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XV CONGRESS

Classification and areal distribution of glaciotectonic features in Estonia

Maris RATTAS, Volli KALM

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Known glaciotectonic phenomena in Estonia were subjected to systematic analysis and mapping for the *Estonian Glaciotectonic Database and Map Project*. The available data allow classification of such features into five main categories. Ridges, hills and composite massifs composed of the Quaternary sediments appear to be the most common glaciotectonic landforms in Estonia. Glaciotectonic ridges and hills, composite massifs and sites in which the buried disturbed Quaternary sediments were estimated, are located mainly in southern and southeastern Estonia where a thickness of the Pleistocene cover varies between 50–200 m, or at the sites where they denote ice margin positions of different stadials (oscillations). Large glacial rafts of the pre-Quaternary bedrock as well as point samples of the disturbed pre-Quaternary bedrock were mapped near the North Estonian limestone escarpment and in northeastern Estonia.

Maris Rattas, Geological Survey of Estonia, Kadaka tee 80/82, EE-12618 Tallinn, Estonia; e-mail: maris.rattas@egk.ee; Volli Kalm, Institute of Geology, University of Tartu, Vanemuise 46, EE-51014 Tartu, Estonia; e-mail: vkalm@math.ut.ee *(received: January 8, 1999; accepted: March 11, 1999).*

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INTRODUCTION

It has been assumed for a long time that a rather flat topography of northern Estonia was formed under the influence of an active ice, whereas a complicated hummocky landscape of southern Estonia was formed predominantly due to a stagnant ice (K. Kajak, 1963, 1965; E. Rähni, 1963). During the last decades this assumption has been rejected and the obvious role of both active and stagnant ice in these two regions became clear (O. Āboltinš *et al.*, 1989; R. Karukäpp *et al.*, in print; A. Raukas, E. Tavast, 1994; A. Raukas, K. Kajak, 1997*b*). Although many different kinds of glaciotectonic landforms and other features, resulting from the active glacier movement, have been mentioned in literature and in unpublished reports, mapping and classification of these forms in Estonia has not been attempted until recently. In 1998 the *Glaciotectonic Map of Estonia* in scale 1:500,000 was compiled as the first result of the *Estonian Glaciotectonic Database and Map Project*, which is a part of the *Central European Glaciotectonic Database Project* (*CEGDP*). Glaciotectonic features in the Estonian database and on the map were classified according to the legend, worked out by *CEGDP*. The objective of this paper is to summarize the data on types and distribution of glaciotectonic phenomena in Estonia, obtained during this project.

GEOMORPHOLOGIC AND GEOLOGIC SETTING

Being a part of the East European Platform, Estonia has a generally flat topography where uplands and bedrock plateaus alternate with depressions, lowlands and valleys. In the continental pattern of glacial geomorphology, Estonia represents a transition zone between the area of strong erosion in the north and west, and the area of predominant deposition in the south and south-east (Fig. 1). Therefore, the study area is characterized by quite a rugged bedrock topography and uneven distribution of the Pleistocene cover. Distinct ice lobe depressions and interlobe uplands (ice-divide zones) alternate as consequence of the repeated Quaternary glaciations.

The pre-Quaternary bedrock in Estonia includes mainly the Ordovician and the Silurian limestones or dolomites (northern and northwestern Estonia), as well as the poorly consolidated Devonian siltstones and sandstones (southern

