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SUBGLACIAL MELTWATER DISCHARGE WITHIN AND AROUND NORTH LATVIA UPLANDS DURING THE LAST GLACIATION

Dainis OZOLS[1]

Abstract. Sediments and landforms of North Vidzeme Uplands are interpreted as a surge-type glacier formation, a development of which began with erosion and glacial lobe movement on an extensive subglacial water layer and ended with drainage through subglacial tunnel valleys and the prevailing accumulation processes. Transport of material and meltwater discharge during the most of the surge persisted from the lowlands to the interlobal areas (uplands) and the ice margin. It took place mainly due to meltwater currents that deposited clastic material within the crevasses and thawed openings on the interlobal risings – up to the englacial water table. High pressure of subglacial water resulted in high water tables within the crevasses on the ice divides. Within the North Vidzeme Uplands, flat tops of closely situated kames have quite similar heights that are explained by a previous uniform englacial meltwater table. Thus, the highest kames indicate the first ice sheet stranding on the ice divides and development of the crevasses by thawing. Subglacial meltwater discharge coincides mainly with routes of ice lobes and then follows the ice margin in the western direction. During the initial and the most active stage of the last surge, the meltwater was drained along valley-like depressions in the SE direction, and then probably, around the eastern part of the Central Vidzeme Upland to the Daugava River. During the final stages of the last glaciation when a kinematic wave over the buoyant part of the surging glacier approached the ice margin and meltwater could flow out freely from the ice sheet, the pressure of subglacial water decreased and the englacial water table fell. The drainage of ice lobes of the North Vidzeme and Vortsjarv was diverted to the eastern and the southern direction through the subglacial tunnel valleys of Rūja, Seda, Vaike Emajogi, Ohne and Pedele rivers and then through the Strenči subglacial basin to the submarginal tunnel valley of the Gauja River that drained the territory into the SW direction. A new kind of mesoform i.e. transverse valley-like depressions, is revealed. Lowlands are a testimony to different types of material transport beneath the ice sheet. Deposits of glaciofluvial currents show crosswise and parallel lamination and current ripples. Turbidite deposits have a coarse and graded structure. Deposits formed under floating earth and slurry flow conditions have a massive and platy structure and presence of rotated clasts of soft rocks and sediments. The material deformed during the very final stages of the surge by subglacial traction of plastic material includes deformed clasts of resistant rocks. Formation of clayey diamicton on top of the most of the sequencies is related to the decrease of hydraulic pressure of subglacial water, when the glacial traction mixed the underlying material and made a muddy mass. After deposition it was transformed into massive or platy clayey sediments, traditionally named a basal till.

Key words: glacial surge, valley-like depression, kame, esker, drumlin, diamicton, subglacial water, englacial water, surge cycle.

Abstrakt. Osady i formy rzeźby Wysoczyzny Północnowidzemskiej są efektem szarży lądolodu. Ich powstawanie zainicjowała erozja i ruch lobu lodowcowego po rozległej warstwie wody subglacjalnej. Proces ten zakończył się drenażem wody tunelami subglacjalnymi i dominacją depozycji. Transport materiału i odpływ wód roztopowych podczas szarży zachodził od obszarów niżej położonych do stref interlobalnych (wysoczyzn) i strefy marginalnej lądolodu. Był on stymulowany głównie przez strumienie wód roztopowych, które deponowały materiał klastyczny w szczelinach i przetainach lodowych występujących na wzniesieniach interlobalnych, aż do wysokości zwierciadła wód inglacjalnych. Wysokie ciśnienie wód subglacjalnych spowodowało, że wysoko występowało również zwierciadło wody w szczelinach położonych na działach lodowych. Na Wysoczyźnie Północnowidzemskiej płaskie powierzchnie wierzchowinowe licznych kemów znajdują się na tej samej wysokości, co można wytłumaczyć jednakowym położeniem zwierciadła wód roztopowych w czasie ich powstawania. A więc najwyższe kemy wskazują na pierwszy etap wkraczania lądolodu na działy lodowe i na rozwój szczelin wskutek topnienia lodu. Odpływ subglacjalny wód roztopowych odbywał się zgodnie z głównymi kierunkami ruchu lobów lodowcowych, a więc ku krawędzi lądolodu na W. Podczas pierwszej i najbardziej dynamicznej fazy ostatniej szarży wody

[1] North Vidzeme Biosphere Reserve Administration, Rīgas iela 2, Rūjiena, LATVIA, LV-4244; biodain@latnet.lv

roztopowe odpływały wzdłuż obniżeń dolinnych ku SE, a następnie prawdopodobnie wokół wschodniego skraju Wysoczyzny Środkowowidzemskiej do Dźwiny. W końcowych fazach ostatniego zlodowacenia, kiedy fala kinematyczna szarżującego lądolodu zbliżała się do jego strefy marginalnej, wody roztopowe mogły wypływać swobodnie spod lodu, ciśnienie wody subglacjalnej malało, a zwierciadło wody inglacjalnej ulegało obniżeniu. Drenaż lobów lodowcowych, północnowidzemskiego i jeziora Vörts, odbywał się ku E i S tunelami subglacjalnymi rzek Rūja, Seda, Vaike Emajogi, Ohne i Pedele, a następnie przez basen subglacjalny Strenči do submarginalnego tunelu rzeki Gauja, która płynęła ku SW. Powstałe poprzeczne obniżenia pseudodolinne są świadectwem różnego rodzaju transportu materiału pod lądolodem. Osady strumieni wód roztopowych są laminowane przekątnie i równolegle oraz zawierają ripplemarki prądowe, zaś utwory prądów zawiesinowych mają uwarstwienie frakcjonalne. Osady utworzone wskutek upłynnienia i spływów masowych mają strukturę masywną bądź warstwową i zawierają zrotowane klasty miękkich skał i osadów. Materiał, który został zdeformowany w warunkach subglacjalnych w końcowej fazie szarży wskutek trakcji materiału plastycznego, zawiera zdeformowane klasty skał odpornych. Powstanie ilastego diamiktonu w stropie większości sekwencji wynika ze zmniejszenia ciśnienia hydraulicznego wody subglacjalnej, kiedy transport trakcyjny przez ladolód spowodował mieszanie materiału podścielającego i utworzył masę mułową, która po depozycji była przekształcana w ilaste osady masywne lub uławicone, określone na ogół jako glina lodowcowa bazalna.

