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Abstract Reconstruction of glacial dynamics in the southeastern sector of the Scandinavian continental glacier indicates that the palaeo-ice streams were considerably persistent in time and space and their length depended on the width of peripheral cover of the continental glacier during retreat. Reconstruction of glacial dynamics in the southeastern sector of the Scandinavian continental glacier demonstrates that the westerly oriented parts of the glacial streams and lobes were more active than the other parts of the glacier. This is reflected in asymmetry of the eroded bedrock forms at the margins of glacial troughs and in the form of drumlins within troughs. For discussion it is proposed that the preferred rightward flow of the glacier during its movement was influenced by the Coriolis force directly or through the subglacial melt water dynamics.

Keywords *Scandinavian glaciations, late glacial processes, asymmetry of the glacial topography.*

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INTRODUCTION

The flow patterns of the southeastern sector of the Scandinavian ice sheet during the Weichselian glaciation are revealed most clearly by alternation of glacial troughs and elevated interstream and -lobate formations. Landforms and deposits associated with these troughs and elevations between them indicate that the ice sheet developed several ice-streams during the Late Weicshelian. The till deposition and preservation of the earlier deposited till dominated in interstream areas, and the interlobate heights were formed. These associations of glacially formed landscapes are found in Estonia, Latvia, northern Lithuania and northeastern Russia (Fig. 1). The area under discussion does not include the terminal zone of the last glacial maximum (LGM). The processes active in LGM were different from those in the transitional glacial flow/interflow areas, and therefore the genesis of the LGM topography will not be discussed here.

The reconstruction of the time-transgressive deglaciation (Fig. 1) is based on author's investigations and published data (Aseev 1974, Aboltinš 1975, Aboltinš et al. 1976, Znamenskaya et al. 1977, Ekman et al. 1981, Isachenkov 1981, Punkari 1993, Dreimanis & Zelčs 1995) and reflects everywhere the last active stages of various glacier lobes.

Former ideas on ice streams in the area

The late glacial history has been earlier recorded mainly by recession lines expressing positions of the glacier margin, while indication of ice flow directions was not of primary importance (Serebrjanny & Raukas 1967). As the existing end moraines and other marginal landforms are fragmented and infrequent in the southeastern sector of the Scandinavian ice sheet, different interpretations of the deglaciation have been made (summarised in: Karukäpp & Raukas 1999, p.128). The first attempts to establish ice flow directions for eastern Baltic and northeastern Russia took place in the early 1960s. Ice flow directions were reconstructed on the basis of erratic boulder distribution (Raukas 1963, Jakovleva 1966, Viiding et al. 1971), till