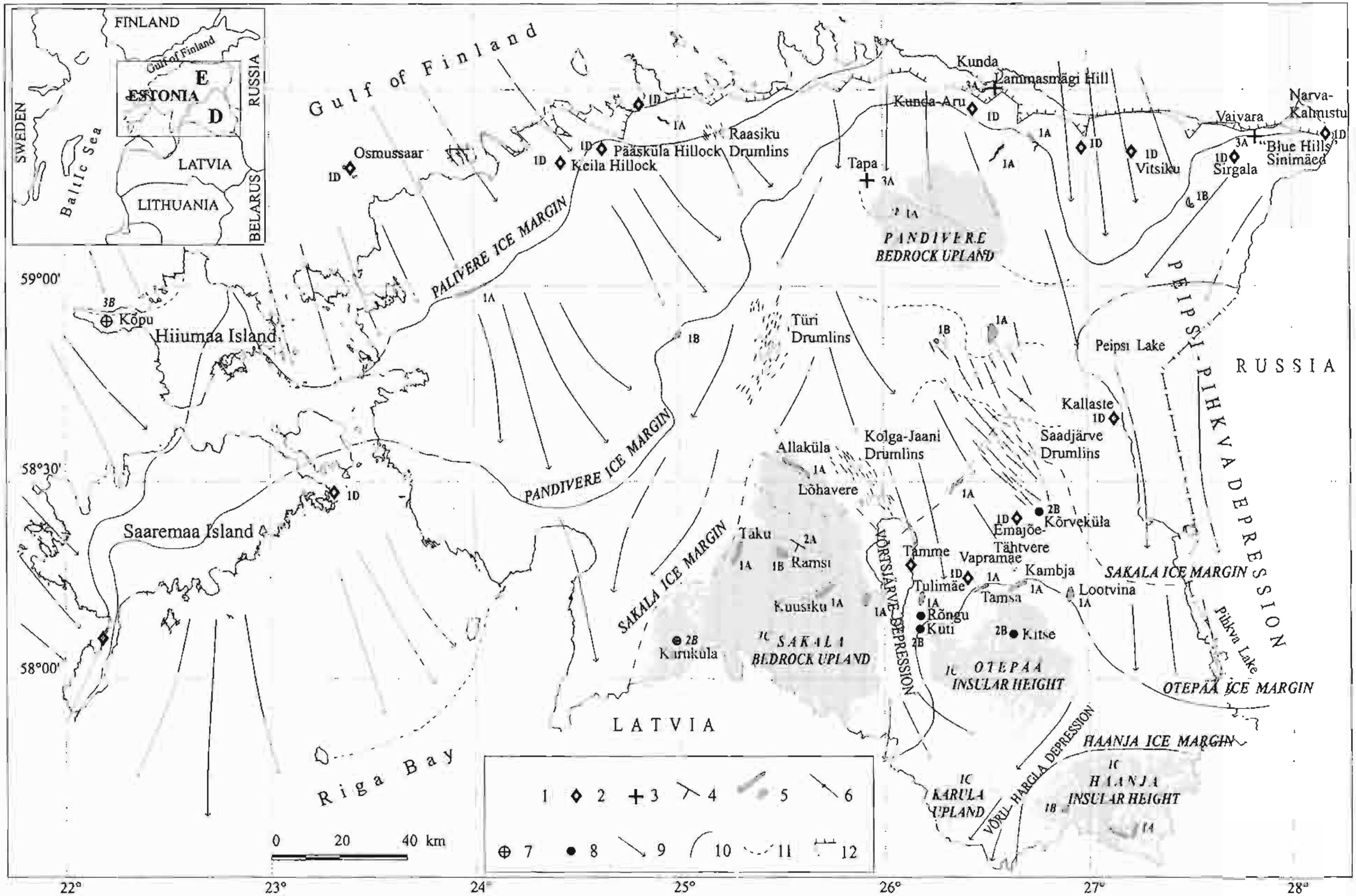

Fig. 1. Map of glaciotectonic features in Estonia (*cf.* Table 1); general location of the study area (Estonia) and approximate boundary between the areas of strong erosion (E) and predominant deposition (D)

1 — composite massifs; 2 — point samples of disturbed pre-Quaternary bedrock; 3 — large glacial raft of pre-Quaternary bedrock; 4 — buried disturbed sediments in an exposure; 5 — ridges and hills in scale; 6 — drumlins; 7 — large glacial raft of Quaternary sediments; 8 — buried disturbed sediments in a single boring; 9 — ice flow direction at a final stage of its activity; 10 — stadial limit; 11 — oscillation limit; 12 — North Estonian escarpment (Klint)

Estonia). To the north of the limestone belt and the North Estonian escarpment, along the coast of the Gulf of Finland, a narrow band of the Cambrian sandstone and clay crop out. In northern and western Estonia, on the outcrops of carbonate rocks, a thickness of the Pleistocene cover is usually less than 5 m. Occasionally it may even be lacking. The Pleistocene deposits are the thickest (50–200 m) in the Haanja and Otepää heights, in the Saadjärve Drumlin Field area and in the buried valleys of northern and southern Estonia (K. Kajak, 1995). Five tills, often considerably thick, can be recognized more or less distinctly. Only in few cases they are separated from one another by deposits of interglacial or interstadial origin, which considerably aggravates the correlation and dating of the glacial strata (A. Raukas, 1978). At present state of knowledge we assume that most different features of a glaciotectonic relief were formed during the last glaciation, i.e. the Late Weichselian. However, there are some bedrock deformations or deeply buried dislocations in the Quaternary cover, which may have survived the ice sheet advance during the last glaciation and thus, may have been formed during the earlier glaciations.