Słowa kluczowe: szarża lodowcowa, obniżenia pseudodolinne, kem, oz, drumlin, diamikton, wody subglacjalne, wody inglacjalne, cykl szarżowania.

INTRODUCTION

The study area is a nature protection territory – the North Vidzeme Biosphere Reserve in the northern part of Latvia (Fig. 1). The objective of the paper is to come up with the concept of landforms of the territory as a result of processes of glacial surges where a subglacial and englacial meltwater action played a very important role.

In general, landform formation of the North Vidzeme has been known since geological mapping (scale 1:200,000) in 1960's, with the results codified by Straume (1979). There are two uplands in North Vidzeme Region, which are small and rather specific. The Idumeja Upland developed between the ice lobes of the Gulf of Riga and the North Vidzeme (Zelčs

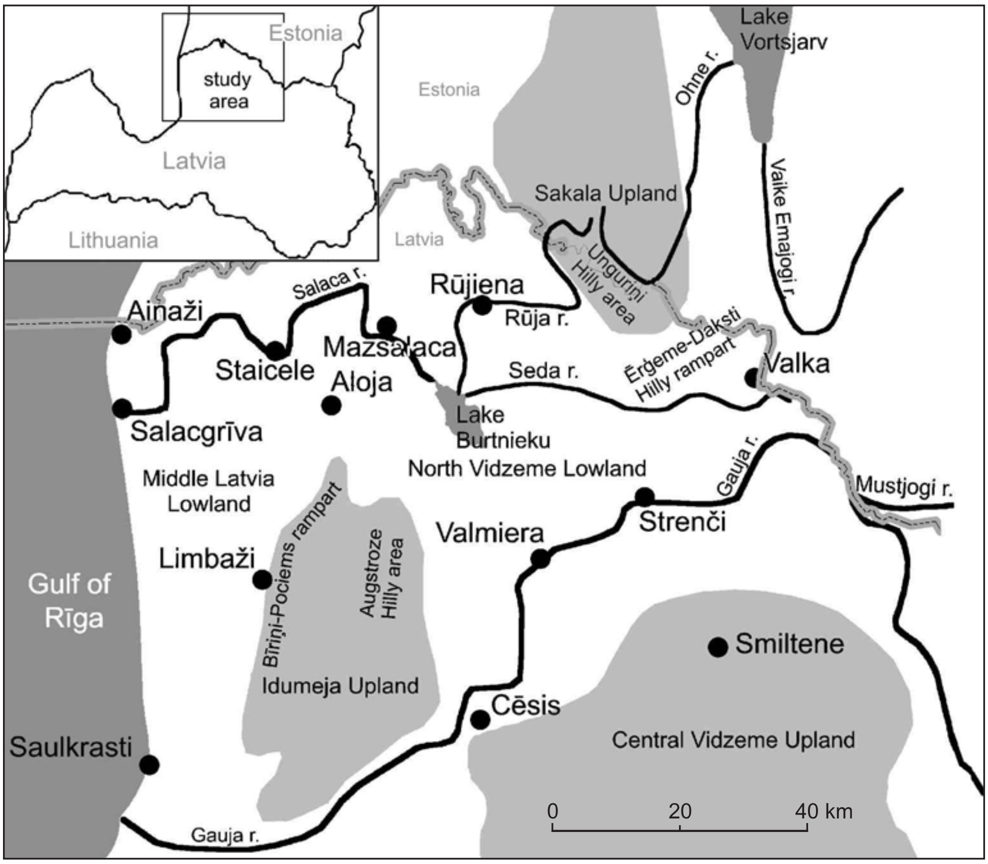

Fig. 1. The study area

1993). The Unguriņi hilly area and the Ērģeme-Daksti hilly rampart are fragments of the Sakala Upland of South Estonia. Uplands are surrounded by lowlands, formed by three ice lobes – the main along the Gulf of Riga is the Middle Latvia (Viduslatvijas) Lowland, the smaller – along the depression of Lake Burtnieks – is the the North Vidzeme (Ziemeļvidzemes) Lowland, and the third starts from the Lake Vortsjarv depression in the southern direction (Karukäpp, 2004). Each lowland and upland in the territory corresponds to a former ice lobe or an interlobal rising. The thickness of the Quaternary varies from 10 to 50 m on the uplands and from 0 to 20 m in the lowlands.

The Pleistocene glacial lobes were subjected to surges – cyclic processes that took place due to internal evolution of the ice sheet as well as depended on climate and weather conditions, local bedrock, topography, etc. Meier and Post (1969) emphasized that surges could be involved from changes of bed friction, which might be related to water, found in the bed as a thin film or in isolated pockets. Kamb (1987) demonstrated that surge mechanism arose from two regimes of subglacial drainage. One regime is the quiescence of the surging glacier, when single or a few channels exist beneath the axial part of an ice lobe. In the surging state, a network of linked cavities is formed by ice-bedrock separation. During the surge the water pressure within the cavities is close to the buoyancy point of the glacier. High water pressure and glacier sliding open up cavities for water to get in.

There are very different opinions concerning formation of the landform set. The prevailing opinion of Latvian researchers explains generation of drumlins and the landform set of interlobe elevations by the direct impact of ice sheet pressure. Some North American researchers explain drumlin formation by an impact of catastrophic flood discharges from subglacial lakes (Shaw, Kvill, 1984; Shaw, Gilbert, 1990; Beaney, Shaw, 2000, and others). According to the author, the evolution of hydraulic systems within and beneath surge-type glacial lobes plays a crucial role in a development of sediments and landforms of the North Vidzeme Region – both lowlands and uplands, but those are processes of a normal evolution of the ice sheet in a temperate zone and are not catastrophic events (Ozols, 2006).