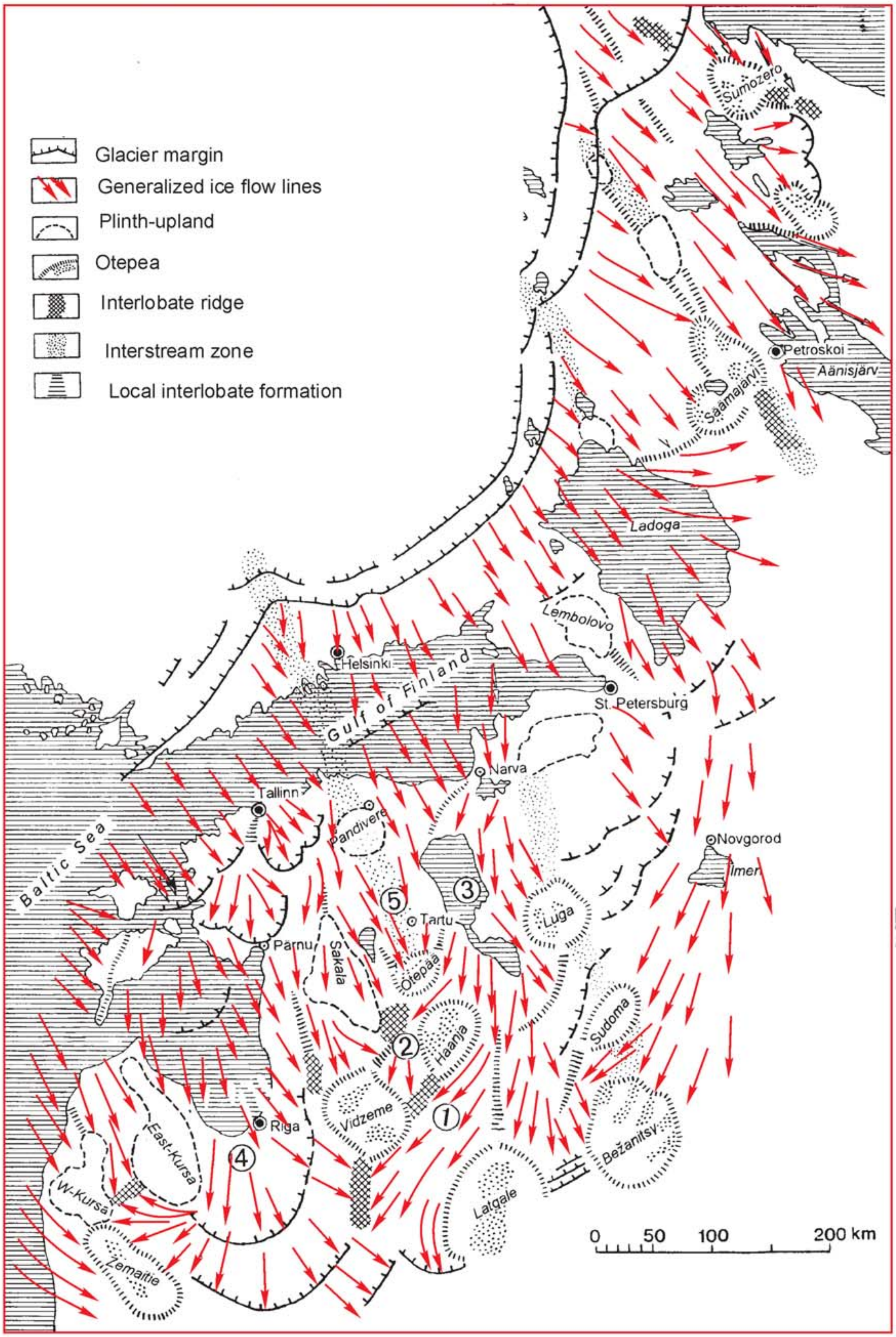

Fig. 1. Time-transgressive flowlines in the southeastern sector of the Scandinavian glaciation. Compiled by R.Karukäpp using published data by O.Aboltinš, J.Straume, I.Ekman, M.Punkari & V.Isachenkov.The numbers in circles mark the lobe depressions mentioned in text.

fabric orientation and topographic lineations, such as drumlins, flutings and erosional troughs (Raukas 1961, Basalykas 1965, Aseev 1966). In his reconstructions for the last two glaciations. Aseev (1974) depicted the ice streams as actively moving ice bodies several hundred kilometres long, and terminating as lobes. The ice streams and lobes were separated from each other by interstream and interlobate zones of various types.

The distribution fans of erratic boulders from the Baltic States are represented by almost straight and symmetrically widening flow lines (Viiding et al. 1971). For the first time, the deflection to the right for the eastern sector of the Scandinavian ice sheet was depicted by Jakovleva (1966), on the bases of the distribution of erratic boulders in northwestern Russia.

Bedrock topography and geology

The level of bedrock in the area varies from sea level up to 150 m a.s.l., but is typically at a heights less than 100 m. The composition of bedrock differs with area: lithologies more resistant to glacial erosion are represented by limestones and dolomites, whereas those easily eroded are the Palaeozoic and Mesozoic soft sandstones, siltstones and shales. However, differences in composition are not clearly reflected in the bedrock topography, and every single trough discussed below is characterized by homogeneous bedrock conditions (Karukäpp 1999).