GLACIOTECTONIC FEATURES AND DATA BASE SOURCES

Previous investigations in Estonia have dealt with glaciotectonic features only as with by-effects to other glacial formations. However, in several published and unpublished studies such features have been mentioned and occasionally, non-systematically described. Data on glaciotectonic phenomena used in this project have been derived from various available sources (e.g. G. Eltermann, 1993; E. Kadastik, 1994; K. Kajak, 1963, 1964; R. Karukäpp, 1997; R. Karukäpp *et al.*, 1996; E. Liivrand, 1991; J. Lutt, A. Raukas, 1993; E. Lõokene, 1961; A. Miidel *et al.*, 1969; A. Miidel, R. Vaher, 1997; K. Orviku, 1930, 1933, 1934, 1936; V. Puura, R. Vaher, 1997; A. Raukas *et al.*, 1971; A. Raukas, 1978; A. Raukas, H. Hyvärinen, 1992; A. Raukas, Kajak, 1997*a*, *b*; A. Raukas, E. Tavast, 1994; N. Thamm, 1962; unpublished reports in archives of the Estonian Geological Survey and the Institute of Geology, University of Tartu; pers. comm. of L. Ainsaar, E. Kadastik, T. Kurvits, K. Suuroja and K. Orviku). The geographic base of the glaciotectonic map, location and distribution of different glaciotectonic features were derived from or controlled with the help of available digital basic geography, geomorphology, Quaternary geology, bedrock geology and hydrology maps.

CLASSIFICATION OF GLACIOTECTONIC PHENOMENA IN ESTONIA

In 1997, during the first meeting of the national coordinators of the *Central European Glaciotectonic Database Project* (*CEGDP*) a unified classification and legend, to be used in the all involved countries, was worked out. Applying this legend (*Central European* ..., 1997), glaciotectonic features in Estonia were classified in the following categories (see also Table 1):

— ridges, hills and composite massives built of the Quaternary sediments,

— point samples of the disturbed pre-Quaternary bedrock,

— buried disturbed sediments, non-expressed in the present landscape,

— large glacial rafts expressed in the present landscape,

— depressions associated with disturbed pre-Quaternary bedrock and sediments.

DISTRIBUTION AND NATURE OF GLACIOTECTONIC FEATURES

RIDGES, HILLS AND COMPOSITE MASSIFS BUILT OF THE QUATERNARY SEDIMENTS

Large composite massifs have clear topographical expression and consist of individual glaciotectonic landforms like hills and ridges. Accumulative insular heights, the Haanja height and the Otepää height in southeastern Estonia are the most expressive composite massifs, built of heaped and subsequently deformed glacial sediments (O. Āboltinš *et al.*, 1989; R. Karukäpp *et al.*, in print). These heights are characterized by hummocky topography and considerable thickness (50–200 m) of the Quaternary deposits. Four morphogenetic stages: subglacial, englacial, marginal accumulation and a dead ice stage were distinguished in their formation during a single glaciation (O. Āboltinš, 1989; O. Āboltinš *et al.*, 1989; R. Karukäpp *et al.*, in print). Ice-shoved hills and ridges (end moraines, marginal eskers and kames composed of disturbed morainic or waterlain sediments) are concentrated at the peripheries of the uplands (Lootvina, Kambja, Tamsa and Tulimäe push moraines on the Otepää height), as well as are denoting ice margin positions of different stadials or oscillations.

The Karula Upland in southeastern Estonia (Fig. 1) is interpreted as an interlobal formation between the Võru–Hargla and Võrtsjärve glacial streams, consisting of the 2 km long moraine ridge along a contact zone of the two ice lobes (R. Karukäpp, 1997).

On the Sakala Upland several ice-marginal positions of a retreating ice sheet were described in detail by E. Lõokene (1961). In the present landscape the ice-marginal zones are marked by interrupted chains of end moraines (Kuusiku) and marginal eskers (Allaküla–Lõhavere, Täku, Ramsi), consisting of folded and compressed glacial and glaciofluvial deposits (Fig. 1). Regardless of the only 20 m thick Quaternary cover on the Sakala Upland, number of estimated glaciotectonic features allow to classify it as a composite massif.

Another bedrock upland in Estonia, the Pandivere Upland was an area of erosion through time and the Quaternary cover is often less than 5 m thick and in some places even lacking.