Landforms and sediments of the North Vidzeme Region are testimonies to the evolution of glacial processes within the last surge. The observed sequence from the very beginning of the surge to the end of the glacier activity makes almost a full surge cycle.

The author's study enables disclosure of some additional features. The elaborated map gave the author the understanding of diversity, shape and layout of landforms. The study of terrain and outcrops provides a more detailed insight into internal composition and genesis of several landforms.

METHODS

Documentation of sections was made in gravel pits, river banks and coastal outcrops of the Baltic Sea. It included description of outcrops, their photographic documentation and sketch drawings. Special attention was paid to identification and interpretation of sedimentary and deformation structures, such as fluvial lamination (primary sedimentary bedding – cross-bedding, current ripples and grading), platy structures with parallel bands, belts and rotated clasts testifying to material movement as a laminar flow in a state of floating earth, slurry and plastic deformations of deposited sediments.

Observation of the territory accompanied the everyday work of the geologist of the North Vidzeme Biosphere Reserve: inspection of extraction of mineral resources (sand and gravel pits) and evaluation of nature monuments (big boulders, outcrops of Devonian rocks, etc.). The character of landforms and location of boulder pavement distribution were recorded.

The map of landforms was prepared by deciphering large-scale (1:10,000) topographic maps. The total area of the territory covered by the map is 2000 sq km (fragment of the map – Figs 4, 6). The outlined landforms on the map show relative heights according to the surrounding surface. There is no computer programme that could enable such graphic operation. Therefore the map was made by careful drawing on a raster topographic map with consecutive inclusion into the ArcGIS environment.

The following units were distinguished: (1) expressive depressions (subglacial tunnel valleys) formed by glaciofluvial erosion, (2) gentle valley-like depressions that are located amidst drumlins and other positive landforms, (3) gentle and low risings up to 2 m high, (4) hills, 2–5 m high, and (5) higher hills. The shape of positive landforms allowed the author to judge their genetic classification namely drumlins, ribbed moraines, eskers, kames or inland dunes.

RESULTS

MESOFORMS

There are several problems with terminology concerning mesoforms of glacial origin. Some of them that can be clearly identified within the North Vidzeme Region do not possess any specific name. Here author can give the list and the scheme of connectedness of the mesoform types (Fig. 2):

1. Valley-like depressions are gentle features that are create a common network, mainly slightly diverging or subparallel.

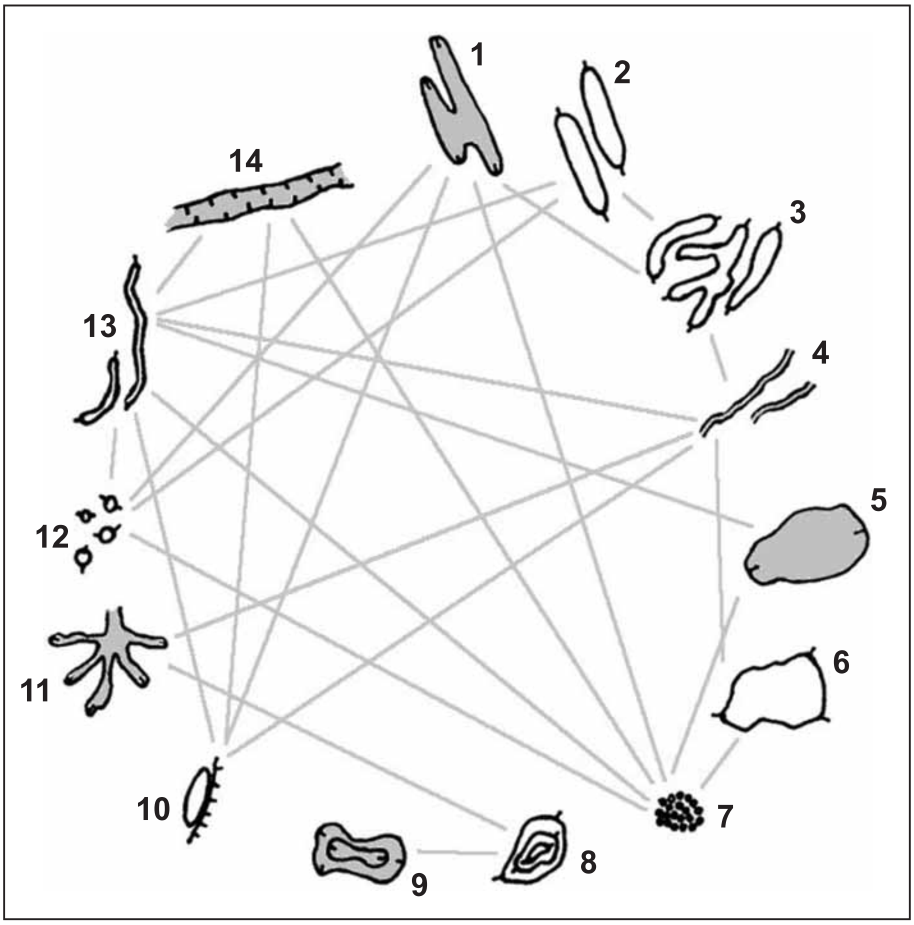

Fig. 2. Spatial and genetic connectedness of glacial mesoforms. The lines present the observed connection

1 – valley-like depressions, 2 – drumlins, 3 – ribbed moraines, 4 – transverse valley-like depressions, 5 – irregular depressions, 6 – flat plains and risings, 7 – boulder fields and pavements, 8 – big dome-like kames and kame massifs, 9 – glacier moulin depressions, 10 – gentle ramparts along the edges of depressions and subglacial valleys, 11 – forked valley-like depressions, 12 – small kames, 13 – eskers, 14 – subglacial valleys

Fig. 3. Slightly deformed laminated glacifluvial sediments in a kame section in the Augstroze hilly area near Rijnieki; section on the rod is equal to 10 cm

2. Drumlins are gentle forms, their core mainly composed of sand and gravel with structures of a laminar flow that resemble laminae of fluvial sedimentation. Some exceptions are bodies made of very coarse pebble and gravel material that in some places maintain their entirety with grading and some cross-bedding. The Švākas gravel pit presents evidence of floating of resistant coarse layers – like solid desks within semi-liquid sand mass during deposition (Ozols, 2009). The greatest part of drumlins is covered with a thick layer of clayey diamicton.