INTERSTREAM AND INTERLOBATE ELEVATIONS

Otepeas

Against the background of flat surface topography with small absolute and relative (generally less than 100 m) heights of the East European Plain, the glacial accumulative island-like (insular) heights (*otepeas*) have a remarkable position projecting 80-200 m above their surroundings. They cover thousands of square kilometres and form submeridional systems of 2–4 heights in each (Fig. 1). The otepeas are hummocky dissected topography, separated from each other by

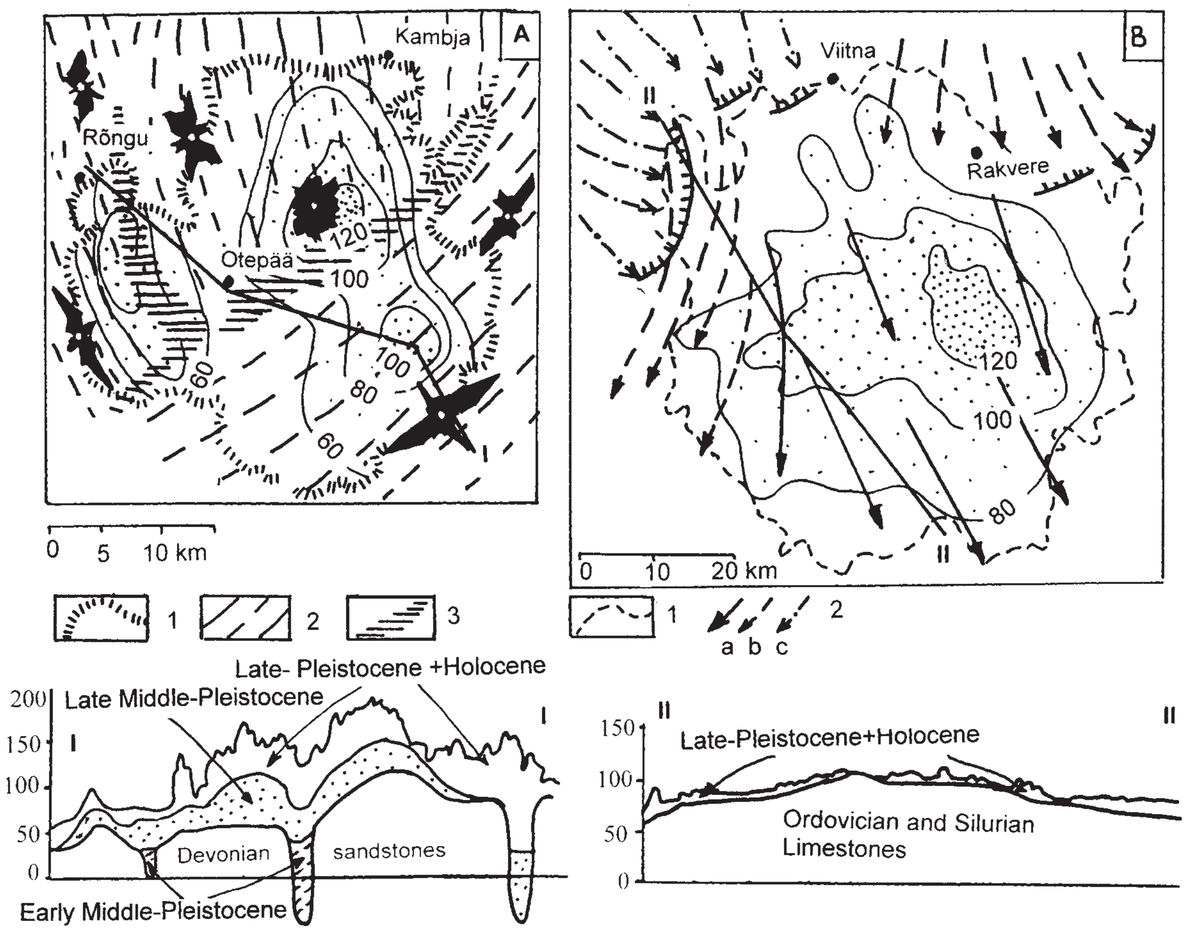

Fig. 2. Generalized flowlines for a typical otepea (A) and plinth-upland (B) on the background of bedrock topography and schematic geological cross-sections. *A: Otepää Heights.* 1–foot line; 2–flowlines (without age relationship) based on till fabric and elongated landforms orientation; 3–local interlobate junctions. *B: Pandivere Upland.* 1–foot line; 2–different generations (a, b & c, from older to younger) of flowlines show divergence in the borders of upland. Compiled by R.Karukäpp.

lowlands. Usually the otepeas have a bedrock core and Quaternary cover 100–150 m thick, composed of several till beds with related intermorainic deposits. The thickest glacial deposits are located in the central high part of the otepea. The name *otepea* is derived from the best investigated Otepää Heights in southern Estonia (Hang & Karukäpp 1979, Karukäpp et al. 1999).