Drumlins in Estonia are built of the Quaternary sediments and only occasionally have a bedrock core. They are ice-sho-

Table 1

Classification and estimated number of glaciotectonic features in Estonia (*cf.* Fig. 1)

Index on the map	Glaciotectonic features	Number of features
1A	Ridges (in scale) composed of the disturbed Quaternary sediments	16
	including drumlin fields: Saadjärve, Türi, Kolga-Jaani, Raasiku	4
1B	Hills in scale composed of the disturbed Quaternary sediments	6
1C	Composite massifs composed of the disturbed Quaternary sediments	4
1D	Point samples of the disturbed pre-Quaternary bedrock	13
	Buried disturbed sediments, non-expressed in the present landscape:	
2A	studied in exposures	1
2B	noted in boreholes or a single boring	7
	Large glacial rafts expressed in the present landscape:	
3A	of the pre-Quaternary bedrock	3
3B	of the Quaternary sediments	1
	Depressions: Võru-Hargla, Võrtsjärve, Peipsi-Pihkva, Läänemeri	4

ved ridges with crests parallel to former ice movement direction, in some cases containing several tills of varying age (A.-M. Rõuk, A. Raukas, 1989). Drumlin fields form huge crag-and-tail features, consisting of a complex of single glaciotectonically moulded ridges (drumlins, drumlinoids) with erosional depressions between them. Four drumlin fields in Estonia are located behind bedrock elevations where the glacier advanced down-slope (Saadjärve, Kolga–Jaani), or in lowland conditions in marginal areas of depressions (Türi, Raasiku) (Fig. 1).

POINT SAMPLES OF THE DISTURBED PRE-QUATERNARY BEDROCK

Major glaciotectonic deformations of the pre-Quaternary carbonate bedrock are concentrated at the limestone escarpment (North Estonian Klint) along the shore of the Gulf of Finland (Fig. 1). Some glaciotectonic features in northwestern Estonia are related to the upper surface of the Lower Cambrian clay, on the top of which separate limestone blocks of the Ordovician (Osmussaar, Narva–Kalmistu) were shifted by a pressure of active ice. According to N. Thamm (1962), the 5 km long and 1.5 km wide limestone-cored Island of Osmussaar was rotated by ice pressure 17°30' from NW to NWW as a single block of the bedrock. The Pääsküla Hillock and the Keila Hillock in northwestern Estonia, composed of the Ordovician limestone, have been probably shifted southwards along the plastic volcanic ash beds (K-bentonite) between the limestone strata (O. Hints *et al.*, 1997; pers. comm. by L. Ainsaar, 1996).

Bedrock dislocations, fracture disturbances, folds and fissures, conditioned by an active glacier, were mentioned in several exposures in limestone or oil-shale open-cast quarries, for example at Kunda–Aru, Vitsiku and Sirgala. (A. Raukas *et al.*, 1971; A. Raukas, 1978). Fracture deformations of the Devonian terrigeneous bedrock were observed in several outcrops of river valleys and lake banks of southern and central Estonia, namely at Tamme, Kallaste, Vapramäe, Emajõe–Tähtvere (Fig. 1).

BURIED DISTURBED SEDIMENTS, NON-EXPRESSED IN THE PRESENT LANDSCAPE

Deformation structures in the Quaternary sediments which have no morphologic expression in the landscape were often described in connection with buried interglacial deposits. According to E. Liivrand (1991), most interglacial sediment occurrences in Estonia form erratics in glacial deposits. Recognition of glaciotectonic dislocations in localities of interglacial deposits was possible due to a very dense net of core sections from stratigraphically important sites. Disturbed and dislocated interglacial deposits are found at Karuküla and Kõrveküla (correlated to the Holsteinian Interglacial), at Puiestee (Saalian) near Karuküla, at Rõngu, Küti and Kitse (Eemian) (Fig. 1). Positive correlation between density of drillings and frequency of dislocations suggests that glaciotectonic features, which are not expressed in the landscape, may be much more common than it has been expected until now.

LARGE GLACIAL RAFTS EXPRESSED IN THE PRESENT LANDSCAPE

Three large glacial erratic blocks of the pre-Quaternary rocks (Lammasmägi Hill at Kunda, "Blue Hills" at Vaivara and Tapa glacial raft) are expressed in the present landscape. The Lammasmägi Hill at Kunda has a core of a huge bedrock block which was dragged to a surface of glaciolacustrine deposits and, relative to its normal bedding conditions, turned in an almost vertical position. The altitude of the hill is 50.6 m, rising about 4 m above a surrounding plain (R. Karukäpp, 1997).