In a cross-section, the surface of valley-like depressions and drumlins presents a line like a sine curve.

3. Ribbed morains show gradual transitions to drumlins and are orientated athwart a direction of glacier movement. A discontinuous belt of ribbed moraines crosses the northern part of the Burtnieki drumlin field – from the Sakala Upland to the Idumeja Upland.

4. Transverse valley-like depressions are narrow and shallow landforms that stretch across a glacier movement and across the common valley-like depressions and drumlins. These landforms cuts drumlins and disappear when crossing

valley-like depressions. The length of the longest transverse valley-like depression is up to 7.5 km.

5. Irregular depressions are wide and gentle and are distributed both within flat lowlands and uplands.

6. Flat plains and risings are typical for lowlands.

7. Boulder fields and pavements are typical for territories on the slopes and along the subglacial valleys as well as other kinds of depressions. Boulder clusters are often located on crests of the eskers.

8. Big dome-like kames and kame massifs are distributed mainly within uplands, but some of them have developed in lowlands as well. Kames of the Augstroze hilly area are high dome-like hills with flat tops. The material provides evidence of initial aqua-glacial sedimentation structures with a smaller impact of glacigene and gravity deformations (Fig. 3). Hills are made of aqua-glacial material of varying grain size. Mainly laminated sand, silt and gravel material predominate. Fine to coarse-grained sands are prevailing. Some kames

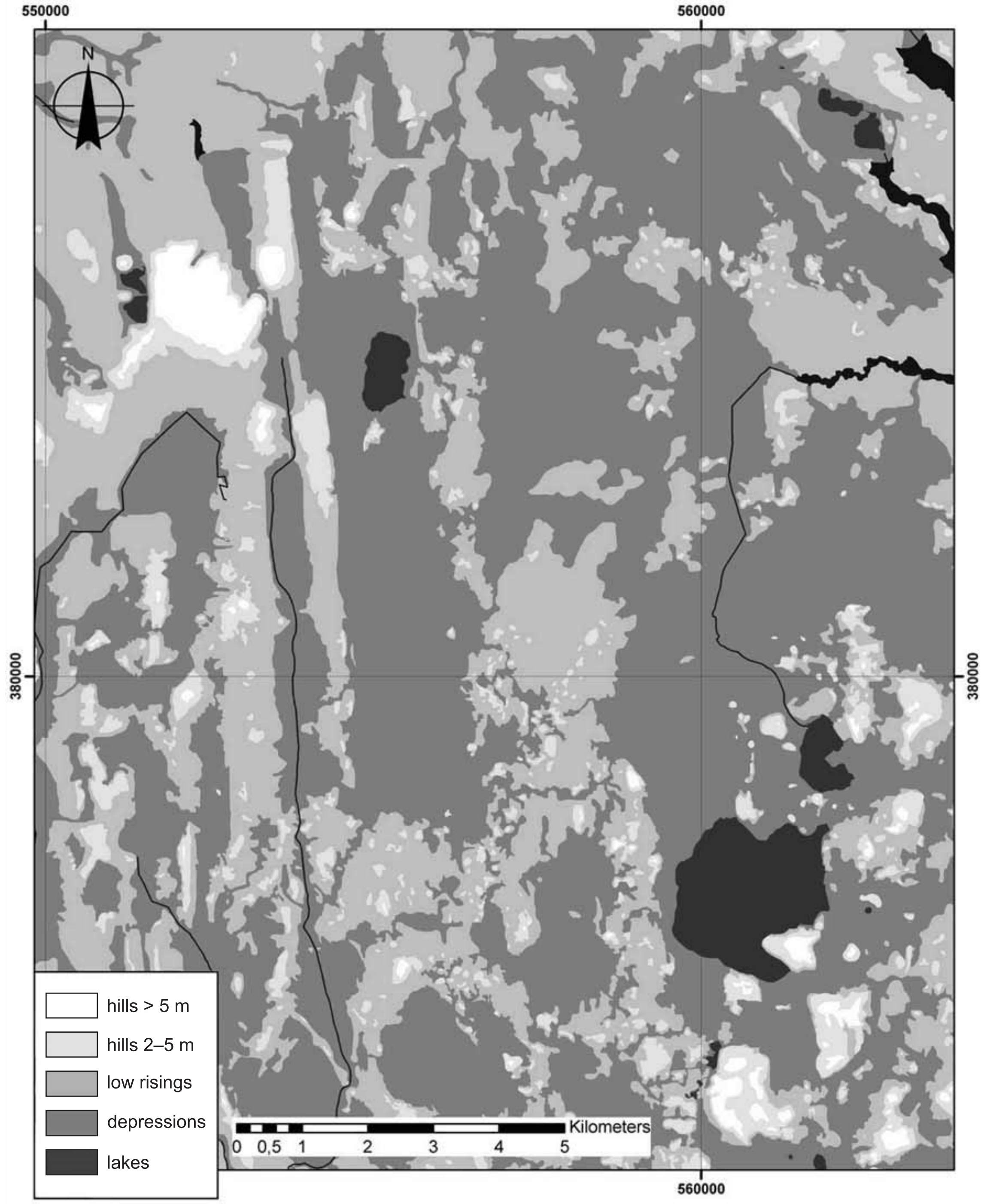

Fig. 4. Landform map of the northern extension of the Idumeja Upland. NW side – the end of Bīriņi–Pociems rampart, SE side – Augstroze hilly area. All maps are in the LKS-92TM system of coordinates

have indications of glacier pressure from a proximal or side direction. The resulting slopes are steep – straight or concave. Typical smaller features are shallow channels on slopes of bigger kames, in some places crossing the top areas. The latter have been occasionally defined as gullies, but absence of wash-away cones at the foot of the slope does not allow for such interpretation.