The highly dissected topography of the otepeas does not display so evident a lineation pattern as the surrounding troughs, but the convergence of lineations is quite clearly traceable (Fig. 2A; Hang & Karukäpp 1979, p.61). The age relationship of the lineations is not clear.

Erosional plinth-uplands

Upflow the interstream areas are composed of bedrock uplands of glacier erosion. To differentiate them from the otepeas, these forms, with thin Quaternary cover on outstanding bedrock core, were named *plinth uplands* (Pandivere, Sakala and Kurzeme upland, Dreimanis & Zelčs 1995). These uplands rise up about to 170 m a.s.l., their relative height being about 100 m. The topography is mostly flat to undulatory. The most dissected areas are associated with glaciofluvial deposition, such as eskers and kames. The thin Quaternary sediment cover consists mainly of deposits from the last glaciation with the thickest glacial deposits found along the footline of the uplands or in ancient buried valleys. The topography of the plinth uplands has obvious lineations, which show divergent direction of the ice flow (Fig. 2B).

According to Aseev (1974), the central glacier dome was drained into peripheral areas by radially alternating ice streams and interstream areas. During the LGM the onset zone along the outer limit of central dome followed a change in the interstream belts, where ice erosion started to prevail and plinth-uplands were formed. The border between these two types of the glacial morphogenesis of the uplands coincides in general with the 0-line of postglacial glacioisostatic uplift.

TROUGHS

The erosional troughs and depressions are usually easily traceable in the bedrock surface and can be seen on topographical maps of bedrock (Tavast & Raukas 1982). Troughs, which are not buried under marine or glaciolacustrine deposits, display a lineation pattern in their glacially shaped topography. The lineation pattern, the till fabric orientation, and the distribution of erratics make the basis for reconstruction of local ice movement directions (Fig. 1).

To-the-right deflection of troughs and lobes

Analysis of trough orientation based on lineation pattern and till fabric orientation shows that they have tendency to deflect to the right from a truly radial pattern (Fig.1). As the ice sheet thinned, the subglacial topography exerted an ever increasing effect on direction of ice movement. Nevertheless, detailed investigations in Skåne (Lidmark-Bergström et al. 1991) proved that even big differences (about 250 m) in altitudes of the bedrock, oriented perpendicular to the ice movement, did not prevent the ice lobe (Low Baltic Ice) from moving to the right by 140°. The tendency for to-the-right deflection is clearly revealed by the NE—SW orientation of the local ice divide zones formed by plinth uplands and otepeas (Fig. 1). If energy of the ice movement had been equal radially in all directions, the interlobate formations would have been overwhelmingly of NW—SE orientation. Yet, they show deflection to the right along the ice flow.

Reconstruction of the glacial dynamics shows that the westerly oriented portions of the glacial lobes were generally much more active than those of any other direction. This asymmetry led to the bifurcation of the glacial streams, which took place in their right side towards the west in the form of lobes. For example (Fig. 1), the Lubane (Eastern Latvian, *1*) and Võru—Hargla *(2)* lobes branched off from the Peipsi glacial stream *(3)* and formed a distinct, radially oriented glacial topography (Karukäpp 1975). The western wing of the Central-Latvian glacier lobe *(4)* deviated from its main direction by up to 140° and moved around the Eastern