Bedrock blocks of the Lower Ordovician limestone, forming a core of Vaivara "Blue Hills", were broken from the edge of the North Estonian escarpment and transported 4–5 km to the south. Details of bedding, revealing clear traces of pressure, and till lenses between the folds point to the glaciotectonic character of the dislocations (A. Miidel *et al.*, 1969). At present the three elongated "Blue Hills": Tornimägi Hill (70 m), Põrguhauamägi Hill (83 m) and Pargimägi Hill (85.5 m a.s.l.) with bedrock rafts inside, form a ridge projecting above the generally flat topography with a relative height of 40–50 m. The described ridge was interpreted as a complex of glacial marginal formations (end moraines) including fractures, thrusts and rotated bedrock blocks in a proximal part and a glaciofluvial outwash plain in a distal part of the formation (A. Raukas *et al.*, 1971).

In the western part of the Hiiumaa Island a huge glacial raft of the Quaternary sediments was described in boreholes. The Kõpu moraine erratic, consisting of the older till of the Pandivere Stage (24 m thick), was pushed during the Palivere ice sheet advance to the surface of the glaciolacustrine deposits of the Pandivere Stage (G. Eltermann, 1993). In the present landscape it makes a core of the Kõpu Hill, the highest elevation (68 m a.s.l.) on the Hiiumaa Island.

Described bedrock blocks at Vaivara could have been pushed in front of the advancing ice sheet, but in other cases in Estonia the glacial rafts seem to have been dragged along in a lower part of the glacier and left behind from the ice by melting. Therefore the rafts are partly or entirely buried under deposits (at Kunda and Tapa) or known only from drilling records (on the Hiiumaa Island). The provenance of the rafts is poorly identified or unknown. Most probably they originate from the areas of only some kilometres apart from their present location.

DEPRESSIONS ASSOCIATED WITH DISTURBED BEDROCK AND SEDIMENTS

During every glaciation, Estonia was affected by the Baltic and the Peribaltic ice streams (A. Raukas, K. Kajak, 1997*b*), and areas of accumulation and erosion remained relatively stable (A. Raukas, E. Tavast, 1994). Ice lobe depressions were subjected to intensive glacial erosion and therefore served repeatedly as source areas for glacial deposits. In general, there are 4 glacial depression in Estonia: Läänemeri, Võrtsjärve, Võru–Hargla and Peipsi–Pihkva ones (Fig. 1). All the depressions are reflected also in the present-day bedrock topography. Only a few glaciotectonic features, namely bedrock deformations are known in these depressions (on the Saaremaa Island, at Tamme and Kallaste). The only exception to the mentioned conclusion is the Kolga–Jaani Drumlin Field in the northern part of the Võrtsjärve depression.

CONCLUSIONS

The quantitative summary (Table 1) provides an overall view of the distribution of different glaciotectonic phenomena in Estonia. Analysis and classification of all the data on the studied phenomena reveals that ridges built of the disturbed Quaternary sediments, including drumlins, are the most common glaciotectonic landforms in Estonia. Among the numerous bedrock dislocations, the fracture deformations prevail. Composite massifs (Otepää, Haanja, Karula and Sakala heights) are the biggest complex glaciotectonic features, have clear topographic expression and consist of individual glaciotectonic landforms. Bedrock dislocations, fracture disturbances, folds and fissures, also large glacial rafts of the pre-Quaternary bedrock are predominantly observed in the northern and central part of Estonia. Disturbed sediments of the Quaternary sediments are concentrated mainly in the areas of accumulation in southern Estonia, as well as in the sites where they denote ice margin positions of different stadials or oscillations. Positive correlation between density of boreholes and frequency of estimated dislocations suggests that glaciotectonic features, which are not expressed in the landscape or known from the outcrops, may be more common than it has been expected previously.

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KLASYFIKACJA I ROZMIESZCZENIE FORM GLACITEKTONICZNYCH W ESTONII

Streszczenie

Wszystkie dotychczas rozpoznane formy glacitektoniczne w Estonii zostały poddane systematycznej analizie i kartowaniu w trakcie opracowania *Glacitektonicznej Bazy Danych i Mapy Estonii* (fig. 1). Uzyskane materiały umożliwiły klasyfikację tych form w 5 głównych kategoriach (tab. 1). Najczęstszymi glacitektonicznymi formami rzeźby w Estonii są grzbiety, wzgórza i masywy z utworów podłoża czwartorzędu. Grzbiety i wzgórza glacitektoniczne oraz masywy i stanowiska, w których stwierdzono zdeformowane osady czwartorzędu, występują głównie w S i SE Estonii, gdzie miąższość pokrywy plejstoceńskiej wynosi 50–200 m. Stwierdzono je również w strefach marginalnych lądolodu podczas różnych stadiałów (oscylacji). Duże kry lodowcowe skał podłoża oraz stanowiska zdeformowanych utworów podłoża czwartorzędu stwierdzono w pobliżu NE kuesty wapiennej oraz w NE Estonii.