9. Glacier moulin depressions are deep rounded or irregular depressions, formed mainly along the slopes of uplands and filled by lakes and mires.

10. Gentle ramparts along the edges of depressions and subglacial valleys are characteristic for lowlands.

11. Forked valley-like depressions are located on proximal slopes of the uplands.

12. Small kames are commonly found within lowlands as continuation of esker chains or as individual forms within depressions.

13. Eskers of the territory are diverse, varying in their shape and composition. More widespread are chains of low (2–6 m high) eskers that consist of coarse and clayey material with evidence of very variable sedimentation regimes, often structures of laminar flow of the material and less frequently occurring fluvial crosswise or parallel lamination, with a lot of plastic deformations. Some bigger eskers near the slope of the Sakala Upland consist of fine and medium-grained sand with well developed cross-laminated series.

14. Subglacial valleys are the best developed negative landforms that are 5–20 m deep, with steep slopes and varied morphology. Some subglacial valleys have tributaries and parallel channels (Salaca, Svētupe), others contain eskers and terraces, either accumulative (Rūja, Lake Saruma) or erosive ones and covered by boulder pavements (Salaca, Rūja, Vitrupe).

MACROFORMS

The Idumeja Upland includes three very different glaciomorphological units formed upon the rising of the bedrock surface. The Bīriņi–Pociems rampart delimits the upland from the west (Straume, 1979). The latter was created partly as a subglacial, partly marginal formation. Some forked valley-like depressions were incised into the western slope of the rampart and testify to meltwater flowage in a SE direction – from the periphery of the Gulf of Riga ice lobe to the local ice divide (Fig. 4).

The undulated plain of Limbaži – the territory with valley-like depressions, drumlins and subglacial valleys – is located in the centre of the upland.

The third part – the Augstroze hilly area in the east of the upland has peculiar and expressive topography with widespread extensive and flat depressions occupied by peat mires and steep and high dome-like flat topped hills – kames. The higher kames of the Augstroze hilly area are located 1–2 km from one another, with tops at 124.7 m, 125.1 m and 125.4 m a.s.l. respectively. The top of the Zilaiskalns hill, 12 km to the NE in the neighbouring lowland, occurs at

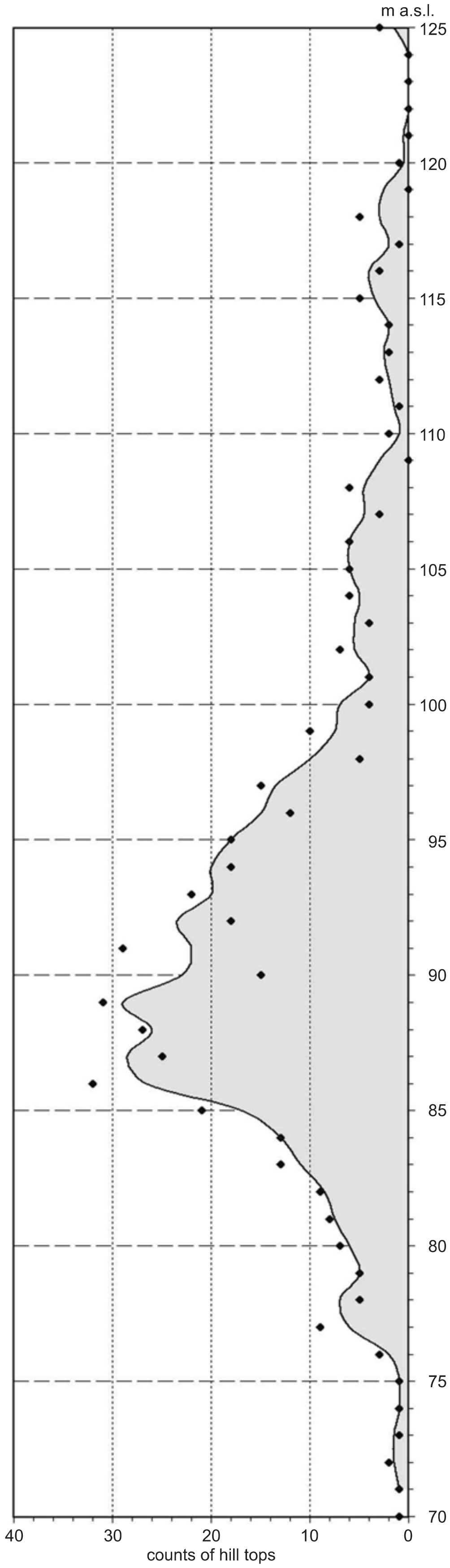

Fig. 5. Tops of kames in the Idumeja Upland; the solid line presents a trend with a period of 2 pts

127.1 m a.s.l. Lower tops of kames are located at 102–108 m, 112–118 m, and (most widespread) 85–95 m a.s.l. (Fig. 5).

The greatest part of the Sakala Upland lies in the territory of Estonia. It is situated on a rising of the bedrock, with higher places of the bedrock surface to the north from Viljandi – up to 80 m a.s.l. The upland is interweaved with subglacial valleys and valley-like depressions that were formed in a subglacial environment. There are some regions with drumlins, esker-type features and undulated sandy plains (Liokene, 1959).

The southern end of the Sakala Upland juts into the territory of Latvia, where it constitutes two different regions – the hilly area of Unguriņi and the Ērģeme–Daksti hilly rampart (Fig. 6). Within the hilly area of Unguriņi, the Sakala Upland comprises gentle landforms without clear orientation and gradually turns into the North Vidzeme Lowland. Within this area, the earth surface gradually rises in the direction of the upland – to the northeast. Close to the state border of Latvia there is the highest part of the Unguriņi hilly area (a hill Pīkas kalns 105 m a.s.l.).