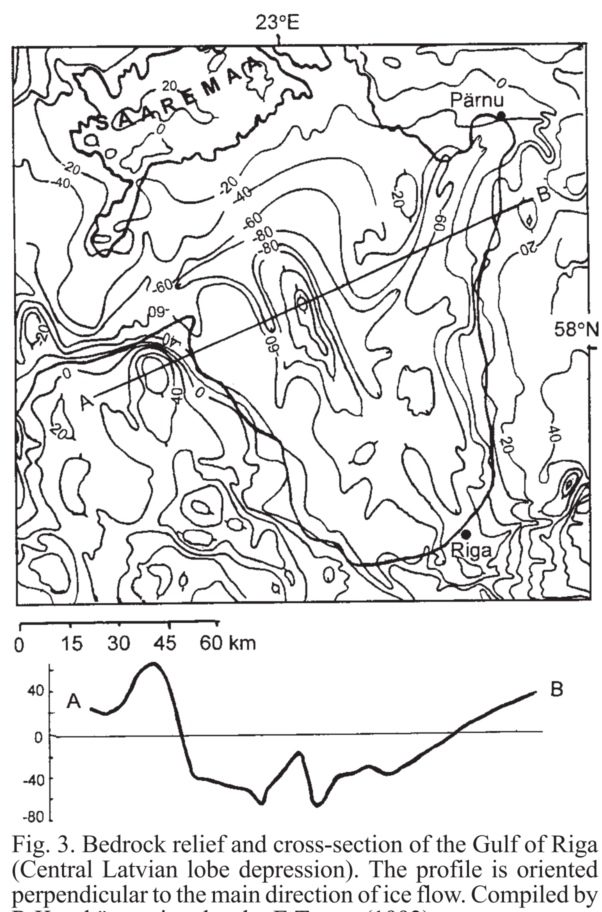

Fig. 3. Bedrock relief and cross-section of the Gulf of Riga (Central Latvian lobe depression). The profile is oriented perpendicular to the main direction of ice flow. Compiled by R.Karukäpp using data by E.Tavast (1992).

Kursa Upland towards another lobe from the depression of the Baltic Sea (Dreimanis & Zelčs 1995). At about the same time the western wing of the Baltic ice stream formed a westward-moving ice lobe (Low Baltic readvance) in southern Sweden and on the Danish Islands (Ringberg 1988).

Landform asymmetry

A number of bedrock depressions of the Eastern Baltic and particularly, Estonia which have been considered to be eroded by glacial ice, show evident asymmetry in their morphology. Analysis of the topography of the thoroughly studied Pandivere and Ahtme bedrock uplands and Toompea elevation in Tallinn, which are composed of Ordovician limestones and dolomites (Tavast & Raukas 1982) shows that their east facing slopes are steeper than those facing west. The same regularity is evident in the cross-section of the Riga lobe depression (Fig. 3) in the Devonian sandstones.

The asymmetry of erosional bedrock troughs demonstrates the asymmetry in dynamics of the ice stream as a whole. To analyse morphology within the ice stream itself, we have chosen the depression of the Gulf of Finland on the east margin of the Baltic ice stream (Fig. 4). Large drumlin-like forms, up to 90 m high and 10 km long, reveal the glacier flow direction. Coring on the Prangli Island and seismic profiling of the inner structure allow these forms to be classified predominantly as glacial erosional. The cores of drumlins contain Lower Palaeozoic sedimentary bedrock, tills of earlier glaciations, and interglacial deposits (Kajak et al. 1976, Karukäpp & Vassiljev 1992). In the area under consideration the northeastern slopes of these huge drumlins are somewhat steeper than the southwestern slopes (Fig. 4).

For comparison, the topography of a classical drumlin field from eastern Estonia? (Fig. 1) was analysed. The slopes of the Saadjärve drumlins in the central part of this field were measured (Karukäpp 1999, Fig. 5A). As the depressions between drumlins are occupied by glaciolacustrine deposits, lakes or mires, only the upper parts of the slopes are available for investigations. Nevertheless, the tendency of asymmetry of the slopes was traceable but not so evident as in the Gulf of Finland: the SW slopes of the inter-drumlin depressions are slightly steeper than NW slopes. Recently the author measured a great number of small-scale glacial landforms (drumlins and drumlinized surfaces) in Estonia and Latvia. In the low topography (1–5 m) no evident asymmetry of slopes was observed.

The results of the slope measurements showed that asymmetry is present on the erosional trough slopes and big (higher than 15-20 m) drumlins only.

