, J., Vîtola, Z., Džeriņs, P., 2021. Evidence of ice streaming and ice tongue shutdown in western Latvia: revealed from the mapping of crevasse-squeeze ridges. Baltica, **34**: 1–16. https://doi.org/10.5200/baltica.2021.1.1

Lang, J., Lauer, T., Winsemann, J., 2018. New age constraints for the Saalian glaciation in northern central Europe: implications for the extent of ice sheets and related proglacial lake systems. Quaternary Science Reviews, **180**: 240–259. https://doi.org/10.1016/j.quascirev.2017.11.029

Mikalauskas, A., 1985. Glaciofluvial Plains of Lithuania (in Russian). Mokslas, Vilnius.

Mikalauskas, A., Mikutienė, L., 1971. Glaciofluvial deposits (in Russian with English summary). In: Structure and Morphogenesis of the Middle Lithuanian Morainic Plain (eds. V. Gudelis and A. Gaigalas): 92–124. Academy of Sciences of the Lithuanian SSR, Vilnius.

Rinterknecht, V.R., Bitinas, A., Clark, P.U., Raisbeck, G.M., Yiou, F., Brook, E., 2008. Timing of the last deglaciation in Lithuania. Boreas, **37**: 426–433. https://doi.org/10.1111/j.1502-3885.2008.00027.x

Roman, M., 2019. Ice-flow directions of the Last Scandinavian Ice Sheet in central Poland. Quaternary International, **105A**: 4–20. https://doi.org/10.1016/j.quaint.2017.11.035

Spagnolo, M., Phillips, E., Piotrowski, J.A., Rea, B.R., Clark, C.D., Stokes, C.R., Carr, S.J., Ely, J.C., Ribolini, A., Wysota, W., Szuman, I., 2016. Ice stream motion facilitated by a shallow-deforming and accreting bed. Nature Communications, **7**: 1–11. https://doi.org/10.1038/ncomms10723

Stankevičius, V., 1994. Akmenės rajono Vegerių klinties telkinio žvalgyba. Vilniaus valstybinė geologijos imonė. Report (in Lithuanian). Archive of the Lithuanian Geological Survey. Inventory no. 4 309.

Stonkus, P., Laurinaitytė, D., 1963. Lietuvos TSR Mažeikių rajono rytinės dalie geologinė sandara ir hidrogeologinės sąlygos. Report (in Lithuanian). Archive of the Lithuanian Geological Survey. Inventory no. 1693.

Stokes, C.R., Clark, C.D., 2003. The Dubawnt Lake Palaeo-Ice Stream: evidence for dynamic ice sheet behavior on the Canadian Shield and insights regarding the controls on ice stream location and vigor. Boreas, **32**: 263–279. 10.1111/j.1502-3885.2003.tb01442.x

Stokes, C.R., Spagnolo, M., Clark, C.D., Tulaczyk, S.M., Cofaigh, C.Ó., Lian, O., Dunstone, R.B., 2013. Formation of mega-scale glacial lineation on the Dubawnt Lake Ice Stream bed: 1. Size, shape, and spacing from a large remote sensing dataset. Quaternary Science Reviews, **77**: 190–209. https://doi.org/10.1016/j.quascirev.2013.06.003

Szuman, I., Kalita, J.Z., Ewertowski, M.W., Clark, Ch.D., Slivingstone S.J., Kasprzak, L., 2021a. GIS dataset: geomorphological record of terrestrial-terminating ice streams, southern sector of Baltic Ice Stream Complex, last Scandinavian Ice Sheet, Poland. Earth System Science Data, **13**: 1–26. https://doi.org/10.5194/essd-2021-59

Szuman, I., Kalita, J.Z., Ewertowski, M., Livingstone, S.J., Clark, C.D., Kasprzak, L., 2021b. LiDAR-based glacial geomorphological dataset, southern sector of Baltic Ice Stream Complex, Last Scandinavian Ice Sheet, Poland. Zenodo. https://doi.org/10.5281/zenodo.4570570

Szuman, I., Kalita, J.Z., Ewertowski, M.W., Clark, C.D., Livingstone, S.J., 2021c. Dynamics of the Last Scandinavian Ice Sheet's southernmost sector revealed by the pattern of ice streams. Boreas, **50**: 764–780. https://doi.org/10.1111/bor.12512

Szuman, I., Kalita, J.Z., Diemont, Ch.R., Livingstone, S.J., Clark, Ch.D., Margold, M., 2023. Evaluation of the role of the Baltic depression during deglaciation of the Last Scandinavian Ice Sheet; a landform-driven investigation. The Cryosphere. Discussions. https://tc.copernicus.org/preprints/tc-2023-107/

Šliaupa, A., 2004. The Pre-Quaternary rock surface (in Lithuanian with English summary). In: Evolution of Earth Crust and its Resources in Lithuania (ed. V. Baltrūnas): 254–258. Petro ofsetas, Vilnius.

The National Atlas of the Republic of Lithuania, I, 2014: 44–51. Vilnius. https://www.geoportal.lt/map/#

Tylmann, K., Rinterknecht, V.R, Woźniak, P.P., Guillou, V., ASTER Team, 2022. Asynchronous dynamics of the Last Scandinavian Ice Sheet along the Pomeranian Ice-Marginal Belt: a new scenario inferred from surface exposure ^{10}Be dating. Quaternary Science Reviews, **294**: 1–17. https://doi.org/10.1016/j.quascirev.2022.107755

Vaitonis, V., 2000. Morphostructural analysis of glacigenous relief of Lithuania (in Lithuanian with English summary). Geological Survey of Lithuania, Vilnius.

Zelčs, V., Markots, A., 2004. Deglaciation history of Latvia. In: Quaternary Glaciations – Extent and Chronology (eds. J. Ehlers and P.L. Gibbard): 225–243. Part I: Europe. Elsevier, Amsterdam; https://doi.org/10.1016/S1571-0866(04)80074-5

Zelčs, V., Nartišs, M. 2014. Outlines of the Quaternary geology of Latvia. In: Excursion guide and abstracts of the INQUA Peribaltic Working Group Meeting and field excursion in Eastern and Central Latvia (eds. V. Zelčs and M. Nartišs): 9–15. University of Latvia. https://doi.org/10.22364/lqtpsh.2014