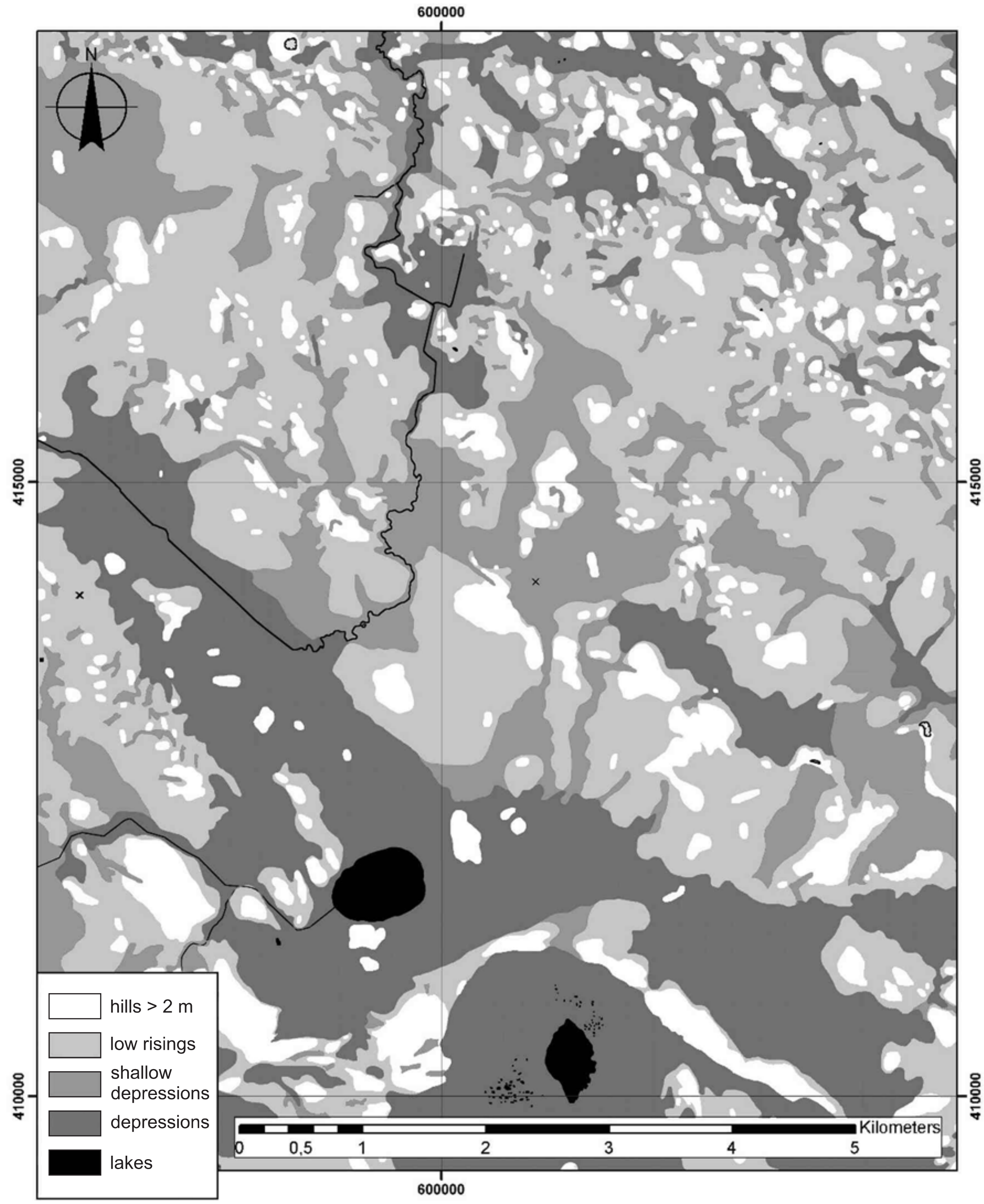

Fig. 6. Landform map of a transition zone between the Unguriņu hilly area and the North Vidzeme Lowland

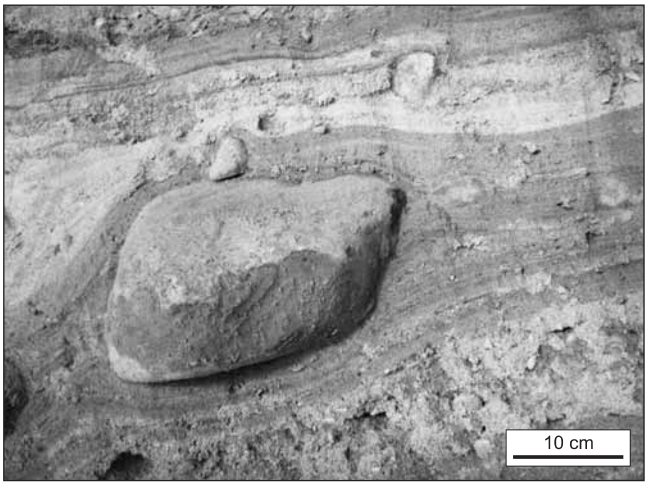

Fig. 7. Platy structures with parallel bands and belts testifying to material movement as a laminar flow in slurry and plastic deformations of highly water-saturated sandy deposits. Section within a gravel pit, the Unguriņi hilly area

There landforms are covered by a thick layer of clayey diamicton and cored by sand and gravel deposits (fields Unguriņi, Alēni etc.). These sand and gravel deposits have a very complex structure with heavy diamicted (platy) and deformed material and laminar flow structures (Fig. 7).

The Ērģeme–Daksti hilly rampart marks the border of two ice lobes. It stretches in the SW–NE direction and is partly detached from the main part of the Sakala Upland by valley-like depressions. There is a fine pattern of landforms that is made of forked valley-like depressions and small dome-like hills. The hilly rampart from the south and the east is surrounded by more extensive valley-like depressions and dome-like hills – kames. The biggest one – Pentes kalns (88 m a.s.l.) is more than 1 km wide and 30 m high. It is similar to the Zilaiskalns hill and resembles the landforms of the Augstroze Upland.