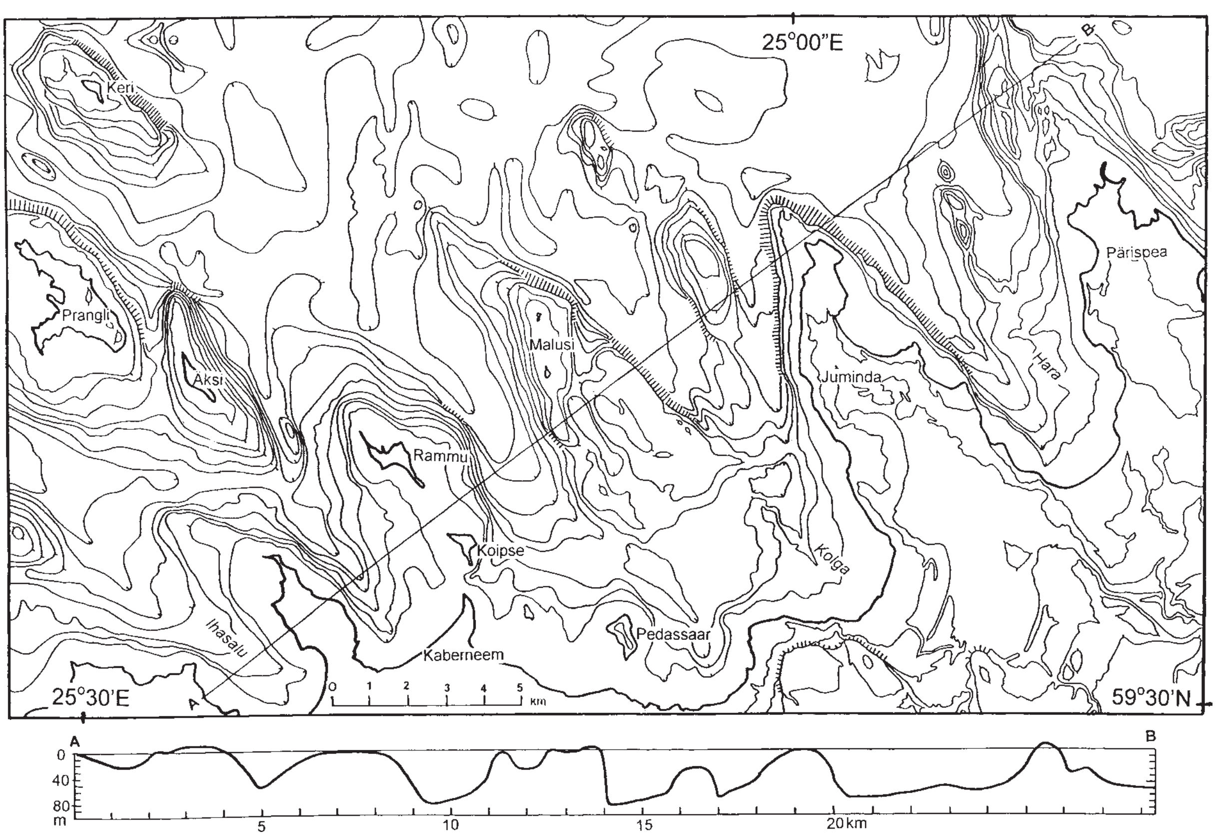

Fig. 4. Example of the bottom relief of the Gulf of Finland compiled by R.Karukäpp and J.Vassiljev. The profile A–B is oriented perpendicular to the main direction of ice flow.

DISCUSSION

Aseev (1974) suggested that radial ice streams existed at least throughout the whole post-LGM time and drained the central ice dome and fed peripheral ice cover with ice. Thus the possible length of an ice stream could have been 200–500 km and been active in the period prior to the glacial maximum up to the Salppauselkä stage, i.e., more than 5000– 6000 years.

Owing to the branching of ice streams towards the distal direction, the ice divides were not so continuous as the ice streams, but they formed chains of otepeas and plinth-uplands (Fig. 1). The structure of the otepeas indicates an inherited character from glacial accumulation through several glaciations. The surface of otepeas has a complex high hummocky topography. This may be the result of low flow velocities in interstream zones, or a frozen glacier-bed interface, as suggested by Boulton (Boulton et al. 2001). This suggests that, in general, the location of ice streams coincided with those of previous glaciations. Evidence for this is also derived from the structure of the big drumlins, the cores of which contain sediments left by more than one glaciation. For instance, in the drumlins of Saadjärv Drumlin Field two tills of Weichselian age and one of Saalian age have been identified (Rattas & Kalm 2001). But this did not exclude variations in ice flow directions within an ice stream, especially in its last – the lobate stage of life.