LOWLANDS

In the lowlands there are low and gentle landforms (valley-like depressions, drumlins, etc.) and a smaller number of higher and steeper landforms (eskers, kames).

Two uplands are separated from each other by the central part of the North Vidzeme (Ziemeļvidzemes) Lowland with the area of widespread drumlins – the Burtnieki drumlin field. A discontinuous belt of ribbed moraines stretches between the two uplands. The Burtnieki drumlin field can be subdivided into smaller units – the depression of the Lake Burtnieks, which is the flat plain occupied by a lake and by mires, and three other drumlin fields around the towns Mazsalaca, Rūjiena and Rencēni.

The Ērģeme–Daksti hilly rampart is located at the south border with the Strenči depression of the North Vidzeme Lowland where, at the end of the last glaciation, there was a subglacial lake. Now, the depression is occupied by the wide Seda moss mire and by sandy plains with dunes.

The Idumeja Upland occurs at the west border with the Middle Latvia (Viduslatvijas) Lowland. The transition is clear and sharp – mainly as an ice contact slope that is accompanied by a chain of subglacial valleys, now occupied by river valleys and lakes. The Middle Latvia Lowland is mainly flat with some subglacial valleys and a smaller number of valley-like depressions and drumlin-like landforms.

CONCLUSIONS

Landforms and sediments of the North Vidzeme are the evidence of the last glacial surge cycle. New mesoforms, regularities in landform disposition and features of internal structure were revealed and permitted a new interpretation concerning the genesis of landforms and glacial deposits. The author interprets a development of sediments and landforms of the North Vidzeme as a surge-type glacial formation, initiated by erosion and glacial lobe movement on the extensive subglacial water layer (initial stage) and terminated with drainage through subglacial valleys, a prevailing accumulation processes (final stage) and glacier stoppage (Ozols, 2006).

The study area comprises a territory of activity of three glacial lobes. The bigger one is the lobe of the Gulf of Riga with the North Vidzeme ice lobe as its branch. Meltwater drainage routes as well as disposition of the Ērģeme–Daksti hilly rampart indicate that these lobes were more active during the final stages of the glaciation. Another ice lobe came from Vortsjärv and probably, the up-stream part of the Mustjogi River have been active earlier. Similar conclusions about the glacial lobe activity were done by Straume (1979), but he presented a different interpretation of genesis of the macroforms.

Āboltiņš (1989) noted that numerous researchers recorded a differentiated influence of erosion within the macroforms, and he stressed that differentiation had increased with each glaciation. Āboltiņš evaluated the depth of erosion along submeridional depressions for 50–100 m and up to some tens of metres along the branches. The author expects that there were several surge cycles during each glaciation, with erosion in the lowlands and accumulation on the uplands. An erosion activity was very closely interconnected with the bedrock resistance. In the eastern Baltic region a softer bedrock (Ediacaranian, Cambrian, Middle Devonian) runs in subparallel belts. During the last glaciation, the ice sheet moved mainly from the north to the south and created submeridional belts of erosion. To sum up, this makes a lattice, where uplands are situated on the more resistant bedrock between the main routes of the glacier movement (Fig. 8). Such regularity was noticed by Aseev (1974), Āboltiņš (1989) and others.

Within the lowlands, a network of linked cavities was formed beneath the surging ice sheet by ice-bedrock separation. During a surge, water pressure within the cavities was close to the buoyancy point of the ice body. High water pres-

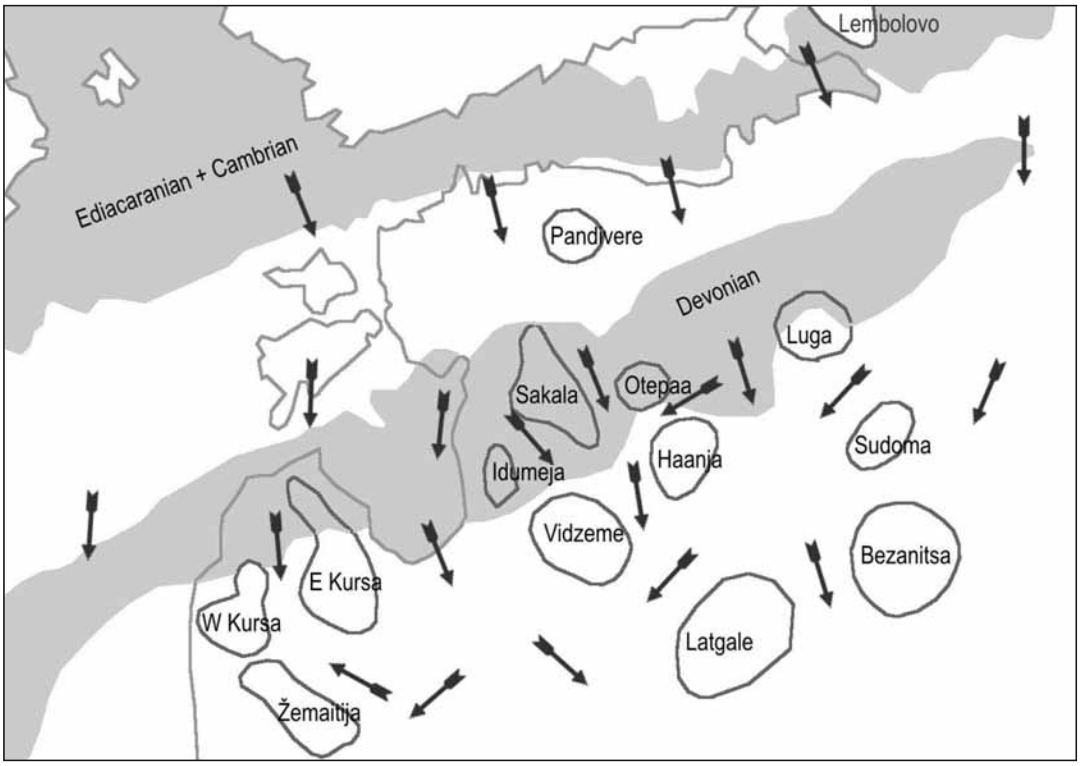

Fig. 8. Distribution of uplands, soft bedrock units (grey coloured) and glacial streams. Compiled by author, using the material of Karukäpp (2004)

sure and glacier sliding opened up cavities for water to get in (Kamb, 1987). This led to higher activity of erosion and supplied plenty of clastic material transported by meltwater currents, water head gradient and glacier traction.

The testimony to such interpretation is the pattern of valley-like depressions that make a unitary network within the lowlands, and their different pattern (forked valley-like depressions, etc.) on the uplands. The lowlands demonstrate two obvious generations of negative landforms. The younger one includes subglacial valleys and transverse valley-like depressions. The outcrops within lowlands testify to different types of material transport beneath the ice sheet. These types are fluvial currents (cross-lamination and parallel lamination, current ripples), turbidite currents (grading), floating earth

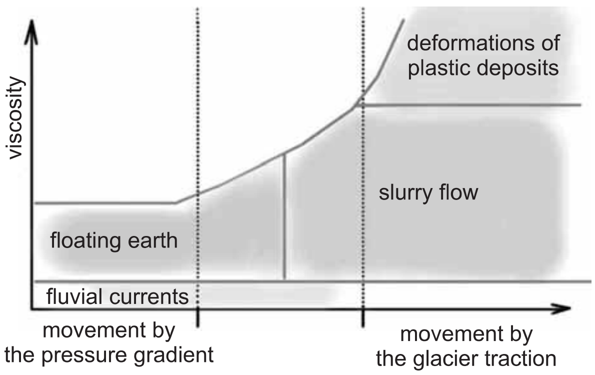

Fig. 9. Different types of material transport beneath a glacier

conditions and slurry flows (massive and platy structure, presence of rotated clasts of soft rocks and sediments), as well as subglacial traction of plastic material (deforming the layer with deformed clasts of resistant rocks) during the very final stages of the surge cycle (Fig. 9).

Levels of flat tops of kames in the uplands of the North Vidzeme are a good evidence for different englacial meltwater tables. Sediment structures of kames testify to deposition, mainly in a quiescent dead ice environment with insignificant impact of glacigene and later landslides, and slump deformations.

INITIAL STAGE OF GLACIAL SURGE

Discharge of meltwater and transport of material from beneath the ice sheet took place mainly due to meltwater currents that deposited clastic material within the crevasses and thawed openings on the interlobal risings of subglacial bedrocks. Such deposition was described by Kudaba (1986).

The grounding line coincided with a subglacial surface where hydrostatic pressure of the ice sheet was compensated by pressure of englacial water. Where the subglacial surface was higher than the grounding line, the glacier was impeded by stranding. Formation of crevasses took place, and development of through thawings started.

It is obvious that the abundance of material and water discharge was crucial for accumulation activity on the ice divides. The material was supplied by erosion within the surrounding lowlands. Erosion was most active when movement of the ice during the surge was the most rapid. At this time, discharge from beneath the ice sheet persisted as a thin and very changeable water layer. Erosion in the lowlands formed valley-like depressions, roughly parallel to the ice lobe movement. Forked valley-like depressions formed in front of the risings of the ice sheet bed, where meltwater currents found exit to the zone of crevasses and through thawing.

High pressure of subglacial water indispensable for ensuring the buoyancy of the glacial lobe caused high water levels within the crevasses on the ice divides. Material was carried and squeezed into the empty space up to the table of englacial water. The channels on slopes of kames are remains of meltwater routes from flat subglacial depressions to the through thawings on the ice sheet surface. Kames formed in the same time and close to each other had similar heights. Thus, the highest kames mark the initial places of ice sheet stranding on the ice divide (the Idumeja Upland – between ice lobes of the Gulf of Riga and the North Vidzeme). The origin of the Zilaiskalns hill can be explained in a similar way. It has developed within the ice sheet crevasses in a lowland and were connected with the same hydraulical water table as kames of the Augstroze hilly area.

The Unguriņi hilly area of the Sakala Upland is an evidence of a more active glacial impact with structures of laminar flow, squeezing and folding the previously deposited aqua-glacial material within a subglacial environment with high water saturation and pore water pressure (Fig. 7).

The subglacial meltwater discharge mainly coincides with routes of ice lobes. During the initial and the most active stage of the last surge cycle, meltwater from the North Vidzeme lowland was drained along valley-like depressions in the SE direction, and then, probably, around the eastern part of the Central Vidzeme Upland to the Daugava River.

FINAL STAGE OF GLACIAL SURGE

When a kinematic wave over the buoyant part of the surging ice sheet approached the ice margin and meltwater could freely outflow from the ice, the pressure of subglacial water decreased together with the englacial water table as well (Ozols, 2006). Thawing of the interlobal glacial ice and the lowering of the englacial water level resulted in development of kames in wide area. The most widespread formation of kames in the Augstroze hilly area is referred to water tables of 85–95 m a.s.l. (Fig. 5).

Glacier moulin depressions are spread along the southern ending of the Sakala Upland (lakes of Turna, etc.) and were formed together with kames in places where meltwater got into the crevasses of a stagnant ice sheet.

Eskers formed mainly in lowlands at the end of the surge cycle when ice movement ceased and subglacial meltwater discharge has been rearranged according to the converging pattern. Testimony to this is the evident connection between eskers and transverse valley-like depressions. Some smaller eskers include deformations of a final movement of the ice sheet.

Development of boulder fields and pavements is connected with the final stage of the glacial surge when boulders disengaged from ice glissaded and fell down.

During the final stages of the last glaciation, ice lobes of North Vidzeme and Vortsjarv were drained through Rūja, Seda, Vaike Emajogi, Ohne and Pedele subglacial valleys in the eastern and southern direction, and then through the Strenči subglacial basin to the subglacial valley of the Gauja River ("Urstrom" with minor subparallel valleys) that drained the whole territory in the SW direction.

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