Landform asymmetry is related to deflection of lobes

If the glacial streams and lobes tended to deviate to the right, the effect of the glacier (erosion, transport, accumulation) on lobe depression must have been asymmetric. Most of the glacially shaped landforms of considerable size, as bedrock troughs, megadrumlins and big (more than 15 m high) drumlins show asymmetry in their cross sections: the slope, situated to the right of the ice flow direction is usually steeper than the slope to the left.

This prevailing tendency in morphology seems to support the statement according to which erosion by any moving portion of the glacier ice was more intensive to the right of its axis.

Ehlers (1990, p. 81) described the Pomeranian stage of deglaciation in northwestern Germany and called attention to the tendency of clockwise rotation of the flow lines, explaining the phenomenon with increasing control by the Baltic Sea depression. The westerly more powerful ice streams were mentioned already by Chebotareva (1969, p. 281). She explained this with increase of precipitation amount towards the West. Matoshko & Chugunny (1993, p. 145) suggested that glaciers of the Dniepr Glaciation (Middle Pleistocene) tended to curve to the right due to the Coriolis force effect.

The present author also proposed for discussion (Karukäpp 1996) the idea that the declination of glacier towards the right during its movement was due to the Coriolis force. Naturally, this does not exclude the possibility that in its sphere of influence and immediate vicinity of the Baltic depression controlled the direction of the ice movement. However, it is hard to believe that topography of the Baltic depression alone could control the great deflection of Ladoga and Onega ice flows (Fig. 1).

The possible influence of Coriolis force on glacial processes

The Coriolis force is apparent force acting on a moving object due to the rotation of the coordinate system in which the object's velocity is measured. The force is directed perpendicular to the velocity: to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere. The Coriolis effect is considered in a great variety of phenomena in which motion over the surface of the Earth is involved. It includes, in addition to rivers, air movement and streams in oceans. Caspard Gustave de Coriolis (1792-1843), the French civil engineer, did not apply his theory to any natural process.

Karl Ernst von Baer (1792-1876), the founder of embryology, was the first to publish his observations on the asymmetry of the river erosion in Russia in 1854 (see Müürsepp, 1984). At that time he had not the faintest notion of Coriolis' theory. Jacques Babinet (1794-1872) was the first to formulate (1859) correctly the regularity of river erosion that was based on mathematical calculations and Coriolis' theory. In the course of long-lasting discussions, the regularity was formulated as the *Baer-Babinet law*.

The idea that the Coriolis effect impacted glacier flow has been criticized by mathematician, Prof. Salamatin from Kazan University (unpubl. inf.), who asserted that the speed of ice movement is too slow for the Coriolis force to have a considerable effect. The ice stream directions were determined mostly by orientation of the troughs, but the morphology of the troughs of the SE sector of the Scandinavian glaciation is in its turn, mostly the result of glacial erosion – determined by the ice flow direction.

The glacier streams and lobes during the deglaciation were up to several hundred kilometres in length, active and rapidly moving. The basal temperatures were likely close to the melting point, and high water pressure was able to decouple the ice from the bed. Consequently, subglacial water might have been an important agent in the glacier dynamics and formed a favourable environment for Coriolis force influence.

CONCLUSIONS

The southeastern sector of the Late Weicshelian continental glacier left a geomorphological pattern that enables to reconstruct a system of continuous glacial streams and lobes and fragmental interstream and interlobate formations. The genesis of the latter had inherited character through several glaciations. The glacial streams and lobes of the deglaciation had considerable length (up to several hundred kilometres); they were active and rapidly moving, probably at the melting point. It is possible that the ice movement was driven by high basal water pressure sufficient for ice-bed decoupling.

The tendency of the asymmetry of the glacial morphogenesis is observable in the different scale of topography shaped by active glacier: flow lineations in the whole sector of glacier, the erosion asymmetry in a single lobe depression and prevailing slope asymmetry of landforms within a lobe depression. The reason for this phenomenon is still a topic of future investigation.

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